IASS/APCS 2022

September 19th - 22nd 2022

The 2022 Annual Symposium of the International Association for Shell and Spatial Structures
The 13th Asian-Pacific Conference on Shell and Spatial Structures

Innovation, Sustainability and Legacy

Edited by: Su-duo Xue, Jin-zhi Wu and Guo-jun Sun

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—— About the IASS ——

In September 1959, the leading structural engineer, Eduardo Torroja organised and convened an international colloquium on Shell Structures in Madrid. During this colloquium, Professor Torroja proposed the founding of the International Association for Shell Structures (IASS), because at the time shell structures were frequently used all over the world for a variety of programmes. He wanted to create a platform where the top engineers, designers and constructors would meet and exchange their ideas and experiences. There should be regular meetings, correspondence and a bulletin published regularly. His proposal was enthusiastically accepted by the distinguished group of designers and engineers at the colloquium, and the IASS was born with Torroja as both the inspiration and the founding president.

The IASS welcomes to membership all individuals and organisations who share its aims, with reduced rates available for students. Members receive benefits including electronic access to the journal of the IASS, the proceedings of annual symposia and reports and recommendations of IASS working groups. A comprehensive list of membership benefits and the possibility to join online are available on the IASS website: iass-structures.org.

Currently Active Working Groups

WG No.	**WG TITLE**
WG 3	Technical Expert Group on Cooling and Solar Updraft Towers
WG 4	Technical Expert Group on Masts and Towers
WG 5	Concrete Shell Roofs
WG 6	Tension and Membrane Structures
WG 8	Metal Spatial Structures
WG 12	Timber and Bio-based Spatial Structures
WG 13	Computational Methods
WG 15	Structural Morphology
WG 17	Historical Spatial Structures
WG 18	Life-Cycle Design and Assessment of Shell and Spatial Structures
WG 20	Teaching of Shell and Spatial Structures
WG 21	Advanced Manufacturing and Materials

—— About the APCS ——

The Asian Pacific Conference on Shell and Spatial Structures(APCS) was originated from the Korean-Japan Colloquium on Shell and Spatial Structures and held first time at Cheju, Korea in 1984. This colloquium was co-organized by the late Professor Yosuhiko Hangai and Professor Taek-Jin Kwun. The colloquium provided a working forum to discuss and exchange both the traditions and innovations in conception, analysis, design and construction of shell and spatial structures. The following colloquia were held alternately in Japan and Korea triennially(Tokyo, Japan 1987, Daegu, Korea 1990, Tokyo, Japan 1993).

In 1996, as an extension of the colloquium, the Asian Pacific Conference on Shell and Spatial Structures was held in Beijing, China. The name of APCS was first adopted with a prospect that such fruitful meetings be extended to Asian Pacific regions pursuing the same goal. In 2000, the 6th APCS was held in Seoul, Korea which was designated as a memorial conference dedicated to the late professor Hangai, who passed away in 1998. The 7th APCS was held in Taiwan, China in 2003. The 8th APCS was held as a joint conference in cooperation in IASS in Beijing, China in 2006. The 9th APCS was held in Nagoya, Japan in 2009. The 10th APCS was held as a joint conference in cooperation in IASS in Seoul, Korea in 2012.The 11th APCS was held in Xi'an, China in 2015. The 12th APCS was held in Penang, Malaysia in 2018.

The 13th APCS is held as a joint conference in cooperation in IASS in Beijing, China in 2022.

02 Forward from the IASS President

The International Association for Shell and Spatial Structures is delighted to have its Annual Symposium, IASS-APCS 2022, in Beijing, China, co-organized by the Beijing University of Technology, the Association for Spatial Structures of the China Steel Construction Society, and several other universities. The IASS returns to China after the very successful symposia held in Beijing (2006) and Shanghai (2010). The IASS Symposium 2022 partners with the 13th Asian-Pacific Conference on Shell and Spatial Structures (APCS), a triennial series initiated in 1984, marking the fifth time that APCS has been held in conjunction with an IASS annual symposium. The topic of the symposium is "Innovation, Sustainability and Legacy"; it fittingly reflects the fundamental lines to follow towards a better future for the next generations. Remarkably, the symposium takes place in Beijing, a city with iconic spatial structures, that has held the 2008 Summer Olympic Games as well as the 2022 Winter Olympics.

The organizing committee, led by Professors Su-duo Xue and Jinzhi Wu has done a superb work to put together a program that reflects the state-of-the-art in spatial structures. There are 18 invited lectures by international and local experts, including the newest IASS Torroja Medalist and IASS Honorary Members. The plenary lectures will cover realizations for the Winter Olympic Games and provide a panoramic of the advances in the field of spatial structures in Asia and all over the world. Around 300 technical presentations are distributed in 51 sessions shaping an intense program that has been designed to allow participants from all the world to attend the symposium online.

This year, the Association confers the IASS Torroja Medal on former IASS President, Professor Sergio Pellegrino, and names Professors John Chilton and Yeon-Bin Yang Honorary Members of the IASS. As customary, the recipients of the prestigious Tsuboi Awards 2022 will be announced during the symposium. Additionally, 2022 marks the 20th anniversary of the IASS Hangai Prize competition for participants under the age of 30, held annually in memory of the late Professor Yashuhiko Hangai. The Hangai Prize encourages students and young professionals to participate in IASS symposia, and many former recipients of the Prize are now leading experts in the field and play an active role in the Association. The winners of this year's Hangai Prize competition will be announced during the symposium and their plenary presentations will be a highlight of this symposium. To commemorate the anniversary, a message from Mrs. Hangai will be shown during the award conferral ceremony.

After the experience of the IASS 2020/21 Symposium we know that a fully virtual conference can be as successful as an in-person one, each of them having a different flavor. This year, due to ongoing COVID19 restrictions in Beijing, it has been still not possible to return to a full in-person meeting. A hybrid model, with local in-person participants and simultaneous online participants, has been carefully designed by the organizers. I am confident that this mixed model will allow us to reconnect with colleagues and friends, meet new ones and encourage new participants to join the Association.

On behalf of the IASS and of all the Symposium participants, I wish to thank all members of the organizing and scientific committees, the Beijing University of Technology and the supporting institutions, universities and companies for their inestimable contributions towards the success of the symposium. In particular, I would like to acknowledge appreciatively Professors Su-duo Xue and Jinzhi Wu for their enthusiastic efforts and successful organization of IASS-APCS 2022.

Carlos Lázaro
President of the IASS

03 Message from the Conference Chair

Since 1959, IASS conferences have been successfully held in Spain, the USA, the UK, Japan, China and other countries for more than 60 years. In 2008 and 2010, China successfully hosted the Beijing Olympic Games and Shanghai World Expo; with this background, IASS 2006 and IASS 2010 were held in Beijing and Shanghai, respectively. These conferences have given a strong impetus to the exchange and cooperation between China and its international counterparts in spatial structures.

In the past decade, the scale of constructing spatial structures in China has expanded widely, and many new large-span spatial structures have been built. In February 2022, the 24th Winter Olympic Games were successfully held in China. Some new Winter Olympic venues, like the National Speed Skating Oval (Ice Ribbon), have been constructed employing spatial structures with innovation. Besides, sports facilities built for 2008 Summer Games, like the National Stadium and the National Aquatic Center have been renovated on the legacy from 2008. Taking this opportunity, the Beijing University of Technology and the China Association for Spatial Structures started careful planning and gained approval to hold IASS symposium in Beijing from the Executive Council of IASS in 2018. During the 2019 IASS Executive Council meeting in Spain, I reported the preparation for the symposium. It was agreed that the symposium should be co-hosted by the Beijing University of Technology and the China Association for Spatial Structures and with the confirmation of the proposed theme, dates, venue, schedule and cost of the conference. In addition, it was also confirmed that the 13th Asian-Pacific Conference on Shell and Spatial Structures (APCS) would be combined with IASS annual symposium in Beijing.

Due to the influence of the Covid-19 pandemic, IASS 2020 was postponed, and IASS 2020/2021 was held in the UK as an online conference. The conference we initially proposed was also postponed to 2022. Considering the situation of the pandemic, IASS/APCS 2022 will be held both online and in person. This is a challenging step, and we would like to thank Carlos Lázaro, President of the IASS, and Makoto Ohsaki, the conference coordinator, for their valuable guidance and advice for organizing this conference. We would also like to thank the Advisory Committee, the Academic Committee and the Organizing Committee for their support, including reviewing the abstracts and papers, recommending outstanding papers and planning the conference.

With the theme of "Innovation, Sustainability and Legacy", the conference includes 18 plenary lectures (7 for APCS), 51 parallel sessions with 275 presentations, 364 conference papers, and a technical tour of the National Speed Skating Oval. The conference aims to provide a high-level platform for experts, scholars and engineers from all over the world and to promote the technological progress of international spatial structures. We look forward a successful complete of the conference and we hope you enjoy IASS/ACPS 2022.

Su-Duo Xue
Chair of Scientific Committee and Organizing Committee

04 Plenary Sessions

Program of IASS/APCS 2022

Date/ Time	8:30	8:45	9:00	9:15	9:30	9:45	10:00	10:15	10:30	10:45	11:00	11:15	11:30	11:45	12:00	12:15	12:30
Mon, 19 Sep.	Registration of Participants in Beijing Friendship Hotel														Lunch		
	14:30	14:45	15:00	15:15	15:30	15:45	16:00	16:15	16:30	16:45	17:00	17:15	17:30	17:45	18:05	18:15	18:30
	Co Chairs: Ruy Pauletti & Jinzhi Wu			Chair: Ken'ichi Kawaguchi				Co Chairs: Makoto Ohsaki & Mike Xie									
	Conference Opening - BJUT President welcome, IASS President Welcome, Conf. Chair Welcome	IASS TAC Chair Address: Sigrid Adriaenssens		Awards Conferrals: Torroja Medal; IASS Honorary Membership x 2; Tsuboi Prize(s) x 2; Hangai Prize(s) x 4; Message from Mrs. Hangai		Coffee Break 30 minutes		Plenary Lecture 1 Su-Duo Xue: Cable-supported Structures Recently Built in China		Plenary Lecture 2 John Chilton:My Journey through Spatial Structures		Plenary Lecture 3 Yeong-Bin Yang: Invariant Isogeometric Formulation for Buckling Analysis of Spatial Curved Kirchhoff Rods		Hangai Prize Lecture 1 Yao Lu: A Method for Designing Multi-layer Sheet-Based Lightweight Funicular Structures	Welcome reception		

Date/ Time	8:30	8:45	9:00	9:15	9:30	9:45	10:00	10:15	10:30	10:45	11:00	11:15	11:30	11:45	12:00	12:15	12:30
Tue, 20 Sep.	Co Chairs: Su-duo Xue, Seung-Jae Lee & Tetsuo Yamashita						Coffee Break 30 minutes		Co Chairs: Toru Takeuchi & Jingyao Zhang								
	Plenary Lecture 4 (APCS) Yuanwen OuYang: Research on Key Technology and its Application in Large-span Aluminium Spatial Structures		Plenary Lecture 5 (APCS) Ken'ichi Kawaguchi: History and Present of Early Reinforced Comcrete Shell Domes in Japan		Plenary Lecture 6 (APCS) Jat Yuen Richard Liew: Design, Fabrication and Erection of Long Span Spatial Steel Structures				Plenary Lecture 7 (APCS) Kok Keong Choong: Saloma Link Footbridge - A New Iconic Footbridge in Kuala Lumpur, Malaysia		Plenary Lecture 8 (APCS) Feng Fan: New Progress of Research on Roof Snow Load for Long-span Structures		Plenary Lecture 9 (APCS) Guoxing Lu: Impact Behaviour of Origami Structures and Materials		Plenary Lecture 10 (APCS) Seung-Jae Lee: Development Quantum-based Q-HS Algorithm for Weight Optimization of Truss Structures		Lunch
	14:30	14:45	15:00	15:15	15:30	15:50	16:00	16:20	16:30	16:45	17:00	17:15	17:30	17:45	18:00	18:15	18:30
	Co Chairs: Carlos Lázaro & Alireza Behenejad																
	Plenary Lecture 11 Sergio Pellegrino: Inventing Giant Lightweight Structures		Plenary Lecture 12 Jieming Ding: Mechanics and Aesthetics in the Structural Design of Long-span Pedestrian Bridges		Plenary Lecture 13 Sigrid Adriaenssens: Geometry, Mechanics and Building Forms		Hangai Prize Lecture 2 Kanata Warisaya: Freeform Auxetic Mechanisms Based on Corner Connected Tiles	Coffee Break 25 minutes		Parallel Sessions: S01~S06 S01: Projects and material of tension & membrane structures (WG6-1) S02: Realized Metal Projects (WG8-1) S03: Concepts for Sustainable Innovation in Construction of Timber and Bio-based Spatial Structures -1 (WG 12-1) S04: Computational methods for spatial structures and collapse (WG 13-1) S05: Sustainable Heritage: Challenges and Strategies in the Preservation and Conservation of 20th Century Historic Concrete Shells-1 (WG17/WG5-1) S06: Aluminum Alloy Structure- 1						Dinner	
	20:00	20:15	20:30	20:45	21:00	21:15	21:30	21:45	22:00	22:15	22:30	22:45	23:00	23:15			
	Parallel Sessions: S07~S12 S07: Masts and Towers (WG4) S08: ETFE Film Applications (WG6-2) S09: Buckling of Metal Spatial Structures - 1 (WG8-2) S10: Concepts for Sustainable Innovation in Construction of Timber and Bio-based Spatial Structures -1 (WG 12-2) S11: Optimisation Methods (WG 13-2) S12: Advanced Manufacturing and Materials, 3D-Printing and Molding-1 (WG21-1)						Coffee Break 15 minutes	Parallel Sessions: S13~S18 S13: Retractable and Other Tension Structures (WG6-3) S14: Connection Design of Metal Spatial Structures (WG8-3) S15: Concepts for Sustainable Innovation in Construction of Timber and Bio-based Spatial Structures -3 (WG 12-3) S16: Advanced Manufacturing and Materials, 3D-Printing and Molding-2 (WG21-2) S17: Innovation in New Concepts and Projects -1 S18: Disaster Prevention and Mitigation of Spatial Structures-1									

Date/ Time	8:30	8:45	9:00	9:15	9:30	9:45	10:00	10:15	10:30	10:45	11:00	11:15	11:30	11:45	12:00	12:15	12:30
Wed, 21 Sep.	Parallel Sessions: S19~S23 S19: Dynamic Performance and Seismic Response of Metal Spatial Structures -1 (APCS, WG8-4) S20: Cable structures (WG6-4) S21: Designing Structures with Computational Methods (WG 13-3) S22: Form-Mobility Relationship: the Study of the Interdependency of Structural Geometry and Transformability (WSG15-1) S23: Life-Cycle Design and Assessment of Shell and Spatial Structures (WG18)						Coffee Break 30 minutes		Parallel Sessions: S24~S28 S24: Pneumatic Structures-1 (APCS, WG6-5) S25: Mechanical Properties and Health Monitoring of Metal Strucures (WG8-5) S26: Optimisation, Form Finding and Parametric Design (WG15-2) S27: Snow and Ice Engineering (WG21-3) S28: Aluminum Alloy Structures - 2						Lunch		
	14:30	14:45	15:00	15:15	15:30	15:50	16:00	16:15	16:30	16:45	17:00	17:15	17:30	17:45	18:00	18:15	18:30
	Co Chairs: Qilin Zhang & M. Mollaert																
	Plenary Lecture 14 Zhongyi Zhu: Roof Cable Structure Design of Lusail Stadium (the Main Venue of FIFA World Cup Qatar 2022)		Plenary Lecture 15 Stefan Lehnert: Latest Applications of the ETFE Technology Perils and Opportunities		Hangai Prize Lecture 3 Jiaming Ma: PrintNervi – Design and Construction of a Ribbed Floor System in the Digital Era	Coffee Break 25 minutes		Parallel Sessions: S29~S34 S29:Future Challenges in the Design and Construction of Shell Structures for Low or Zero Carbon - 1 (WG5-1) S30: Pneumatic Structures-2 (WG6-6) S31: Buckling of Metal Spatial Structures - 2 (WG8-6) S32: Computational Methods for Additive Manufacturing and Origami (WG13-4) S33: Prototyping: Physical and Virtual Model Making and Fabrication (WG15-3) S34: Teaching of Shell and Spatial Structures facilitating Innovation, Sustainability and Legacy (WG20)						Dinner			
	20:00	20:15	20:30	20:45	21:00	21:15	21:30	21:45	22:00	22:15	22:30	22:45	23:00	23:15			
	Parallel Sessions: S35~S40 S35: Mechanical Behavior of Tension Structures (WG6-7) S36: Dynamic Performance and Seismic Response of Metal Spatial Structures -2 (WG8-7) S37: Computional Methods for Shell Design and Geometrical Methods (WG13-5) S38: Geometry: Describing and Controlling (complex) Geometry, Including Parametric Design (WG15-4) S39: Sustainable Heritage: Challenges and Strategies in the Preservation and Conservation of 20th Century Historic Concrete Shells-2 (WG17/WG5-2) S40: Innovation in New Concepts and Projects - 2						Coffee Break 15 minutes	Parallel Sessions: S41~S45 S41: Tensegrity Structures (WG6-8) S42: Graphical Methods and Funicular Structural Design (WG13-6) S43 :Form-Force Relationship: The Study of the Interdependency of Structural Geometry and Mechanical or Kinetic Behaviour (WG15-5) S44: Sustainable Heritage: Challenges and Strategies in the Preservation and Conservation of 20th Century Historic Concrete Shells-3 (WG17/WG5-3) S45: Disaster Prevention and Mitigation of Spatial Structures-2									

Date/ Time	8:30	8:45	9:00	9:15	9:30	9:45	10:00	10:15	10:30	10:45	11:00	11:15	11:30	11:45	12:00	12:15	12:30
Thu, 22 Sep.	Technical tour [National speed skating oval]														Lunch		
	14:30	14:45	15:00	15:15	15:30	15:45	15:55	16:15	16:30	16:45	17:00	17:15	17:30	17:45	18:00	18:15	18:30
					Co Chairs: Su-duo Xue & Ken'ichi Kawaguchi												
	Parallel Sessions: S46~S51 S46: Future Challenges in the Design and Construction of Shell Structures for Low or Zero Carbon - 2 (WG5-2) S47: Dynamic Behavior of Tension & Membrane Structures (WG6-9) S48: Dynamic Performance and Seismic Response of Metal Spatial Structures -3 (WG8-8) S49: Concepts for Sustainable Innovation in Construction of Timber and Bio-based Spatial Structures -4 (WG12-4) S50: Computational Methods for Membranes and Tensegrity (WG13-7) S51: Innovation in New Concepts and Projects - 3				Coffee Break 25minutes		Hangai Prize Lecture 4 Kazuki Hayashi: Assembly Sequence Optimization of Spatial Trusses Using Graph Embedding and Reinforcement Learning	Plenary Lecture 16 Fang Zheng: Integral Design of Form, Structure & Environment for China National Speed Skating Oval		Plenary Lecture 17 Mike Xie: Generalized Topology Optimization for Architectural Design		Plenary Lecture 18 Carlos Lázaro: Lightweight Structures with Fiber-reinforced Concrete		IASS Future Events	IASS/APCS 2022 -Summing Up Conference Closing		Farewell dinner

05 Plenary Lectures

CABLE-SUPPORTED STRUCTURES RECENTLY BUILT IN CHINA

Su-Duo Xue

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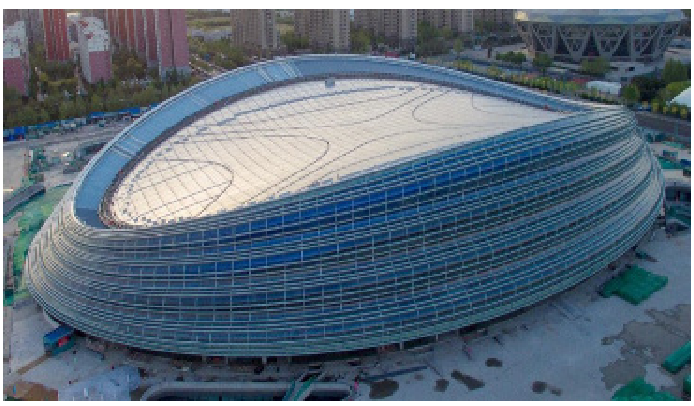
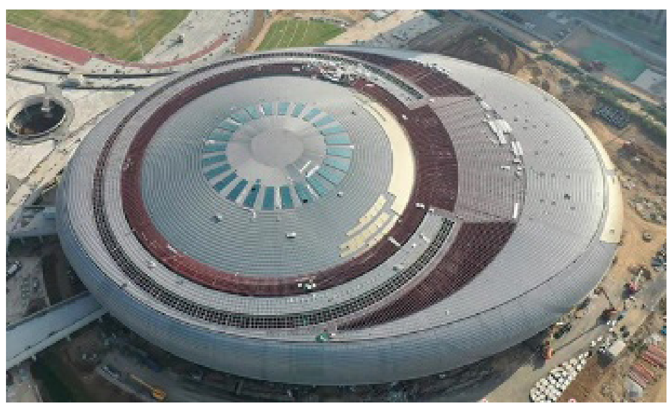
Su-Duo Xue is a professor at Beijing University of Technology and the President of China Association for Spatial Structures. He received his PhD degree from the Hong Kong Polytechnic University. He is the Chair of the IASS/APCS 2022 conference in Beijing. Professor Xue is a current member of the IASS Executive Council and co-chair of Working Group 8 on Metal Spatial Structures. He is a member of the Editorial Committee of the Journal of the IASS, a member of the Editorial Board of International Journal of Space Structures. He also holds following academic positions in China: member of the Standing Council of China Steel Construction Society (CSCS), member of Expert Committee of CSCS, Vice Chairman of Spatial Structures Committee of China, and Chairman of Membrane Structures Committee in China. His research interests are in the areas of shell and spatial structures, earthquake engineering, and structural vibration control. He has published 8 books, obtained more than 50 patents, published over 300 technical papers and received 5 national academic awards.

INTRODUCTION

Cable supported structure is one of the major types of spatial structures. In recent years, with the holding of large sports events, cable supported structures have been mainly applied into stadiums and gymnasiums in China. In this lecture, four types of cable supported structures, including cable net structure, cable dome, wheel-spoke cable structure and suspen-dome, will be introduced. The innovation, development and engineering practice of cable-supported structures recently built in China are presented. First, the cable net structure for the National Speed Skating Oval, which was built for the main venue of Beijing 2022 Winter Olympic Games, is introduced. Second, cable domes for the Gym of Tianjin University of Technology, Tianquan Gymnasium in Ya’an, and the cable dome with large opening for Fenghuangshan Stadium in Chengdu are presented. Third, recent engineering practices of wheel-spoke cable structures in China are illustrated, such as Zaozhuang Stadium, Suzhou Olympic Sports Center Stadium, Zhengzhou Olympic Center Stadium, Sanya Stadium, Dalian Suoyuwan Football Stadium, and others. Finally, details for the suspen-dome of Lanzhou Olympic Sports Center Indoor Stadium and the loop-free suspen-dome for the Gym of Ouhai Olympic Sports Center are presented.





MY JOURNEY THROUGH SPATIAL STRUCTURES

John Chilton

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John Chilton is Emeritus Professor of Architecture & Tectonics, in the Department of Architecture & Built Environment, at The University of Nottingham. His research interests span lightweight and non-conventional structures, sustainable construction and history of engineering construction.
He is a long-standing member of the International Association for Shell and Spatial Structures (IASS), member of the Executive Council from 1998 to 2020 and, currently, the Advisory Board. Reflecting his research interests, he is a member of Working Groups 5: Concrete Shell Structures, 15: Structural Morphology and 17 Historical Spatial Structures. He chaired WG 12: Timber and Bio-based Spatial Structures from 1998 to 2015. From 2001 to 2004 he was a Scientific Coordinator for TensiNet, an EU-funded Thematic Network, contributing to the European Design Guide for Tensile Surface Structures (2004). He was a Vice-Chair of the TensiNet Association (2006-2017) and contributor to the Design Recommendations for ETFE Foil Structures (2013).
He has published books on Space Grid Structures (1999); Heinz Isler (2000); Timber Gridshells: Architecture, Structure and Craft (2016) with co-author Gabriel Tang. His latest book Michael Balz: Shells and Visions is in press.

INTRODUCTION

The lecture will tell how my interaction with IASS since I attended my first symposium in Osaka, in 1986, to present my research into the ‘CUBIC’ Space Frame (CSF), has influenced my research and contributions to the field over more than 35 years - and vice versa.

It will describe my PhD research into the ‘CUBIC’ Space Frame system, supervised by its inventor Leszek Kubik, and how this led to my introduction to the IASS ‘family’ in Osaka, my attendance at the 30th Anniversary IASS Symposium in Madrid, in 1989, and my presentation of a paper on the 170 m x 100 m CSF roof at Stansted Airport - a project I was involved with at the time - for the IASS symposium in Copenhagen, in 1991. In Madrid I first met Heinz Isler. This meeting renewed my interest in shell structures, dormant since my undergraduate studies, and led to my writing a book describing his work, a subject I am still researching to this day.

The lecture will also describe my research into reciprocal frame structures, initiated by Graham Brown - who coined the name now adopted internationally. In Copenhagen, I had participated in the initial meeting of IASS WG15 Structural Morphology Group (SMG) and presented research on reciprocal frames, including built examples in timber, at the 2nd SMG Seminar, in Stuttgart, in 1994. There I was ‘persuaded’ to organize the SMG3 colloquium, held in Nottingham, in 1997. SMG3 was attended by the then IASS President Stefan Medwadowski, who appointed me as chair of WG12 Spatial Wood Structures (at that time), the following year. WG 12 activities, including colloquia in Surrey (2002) and Istanbul (2009), prompted research into gridshell architecture which resulted in a book on timber gridshells, co-authored with Gabriel Tang.

A third area of research that will be described is that of the environmental performance of lightweight membrane and ETFE structures. Participation in the EU-funded Thematic Network TensiNet resulted from a casual meeting at the IASS symposium in Sydney in 1998.
Finally, research into historic shell structures, undertaken since ‘retirement’ in 2016, will be presented. This is related to the sustainability and legacy themes of this symposium and my membership of WG5 Concrete Shell Roofs and WG17 Historical Spatial Structures.

INVARIANT ISOGEOMETRIC FORMULATION FOR BUCKLING ANALYSIS OF SPATIAL CURVED KIRCHHOFF RODS

Yeong-Bin Yang

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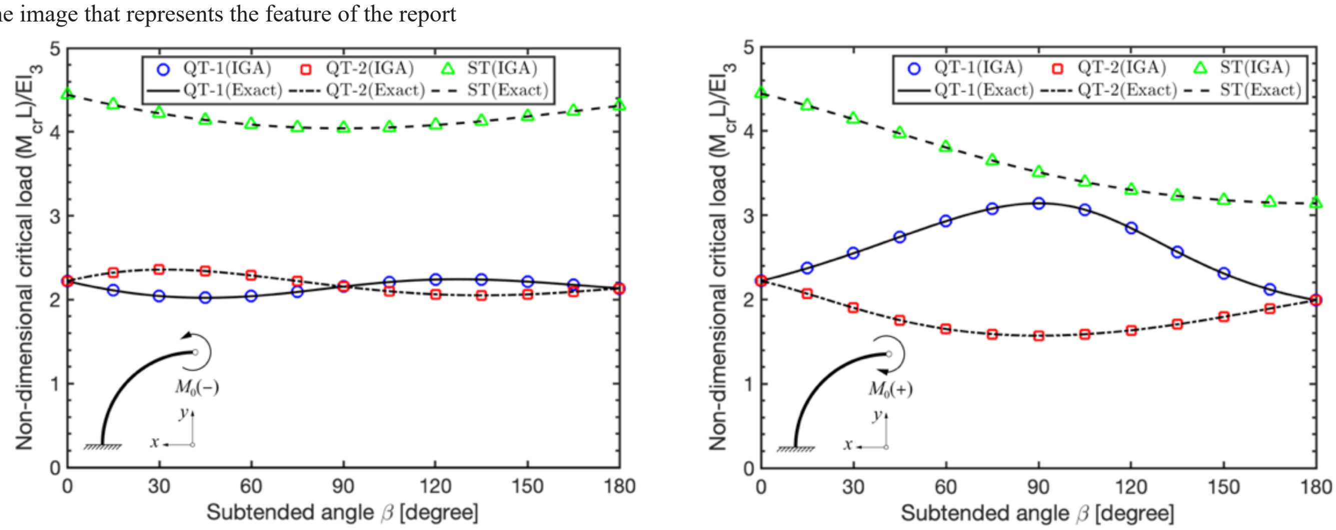
Professor YB Yang, received his Ph.D. from Cornell University in1984. He is the Honorary Dean of the School of Civil Engineering, Chongqing University, Academician of the Chinese Academy of Engineering, Foreign Member of the Austrian Academy of Sciences, Member of the EU Academy of Sciences, Editor-in-Chief of the International Journal of Structural Stability and Dynamics (IJSSD), former President of the Asian-Pacific Association of Computational Mechanics (APCOM), and former Chairman of the International Steering Committee, East Asia-Pacific Conference on Structural Engineering and Construction (EASEC). He has published more than 290 academic papers, and his Google Scholar citation has reached 13,700 times with an h-index of 58.

INTRODUCTION

This paper presents an invariant isogeometric formulation for the geometric stiffness matrix of spatial curved Kirchhoff rods considering various end moments, i.e., the internal (member) moments and applied (conservative) moments. There are two levels of rigid-body qualification, one is on the buckling theory of the rod itself and the other on the isogeometric formulation for discretization. Both will be illustrated. Based on the updated Lagrangian formulation of three-dimensional continua, the rotational effect of end moments is naturally included in the external virtual work done by end tractions without introducing any definition of finite rotations. Both the geometric torsion and curvatures of the rod are considered without any approximation to the centroidal axis. The geometric stiffness matrix for internal moments is consistent with that of the geometrically exact rod model with its rigid-body quality demonstrated. For structures rigorously defined for the deformed state, the geometric stiffness matrix after global assembly is always symmetric, for both the internal and external moments. By adopting the invariant isogeometric discretization following our previous work, a series of numerical examples, including the cases of external conservative moments, angled joint and complicated spatial geometry, were solved for buckling analysis, by which the reliability of the geometric stiffness matrix derived is verified via comparison with the analytical or straight beam solutions.

One image that represents the feature of the report



(a) (b)

Fig. 7. Non-dimensional critical loads for lateral buckling of a cantilevered arch under end moments: (a) positive; (b) negative.

RESEARCH ON KEY TECHNOLOGY AND ITS' APPLICATION IN LARGE-SPAN ALUMINIUM SPATIAL STRUCTURE

Yuanwen OUYANG

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Yuanwen OUYANG, professorate senior engineer, Chairman of Shanghai Jianke Aluminium Structure & Engineering Research Institute, founder & CEO of Shanghai Tongzheng Construction Technology Group. His main research direction includes aluminum structure, light large-span structure, solutions of complicated architectural surface's system, etc. Over the years, Ouyang has completed 38 national, provincial and all levels scientific research projects, participated 22 national, local and industrial technical standards, published 67 papers, won 20 awards at provincial and ministerial levels and other levels, such as ' Second Prize for Shanghai Science and Technology Progress Award ' and ' First Prize for Sichuan Science and Technology Progress Award '.Ouyang presided over the completion of many major projects of scientific research and construction implementation, such as Nanjing Usnisa Palace, Beijing Daxing Int' Airport Terminal, Shanghai G60 Science and Technology Cloud Gallery.

INTRODUCTION

The lecture presents the latest development of key technologies and its' application in large-span aluminium spatial structure in China. Aluminium has been favorably utilized by designer in terms of its superior architectural performance and engineering properties. The high-strength Aluminium Alloy has outperformed other conventional structure materials in large span structure as it's light weight, recyclable and durable. Aluminium Structural members are fully prefabricated by digitalized manufacturing process, integrable in structure system.

The latest research topics in large-span aluminium spatial structure can be categorized into the following fields:
1. R&D of higher strength aluminium alloy and aluminium structural profiles.
2. R&D of new structural connection type and new hybrid structural system.
3. Application of integrated complex facade systems with aluminium spatial structure.
4. Prefabrication and digitalized manufacturing process of aluminium structural components.
5. Implementation of latest aluminium design standards.
6. R&D on the fire safety performance of aluminium structure.
7. Life cycle carbon analysis of aluminium structure (building).

The lecture further showcases how these research outcomes have made possible for some structural marvels to be constructed in China, such as the Nanjing Usnisa Palace, Shanghai G60 Cloud Gallery and Shanghai World Expo Botanic Garden.

Fig. 1 Nanjing Usnisa Palace

Fig. 2 Shanghai G60 Science and Technology Cloud Gallery

HISTORY AND PRESENT OF EARLY REINFORCED CONCRETE SHELL DOMES IN JAPAN

Ken'ichi Kawaguchi

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Dr. Ken'ichi Kawaguchi is a professor in the Institute of Industrial Science, the University of Tokyo. He is currently serving as one of the vice presidents of IASS and the chair of WG6, tension and membrane structures. He is also one of the founders of IASS Hangai Prize. He is a board member of SEWC and a vice president of AIJ. After he attended IASS symposium in 1988, he became a member of IASS for a long time. He started his academic carrier in theoretical and numerical study of kinematically indeterminate structures using generalized inverse. He also works for practical structural design and development of seismic devices, such as tension truss system, a world first typical tensegrity structure, new faculty building for engineering Dept. in the University of Tokyo, new seismic base-isolation systems, etc. All of them have been really constructed and used. He has kept warning the danger of accidental fall of ceilings in large public spaces since Kobe earthquake in 1995 and promoting lighter ceiling material, which has been getting popularity in Japan, especially after the East Japan earthquake in 2011. Some of his new research topics are "collaboration with plant-physiologists", "digital archive and analysis of large spatial structures" and " historical shells in Japan".

INTRODUCTION

More than sixty years has passed since foundation of IASS and its publications, proceedings of symposia, bulletins and journals are rich repositories of records of development of spatial structures in worldwide scale. However, the structures of earlier time were not necessarily well documented nor well-known. Some of the earliest structures are more than hundred years old and still exist. In the lecture, general historic view of early spatial structures in Japan is briefly reviewed. Then some examples of early reinforced concrete shells, such as Gokokutou in Kasuisai, Nicholai-do (Holy Resurrection Cathedral in Tokyo), Meiji Memorial Picture Gallery and Imabari Radium Hot Spring, and their current situation will be reported. This study is a part of ongoing research with Kazutaka Uemura(Ken Nagasaka Engineering Network), Kenji Oka (Japan Cultural Heritage Consultancy) and Yangyang Li (Graduate school of the university of Tokyo) [1].

Figure 1: Gokoku Tower in Kasuisai

Figure 2: Imabari Radium Hot Spring

Reference
[1] K.Kawaguchi et al. "A Preliminary Study of Early Reinforced Concrete Domes in Japan (Part 1-2)", proceedings of AIJ annual meeting (in Japanese), (pp. 753-756), 2019.9.

DESIGN, FABRICATION AND ERECTION OF LONG SPAN SPATIAL STEEL STRUCTURES

J Y Richard Liew

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Department of Civil & Environmental Engineering
National University of Singapore

Prof Richard Liew is currently the head of the Department of Civil and Environmental Engineering at the National University of Singapore. He is a Professional Engineer in Singapore, a specialist professional engineer in protective security engineering. He is a Fellow of the Academy of Engineering Singapore, an Honorary Fellow and the Past President of Singapore Structural Steel Society. Prof Liew is a world-renowned expert of advanced analysis of tall buildings and long-span structures with special focusses on robustness and hazard assessments including the effects due to fire, blast and impact loads. He has authored and co-authored six books and published over 400 technical papers. He received several research and design awards, including the research leadership award from NUS in 2020, best research paper prize from Institution of Structural Engineers, UK in 2017, and the Structural Excellent Award from the Hong Kong Institute of Engineers in 2013. He is a key person responsible for the development of Singapore's codes of practices for steel structures and steel-concrete composite structures.

INTRODUCTION

This lecture presents the design, fabrication and erection of three long span spatial steel structures in Singpaore. The National Stadium roof, at 310m span, is the world's largest free-span dome made of tubular trusses. The moveable roof provides shade and cooling when required and shelter from rainfall. The conservatory structures at the Gardens by the Bays showcase the finest climate-controlled glasshouses that enable plants from around the world to thrive in the tropics. The conservatory structure, spanning up to of 170m, have a unique geometry which is realised by gridshell structure supported by steel arches. Finally, a mixed-use complex at Jewel Changi Airport in Singapore consists of glass roof structure with an oculus, covering an area of 200m x150m, supported by 14 tree-like columns and a ring beam at its edges. It features the world's tallest indoor waterfall which is surrounded by a terraced forest setting. This lecture presents the design issues, fabrication, and erection technologies to construct these beautiful and dynamic spatial structures. These structures have unique shapes and complex joint details which were challenging to fabricate and assemble, and thus special efforts were needed to detail the joints and provide supporting structures for safe construction. The projects, besides being grand, were developed with thoughtful plan to merge with the immediate environments they inhabited. This was made possible with the cooperation of designers and contractors sharing knowledge and working as a team to ensure successful transformation of innovative design to successfully completed projects of architectural and structural marvel.

SALOMA LINK FOOTBRIDGE-A NEW ICONIC FOOTBRIDGE IN KUALA LUMPUR, MALAYSIA

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Choong Kok Keong is currently a professor at the School of Civil Engineering, Universiti Sains Malaysia which is located in the state of Penang in Malaysia. Professor Choong's research interest is in the area of computational analysis of shell and spatial structures. Among research topic studied is application of ideas from nature and other suitable source of inspiration for the forms for shell and spatial structures. Apart from that, Professor Choong also collaborates with industry on the evaluation of structural dynamics of structures, form determination of space frame structure and long term outdoor performance of membrane material. Professor Choong is a professional engineer registered with the Board of Engineers Malaysia.

INTRODUCTION

The structure of the footbridge called Saloma Link(Figure 1), a latest addition to cityscape of Kuala Lumpur, the capital of Malaysia will be presented. Saloma Link is a footbridge designed and constructed to connect a part of Kuala Lumpur called Kampung Baru which are populated with traditional Malay houses with Kuala Lumpur City Center where the well-known Petronas Twin Tower is located. The structural concept of the 69 m span steel footbridge will be presented together with the idea behind the overall appearance of the bridge (Figure 2). Challenges faced during construction of Saloma Link footbridge which crosses over a river and a busy highway will be described together with solution adopted to overcome them.

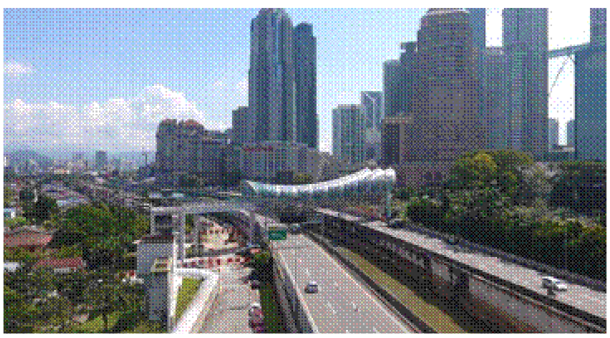

Figure 1: The Saloma Link Footbridge linking traditional and modern parts of Kuala Lumpur

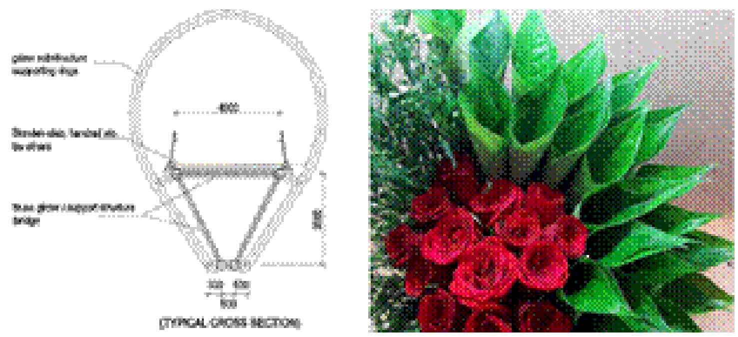

Figure 2: The typical cross-section of Saloma Link Footbridge and the inspiration behind the bridge appearance

NEW PROGRESS IN RESEARCH ON ROOF SNOW LOAD FOR LONG-SPAN STRUCTURES

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Prof. Feng Fan, the Changjiang Distinguished Professor, the recipient of National Science Foundation for Distinguished Young Scholar, the vice-principal of Harbin Institute of Technology, the director of Key Lab of Structures Dynamic Behavior and Control of the Ministry of Education, and the chief structural engineer of Chinese national science project “Five-hundred-meter Aperture Spherical radio Telescope (FAST)”, who has been engaged in the research in the realms as diverse as the wind and snow loads of the long-span spatial structure, the static and dynamic stability of the long-span spatial structure, the seismic performance and the failure mechanism of the long-span spatial structure under the strong earthquake, the innovative study and application of the long-span spatial structure, the mechanism of resistant blasting and impacting, and key technologies of structural analyses of the FAST. And has won awards including but not limited to the Second Award of the Second Prize of State Scientific and Technological Progress, the China Youth Science and Technology Award, and the Zhan Tianyou Civil Engineering Award.

INTRODUCTION

Roofs in cold regions with heavy snowfalls could experience unbalanced or non-uniform snow loads caused by snow drifting or sliding, which could cause significant damage or collapse to the roof. The unbalanced snow load patterns recommended by the Chinese design code have been calibrated several times, but documents to support such codifications are unclear. Besides, the provisions are mainly specified for regular-sized roofs but not long-span space roofs. With the growing of applications of long-span space roofs in recent years in China, there are practical demands for investigations of unbalanced snow loads on them since such investigations are rarely available. Therefore, an investigation of the unbalanced snow loads on roofs, especially for long-span space roofs, is warranted. This lecture summarizes some of the research activities on this subject at Harbin Institute of Technology (HIT). Firstly, relying on the advantages of low temperature and snowy climate in Harbin, the snow distribution of various full-size and scaled roofs has been measured and studied for 12 years. A large number of detailed data about the distribution characteristics of roof snow and meteorological conditions have been obtained and been successfully applied to the revision of Chinese load code. Secondly, based on the traditional multiphase flow theory, an innovative mixture numerical approach was developed and applied to the study on wind-induced snow drift on building roofs. The snow particulate property, snow drift process, and the melting & recrystallization process of roof snow caused by building heating and sunshine were studied by using the proposed approach. Finally, a set of wind-snow joint test system was independently developed, a similarity criterion of wind-snow joint test was proposed, and a large number of studies were carried out on snow distributions for different kinds of roofs. Furthermore, a new special facility, i.e., Simulator of Natural Action of Wind-Rain-Heat-Snow for Space Structures, has been built to more comprehensively consider the drifting, melting and recrystallization processes of roof snow.

Fig. 1 Field measurements of snowdrifts on roofs

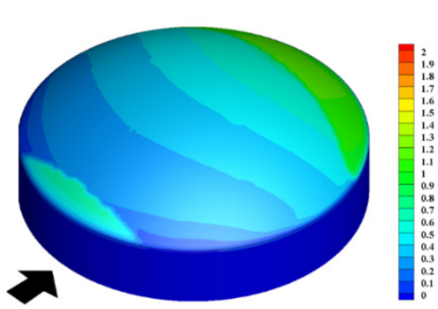

Fig. 2 Numerical simulations of snowdrifts on roofs

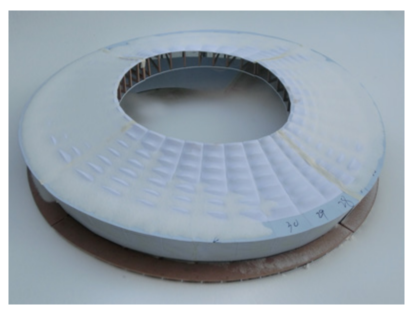

Fig. 3 Wind tunnel tests of snowdrifts on roofs

IMPACT BEHAVIOUR OF ORIGAMI STRUCTURES AND MATERIALS

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INTRODUCTION

This presentation introduces energy absorption and impact response of origami inspired structures and metamaterial, which we have recently studied. Several examples of incorporating the concepts of origami will be presented. They include thin-walled structures under axial loading, Miura metamaterials (Fig 1) and its variations under quasi-static and dynamic compression and origami sandwich panels under quasi-static loading and ballistic impact.

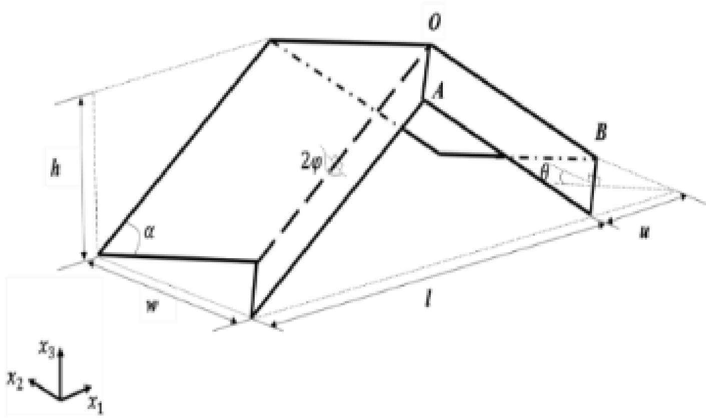
Responses of such materials and structures involve large plastic deformation as well as dynamic effects. For metamaterials, analytical models have been developed to describe the strength and energy absorption capacity in three directions. It is assumed that the base material is ductile and can be approximated as a perfectly-plastic material. The analytical model is verified by the numerical simulations as well as quasi-static compression test of a four-sheet origami specimen. The strength of the such materials is shown to vary as a function of initial folding angle of the units, from being very strong in two directions to similar strength in all the three directions. This demonstrates that the relative strength of such metamaterials can be tuned by changing geometrical parameters of the units only.

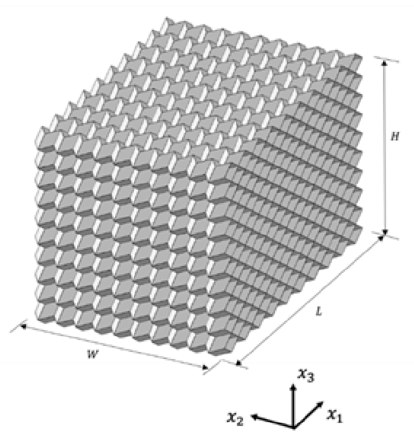
Response of such material under impact loading is also investigated and a shock model is proposed for high velocity impact. In this model, localised plastic deformation occurs first around the impact end while the remaining material does not deform. This plastic shock front then propagates progressively and dissipates energy. The dynamic impact force is composed of two parts, the corresponding quasi-static force and a second term proportional to velocity squared, describing inertia effect.

The analytical solution is able to predict the average impact force compared with the detail finite element analysis results.

Finally, response of an origami sandwich panel under bending is studied. Experiments and finite element analysis are first conducted, in terms of force-displacement curves and hence energy absorption. Based on the detailed experimental observations, a collapse mechanism is idealised with plastic hinge lines. Energy balance approach is employed again and the complete force-displacement curve can be obtained analytically.

The studies demonstrate that origami can be a valuable inspiration for designing structures and materials with desirable mechanical properties.





INVENTING GIANT LIGHTWEIGHT STRUCTURES

Sergio Pellegrino

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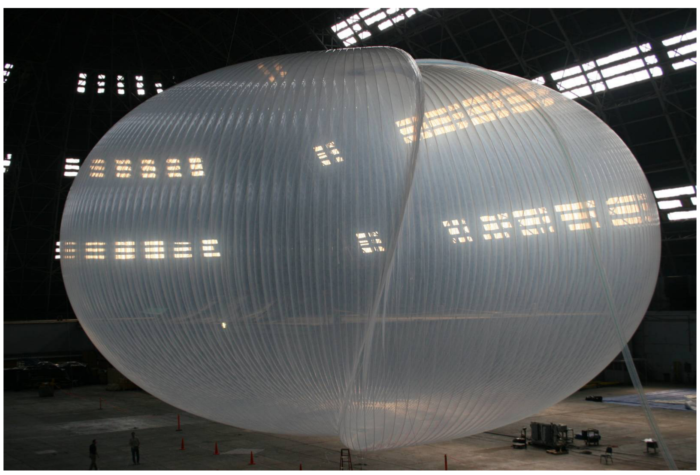
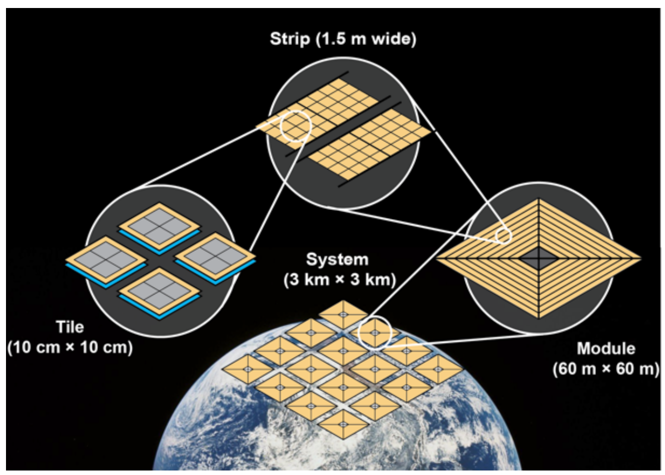
Sergio Pellegrino is the Joyce and Kent Kresa Professor of Aerospace and Civil Engineering at the California Institute of Technology, JPL Senior Research Scientist and Co-Director of the Space Solar Power Project. He is Past President of IASS and Fellow of the Royal Academy of Engineering and the American Institute of Aeronautics and Astronautics. He has developed new concepts for deployable reflector and antenna structures, solar arrays, and ultralight space solar power spacecraft. He has pioneered analytical, numerical and experimental methods that capture the complex behavior of these structures during packaging and deployment, as well as their behavior when fully deployed. These advances have allowed the adoption and further development of new structural concepts in the form of new industry products that have featured in flight missions. He has authored over 350 publications, including the textbook Forms and Concepts for Lightweight Structures (with Koryo Miura) published by Cambridge University Press in 2020 and has received 13 patents for his inventions.

INTRODUCTION

Novel lightweight structures have been a key enabler of many recent space missions and have also allowed reductions in mass and cost to be achieved. As we look forward to future missions, we need to ensure that the further advances promised by the next generation of structural concepts will in fact be realized. While it would be impossible to chart ahead of time the specific path to be followed for the design of structures yet to be invented, there is much that can be learned from recent structures that have broken new ground. This lecture will discuss the basic characteristics of successful high-performance deployable structures. It will be argued that there is a common thread that is applicable to concepts of all kinds. Two specific examples are shown below.



Scaled model (30 m diameter) of NASA superpressure balloon (Courtesy of NASA BPO)



Kilometer-scale Caltech space solar power system concept

MECHANICS AND AESTHETICS IN THE STRUCTURAL DESIGN OF LONG-SPAN PEDESTRIAN BRIDGES

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Professor Ding Jiemin is the Chief Engineer of Tongji Architectural Design (Group) Co., Ltd., a Ph.D. supervisor of structural engineering at Tongji University, a National Engineering Survey and Design Master, a national first-level registered structural engineer, a senior registered structural engineer in British Royal Institution of Structural Engineers, 2017 'Lifetime Honorary Membership' of the Structural Engineers World Congress, the winner of the 2018 Gold Medal Award of the British Institution of Structural Engineers, the winner of the 2019 CTBUH Fellow of the Council on Tall Buildings and Urban Habitat.
Throughout his career, Professor Ding has demonstrated dedication to scientific research and excellence in structural engineering design. He specializes in steel structures, super high-rise buildings and long-span complex structural systems.
Professor Ding has participated in the edition of many national and industry standards, and won nearly 100 design awards. He has published more than 200 academic papers in domestic and international journals. And he has been authorized to 6 invention patents and 13 utility model patents.

INTRODUCTION

With the rapid development of urbanization, the importance of pedestrian bridges is increasing. In recent years, the emergence of new technologies, such as new lightweight and high-strength materials, parametric design technology, and 3D printing construction, has greatly advanced the development and innovation of pedestrian bridges. Commonly used structural systems of pedestrian bridges include beam bridges, arch bridges, cable-stayed bridges, suspension bridges, and some hybrid structure bridges. Unlike building structures, the key points of a pedestrian bridge design include vertical pedestrian load, horizontal wind load and vibration comfort level.

People are increasingly pursuing the expression of urban landscape and bridge aesthetics, pedestrian bridges are developing in the direction of novelty, large-span, light weight and more flexibility. Bridge structure design needs to consider the relationship between mechanics and aesthetics, adhering to the principles of "green, artistic, economical, and applicable". This report selects several typical cases of the reporter's designed projects, then introduces the design thinking of balancing aesthetics and mechanics in the selection of pedestrian bridge structures, and discusses the key design points of pedestrian bridge structures, including structural force distribution, vibration comfort level, wind tunnel testing, construction process, etc.

Silk Bridge in Hangzhou, China

GEOMETRY, MECHANICS AND BUILDING FORMS

Sigrid Adriaenssens

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Sigrid Adriaenssens's research interests lie in the mechanics of large-span structural surfaces under extreme loading and under construction. She has been working on a comprehensive framework with advanced analytical formulations, numerical form finding and optimization approaches, fluid/structure interaction and machine learning models and algorithms to open new avenues for accelerated discoveries and automated optimal designs. In terms of applications, she has used this framework to successfully innovate structural and architectural systems ranging from macroscale adaptive shading shell devices to large-scale storm surge membrane barriers. In 2021, she was named Fellow of the Structural Engineering Institute of the American Society of Civil Engineers (ASCE), elected vice-president of the International Association of Shell and Spatial Structures (IASS), and received the DigitalFUTURES Matthias Rippmann Award (Tongji University, China) and the Pioneers's Award (Spatial Structures Research Centre of the University of Surrey, UK). In 2018 she received the ASCE George Winter Award. She chairs the ASCE Esthetics in Design Committee as well as the IASS Concrete Shell Roofs Working Group. She is the co-editor of the International Journal of Space Structures and directs the Form Finding Lab at Princeton University, where she teaches courses on (non-)linear mechanics of solids and slender structures, structural design and the integration of engineering and the arts.

INTRODUCTION

By 2050, 70% of the world's population will live in cities. Structural engineers envision, design and construct structures that those city dwellers depend on daily. The construction industry is one of most resource-intensive sectors, and yet our urban infrastructure continues to be built in the massive tradition in which strength is pursued through material mass. In contrast, we, at the Form Finding Lab at Princeton University, have focused our research on structural systems that derive their performance from their curved shape, dictated by the flow of forces. As a result, these structures can be extremely thin, cost-effective, and have a smaller carbon footprint. Our core research question is 'What is the relationship between form and efficiency in civil-scale structures?'. Large-span shells, membranes, and rod networks exhibit fascinating mechanical behaviors because geometric nonlinearities arise even when their material properties are linear. Their shape and topology give them properties beyond what is possible with conventional structural systems. We outline how we discovered, studied, designed and even built large-scale structural surfaces that can efficiently carry extreme loading, self-assemble, adjust their stiffnesses, elastically shift from one shape to another, or amplify motion.

Figure 1 self-centering Lightvault (architect magazine)

ROOF CABLE STRUCTURE DESIGN OF LUSAIL STADIUM (THE MAIN VENUE OF FIFA WORLD CUP QATAR 2022)

Zhu Zhongyi

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Dr. Zhu Zhongyi is a Professor-level Senior Engineer and a National Master of Engineering Design and Geotechnique Investigation. He is the Chief Engineer of Beijing Institute of Architectural Design and has been devoted to the research and design of the long-span structures. He has been in charge of the structural design and research of more than 30 large long-span projects, including the active reflector's primary supporting structure of the Five-hundred-meter Aperture Spherical radio Telescope (FAST), the Terminal Building of Beijing Daxing International Airport, the main venue of the FIFA World Cup Qatar 2022. He has been awarded several honorary titles such as the Beijing Scholar, the Outstanding Engineer and the National Model Worker.

INTRODUCTION

This lecture focuses on the roof structure design of Lusail Stadium, the main venue of FIFA World Cup Qatar 2022 which will be held from November to December this year. The stadium can accommodate as many as 92400 spectators and will host a series of matches including the final. The stadium roof has a saddle shape and spans a distance of 278m while the height difference between the highest and lowest points on its periphery is only 15.565m. Cable structure with PTFE membrane cladding is required to be used in the roof to achieve an architectural effect of lightness and transparency. The design of the long-span roof structure is the most challenging work in the whole stadium design mainly due to the flat roof geometry and the adoption of cable technology. This lecture presents the key issues and the corresponding solutions in the roof cable structure design, including the structural system arrangement, the form-finding of the triple-layer cable structure, the shape and prestress control considering boundary deformation, and the cable connection design. A number of technological innovations are involved in the design work, which not only successfully tackle the problems in the design of Lusail Stadium but also can be applied to other similar projects to realize more precise shape and prestress control for cable structures.

LATEST APPLICATIONS OF THE ETFE CLADDING SYSTEMS: OPPORTUNITIES AND RISKS OF A STATE OF THE ART BUILDING TECHNOLOGY

Dr. Stefan Lehnert

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Doctor Stefan Lehnert is Managing Director of Vector Foiltec GmbH Germany. Development of industrial quality welding equipment for flouropolymer foils including ETFE in parallel to developing the TEXLON® roofing systems and the optimizing of the structural engineering approaches towards ETFE foils. This work has paved the way for the adoption of ETFE as a building material worldwide.
2009: Structural analysis of one layer ETFE foil systems.
2006: Development of engineering strategies to combine structural cable nets with ETFE cladding systems.
2002: Revisions of wind load models for ETFE cladding systems.
2001:Development of production systems, welding equipment, scientific based structural engineering advances and the erection technologies for ETFE roofing systems.

INTRODUCTION

To cover the world's need of construction and at the same time to achieve sustainability - and CO 2 reduction goals requires new approaches for architectural concepts and for the demand of innovative building materials. Specific weight comparisons between ETFE and Glass transparent claddings show how efficient ETFE claddings and ETFE specific structures are if designed right.

ETFE foil cladding systems offer the unique combination for building large span structures with energy efficient climate control options with a material with very little specific embodied energy. Ecology at its best.

The material properties of ETFE though ask for new approaches to engineering and evaluating building safety which differ considerably from traditional building materials such as wood, glass or steel.

The most important characteristics of ETFE will be explained such as

Longevity
UV transparency and UV resistance
Self-cleansing properties
High elasticity
Advantageous fire behavior

The elasticity of ETFE has a lot of advantages concerning longevity and safety but at the same time can be a trap for snow – and water ponding which needs to be taken into account when designing ETFE systems and structures for ETFE.

Some graphs and pictures explain in more detail the engineering consequences of the high elasticity especially when it comes to snow – and water ponding and the dangers of the ponding issues.

Several different options and proposals will be presented as solutions to water – and snow ponding issue and the related advantages and disadvantages will be discussed with picture based examples how these solutions work.

A series of project examples prove will show to the auditorium that poor or insufficient engineering will lead to poor projects which endanger the technology. On the other hand, some interesting project photo documentation of most recent projects and insights into the Vector Foiltec Future Lab will also show the current state of the art and visions for the ETFE Technology.

INTEGRAL DESIGN OF FORM, STRUCTURE & ENVIRONMENT FOR CHINA NATIONAL SPEED SKATING OVAL (ICE RIBBON)

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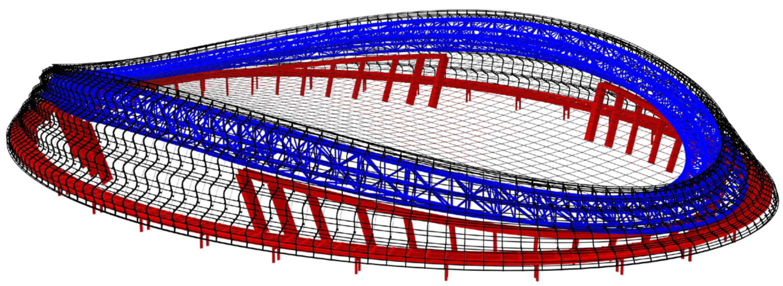
Prof. Dr. Fang Zheng, is the chair professor in School of Architecture and Design, Beijing Jiaotong University, China 1st class registered architect, and senior member of China Society of Architecture. He is the principal architect of 7 Olympic venues, including the Speed Skating Oval (the Ice Ribbon) and the Curling Venue (the Ice Cube) for Beijing 2022, and National Aquatics Center (the Water Cube), National Tennis Center etc. for Beijing 2008. He won 2 IOC/IAKS Sports Building Awards in 2009 and China Youth Scientist Award, Young Architect Award. He also designed many other long span sports venues in China and skyscrapers in Shenzhen Qianhai (New China Life Insurance Headquarter, 192M) and Dongguan (Transit Headquarter, 249M).

INTRODUCTION

China National Speed Skating Oval (the Ice Ribbon) is the only new venue built for Beijing 2022 Winter Olympic Games. It turned to be "the fastest ice" since speed skaters broke 10 Olympic records and 1 world record during the Games. The design concept is to create a compact volume to accommodate the huge 400 meter long track ice rink. The geometry of the whole building is defined by the integral design of form, structure and environment. The double curved form of the saddle roof follows the dynamic shape of the spectator stand with high performance of the widespan cable net structure. The thickness of the structure itself is only 0.2m and by this design we reduced the volume of this enormous interior space, saving the energy for cooling, air conditioning and dehumidification. Outside the competition hall, there are spectator lounge all around, wrapped by curved glass facade. The ribbons are the support structure of the façade, as well as the sunshade for the interior space. The cables support the façade grid structure work together with the roof net system.



GENERALIZED TOPOLOGY OPTIMIZATION FOR ARCHITECTURAL DESIGN

Yi Min 'Mike' Xie

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Professor Xie has been an active participant of IASS symposia since 2015 and will be co-chairing IASS 2023 in Melbourne. Currently he is an Australian Research Council Laureate Fellow and a Distinguished Professor of Royal Melbourne Institute of Technology (RMIT) where he directs the Centre for Innovative Structures and Materials. His team pioneered the evolutionary structural optimization (ESO) and bi-directional evolutionary structural optimization (BESO) methods, which have been widely used by architects and engineers and applied in many real projects. He is a Fellow of the Australian Academy of Technology and Engineering. His research impact in the field of structural optimization has been recognized by the 2017 AGM Michell Medal and the 2017 Clunies Ross Innovation Award. In 2019, he was appointed a Member of the Order of Australia, for 'significant service to higher education, and to civil engineering'. In 2020, he was awarded the Victoria Prize for Science and Innovation. Professor Xie has co-authored two research monographs (published by Springer and Wiley in 1997 and 2010, respectively) and over 300 journal articles, which have attracted more than 24,000 citations in Google Scholar. His team won the DigitalFUTURES World 2020 Coding Award for developing the widely used topology optimization software, Ameba. Recently Professor Xie received the 2022 Sir John Holland Civil Engineer of the Year award.

INTRODUCTION

In recent years, topology optimization has become a popular strategy for creating elegant and innovative forms for architectural design. However, the use of existing topology optimization techniques in practical applications, especially for large-scale projects, is rare because the generated forms often cannot satisfy all the design requirements of architects and engineers.

This lecture will point out the limitations of commonly used assumptions in topology optimization and highlight the importance of having multiple solutions. We show how these limitations could be removed and present various techniques for generating diverse and competitive structural designs that are more useful for architects. Unlike conventional topology optimization, we may include load and support conditions as additional design variables to enhance the structural performance substantially. Furthermore, we demonstrate that varying the design domain provides a plethora of opportunities to achieve more-desirable design outcomes.

A recent bridge design using topology optimization (by Prof. Xie's team in collaboration with T.Y. Lin International)

LIGHTWEIGHT STRUCTURES WITH FIBRE-REINFORCED CONCRETE

Carlos Lázaro

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Carlos Lázaro is PhD in Structural Mechanics, Professional Civil and Structural Engineer and Associate Professor of Structural Mechanics at the Civil Engineering School of the Polytechnic University of Valencia (Universitat Politècnica de València, Spain). He works in the field of lightweight and flexible structures, bridge engineering, and computational mechanics, and has carried out designs of fibre-reinforced thin concrete shells, steel spatial structures, movable structures for solar energy generation, towers and bridges. He is currently leading and participating in research and technology transfer projects on bending-active lightweight GFRP and UHPFRC footbridges, optimisation of composite bridges, design of Hyperloop viaducts, and vibration mitigation in long-span bridges. He received the Pioneers' Award from the Spatial Structures Centre of the University of Surrey in 2021 and is President of the International Association for Shell and Spatial Structures (IASS) since 2021. Dr Lázaro has authored or co-authored over 70 publications and is a member of the editorial committee of the Journal of the IASS and the International Journal of Space Structures.

INTRODUCTION

This lecture presents two different projects of lightweight structures using fibre-reinforced concrete. The first project is a recreation of Felix Candela's famous "Los Manantiales" hypar shell in Xoximilco (Mexico). The Oceanogràfic restaurant roof is considered to be Candela's last built project. It was built in Valencia (Spain) in 2000. The major challenge was to remain true to the principles that guided Candela's building philosophy: in particular, to build the thinnest possible concrete shell, with one-layer mesh reinforcement, allowed by the code in force. The key to build the lightest possible shell and comply with the code was to use fibre-reinforced concrete that provided the required bending strength, improved ductility and smeared cracking. This shell is one of the first examples of use of fibre-reinforced concrete in architectural shell construction. The second project has a very different character: it is an experimental small footbridge with a bending-active ultra-high performance fibre-reinforced concrete (UHPFRC) deck built using the bending-active principle. The aim of the project is to explore the possibility to use this material for bending-active members, i.e. to pre-bend slender UHPFRC members to improve the shape of the structure. The footbridge prototype follows the bending-active bow-string concept. It has a span length of 5.4 m and is composed of a thin UHPFRC prestressed upper slab, a UHPFRC deviator and lower stainless-steel tensioning cables. The upper slab has been bent in the longitudinal direction to achieve the desired structural configuration. The prototype takes advantage of the capacity of UHPFRC to resist traction and bending with microcracking in service conditions. Some lessons learnt from Felix Candela's procedures and works will be presented, and the advantages and drawbacks of using fibre-reinforced concrete will be discussed.

06 Hangai Prize 2022 Winners

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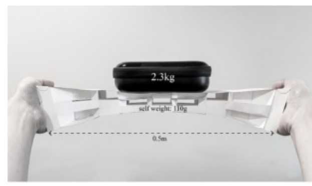
Paper ID:302

A Method for Designing Multi-layer Sheet-Based Lightweight Funicular Structures

Yao Lu, Thamer Alsalem, Masoud Akbarzadeh

Multi-layer spatial structures usually take considerable external loads with very limited material usage at all scales, and Polyhedral Graphic Statics (PGS) provides a method to design multi-layer funicular polyhedral structures. The structural forms usually materialized as space frames. Our previous research shows that the intrinsic planarity of the polyhedral geometries can be harnessed for efficient fabrication and construction processes using flat-sheet materials. Sheet-based structures are advantageous over the conventional space frame systems because sheets can provide more load paths and constrain the kinematic degrees of freedom of the nodes. Therefore, they can take a wider range of load compared to space frames. Moreover, sheet materials can be fabricated to complex shapes using CNC milling, laser cutting, water jet cutting, and CNC bending techniques. However, not all sheets are necessary as long as the load paths are preserved, and the system does not have kinematic degrees of freedom. To find a reduced set of faces, this paper incorporates and adapts the matrix analysis method to calculate the kinematic degree of freedom of sheet-based structure. Built upon this, an iterative algorithm is devised to help find the reduced set of faces with zero kinematic degree of freedom. To attest the advantage of this method over bar-node construction, a comparative study is carried out using finite element analysis. The result shows that, with the same material usage, the sheet-based system has improved performance than the framework system under a wide range of loading scenarios.



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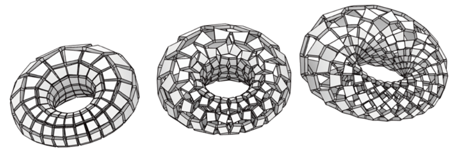
Paper ID:358

Freeform auxetic mechanisms based on corner-connected tiles

Kanata Warisaya, Jun Sato, Tomohiro Tachi

Auxetic mechanisms based on corner-connected polygonal tiles have been used to design deployable structures and are currently applied to programmable surfaces. However, existing surface structures are realized by compliant kirigami, and the realization with rigid-body mechanism, in particular with thick panels, is still limited to configurations with global symmetries due to the mechanism's overconstraining nature. In this study, we generalize the auxetic mechanisms into freeform surfaces by imposing local symmetries on polyhedral surfaces. From the discussion of kinematics, we show that polyhedral surfaces whose edges coincide with a Voronoi diagram of points on the surface can be converted to kinematics systems of corner-connected kinematic tiles. We propose the hard constraints to ensure the Voronoi property required for the kinematics and soft constraints to attain a large expansion ratio. Then, we provide an optimization-based scheme using the proposed constraints to achieve a mechanism from a given target surface. We also propose methods for accommodating the thickness of the tiles and show different variations of joints. As results, we obtained deployable surfaces of positive and negative Gaussian curvature that can deploy and contract with a 1-DOF mechanism. If the structure is viewed as a cellular material, it has an auxetic property with Poisson's ratio of -1. It is also potentially scalable to architectural applications because our mechanism is composed of rigid bodies and hinges.



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Paper ID:36

PrintNervi – Design and construction of a ribbed floor system in the digital era

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Ribbed floor systems, which include ribbed slabs and columns, are used extensively to enhance the structural performance of buildings. With the emerging topology optimization and advanced manufacturing techniques, the material usage and construction process of the ribbed floor systems can be improved significantly to achieve higher efficiency and sustainability. This paper presents a digital design and construction process for ribbed floor systems that combines a modified topology optimization method for ribbed slab design with a hybrid digital fabrication process for large-scale concrete casting. This new approach is tested through digital design and physical realization of a large-scale ribbed floor unit as proof of concept. The topologically optimized result and the constructed unit are compared with a famous historical floor system designed by Pier Luigi Nervi. The paper shows that the proposed design method, based on the bi-directional evolutionary structural optimization framework, can generate a slab design with a continuous rib layout and with higher structural stiffness. The paper also demonstrates that 3D printing of formworks for casting ribbed slabs and complex-shaped columns is feasible and sustainable. The new process presented in this paper can be used to design and construct a wide range of structures while minimizing material usage and labor cost.

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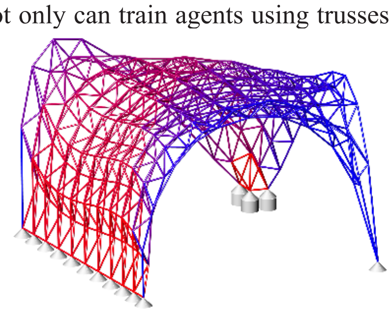
Paper ID:89

Assembly sequence optimization of spatial trusses using graph embedding and reinforcement learning

Kazuki Hayashi, Makoto Ohsaki, Masaya Kotera

We consider a truss as a graph consisting of nodes and edges, and combine graph embedding (GE) and reinforcement learning (RL) to develop an agent for generating a stable assembly path for a truss with arbitrary configuration. GE is a method of embedding the features of a graph into a vector space. By using GE, the agent can obtain numerical information of neighboring members and nodes considering their connectivity. Since the stability of a structure is strongly affected by the relative positions of members and nodes, feature extraction by GE should be effective in considering the stability of a truss. The proposed method not only can train agents using trusses with arbitrary connectivity but also can apply trained agents to trusses with arbitrary connectivity, ensuring the versatility of the trained agents' applicability. In the numerical examples, the trained agents are verified to find rational assembly sequences for various trusses more than 1000 times faster than metaheuristic approaches. The trained agent is further implemented as a user-friendly component compatible with 3D modeling software.



Tue, 20 Sep. 16:45-18:15	**S1**	**Projects and material of tension & membrane structures(WG6-1)**		
	Chair(s): Xiaofeng Wang			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	12	Shichang Zhang	Analysis and design of the accessory structure under the large deformation of a flexible roof	Shichang Zhang, Xiaoming Xu, Gao Feng, Peng Huang, Bin Luo, Weizhou Shi, Qing Fang
	29	Lichen Wang	Experimental research on mechanical properties of CFRP tendons-wedge loaded under transverse compressive loading	Lichen Wang, Xiwen Zheng
	304	Zhengyi Kong	Experimental and numerical analysis of construction process for a saddle-shaped canopy roof in a large stadium	Zhitao Li, Dongyun Jia, Congying Gan, Qinglin Tao, Chenxiao Zhang, Zhengyi Kong, Rencai Jin
	343	Liulu Guo	Study on mechanical properties of prestressed steel cables	Liulu Guo, Hongbo Liu, Zhihua Chen
	393	Migico Sing	PTFE Membrane Roof over Tennis Court of Royal Selangor Golf Club Kuala Lumpur Malaysia	Migico Sing, Kok Keong Choong, Azri Hariz Che Malid, Chong Kiat Ng
	474	Marta Karczewska	BIM in tensile membrane construction: Towards interoperability in a parametric environment	Marta Karczewska
	S2	**Realized Metal Projects (WG8-1)**		
	Chair(s): Zhi Ma and Xiaoqun Luo			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	162	zhangjianing cheng	Design and analysis of an aluminum alloy spatial structure on Sansha Island	Zhangjianing Cheng, Xiaonong Guo, Shaohan Zong
	169	Yunjun Li	Mechanical behavior of the complex intersection steel roof truss in TNFC stadium	Jian Xie, Minghua Wang, Yunjun Li;Shiyu Yang
	261	Yingying Shang	Research on key construction technology of large-span orthogonal arch truss hyperbolic roof	Yingying Shang, Zunsheng Xing, Yiyu Zhang, Shangrui Jia, Suyu Liu
	535	Xi Zhu	Structure design of the steel roof of Hangzhou Xiaoshan International Airport Terminal 4	Jian Zhou, Xi Zhu, Ruifeng Wang
	559	Yang Xiao	National Ski Jumping Center (Xue Ruyi) Overall design strategy for the structure	Yang Xiao, Ge Jiaqi, Li Qingxiang, Miao Lei, Cui Juan, Zhu Duo'e, Yang Zhenrong

Tue, 20 Sep. 16:45-18:15	**S3**	**Concepts for Sustainable Innovation in Construction of Timber and Bio-based Spatial Structures -1 (WG 12-1)**		
	Chair(s): Tetsuo Yamashita and Yinlan Shen			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	52	Nicolas Prevost	Building crossings in wicker: flexible construction of a post-formed footbridge in active bending stiffened during service phase	Nicolas Prevost, Marc Leyral, Marc Hymans, Albin breugnot, Quentin Chef, Sylvain Ebode, Wided Cherif
	140	Koichi Imamura	Buckling experiment of timber arches formed by bending	Koichi Imamura, Tetsuo Yamashita
	143	Lasse W. Rahbek	Stock optimization of naturally curved wood logs on freeform truss structures	Lasse W. Rahbek, Carsten R. Terp, Umberto Alibrandi, Poul H. Kirkegaard
	171	Gengmu Ruan	Planar rectangular, slide-in reciprocal frame structures using salvaged timber and wooden nails	Gengmu Ruan, Günther H. Filz, Gerhard Fink
	408	Denis Grizmann	Characterization of mechanical properties and numerical modeling approaches for mycelium composites	Denis Grizmann, Ulrich Spittel, Dana Saez, Martin Trautz, Anett Werner
	547	Sokol Phon	Basic research on structural properties of bamboo arched reciprocal frame structure with joinery by means of PVC pipe	Sokol Phon, Sovannara Srun, Yilin Lee, Koichiro Ishikawa
	S4	**Computational methods for spatial structures and collapse (WG 13-1)**		
	Chair(s): Carlos Lázaro and Jianguo Cai			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	15	Shuxiang Zhang	TCTM - Analysis program of complex thin-walled member based on Umansky and Vlasov theory	Shuxiang Zhang, Qilin Zhang, Yanke Tan;Xinye Li, Zhiguo Chang
	70	Zhijie Zhang	Research on the collapse performance and collapse capacity improvement method of fabricated free-form single-layer grid shell	Zhijie Zhang, Ruoqiang Feng
	116	Yusuke Sakai	A shape design method of discrete cylindrical structures tiled with auxetic hexagonal units	Yusuke Sakai, Makoto Ohsaki
	160	Simon Thissen	Numerical analysis of sheet metal folded sandwich core structures	Simon Thissen, Marcel Görz, Peter Middendorf
	545	Yuxiang Cai	Parallelized implementation of finite particle method for structural collapse analysis in urban area	Yuxiang Cai, Yanfeng Zheng , Jingzhe Tang,Yaozhi Luo

Tue, 20 Sep. 16:45-18:15	**S5**	**Sustainable Heritage: Challenges and Strategies in the Preservation and Conservation of 20th Century Historic Concrete Shells-1(WG17/WG5-1)**		
	Chair(s): Marisela Mendoza and Stefano Gabriele			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	88	Matthew Gordon	Reality capture and site-scanning techniques for material reuse planning	Zhijia Xiong, Matthew Gordon, Brandon Byers, Catherine De Wolf
	115	Masafumi Tanaka	A study on the structural system and history of the Former Kagawa Prefectural Gymnasium	Masafumi Tanaka, Noriyuki Kawanishi, Mituo Inagaki, Ryoich Shibata
	161	Jonathan M. Broyles	Revisiting the Viipuri Library: Assessing performance and design trade-offs in custom ceiling geometry	Jonathan M. Broyles, Ian P. Self, Nathan C. Brown
	232	Yuta Koda	Preliminary research of preprocessing of images for ceiling damage inspection using machine learning	Yuta Koda, Ken'Ichi Kawaguchi, Teruhiro Mizumoto, Yuki Matsuda
	485	Mauricio Luzuriaga	Cristo del Consuelo church in Ecuador by Luis Monsalve. A replica of Candela's San Vicente de Paúl chapel	Mauricio Luzuriaga
	S6	**Aluminum Alloy Structures - 1**		
	Chair(s): Huiyong Ban and Yuanwen OuYang			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	202	Ruoqiang Feng	Application of 6A13-T6 high-strength aluminum alloy grid structure	Ruoqiang Feng, Changjun Zhong
	250	Jiaojie Ying	Preparation of technical specification for aluminum alloy space frame structures	Hongbo Liu, Jiaojie Ying, Yuechen Xiong, Zhihua Chen
	345	Wenhao Shi	Research status and prospect of modular rapid detachable biological detection aluminum alloy building structure system	Zhihua Chen, Wenhao Shi, Hongbo Liu
	523	Fengjie Tan	Comparison of mechanical performance and stable capacity between aluminum alloy- and steel spatial grid structure in the process of fire	Fengjie Tan, Jiachun Cui

Tue, 20 Sep. 20:00-21:30	**S7**	**Masts and Towers (WG4)**		
	Chair(s): Bo Chen and Xudong Zhi			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	5	Christopher Robeller	Castanea Sativa Reciprocal Frame, inspired by Friedrich Zollinger	Christopher Robeller
	51	Jun Gong	Effect of fold-line transmission tower-line system on seismic responses of long-span truss structures in UHV substation	Jun Gong, Yongbo Shao, Xudong Zhi, Yipeng Du
	175	Patrick Schäferling	Topological optimization of lightweight tower systems for onshore wind turbines	Patrick Schäferling, Matthias Beckh
	S8	**ETFE Film Applications (WG6-2)**		
	Chair(s): Stefan Lehnert and Jianhui Hu			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	39	Hiroshi Aruga	New ETFE film with a glass-like appearance for architectural applications	Hiroshi Aruga, Atsushi Nomura, Kazuhiro Tanishima
	75	Lemei Wang	Design and construction of a large-span integrally tensioned structure with ETFE roof	Lemei Wang, Tao Wei, Wenying Zhang, Jinsong Xiao
	220	Yongsheng Yan	Experimental study on the photoelectric-photothermal-mechanical properties of new PV-ETFE foils	Yongsheng Yan, Wujun Chen, Jianhui Hu, Jian Zhang, Xuetao Zhao
	249	Jinhe Chen	Influence of high and low temperatures on tensile properties of ETFE film	Jinhe Chen, Minger Wu, Hiroshi Aruga
	268	Xiaofeng Wang	Influence of wrinkling deformation on the bearing capacity of ETFE cushions	Xiaofeng Wang, Xujing Cao, Yang Na, Qingshan Yang
	392	Xiaoqun Luo	Comparison of application of STFE and ETFE membrane material in roof structures	Jiangyu He, Xiaoqun Luo, Qilin Zhang

Tue, 20 Sep. 20:00-21:30	**S9**	**Buckling of Metal Spatial Structures - 1 (WG8-2)**		
	Chair(s): Hua Deng and Xiongyan Li			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	134	Midori Hashimoto	Elastic buckling mode of cylindrical lattice shell roofs made of H-shaped steel	Midori Hashimoto, Tetsuo Yamashita
	315	Baoxin Liu	Approximate Equation for Evaluating Global Buckling Load of Single-Layer Cylindrical Space Frames with Crossing Pattern	Baoxin Liu, Pei-Shan Chen, Xiangdong Yan, Jialiang Jin
	330	Yang Zheng	Stability analysis of cable-stiffened latticed shells	Yang Zheng, Pengcheng Li, Shibo Chu, Hao Wang, Bin Jian, Zhigang Zhang
	333	Xiaoxin Qian	Buckling characteristics of key parts of 1.5-layer space frames with lap-units	Xiaoxin Qian, Jialiang Jin, Pei-Shan Chen
	S10	**Concepts for Sustainable Innovation in Construction of Timber and Bio-based Spatial Structures -1 (WG 12-2)**		
	Chair(s): Minjuan He and Yinlan Shen			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	142	Takuo Nagai	Study on mechanical properties of reed and bending-active characteristics of reed-bundled column	Takuo Nagai
	287	Jingxian Zhao	Research Progress and Engineering Practice of Glulam Space Frame Structures	Zhihua Chen, Jingxian Zhao, Hongbo Liu, Shixing Zhao, Shuheng Yang, Jinyuan Liu
	384	Ana Gatóo	Physical to digital: Understanding the flexibility of engineered timber through kerfing	Ana Gatóo, Antiopi Koronaki, Michael H. Ramage
	411	Liam Lasting	Terrene: Sustainable Shellular Structures	Liam Lasting, Isabella Lee, Laia Mogas Soldevila, Masoud Akbarzadeh
	431	Markus Hudert	Deep Learning enhanced robotic fabrication of timber-to-timber connections with densified hardwood nails	Markus Hudert, Morten From Elvebakken, Mark Meagher, László Mangliár, Xuping Zhang, Lukas Esterle
	486	Cong Zhang	Damaged timber dowel-type connections and the application of self-tapping screw reinforcement	Cong Zhang, Su-duo Xue

	S11	Optimisation Methods (WG 13-2)		
	Chair(s): Kai Bletzinger and Yao Chen			
	ID	Speaker	Title of the paper	Author(s)
	34	Ruoqiang Feng	Finding diverse and competitive designs of truss structures	Ruoqiang Feng, Qi Cai
	37	Shaojun Zhu	Generating kinematically-stable 2d trusses for topology optimization by reinforcement learning and graph-embedding	Shaojun Zhu, Makoto Ohsaki, Kazuki Hayashi
	170	Abtin Baghdadi	Application of the geometrical-based mathematical method for classification and investigation of two-dimensional structural elements toward using additive manufacturing	Abtin Baghdadi, Neira Babovic, Harald Kloft
	253	Yafeng Wang	Topology optimization of active structural systems	Yafeng Wang, Ole Sigmund
	300	Vahid Koliyaee	Optimization of architectural and structural parameters of tall buildings in the early stage of design regarding along wind effect: considering outrigger structural system and architectural plan shapes	Vahid Koliyaee, Matin Alaghmandan, Farzad Barazandeh
Tue, 20 Sep. 20:00-21:30	396	Bunji Izumi	A systematic mapping study of the optimization methods of structures in architectural design	Bunji Izumi, Nathalie Labonnote, Anders Rønnquist, Bendik Manum
	S12	Advanced Manufacturing and Materials, 3D-Printing and Molding-1 (WG21-1)		
	Chair(s): Jianguo Cai			
	ID	Speaker	Title of the paper	Author(s)
	61	Lukas Gosch	A controlled shaping method through the shrinkage of clay	Lukas Gosch, Hana Vašatko, Julian Jauk, Elizabeta Šamec, Irena Živcović, Milena Stavric
	64	Arno Pronk	The Ice Torch	Arno Pronk*, Iranzu V. Marina López de Dicastillo a, Vincent Staat a, Jody Tissen
	92	Abtin Baghdadi	Optimization of building floor beam layout by optimization algorithms regarding the concrete printing techniques	Abtin Baghdadi, Robin Doerrie, Harald Kloft
	122	Arno Pronk	Ice composite research	Au Arno Pronk*, Petricica Marian Lucian, Willem Vissers
	375	Yangqing Liu	Practical calculation method for inertia moment of a curved Miura origami-patterned tube	Yangqing Liu, Qin Yu, Tian Deng, Dongping Mei, Jianguo Cai
	467	Mohamed A. Ismail, Emily Baker	Zip-formwork: Fabrication of shape-optimized concrete structures for the Global South	Mohamed A. Ismail, Nebyu Haile, Caitlin T. Mueller, Edmund O. Harriss, Emily Baker

Tue, 20 Sep. 21:45-23:15	**S13**	**Retractable and Other Tension Structures (WG6-3)**		
	Chair(s): Sudarshan Krishnan, Hiroki Tamai and Jianhui Hu			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	48	Shuo Ma	Deployment analysis of a clustered hyperbolic paraboloid cable net	Shuo Ma, Kai Lu, Muhao Chen, Robert E. Skelton
	336	Yu Xue	Experimental study of a new cable dome form with continuous cables	Yu Xue, Yaozhi Luo
	369	Massimo Majowiecki	The new egyptian army stadium in Cairo: a cable suspended roof structure	Massimo Majowiecki, Stefano Pinardi, Giovanni Berti, Elisa Sammarco, Giuliano Aloisio, Monica Mingozzi
	405	Mark Waggoner	Micro-Operable ETFE Panels at SoFi Stadium	Mark Waggoner, Jeff Thompson, Martin Jenni, Jeffrey Carpenter
	560	Igor G. Siotor, Martin Jenni	Use of Lightweight Technology for Kinetic Architecture	Igor G. Siotor, Martin Jenni, Thomas J. Wuerch
	274	Song Yinbo	Configuration measurement and inflating failure analysis of full-scale four-layer ETFE cushion based on 3-D photogrammetry	Song Yinbo, Chen Wujun, Zhao Bing, Hu Jianhui, Lu Jian, Cai Jing
	S14	**Connection Design of Metal Spatial Structures (WG8-3)**		
	Chair(s): Kok Keong Choong and Guojun Sun			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	13	Yaxin Li	Connection detailing for scissor-type deployable structures	Yaxin Li, Sudarshan Krishnan
	53	Niki Georgiou	Comparative analysis of bar linkage systems based on the effective crank-slider method	Niki Georgiou; Marios C. Phocas
	295	Ji Ma	Study on mechanical behavior of welded hollow spheres joint with penetrated sleeves in truss string structure	Guojun Sun, Ji Ma, Jinzhi Wu, Su-duo Xue
	494	Xiaofei Gao	Study on the failure mechanism and design method of the ear-plate connection join	Xiaofei Gao, Guojun Sun, Rundong Yue, Jinzhi Wu, Yigang Zhang
	317	Hao Wang	Mechanical performances of single layer latticed domes with SLO nodes	Dabin Yang, Kai Fan, Yi Sun, Hao Wang
	270	Hiroyuki Tagawa	Proposal of arc- and spiral-shaped Miura-ori and its application to the design of large roof architecture	Hiroyuki Tagawa, Nanami Yoshioka, Toshitomo Suzuki

Tue, 20 Sep. 21:45-23:15	**S15**	**Concepts for Sustainable Innovation in Construction of Timber and Bio-based Spatial Structures -3 (WG12-3)**		
	Chair(s): Minjuan He and Christopher Robeller			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	86	Kan Shiratori	Formfinding and buckling analysis of three-way kagome timber latticed shells using general-purpose FE software	Kan Shiratori, Tetsuo Yamashita
	94	Amin Adelzadeh	Structural performance of the grain-informed glued butt joint system for a large-span segmented CLT shell structure	Amin Adelzadeh*, Hamed Karimian-aliabadi, Marcel Muster, Christopher Robeller
	156	Hannes Löschke	Assembly of lamella roof shell structures	Hannes Löschke, Alexander Stahr, Ryan Hallahan, Marius Zwigart
	266	Ken Noda	Structural design of CLT shells interconnected via multidirectional link elements	Ken Noda, Yoshiharu Kanebako
	332	Mingxi Xu	Static stability of single-layer cylindrical glued timber reticulated shells with X-shaped joints	Mingxi Xu, Wenbin Chen, Jie Zhong, Xuhai Li
	360	Eiesuke Mitsuda	Structural design of Suspension-Arch Structures with members cut from the CLT panels, and Development of its joint system	Eisuke Mitsuda, Yunosuke Ohbayashi
	S16	**Advanced Manufacturing and Materials, 3D-Printing and Molding-2 (WG21-2)**		
	Chair(s): Yangqing Liu			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	65	Arno Pronk	Buoycrete, a light-weight concrete	Arno Pronk*, Guido Visch
	84	Tara Habibi	Use of fiber-polymer composites in bending-active structures	Tara Habibi, Landolf Rhode-barbarigos, Thomas Keller
	179	Xiaoyan Teng	Topology optimization of static stiffness for a multi-material structure using multi-revolution scheme	Xiaoyan Teng, Chuangang Wang, Xudong Jiang
	558	Yelda Gin	Robotic 3D printing with earth: A case study for optimisation of 3D printing building blocks	Yelda Gin, Kamal Haddad, Wassim Jabi, Darshil U. Shah, Michael H. Ramage
	362	Man Chen	Design, fabrication, and characterization of composite architected units with embedded 3D-printed lattice	Man Chen, Xianhua Yao, Lihua Zhu, Feng Li, Nan Hu*
	231	Xiaoyang Lin	Design for 3D printing models via layout and geometry optimization considering overhang constraints	Xiaoyang Lin, Jun Ye, Hongjia Lu

	ID	Speaker	Title of the paper	Author(s)
	S17	**Innovation in New Concepts and Projects - 1**		
	Chair(s): Minger Wu and Jinghai Gong			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	77	Hamid Eldarwich	Conceptual Investigation on the Effectiveness of Hyperbolic Paraboloid Surfaces for Floating Breakwaters	Hamid Eldarwich, Krisna Pawitan, Maria Garlock
	228	Lin Ai	A method of designing multi-compatibility induced multi-stable morphing structures	Lin Ai, Shukun Yin, Jingjing Yang, Yang Li, Miao Li
	290	Baolian Liu	Topological stereotomic design of systems of interlocking stackable modular blocks for constructing multi-storey funicular masonry buildings	Baolian Liu, Qinglu Chen, Pirouz Nourian, Simona Bianchi, Anjali Mehrotra, Shervin Azadi
	303	Arka P. Reksowardojo	Design of an adaptive rib-stiffened slab equipped with a variable post-tensioning system	Arka P. Reksowardojo, Gennaro Senatore, Manfred Bischoff, Lucio Blandini
	306	Juan G. Oliva	Brick vaults for rural housing in Mexico	Juan G. Oliva, Susana Ezeta, Ramón Abud, Rodolfo Rodríguez, Mario Cruz
Tue, 20 Sep. 21:45-23:15	557	Arnaud De Coster	Modular Textile Reinforced Concrete (TRC) shell structures: An exploration through geometrical and structural design	Arnaud De Coster, Tom Van Den Schilden, Lars De Laet And Tine Tysmans
	S18	**Disaster Prevention and Mitigation of Spatial Structures-1**		
	Chair(s): Kiyoshi Shingu and Xiongyan Li			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	133	Yan Zhao	Seismic performance of an innovative cold-formed steel framed building	Yan Zhao, Wenying Zhang
	157	Petra Gidak	Geometry generation and modelling of non-standard cross vaults	Petra Gidak, Elizabeta Šamec, Krešimir Fresl, Damir Lazarević
	294	Fengze Li	Seismic capacity and fragility of fire-fighting piping system of large-span transportation hub structure	Fengze Li, Xudong Zhi, Enchun Zhu, Wenliang Li
	298	Bo Huang	Seismic behavior and failure mechanism of reticulated shells considering the influence of support members	Bo Huang, Minglong Fu, Xudong Zhi
	350	Jesus Gerardo Pérez Vega	Nonlinear behavior of concrete shell roofs of different curvature under seismic loads using the finite element method (fem), located in mexico city.	Jesús Gerardo Pérez Vega, Hector Aureliano Sánchez Sánchez
	363	Xianhua Yao	Gradient design and inelastic response of architected slender structures toward multi-stage energy dissipations	Xianhua Yao, Qian Zha, Ruitong Tian, Haifeng Chen, Nan Hu

Wed, 21 Sep. 8:30-10:00	**S19**	**Dynamic Performance and Seismic Response of Metal Spatial Structures - 1 (APCS, WG8-4)**		
	Chair(s):Jingyao Zhang and Guojun Sun			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	38	Toru Takeuchi	Borderless design between seismic isolation and response-controlled structures	Toru Takeuchi
	56	Zetao Zhao	Research on the method of considering concrete substructures of suspen-dome prototype structure in shaking table test scale model	Zetao Zhao, Su-duo Xue, Xiongyan Li
	132	Nobuyuki Yamato	Seismic response controlled structure based on soft-first-story theory for the new national stadium in Japan	Nobuyuki Yamato, Osamu Hosozawa, Isamu Nakakawaji, Taro Mizutani, Shinichiro Kakamoto, Masaki Murase, Takahiro Kanno
	139	Zhiyuan Gao	Seismic performance evaluation method of double layer spatial truss structures with truss walls subjected to earthquake motion	Zhiyuan Gao, Koichiro Ishikawa, Kaisei Takahashi
	321	Yoshiki Takashima	Yield seismic intensity and seismic performance of pin supported arch structures	Yoshiki Takashima, Naoki Wakayama, Shoji Nakazawa, Yuji Takiuchi, Shiro Kato
	340	Xuhai Li	Seismic responses of double-layer cylindrical reticulated shells under near-fault velocity pulse-like ground motions	Xuhai Li, Jie Zhong, Mingxi Xu, Wenbin Chen
	S20	**Cable Structures (WG6-4)**		
	Chair(s): Minger Wu			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	103	Ningyuan Zhang	Error sensitivity analysis and multiple error coupling analysis for cable-supported grid structure with an internal compression ring	Ningyuan Zhang, Bin Luo, Minquan Zhang, Haixia Liu
	150	Kun Zu	Research on mechanical property and construction technology of spoke tension structure with single-double-combined layer cable	Kun Zu, Bin Luo, Yanhao Hu
	205	Jiaqi Yang	Tensioning simulation and experiment study of the upper-layer crossed wheel-spoke cable-strut structure	Jiaqi Yang, Guangyi Zhou, Yue Wu, Dongfang Li, Huazhang Zhou, Da Qiao
	278	Xu Zhu	Research on multi-step form finding analysis method of single layer spoke cable structure	Guojun Sun, Xu Zhu, Jinzhi Wu, Xiang Zhang, Jie Hu
	504	Yurong Shao	The influence of production and construction errors on single-layer spoke cable structure	Jinzhi Wu, Yurong Shao, Guojun Sun, Xiang Zhang
	507	Yanxia Zhang	Experimental study on static performance of fully-assembly ridge-tube threading cable with annular-struts cable dome	Yanxia Zhang, Ailin Zhang, Guanghao Shangguan, Wenjun Yuan, Jie Wang, Ming Zou, Hao Ma, Lixin Shao

Date/Time	ID	Speaker	Title of the paper	Author(s)
	S21	**Designing Structures with Computational Methods (WG13-3)**		
	Chair(s): Anahita Khodadadi and Yao Chen			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	104	Xingye Wang	A Practical Method for Shape and Size Optimization of Space Arch Truss	Xingye Wang, Xiaonong Guo
	138	Hideyuki Takashima	Creation method for tree-like pillar based on genetic algorithm	Hideyuki Takashima, Bingjie Tang
	267	Ken Noda	Link element arrangement for CLT shells	Ken Noda, Toshiaki Kimura
	327	José Luis Encarnación Miranda	Prefabricated modular pavilion of architectural concrete	José Luis Encarnación Miranda, Juan Gerardo Oliva Salinas, Ronan Bolaños Linares, Mauricio Enrique Reyes Castillo, Carlos Arce, Enrique Hernández, Andrés Vazquez, Eduardo Ruiz Vallejo
	469	Jingyao Zhang	Structural morphology of 2D tree-like supporting structures	Jingyao Zhang, Yuji Nomura
Wed, 21 Sep. 8:30-10:00	**S22**	**Form-Mobility Relationship: the Study of the Interdependency of Structural Geometry and Transformability (WG15-1)**		
	Chair(s): Tomohiro Tachi and Jianguo Cai			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	55	Tianhao Zhang	Preliminary research on shape determination for curved crease origami using bending deformation	Tianhao Zhang, Ken'ichi Kawaguchi
	225	Kentaro Hayakawa	Form generation of rigid origami reflecting the mean curvature and feature lines of target surface	Kentaro Hayakawa, Makoto Ohsaki
	258	Yuan Liao	Deployability and structural performance of spatial scissor units made of zigzag bars	Yuan Liao, Yuan Li, Sudarshan Krishnan
	312	Mostafa Akbari	Continuous Approximation of Shellular Funicular Structures	Mostafa Akbari, Masoud Akbarzadeh
	414	Huizhong Zhang	Zero Poisson's ratio origami structure inspired by Kresling tube	Huizhong Zhang, Wenxing Huang, Xiaoyu Xu, Jianguo Cai, Jian Feng
	438	Jingyuan Hu	Effects of Singular Polygons on the Structural Performance of Irregular Kagome Gridshell with Continuous Rods	Jingyuan Hu, Weixin Huang

	S23	Life-Cycle Design and Assessment of Shell and Spatial Structures (WG18)		
	Chair(s): Kok Keong Choong and Yingying Zhang			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
Wed, 21 Sep. 8:30-10:00	25	Xiaoshun Wu	Expanding dynamic responses triggered by step excitations for spatial trusses	Xiaoshun Wu, Chi Zhu, Runhui Cheng, Tao Zou
	176	Benjamin Schmid	The hanging model for the Mannheim Multihalle and its digital twin	Benjamin Schmid, Christiane Weber, Baris Wenzel, Eberhard Möller
	214	Penghao Yu	Research on key technologies of intelligent monitoring and detection of operation and maintenance security of glass curtain wall	Yingying Zhang*, Penghao Yu, Ziqi Chen
	383	Guansen Dong	Compressive sensing of wind speed data of large-span spatial structures using time-shift strategy	Guan-sen Dong, Hua-ping Wan, Yaozhi Luo*
	387	Jingyu Zhao	Reconstruction of missing structural health monitoring data using attentive neural processes	Jingyu Zhao, Yaozhi Luo
	412	Xi Zhao	High-fidelity measurement and analysis of constructional errors of long-span spatial prestressed steel structures	Xi Zhao, Ailin Zhang, Jie Wang, Yanxia Zhang, Guanghao Shangguan, Hao Ma

Wed, 21 Sep. 10:30-12:00	**S24**	**Pneumatic Structures-1 (APCS, WG6-5)**		
	Chair(s): Ken'ichi Kawaguchi and Xiongyan Li			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	218	Jiabao Li	Force analysis of stratospheric airship with inflatable rings	Jiabao Li, Tiane Li, Haotian Xue, Xuliang Cheng, Yifeng Zhou
	243	Takara Muto	Experimental research of axial elasticity and loading capacity of air-inflated tubes with low slenderness ratio	Takara Muto, Ken'ichi Kawaguchi
	247	Ningrui Wang	Bending-wrinkling and reliability analysis of inflated beams	Ningrui Wang, Minger Wu
	263	Fu Zhang	Beam finite element for nonlinear analysis of inflatable tubes	Fu Zhang, Minger Wu
	319	Zhen Zhang	Initial shape analysis and experimental study of air-supported membrane structure considering cable-membrane contact	Zhen Zhang, Xiongyan Li, Su-duo Xue, He Yanli
	398	Yuki Ozawa	Fabrication and loading tests of semi-rigid airmat beam structures	Yuki Ozawa, Nagiko Hirotania
	S25	**Mechanical Properties and Health Monitoring of Metal Strucures (WG8-5)**		
	Chair(s): Tetsuo Yamashita and Bo Chen			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	23	Zhi Ma	An MPPCA approach for anomaly detection of a retractable roof structure	Zhi Ma, Yaozhi Luo, Chung-Bang Yun, Hua-Ping Wan
	93	Abtin Baghdadi	Sensitive load areas in steel truss arches regarding geometrical and material nonlinearity	Abtin Baghdadi, Shaghayegh Ameri, Harald Kloft
	130	Zhiqiang Li	Research on the design and construction technology of an aluminum alloy string spatial structure	Yuanwen OuYang, Zhiqiang Li, Xiaowei Liu, Liqiu Qiu, Ruixiong Li , Xiaoqun Luo
	415	Jie Xu	Structural health monitoring of large-spatial structure based on unmanned aerial vehicle images	Jie Xu, Xuan Liu, Pengpeng Jia, Qinghua Han
	509	Guanghao Shangguan	Experimental study on structural performance of innovative modular fully-assembly ring-truss steel structural system	Ailin Zhang, Guanghao Shangguan, Yanxia Zhang, Wenjun Yuan, Ming Zou, Jie Wang, Hao Ma, Lixin Shao
	514	Tengteng Zheng	Study on bearing capacity performance of the new type of honeycomb plate hollow floor	Tengteng Zheng, Kun Qian, Liangjian Yuan, Caiqi Zhao

	S26	Optimisation, Form Finding and Parametric Design (WG15-2)		
		Chair(s): Hua Deng and Ruoqiang Feng		
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	69	Yulin Xiong	A high-resolution bi-directional evolutionary structural optimization method for gridshell structures	Yulin Xiong, Xin YAN, Hongjia Lu, Yi Min Xie
	189	Iasef Md Rian	Fractal-Based Perforation Morphology and Structural Optimization of Perforated Steel Beams	Iasef Md Rian, Abdullah Ibrahim
	192	Hiroyuki Shiomi	Form-finding analysis of funicular shells using eccentricity reduction method	Hiroyuki Shiomi, Kenji Yamamoto
	292	Marina Konstantatou	Applications of graphic statics to the plastic design of reinforced concrete structures	Marina Konstantatou, Miguel Fernández ruiz, Pierluigi D'acunto
	454	Fereshteh Khojastehmehr	A review on the curvature and geometrical patterns of elastic gridshells: potentials for structural optimization and architecture	Fereshteh Khojastehmehr, Mohammad Hassan Saleh Tabari, Günther H. Filz
	554	Hua Chai	Structural form-finding of multi-span undulating funicular beam structure	Hua Chai, Mohammad Bolhassani, Masoud Akbarzadeh
Wed, 21 Sep. 10:30-12:00	S27	Snow and Ice Engineering (WG21-3)		
		Chair(s): Qingwen Zhang		
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	66	Arno Pronk	Structural behavior and realization of a monumental ice structure in China for IASS/APCS2022	Arno Pronk*, Qingpeng Li, Elke Mergny, Yilling Zhou
	199	Shuoyong Yang	Design optimization of complex ice shell based on machine learning model driven by construction logic and performance simulation	Shuoyong Yang, Peng Luo, Yue Wang, Chenghu Xin, Xuanyu Wang
	291	Rui Li	Experiment investigation of snow loads on Qiyang airport terminal roof based on a new similarity criterion	Rui Li, Qingwen Zhang, Feng Fan
	296	Yuanyuan Li	Probabilistic modeling of 10-min mean wind speed for the purpose of analytical simulation of snowdrift	Yuanyuan Li, Huamei Mo, Feng Fan
	318	Jialin Zou	Wind tunnel test and CFD simulation of snowdrift on an air-supported membrane structure	Zou Jialin, Sun Xiaoying, Wu Yue
	420	Haoming Huang	Multistable grid shell as a flexible and reusable formwork for the sustainable construction of snow and iced structures	Haoming Huang, Jian Wen, Zhixiong Huang, Xiaofan Gao, Yangsheng Lin, Lu Xiong, Nan Hu

	S28	Aluminum Alloy Structures - 2		
	Chair(s): Hongbo Liu and Ruoqiang Feng			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
Wed, 21 Sep. 10:30-12:00	195	Shaozhen Chen	Study on out-of-plane flexural behavior of aluminum alloy gusset joints after fire	Shaozhen Chen, Xiaonong Guo
	198	Zhongxing Wang	Buckling behaviour and design of aluminium alloy I-sections in fire	Zhongxing Wang, Mengyu Li, Qinghua Han
	349	Huiyong Ban	Tensile tests on high-strength aluminum alloy at elevated temperatures	Huiyong Ban, Weijia Tian
	519	Xinhang Zhi	Structural behaviour of 7A04-T6 high-strength aluminium alloy CHS stub columns under axial compression	Xinhang Zhi, Yuanqing Wang, Beibei Li, Yuanwen OuYang, Huanxin Yuan, Ying Zhang

Wed, 21 Sep. 16:15-17:45	**S29**	**Future Challenges in the Design and Construction of Shell Structures for Low or Zero Carbon - 1 (WG5-1)**		
	Chair(s): Stefano Gabriele and Joshua Schultz			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	82	Homam Spartali	Stress redistribution capacity of textile-reinforced concrete shells folded utilizing parameterized waterbomb patterns	Homam Spartali, Jan Dirk van der Woerd, Josef Hegger, Rostislav Chudoba
	90	Abtin Baghdadi	Application of energy method to investigate the stability of structural shells and arches with the threshold capacity	Abtin Baghdadi, Mahmoud Heristchian, Harald Kloft
	100	Toshiaki Kimura	Form finding for free-curved RC shell using multi-objective optimization considering structural performance and formwork manufacturability	Toshiaki Kimura, Shuhei Ogawa, Sei Hayashi, Tatsuya Muto, Kozo Yamasaki, Yusuke Sakai, Tomoyuki Gondo
	201	Yuchao Zhao	Digital construction technology of double helix spatial free-form concrete thick shell of Shanghai Grand Opera House	Yuchao Zhao, Ming Zhang, Qilin Zhang, Jie Cai
	481	Chuanping Liu	Practice and research of complex concrete reticulated shell structure in high speed railway station	Chuanping Liu, Mengdi Liu *, Jian Jia
	450	Marisela Mendoza	Felix Candela's architectural heritage at the intersection of sustainable development	Marisela Mendoza, Mariana Esponda, Juan Ignacio del Cueto Ruiz-Funes, Andrés López, N.Cassandra Ruiz-Gómez
	S30	**Pneumatic Structures-2 (WG6-6)**		
	Chair(s): Ken'ichi Kawaguchi and Yingying Zhang			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	110	Fei Yan	Collapse property of Air-supported structures	Su-duo Xue, Fei Yan, Guojun Sun
	126	Junbin Zhao	Research on the wind-induced failure mechanism of an inflatable membrane structure	Zhaoqing Chen, Junbin Zhao, Keye Yan, Yue Wu, Lixiang Tang
	277	Zhihao Li	Simulation deployment behavior of air-inflated fabric arches based on modified Control Volume method	Guojun Sun, Zhihao Li, Su-duo Xue, Xiongyan Li
	335	Keye Yan	Experimental study on aeroelastic response of air-supported membrane structures	Keye Yan, Yue Wu, Zhaoqing Chen
	524	Yan Pang	A simulation method of weld seams for precise forming of inflated membrane structure	Yan Pang; Jinghai Gong; Guozhi Qiu

Wed, 21 Sep. 16:15-17:45	**S31**	**Buckling of Metal Spatial Structures - 2 (WG8-6)**		
	Chair(s): Huiyong Ban and Xudong Zhi			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	32	Lin Yuan	Local buckling strength of high-strength aluminum alloy H-sections under combined compression and major-axis bending	Qilin Zhang, Lin Yuan, Yuanwen OuYang
	137	Hua Deng	Arranging active bars to improve stability of loaded pin-bar mechanisms	Hua Deng, Wei Wang, Zijian Wang
	177	Yuto Kato	Evaluation on plastic buckling load of axially compressed latticed cylinders	Yuto Kato, Tetsuo Yamashita
	479	Hao Lin	Structural stability analysis of eye of the yellow sea, a large-span arched pedestrian bridge	Hao Lin, Zhihua Chen, Xiaodun Wang, Hongbo Liu, Ken'ichi Kawaguchi, Minoru Matsui
	S32	**Computational Methods for Additive Manufacturing and Origami (WG13-4)**		
	Chair(s): Makoto Ohsaki and Ruoqiang Feng			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	108	Davide Tanadini	Exploring the potential of equilibrium-based methods in additive manufacturing: the Digital Bamboo pavilion	Davide Tanadini, Patrick Ole Ohlbrock, Marirena Kladeftira, Matthias Leschok, Eleni Skevaki, Benjamin Dillenburger, Pierluigi D'Acunto
	121	Deyan Quan	Prototyping parametrically designed fiber-reinforced concrete façade elements using 3D printed formwork	Deyan Quan, Christiane M Herr, Davide Lombardi, Ziyue Gao; Jun Xia
	125	Teong Yen Tong	Free-form folded shell structure inspired by no-crease origami	Teong Yen Tong, Kok Keong Choong
	147	Yao Chen	Design and fatigue life prediction of origami creases	Jiaqiang Li, Yao Chen, Jian Feng, Pooya Sareh
	148	Yao Chen	Stretch responses of kirigami inspired metamaterials based on rotating units	Yue Sun, Ruoqi He, Yao Chen, Jian Feng, Pooya Sareh
	550	Yinan Xiao	A structure- and fabrication-informed strategy for the design of lattice structures with Injection 3D Concrete Printing	Yinan Xiao,Yuchi Shen, Norman Hack, Pierluigi D'Acunto

Wed, 21 Sep. 16:15-17:45	**S33**	**Prototyping: Physical and Virtual Model Making and Fabrication (WG15-3)**		
	Chair(s): Hiroki Tamai and Rupert Maleczek			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	276	Mingyu Sun	Micro-structural biomimetic: new perspective of shell structural morphology innovation	Mingyu Sun
	364	Pan Liu	Design and assembly of origami-inspired modular adaptive flow regulations	Nan Hu, Pan Liu, Weining Mao, Zhantu Gan, Dongdong Zhao
	400	Yuanyuan Li	Programmable origami bolt tightening robot	Yuanyuan Li, Qian Zhang, ;Xiaohui Zhang, Jianguo Cai;Jian Feng
	407	Lu Zhu	Conceptual design and fabrication of modular deployable origami structures for architectural-scale applications	Lu Zhu, Peng Qiu, Zhixiong Huang, Yiwei Yin, Yikang Hong, Guangyi Xie, Dongdong Zhao, Nan Hu
	468	Katherine A. Liapi	Expandable cube: A reciprocal reconfigurable structure for the activation of public spaces	Katherine A. Liapi, Katerina Voukelatou, Elena Ckrysanthakaki
	S34	**Teaching of Shell and Spatial Structures facilitating Innovation, Sustainability and Legacy (WG20)**		
	Chair(s): Alireza Behnejad, Juan Gerardo Oliva Salinas and Koichiro Ishikawa			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	114	Anahita Khodadadi	Open educational resources in structural engineering education	Anahita Khodadadi
	146	Yi Lin Lee	The mechanical properties of bamboo arched reciprocal structure based on parameters of configurations	Yi Lin Lee, Sovannara Srun, Sokol Phon, Koichiro Ishikawa
	155	Chie Matsuo	Timber 1/10 scaled model of Yakushiji's West Tower built by Mamoru Kawaguchi Laboratory	Chie Matsuo
	308	Elisa Drago Quaglia	Tradition and heritage on teaching of shell and spatial structures in Mexico	Juan Ignacio del Cueto Ruiz-Funes, Juan Gerardo Oliva Salinas, Elisa Drago Quaglia, Marcos J. Ontiveros Hernández
	397	Denis Zastavni	What is the legacy of structural design expertise? The parametric design approach to high-rise buildings.	Denis Zastavni, Mark P. Sarkisian, Jean-Philippe Jasienski, Luca Sgambi
	421	Thian-Siong Choo	Design-Translate-Manufacture-Assemble framework for designing and building a segmented plywood shell	Thian-Siong Choo

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	S35	**Mechanical Behavior of Tension Structures (WG6-7)**		
	Chair(s): Massimo Majowiecki and Wujun Chen			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	40	Akira Tanaka	The effect of changing boundary conditions at the arch End on the structural behavior of String Crescent Structure	Akira Tanaka
	60	Naoya Miyasato	Study on the basic structural characteristics of hp type cable-net structure consisting of hexagonal mesh	Naoya Miyasato, Akira Okada, Shuzo Hiroishi, Asami Matsuda; Koki Matsumoto
	72	Karim Abedi	A parametric study on the instability behavior of a new hybrid cable dome	Karim Abedi, Rasoul Asghari, Mohammad Reza Chenaghlou, Behzad Shekastehband
	149	Yao Chen	Automatic design of origami patterns for deployable conical structures using deep neural network	Yao Chen, Weiying Fan, Li Wan, Jian Feng, Pooya Sareh
	285	Manyu Deng	Influence study of members' area-loss in cable-strut structures	Manyu Deng, Xingfei Yuan
	322	Weijing Zhang	Progressive collapse analysis of Levy type open cable domes	Weijing Zhang, Pengwei Li
	S36	**Dynamic Performance and Seismic Response of Metal Spatial Structures -2 (WG8-7)**		
	Chair(s): Toru Takeuchi and Xian Xu			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	20	Yuki Terazawa	Computational morphogenesis based on generalized response spectrum analysis considering both dead load and seismic response of metal gridshell with buckling-restrained braces	Yuki Terazawa, Atsuya Niimi, Deepshikha Nair, Toru Takeuchi
	26	Deepshikha Nair	Preliminary seismic design of double-layered domes with nonlinear multistorey substructures	Deepshikha Nair, Yuki Terazawa, Toru Takeuchi
	136	Wenxuan Zhao	Seismic behavior of a single-layer spherical lattice shell structure with superelastic-friction pendulum bearings	Wenxuan Zhao, Peng Zhuang, Shiqi Sun
	279	Shuo Xiao	Numerical simulation on seismic performance of suspen-dome structure	Shuo Xiao, Guojun Sun, Jinzhi Wu, Linling He, Longjun Li
	356	Susumu Yoshinaka	Vibration control of large-span arch structure, Eye of the yellow sea, by Houde damper system using mass of double floor	Susumu Yoshinaka, Ken'ichi Kawaguchi, Minoru Matsui, Zhihua Chen, Xiaodun Wang
	500	Yang Li	Static and seismic performance analysis of the long-span full-steel structure of a gymnasium	Jinzhi Wu, Yang Li, Guojun Sun, Mingliang Liu, Yijun Hou

Wed, 21 Sep. 20:00-21:30	**S37**	**Computional Methods for Shell Design and Geometrical Methods (WG13-5)**		
	Chair(s): Anahita Khodadadi and Ruoqiang Feng			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	28	Makoto Ohsaki	Gaussian curvature flow for constant Gaussian curvature surface with triangular mesh	Makoto Ohsaki, Kazuki Hayashi, Yoshiki Jikumaru, Takashi Kagaya, Yohei Yokosuka
	71	Iurii Vakaliuk	Initial numerical development of design procedures for TRC bioinspired shells	Iurii Vakaliuk, Tom Goertzen, Silke Scheerer, Alice C. Niemeyer, Manfred Curbach
	206	Shinnosuke Fujita	Discrete surface control using amount of change in surface gradient	Shinnosuke Fujita, Kairi Saito
	210	Minghao Bi	Creating novel dynamic architectural forms from kinetic elastica-ruled surfaces	Minghao Bi, Yunzhen He, Zhi Li, Ting-Uei Lee, Yi Min Xie
	357	Xiao Xiao	Free-form deformation based isogeometric shape optimisation of thin-shell structures	Xiao Xiao, Fehmi Cirak
	391	Kam-Ming Mark Tam	Trans-topological learning and optimisation of reticulated equilibrium shell structures with Automatic Differentiation and CW Complexes Message Passing	Kam-Ming Mark Tam, Tom VAN Mele, Philippe Block
	S38	**Geometry: Describing and Controlling (complex) Geometry, Including Parametric Design (WG15-4)**		
	Chair(s): Niels De Temmerman and Jinghai Gong			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	74	Ryo Watada	Design of N-fold-symmetric multi-layered hinge frame deployable from bundle to surface of revolution	Ryo Watada, Makoto Ohsaki
	81	Rupert Maleczek	Rapid prototyping for non-developable discrete and semi-discrete surfaces with an overconstrained mobility	Rupert Maleczek, Kiumars Sharifmoghaddam, Georg Nawratil
	158	Serenay Elmas	The structural geometry of a beam element from 4 torqued strips: A comparison to standardized profiles and applications	Serenay Elmas, Günther H. Filz, Athanasios A. Markou
	394	Zherui Wang	A polyhedral approach for the design of a compression-dominant, double-layered, reciprocal frame, multi-species timber shell	Zherui Wang, Masoud Akbarzadeh
	409	Boxu Chen	Research on the parametric design and optimization of the hexagon-cell shell structure	Boxu Chen, Lingling Li, Rui-nan Zhang, Sitong Yu
	437	Serge Monnot	5 Platonic bodies, 5 Chinese elements: two isomorphic expressions of the same general system?	Serge Monnot

Wed, 21 Sep. 20:00-21:30	**S39**	**Sustainable Heritage: Challenges and Strategies in the Preservation and Conservation of 20th Century Historic Concrete Shells-2 (WG17/WG5-2)**		
	Chair(s): Marisela Mendoza and Atsushi Mutoh			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	33	Mohammad Bolhassani	Structural muqarnas: Reconstructing muqarnas using graphic statics	Hossein Kamyab; Mansour Yegane; Mohammad Bolhassani
	46	Federico Bertagna	Gengo Matsui: the contribution of a structural engineer to post-war Japanese architecture	Federico Bertagna, Viktoriya Maleva, Alessandro Garzanti, Yasumasa Shimizu, Federico Bertagna
	87	Zhen Lu	Dynamic characteristics and shaking table tests on suspend-dome structure with the center-hung scoreboard	Zhen Lu, Xiongyan Li, Renjie Liu, Su-duo Xue
	101	Valentina Beatin	Why collapsed ancient hellenic temples? the case study: athena pronaia tholos at delphi.	Valentina Beatin, Valentina Beatini, Attilio Pizzigoni, Vittorio Paris
	120	Jelena Milosevic	A continuum between sculptural and structural form in the sutjeska memorial	Jelena Milosevic, Jelena Milošević, Miodrag Nestorović
	127	Yangyang Li	Measuring and comparing digital images of a historical Japanese reinforced concrete dome obtained by using LiDAR and SfM	Yangyang Li, Atsushi Mutoh, Ken'ichi Kawaguchi, Yosuke Nakaso, Shinya Matsumoto
	S40	**Innovation in New Concepts and Projects - 2**		
	Chair(s): Juan Gerardo Oliva Salinas and Jianhui Hu			
	ID	**Speaker**	**Title of the paper**	**Author(s)**
	62	Minori Ogoshi	Finite element analysis of the bi-valve shell based on solid and shell elements	Minori Ogoshi, Masaki Teranishi, Doppo Matsubara
	197	Zibin Zhao	Model Selection for Super-Long Span Suspension Mega-Latticed Structures	Zibin Zhao, Qingwen Zhang, Feng Fan
	305	Juan G. Oliva	Bamboo gridshells for rural housing in Mexico	Juan G. Oliva, Magdalena Trujillo, Susana Ezeta, Ramón Abud, María I. Verhulst
	456	Mohammad Hassan Saleh Tabari	Parametric thinking for decision-making in elastic gridshell design	Mohammad Hassan Saleh Tabari, Fereshteh Khojastehmehr, Günther H. Filz
	506	Marta Gil Perez	Coreless filament-wound structures: toward performative long-span and sustainable building systems	Marta Gil Pérez, Christoph Zechmeister, Achim Menges, Jan Knippers
	21	Yuqing Yang	Study on shear strength of partially connected steel plate shear wall	Yuqing Yang, Zaigen Mu, Boli Zhu

	S41	**Tensegrity Structures (WG6-8)**		
	Chair(s): Sudarshan Krishnan and Renjie Liu			
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	211	Shaoxiong Huang	Stress to stiffness response of tensegrity structure networks	Shaoxiong Huang, Xian Xu
	265	Meijia Wang	30-strut locomotive tensegrity robot	Meijia Wang, Xian Xu, Yaozhi Luo
	355	Yohei Yokosuka	Form-finding of hybrid tensile structures with active bending using finite element technique assuming nodal coordinates	Yohei Yokosuka, Sakura Torigoe, Toshio Honma
	423	Yafeng Wang	Equilibrium and stability of general tensegrity structures with rigid bodies	Yafeng Wang, Xian Xu, Yaozhi Luo
	S42	**Graphical Methods and Funicular Structural Design (WG 13-6)**		
	Chair(s): Juan Gerardo Oliva Salinas and Kazuki Hayashi			
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	73	Federico Bertagna	Graphical methods as the key to holistic design: bringing together structural design and solar control strategies	Federico Bertagna, Joseph Schwartz, Pierluigi D'acunto
	107	Shuyuan Han	A historical graphical analysis method for rigid frames	Shuyuan Han, Denis Zastavni
	174	Francesco Ranaudo	On the thrust line of piecewise-linear-elastic continuous funicular structures	F. Ranaudo, T. Van Mele, P. Block
	252	Zifeng Guo	Enhancing structural form-finding through a text-based AI engine coupled with computational graphic statics	Zifeng Guo, Karla Saldana Ochoa, Pierluigi D'Acunto
	320	Chuanhao Zhao	Exact solutions for out-of-plane buckling of funicular arches considering warping deformations	Chuanhao Zhao, Wenhao Pan, Yaozhi Luo, Guomin Liu, Wei Chen
	389	Kam-Ming Mark Tam	Performance-informed pattern modification of reticulated equilibrium shell structures using rules-based Graphic Statics, CW Networks and Reinforcement Learning	Kam-Ming Mark Tam, Daniel Kudenko, Megha Khosla, Tom Van Mele, Philippe Block

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<tr><td colspan="4">Chair(s): Rupert Maleczek and Marina Konstantatou</td></tr>
<tr><td>ID</td><td>Speaker</td><td>Title of the paper</td><td>Author(s)</td></tr>
<tr><td>85</td><td>Daniel Robertz</td><td>Semi-symmetric origami waterbomb cell kinematics and tessellation for the design of thin-walled folded shells</td><td>Daniel Robertz, Homam Spartali, Wilhelm Plesken, Rostislav Chudoba, Alice C. Niemeyer</td></tr>
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	470	Andrew South	Adoption of air-supported forms for thin-shell concrete structures: understanding uses, benefits, and barriers to scale	Andrew South, Evan Bingham
	S47	**Dynamic Behavior of Tension & Membrane Structures (WG6-9)**		
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	223	Zhou Zhang	Aerodynamic characteristics of an umbrella-shaped membrane structure in high turbulence flow	Dong Li, Xiakai Zhou, Zhou Zhang
	359	Tengfei Wang	Nonlinear motion-induced aerodynamic forces on large-scale membrane roofs	Tengfei Wang, Qingshan Yang, Kunpeng Guo
	386	Feixin Chen	Effect of the mass-damping ratio on the wind-induced response of a tension membrane structure based on FSI simulations	Feixin Chen, Tian Li, Qingshan Yang

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	Chair(s): Koichiro Ishikawa and Zhi Ma			
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	181	Lingzhao Meng	Dynamic response research on axially preloaded aluminum alloy circular tubes under lateral impact loadings	Lingzhao Meng, Ximei Zhai, Guangming Cui
	273	Mehdi Poursha	Investigation into the seismic behavior of space structures and extraction of modification factor of seismic responses	Karim Abedi, Mehdi Poursha, Hamed Jafarzadeh, Pouya Heidarian, Ali Abdollahi
	275	Javad. Shaki Masouleha	Dynamic instability analysis of industrial buildings with flat double layer grid floors and walls under impact loading	Karim. Abedi, Javad. Shaki Masouleha
	S49	**Concepts for Sustainable Innovation in Construction of Timber and Bio-based Spatial Structures -4 (WG12-4)**		
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	323	Lu Xiong	Cable-driven self-assembly of elastic grid formworks toward sustainable shell constructions	Lu Xiong, Xiaofan Gao, Haoming Huang, Jianming Chen
	455	Alexander Curth	Parametric waffle slabs: Optimal geometry materialized with additive construction	Alexander Curth, Ashley Hartwell, Tim Brodesser, Caitlin Mueller
	511	Qiu Zhang	Development of an active bending formwork based on bamboo mortar shells: preliminary results	Qiu Zhang, Fengyang Ye, Zhehui Li, Xinyi Zhu, Zhiyun Shi, Francesco Marmo, Zhi Li, Junsong Wang, Cristoforo Demartino

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	167	Gabriela Gonzales Allende	Computational form-finding of a biotensegrity hybrid textile structure	Gabriela Gonzales Allende, Rui Liu, Diane Davis-Sikora, Linda Ohrn-McDaniel
	219	Yota Ohtsuka	Numerical analysis of interaction between air-inflated membrane and water using MPS method for simulation of an inflatable personal shelter in water disaster	Yota Ohtsuka, Ken'ichi Kawaguchi
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	S51	**Innovation in New Concepts and Projects - 3**		
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	83	Tara Habibi	Self-stress distribution in large-scale cylindrical tensegrity structure	Tara Habibi, Landolf Rhode-Barbarigos, Filippo Broggini, Luca Diviani, Thomas Keller
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SESSION 1

Tue, 20 Sep.

Parallel Sessions,
16:45-18:15
(90 minutes)

Projects and material of tension & membrane structures(WG6-1)

Chair(s): Xiaofeng Wang

12

Analysis and design of the accessory structure under the large deformation of a flexible roof

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When a flexible structural system such as a cable net is applied in a large-span stadium, the roof will deform significantly under the self-weight and wind load. Roof accessory structures such as catwalks, radial drainage pipes, circular drainage channels, and radial cable trenches need to cooperate with the large deformation of the roof. This paper introduces the design idea of the accessory roof structure in detail. First, a wind tunnel test was conducted to determine the wind load of the structure. Then, the gust response factors of each roof area and the dynamic amplification coefficient of the accessory structure considering the roof vibration were determined. Next, circular and radial catwalks were designed based on static analysis. A sliding joint was set in the accessory structure to adapt to the large deformation of the roof. Finally, the required deformation of the sliding joint was determined, and the time history analysis of the accessory structure was carried out to ensure the safety of the structure.

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Experimental research on mechanical properties of CFRP tendons-wedge loaded under transverse compressive loading

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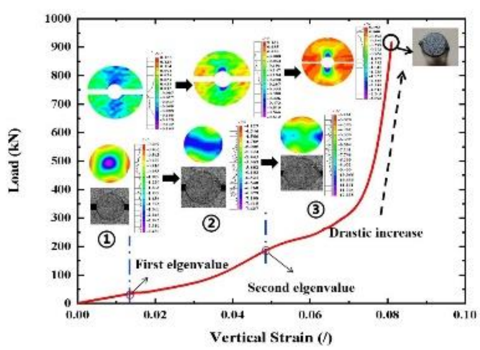

Carbon fiber reinforced polymer (CFRP) tendons have become a viable alternative for steel cable in the cable roof structures due to their high tensile strength, low weight and corrosion resistance. However, the effective anchoring is a challenge for CFRP tendons due to its poor transverse mechanical properties. Therefore, the mechanical properties of CFRP tendons and tendon-wedge assembly under transverse compression are investigated through simulating the force environment of CFRP tendon inside the integrated wedge anchorage. The deformation and local damage of CFRP tendons under transverse compression was discussed by load-strain curves and full-field strain measured by digital image correlation (DIC). The effect of tendon size and aluminum plate on the mechanical properties of CFRP tendons were compared based on the transverse compression testing. Experimental results show that the large diameter CFRP tendons with length from 90 mm to 110 mm have better cross-sectional deformation resistance and more stable transverse mechanical properties. Furthermore, the contact compressive stress on the surface of CFRP tendon were discussed through numerical analysis. At last, some suggestions of tendon size selection and integrated wedge design details are proposed for improving the anchoring properties and efficiency of integrated wedge anchorage.

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Experimental and numerical analysis of construction process for a saddle-shaped canopy roof in a large stadium

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The tensioning of prestressed cables during the construction of the large-span cantilever in a stadium is crucial to the safety of the structure. In this work, a saddle-shaped canopy roof with the height varies from 28.0 m to 46.6 m in a stadium is investigated. Finite element analysis for the tensioning process of the prestressed cables is carried out. According to the symmetry of the roof, the tensioning process of cables in the stadium is divided into twelve zones. Deformation control is used to control the prestressed values of cables. The results show that the roof deformation is uniform in the actual construction process, and the maximum displacement of the roof is less than the allowable deflection in GB50017-2017. The stress at the final state of the roof after removing the temporary frame is at a state with small values. The cable force, the displacement of the cantilevered end, and the stress of the members near the end of the radial tube truss are also monitored by field experiment. By comparing with the results of experiment, finite element analysis can effectively predict the construction process for a saddle-shaped canopy roof in a large stadium. The application of finite element analysis for the construction process can ensure the safe construction of the large-span cantilever and can provide a reference for the construction of large stadiums in engineering.

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Study on mechanical properties of prestressed steel cables

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High-strength prestressed steel cables serve as main load-bearing components for cable-supported structures, the mechanical properties are related to the safety of the whole structure. The authors have carried out a series of studies on the mechanical properties of high-strength steel wire, steel strand, Galfan strand, Semi-parallel wire cable and locked coil wire ropes. Through static tensile tests, bending tests, relaxation tests and steady-state tests at elevated temperatures, the tensile property, bending behavior, relaxation law and mechanical property reduction law under fire are obtained. Based on finite element software, the semi-refined and refined modeling method is proposed. The local stress distribution, interaction between steel wires, plastic development law and failure mode of the cable are studied. The calculation method and prediction method of relevant mechanical properties of cables is proposed, which provides a theoretical basis for the design and evaluation of prestressed structures.

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PTFE Membrane Roof over Tennis Court of Royal Selangor Golf Club Kuala Lumpur Malaysia

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This paper describes a design-and-build contract to provide cover to the tennis court of Royal Selangor Golf Club in Kuala Lumpur, Malaysia. The size of the roof structure is 40m×60m. The scopes of work cover design, engineering, fabrication and installation of PTFE membrane with hot dipped galvanized structure with build-in gutter and HDPE façade. The contract was awarded in June 2021. As the contract was awarded during COVID-19 pandemic time, various issues were faced which include limited site access due to strict standard operating procedures related to COVID-19 pandemic imposed by the government, increase in steel prize globally, difficulty in procurement of materials from oversea and inability to proceed with site as built to start production drawing. Value engineering was carried out with the consent of the client to reduce steel tonnage to overcome increase in price of steel. Various challenges were still faced even after some restrictions due to COVID-19 pandemic were lifted which include inability of supplier to supply and deliver raw materials and inability of galvanized factory to commit. Other than the above challenges faced, technical issues such as ground water level which affects the footings and necessity to design and fabricate steel members and PTFE membrane to be of smaller size to overcome logistic and installation issues. The above issues are elaborated in this paper together with solutions to overcome them.

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BIM in tensile membrane construction: Towards interoperability in a parametric environment

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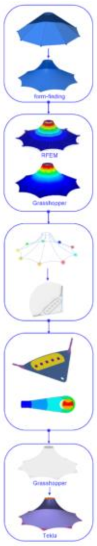

To enable transparent, collaborative processes in construction, Building Information Modeling (BIM) is becoming increasingly important. This working method can be implemented in different sectors such as civil, bridge and underground engineering. In tensile membrane construction, the advantages still remain unused because the framework is not available. Previous tools are insufficient because they are not compatible with each other and there is no uniform standard for data exchange, which makes collaboration in project planning difficult. The goal of this work is interoperability for a BIM toolchain in tensile membrane construction. Previous work has focused solely on the analysis of issues in the application of BIM in tensile membrane construction and highlights that there is no approach for a BIM toolchain. Against this background, the programming of a plugin and the use of additional components will enable the BIM process chain and thus interoperability. The goal is the elaboration and definition of a process chain, which includes a smooth exchange of data and different planning actors. This increases the BIM maturity level for tensile membrane construction and has the potential to optimize work processes in the long term. Since the planning process mainly takes place in the parametric environment Grasshopper, a higher computation time proves to be disadvantageous and depends on the project size. However, the application of the designed process chain allows the participants a collaborative process, which is of central importance for the architecture in tensile membrane construction, especially at the beginning of the project. In the course of this, an open, transparent and continuous planning process can be ensured. The individual planning actors are able to constantly expand and update the model. The holistic, continuous view allows to bundle the competencies of all and prevent errors at interfaces of cooperation.

SESSION 2

Tue, 20 Sep.

Parallel Sessions,

16:45-18:15

(90 minutes)

Realized Metal Projects (WG8-1)

Chair(s): Zhi Ma and Xiaoqun Luo

162

Design and analysis of an aluminum alloy spatial structure on Sansha Island

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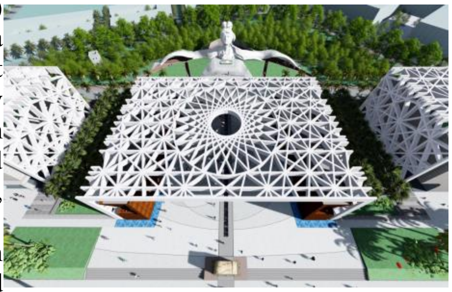

In order to promote the development of tourism, a landmark building (Figure 1) will be built on Sansha Island, Hainan Province, China. The structure consists of a kind of special grid (Figure 2), with a span of 60.2m, a width of 38.9m and a height of 15.1m. Aluminum alloy is widely used in the field of space structure as a new building material, because of its good corrosion resistance, light weight, high strength, good ductility and good moldability. And because of marine and atmospheric environments, aluminum alloy, which has good corrosion resistance, will be used as the main structural material of the building.
Firstly, the corrosion resistance of aluminum alloy and the reasons for the selection of main structural materials are introduced. Then the design difficulties and analysis process of the main structure are also introduced. At last, Three key issues are discussed: 1) how to reduce the deflection of the structure under the large island wind load; 2) how to realize the application of large section aluminum alloy beams; 3) how to improve the corrosion resistance of structure.

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Mechanical behavior of the complex intersection steel roof truss in TNFC stadium

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The Steel Structure roof in TNFC (Tianchang National Fitness Center) stadium is constituted with complex intersection steel truss, with diamond-shape. The main structure is composed of the radial plate truss, the outer annular three-dimensional truss and the folded plane truss. The staggered chord arrangement has the characteristics of complex force transmission way and difficult installation. Designning and construction analysis about the steel truss strcture in TNFC stadium were conducted in the meantime. In addition, disigning alaysis mainly included elastical and nonlinear method under dead load, live load, wind, snow, and temperature conditions. Nongeometric and material plastic were implemented in nonlear analysis. The construction area of steel roof was divided into zones 1~8 counterclockwise according to the building plane, and gradually installed from zones 1 and 8 clockwise and counterclockwise respectively. The construction sequence was as follows: Zone 1, Zone 8 → Zone 2, Zone 7 → Zone 3, Zone 6 → Zone 4, zone 5. 3D3S software was used to analyze the key construction points such as tube truss assembling frame, tube truss hoisting unit, tube truss temporary support scheme, tube truss closing and tube truss unloading scheme. Designning alaysis showed that the complex intersection steel truss roof in TNFC statium have a good mechnichal performance, the weak joints and manbrances were selected through nonlinear alaysis, beyond that some strengthed methods were applied into the steel tructrue. The construction analysis results showed that the hoisting point arrangement of pipe truss hoisting, the location and quantity setting of temporary supports, and the sequence of supporting and unloading have great influence on the stress of steel structure roof. Through several trial calculations, the reasonable lifting, supporting and unloading scheme was finally optimized.

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Research on key construction technology of large-span orthogonal arch truss hyperbolic roof

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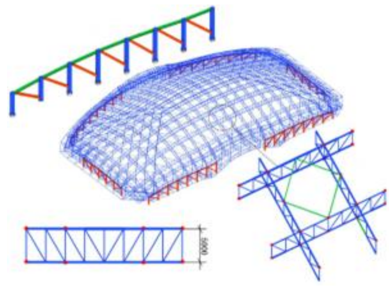

The large-span orthogonal arch truss hyperbolic roof can provide larger interior space, and can achieve ultra-high net height requirements by increasing the vector height [1]. In this paper, the structural characteristics of the central roof of China Motorcycle (Chongqing) entertainment complex project are analyzed. The roof structure is a bidirectional orthogonal grid with continuous changes in height, and the selection of construction scheme is limited by many factors. In view of the construction difficulties, the key technologies in each construction stage were simulated, analyzed and verified, and a reliable, economic and effective construction scheme was determined. Since the hyperbolic roof had few fulcrum points and large boundary expansion deformation occurred under vertical load, the construction scheme of "multi-point layered cumulative lifting & in-situ hoisting around the roof" was adopted. Considering the horizontal thrust of the roof was released through sliding supports, the whole roof structure was pre-deformed and the supports were pre-biased during installation to ensure that the sliding supports automatically reset to the center of the support column after unloading. Besides, in order to avoid sudden increase of structure deformation in unloading process or structural members exceed design capacity, the support frames in hoisting area were unloaded in batches before lifting points unloaded.

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Structure design of the steel roof of Hangzhou Xiaoshan International Airport Terminal 4

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To achieve architectural effect and effective structure performance, the integrated expression of architecture and structure has been more concerned in the long-span spatial structure design by unifying the architectural morphology and the structural mechanics logic. This article focuses on this topic from the following two aspects. First, the selection of supporting columns in long-span spatial structure was discussed in three dimensions which were the influence of roof shape, the constraints of substructure conditions and the expectations of architectural effect. The case study would give guidance for the supporting columns selection in spatial structure to achieve the coordination between attractive architecture and reasonable structure. Second, the steel roof structure design of Hangzhou Xiaoshan International Airport Terminal 4 which took the supporting column as the expression focus was introduced in detail. The introduction mainly focuses on the architectural intention and structure design of the lotus leaf column and the lotus valley column, which will illustrate how the integrated expression of architecture and structure worked in the building with long-span space design.

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National Ski Jumping Center (Xue Ruyi) Overall design strategy for the structure

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This paper briefly introduces the structural design strategy of National Ski Jumping Center （Xue Ruyi） from the aspects of engineering overview, natural conditions, reasonable value of wind load, the overall spatial stress system composed of roof truss, floor truss and internal and external ring diagonal bracing, the application of horizontal curve prestress, the control of structural personnel activities and wind-induced vertical vibration, foundation and so on.

SESSION 3

Tue, 20 Sep.

Parallel Sessions,

16:45-18:15

(90 minutes)

Concepts for Sustainable Innovation in Construction of Timber and Bio-based Spatial Structures -1 (WG 12-1)

Chair(s): Tetsuo Yamashita and Yinlan Shen

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Building crossings in wicker: flexible construction of a post-formed footbridge in active bending stiffened during service phase

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The first traces of basketry date back to the Sumerian's period (4000 years BC). From now on, these braiding techniques have been used to craft vernacular shelters, clothes, furniture and tools. However, they are uncommonly used in architecture and are generally limited to non-structural filling elements.
To our knowledge, the Baya project (named after the nests of bayaweavers, birds which are experts in the art of braiding), was one of the first examples of a braided wicker structural shell in architecture. Based on the braiding optimization algorithm developed during this previous project, our research intends to question one step beyond: crossings. This innovative research is demonstrated by the realization of a 12.8-meter-long footbridge for the Utopies Constructives festival in Richelieu's Park.
The footbridge, which echoes the reed boats of the Uros, a Peruvian tribe, will be braided flat before being moistened and shaped by buckling; then it will be stiffened post-buckling by braiding the railings together. Building in a flexible way, then stiffening during the service phase is both the constructive process of elastic gridshells and the one used by basket weavers who braid the green wicker, which then stiffens once the object is formed. Using light material and an inverted quasi-catenary arc raises two questions: 1- How to maintain the shape when the live loads are far more important than the dead loads? 2- How to avoid the sliding of the wicker braiding stitches along with the deformation of the structure? Our study will compare the measurements obtained on physical models of different scales with those anticipated by calculation using the dynamic relaxation method.

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Buckling experiment of timber arches formed by bending

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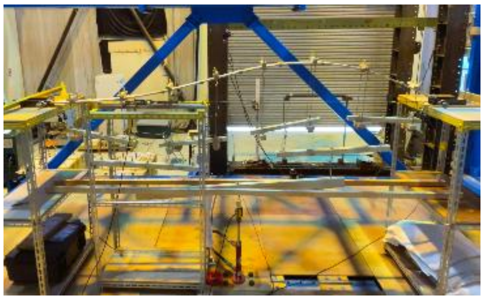

To date, there have been many studies on form-finding of elastic grid shells, however not enough studies on buckling capacity on them. Since elastic grid shells are constructed by deforming the members, pre-stress is introduced, and it decreases the buckling capacity. This study focuses buckling of timber arches formed by "active" bending (called "pre-stressed arches" hereafter) and investigates reduction of buckling capacity due to pre-stress through experimental study. Firstly, a pre-stressed arch was formed by applying Euler's critical compression to a flat timber bar, then equally distributed gravity loads was given until the arch was buckled and collapsed. Secondly, the simulation of the experiments considering above-mentioned test procedure with nonlinear FE analysis was conducted. As a result, good agreement is obtained between the buckling behavior of the experiments and the analysis. Besides, the result of this study has been validated by comparison with previous similar studies that were conducted by others. This validated result will give a solid fundamental to our future study on timber pre-stressed shells' buckling capacity.

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Stock optimization of naturally curved wood logs on freeform truss structures

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This paper presents an optimization method for incorporating discarded naturally curved wood logs onto a freeform gridshell with a predefined topology. Though still little explored, the research field of reusing structural elements is experiencing increasing attention owing to its significant potential to reduce the environmental impact of building design. However, several constraints must be considered as the optimal structure depends on stock availability and the corresponding geometry and material properties of that given stock. Therefore, focus is on determining the best configuration of stock elements considering the defined design objectives and constraints. The proposed method is a topdown approach, as the global topology of the structure is predetermined. Multi-objective optimization is conducted using the Strength Pareto Evolutionary Algorithm 2 (SPEA2) and a modified genetic algorithm with permutation encoding in the form of ordered crossover and scramble mutation. Furthermore, this paper introduces a Team-Based Repair (TBR) algorithm that increases the likelihood of each solution being valid for analysis. The performance of the optimization method is demonstrated on a curved gridshell structure, and the effect of the different design objectives and stock sizes on the final design is analysed and discussed.

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Planar rectangular, slide-in reciprocal frame structures using salvaged timber and wooden nails

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In this paper, we present a preliminary investigation of planar rectangular reciprocal frame (RF) structures considering structural, architectural, environmental, fabrication and assembly aspects. Following a timber-only concept and a low-tech design philosophy, we specifically propose to use salvaged timber and wooden nails only, as materials for fabricating and connecting RF structures, which is in line with an ongoing research project that has initially investigated the characteristics of salvage timber and the structural behavior of wooden nail connection. The present experimental investigation focuses on the single multi-layered element in a basic layout of a four-element planar rectangular RF unit. The single elements are fabricated out of small timber boards to create an opening that serves as a slide-in connection for the ease of assembly. We experimentally investigated the structural behavior of the single element in the proposed unit under bending loads. We also explored the assembly process and the resulting patterns by using the proposed approach to build RF structures. Moreover, to showcase the structural and architectural features of the proposed RF unit, a design case was physically realized.

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Characterization of mechanical properties and numerical modeling approaches for mycelium composites

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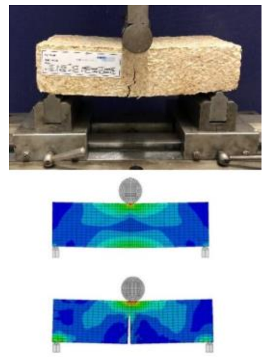
Mycelium-based composite materials are currently enjoying great popularity, and their use is widely discussed, especially for technical applications. For the use of mycelium-based composite materials as load-bearing material, knowledge about the mechanical properties of the material and its performance in load scenarios is of central importance. Besides experimental investigations, the simulation of the material in a numerical model presents itself as a useful tool to evaluate the load-bearing behavior of structural components, which can be used to predict the load-bearing capacity. In this paper, different approaches for the numerical representation of the material behavior are investigated and discussed. Comparing three material modeling approaches shows that their use can successfully represent the essential characteristics of the load-deformation behavior of the simulated experimental tests.

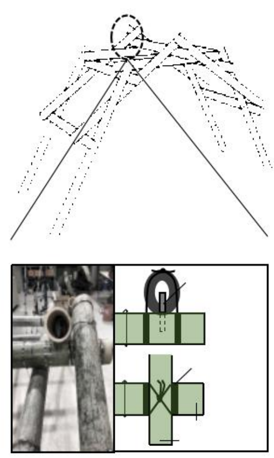


547

Basic research on structural properties of bamboo arched reciprocal frame structure with joinery by means of PVC pipe

Sokol Phon. The University of Fukui sokolphon@gmail.com

Bamboos have the potential to contribute to the development of more sustainable construction industry. However, Bamboos in the construction field are limitedly used as only a non-structural material such as a finishing material and are rarely used as a structural material, due to the limited understanding of the use of bamboo culms as building materials, including suitable methods for determining its material mechanical properties, joinery techniques and structural systems. This study will explore the possibility of expanding the use of bamboo materials by fundamentally investigating the structural properties of the bamboo arched reciprocal frame structure (ARF) considering the stiffness of the joint system by means of PVC pipes. The Moso bamboo bending experiment will be carried out and the parameters necessary for the connection modeling can be accumulated based on the connection experiment considering variation in external diameters of PVC pipes. The configuration processing is by means of a computational geometric algorithm. Elasto-plastic numerical analysis and full-scale tests are conducted and compared to investigate the force flow and the collapse behavior of the structure. The empirical data of Moso bamboo culms, the results of connection modeling, and the basic investigation of the structure provided in this study will be useful for the structural analysis of the whole ARF, thereby encouraging the use of bamboos in ARF for sustainable construction.



SESSION 4

Tue, 20 Sep.

Parallel Sessions,

16:45-18:15

(90 minutes)

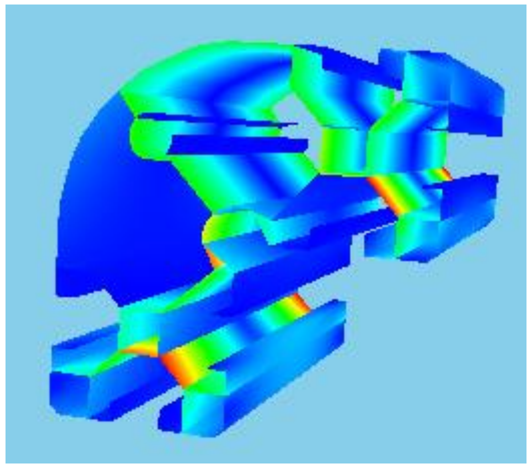
Computational methods for spatial structures and collapse
(WG 13-1)

Chair(s): Carlos Lazaro and Jianguo Cai

15

TCTM - Analysis program of complex thin-walled member based on Umansky and Vlasov theory

Shuxiang Zhang. Tongji University. 2110051@tongji.edu.cn

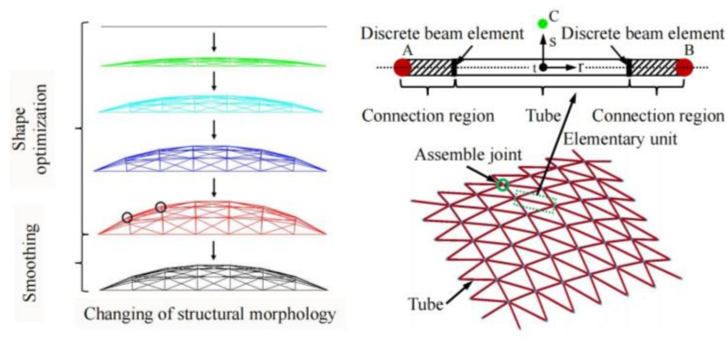


Due to the characteristics of light weight, high strength and full utilization of materials, thin-walled members are widely used in structures. This paper introduces the fundamentals and explains the application and potential of TCTM (Torque Calculator of Thin-walled Members). Based on Umansky's closed cross-section theory and Vlasov's open cross-section theory, combined with computer graphics, the program can complete the section characteristic calculation and mechanical analysis of any complex thin-walled section. The main functions of the software are (1) to analyze the section characteristics of complex thin-walled sections, including open, closed and open closed mixed sections (2) to analyze the internal force according to a variety of boundary conditions and loads. In particular, the derivation and display of relevant parameter distribution formula are included for torque load (3) draw the nephogram of analysis results. After briefly describing the basic theory of TCTM, this paper introduces the capabilities and innovative aspects of the program, and explains it through several related examples. In addition, this paper describes the graphical user interface of the program, and mention the relevant options and calculation process in the main program.

70

Research on the collapse performance and collapse capacity improvement method of fabricated free-form single-layer grid shell

Zhijie Zhang. School of Civil Engineering, Southeast University. 230198116@seu.edu.cn

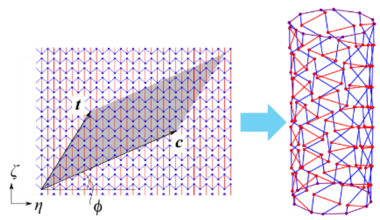


To prevent progressive collapse when accidental loads occur, research on the collapse performance, collapse mechanism and optimization method to improve the collapse capacity of fabricated free-form single-layer grid shells were conducted. Firstly, a free-form single-layer grid shell was designed with the shape optimization method considering the influence of structural imperfection. Then, the refined analysis model was established by using the discrete beam element to simulate the semi-rigid performance, bearing capacity degradation and rigidity degradation of assemble joint. The accuracy of the analysis model was verified by comparing with the experimental results. Besides, the computational formulas of the component importance index and the structural robustness indicator were proposed considering both the sensitivity and vulnerability of components. Finally, the collapse process of the fabricated free-form single-layer grid shell was analyzed and the effect of component failure on the structural collapse process was discussed. The research results realized the collapse process simulation and collapse resistant capacity evaluation of fabricated single-layer grid shell structures.

116

A shape design method of discrete cylindrical structures tiled with auxetic hexagonal units

Yusuke Sakai. Department of Architecture and Architectural Engineering, Kyoto University (currently: Sony Computer Science Laboratories, Inc. Kyoto Laboratory). yuusuke.sakai.1@gmail.com

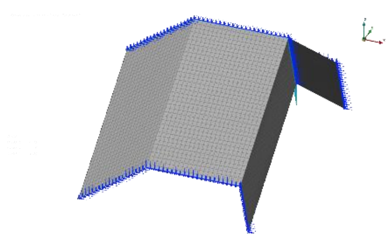


We propose a method for shape design of a cylindrical structure tiled with hexagonal units. Auxetic structures, which have a negative Poisson's ratio, compressed in a uniaxial direction shrink in the transverse direction. Their specific mechanical property is caused by the geometrical configuration. A cylindrical structure consisting of auxetic units designed by discrete members is used as a flexible actuator, energy absorber, and so on. However, there have been still few shape design methods for discrete cylindrical structures. To develop a variety of discrete cylindrical structures, it is crucial to propose a shape design method easy to use by general designers. We utilize the existing formulation representing a geometrical configuration of carbon nanotube, and extended it to obtain a surface of a discrete cylinder by rolling up a parallelogram filled with uniform hexagonal units with 2-rotational symmetry. This extended method enables us to generate a variety of geometrical configurations of discrete cylindrical structures from those close to a carbon nanotube to those composed of units with negative Poisson's ratio arranged in spiral. In the numerical examples, various shapes of discrete cylindrical structures are parametrically generated, and we investigate the mechanical properties of several models by carrying out large-deformation analysis. Note that the models exhibit a remarkable specific deformation behavior, namely a torsion–compression coupling.

160

Numerical analysis of sheet metal folded sandwich core structures

Simon Thissen. Insitute of Aircraft Design (IFB), University of Stuttgart, Pfaffenwaldring 31, 70569 Stuttgart, Germany. simon.thissen@ifb.uni-stuttgart.de

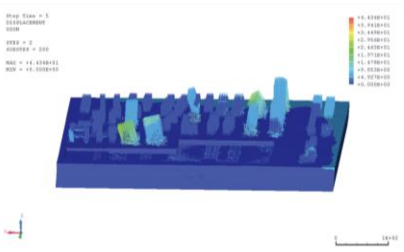


The use of sheet metal materials for folded origami sandwich core structures offers excellent weight-specific mechanical properties for a wide range of applications. The thin-walled metal sheets yield high stiffness and compressive strength compared to previously used thin paper, plastic or aluminum sheets. However, the folding process of the sheets requires increased tooling effort and results in significant deviations from the design geometry called imperfections. Furthermore, adequate preforming of the folding edges becomes necessary. For design and prediction of the mechanical properties of the sheet metal foldcores, a finite element analysis (FEA) approach is used. In the analysis, the effects of changed material properties and its high anisotropy as well as the influence of imperfections and pre-forming at the folding edges are considered. The numerical simulations are validated with test data of sheet metal foldcore samples based on an adapted Miura-Ori tessellation. The FEA shows good agreement with the mechanical tests and is therefore suitable to be used for the design of foldcore structures made of sheet metal material.

545

Parallelized implementation of finite particle method for structural collapse analysis in urban area

Yuxiang Cai. Zhejiang university. 11812051@zju.edu.cn



This paper develops a GPU-accelerated parallel computing program with finite particle method using the Compute Unified Device Architecture (CUDA) based on Finite Particle Method (FPM) in dealing with large-scale nonlinear problems and efficient simulation. this paper applies the FPM computing program in two collapse cases in urban area. Case 1 simulates the seismic response of a regional-scale building group considering the structure-soil interaction to research the impact of the effect of the building group on the dynamic response of a single building, and briefly analyzes the computing efficiency of FPM platform with ABAQUS in dealing with this large-scale complex model. Case 2 is an actual engineering model, which simulates a urban area including foundation pits, tunnels and surrounding buildings, and discusses the catastrophe of the structure-soil system under the condition of strong nonlinear discontinuity such as fracture and damage of the structure during an earthquake response.

SESSION 5

Tue, 20 Sep.

Parallel Sessions,

16:45-18:15

(90 minutes)

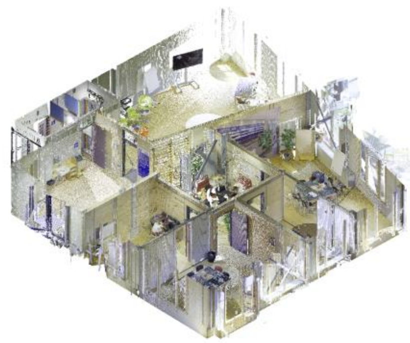
Sustainable Heritage: Challenges and Strategies in the Preservation and Conservation of 20th Century Historic Concrete Shells-1 (WG17/WG5-1)

Chair(s): Marisela Mendoza and Stefano Gabriele

88

Reality capture and site-scanning techniques for material reuse planning

Matthew Gordon. ETH Zurich. mgordo@ethz.ch



The reuse of building materials requires both broad-ranging and detailed information on available building stocks in order to effectively plan for connecting available materials with their eventual reuse in new buildings. Critical information includes component counts, dimensions, and on-site locations. Currently, this information is usually gathered using manual measurements, though contemporary digitization and scanning technology can be used to efficiently gather dimensional and geometric data about pre-demolition sites. The primary digital technologies to automate this data gathering, being photogrammetry and terrestrial Light Detection and Ranging (LIDAR), have historically shown significant gaps in efficiency and accuracy, while their hardware and software systems are rapidly advancing in capabilities. In this study, contemporary implementations of these methods are compared for their efficiency, interior coverage, and raw accuracy across two case studies with significant geometric differences. These results inform decision-making regarding the appropriate integration of these technologies in industry and identify technologies that require more development for effective use.

115

A study on the structural system and history of the Former Kagawa Prefectural Gymnasium

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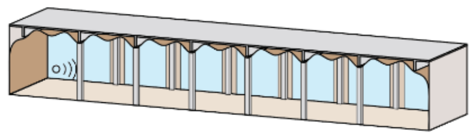
The former Kagawa Prefectural Gymnasium was built on August 10, 1964, to serve as a place for the people of Kagawa to meet and promote sports culture.At present, 57 years have passed since the museum opened. The building was closed in September 2014 due to concerns about aging equipment and insufficient seismic performance. However, despite three unsuccessful bids and an increase in the budget, the current situation could not be improved, and plans for demolition and construction of a new Kagawa Prefectural Gymnasium are underway. The buildings under study were designed by architect Kenzo TANGE and have strong ties to the region of Kagawa Prefecture, making them important architectural works[1]. The site was included on the 2018 World Monuments Watch. The purpose of this study is to analyze the transition and structure of the former Kagawa Prefectural Gymnasium, which is a spatial structure, and to provide clues for proposals regarding its preservation and utilization.

161

Revisiting the Viipuri Library: Assessing performance and design trade-offs in custom ceiling geometry

Jonathan M. Broyles. The Pennsylvania State University. j.broyles@psu.edu



The undulating ceiling in the lecture hall of Alvar Aalto's Viipuri Library was designed based on ray-tracing drawings to estimate the acoustic performance. This is an example of graphical analysis that was more common before computers. However, recent research has questioned Aalto's original acoustical claims. While computational methods might provide opportunities for more accurate early performance assessment, acoustic goals remain difficult to define and simulate. Furthermore, building design is increasingly driven by sustainability objectives, which have stimulated interest in shaping spanning structures to reduce structural material. For both the Viipuri example and other future buildings, questions remain about how designers should consider room acoustics when designing floor and ceiling assemblies. In response, this paper investigates the influence of custom ceiling geometry on acoustical and sustainability objectives, using the Viipuri Library as a case study. A parametric design space was created to range from a flat ceiling through the actual Viipuri geometry to other curved ceilings. Both an acoustic analysis using ray-tracing and image sourcing and a structural analysis are conducted for each design candidate. The results indicate that shaping influences both structural efficiency and room acoustics when floor-to-floor height is significantly constrained. Geometric changes have a similar magnitude of impact as material changes for sound intelligibility and attenuation but altering the surface material has a larger effect for sound decay and clarity.

232

Preliminary research of preprocessing of images for ceiling damage inspection using machine learning

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Ceiling collapse is extremely dangerous especially in rooms with wide space and high ceiling height. Facility managers of such rooms strive to find signs of ceiling failure through regular or ad hoc inspection. However, it is very difficult to detect unfavorable change without comparing past situation in detail. In the research, a defect identification system is developed by researching automatic comparison of the latest image with the past image of the facility. These images may be collected by managers with a smartphone at almost the same position during daily check. These images normally involve not only signs of dangerous failure but also difference due to sunlight condition or photographic position. There are possibilities to develop intelligent inspection systems that detect only dangerous change, using machine learning. In this report, the authors propose a novel preprocessing method that excludes changes which are not significant and check its validity through case studies.

485

Cristo del Consuelo church in Ecuador by Luis Monsalve. A replica of Candela's San Vicente de Paúl chapel

Mauricio Luzuriaga. Universidad San Francisco de Quito. mluzuriaga@usfq.edu.ec

From 1950 to 1970 Félix Candela, the Wizard of the Shells, became one of the most visible architects in the world. He popularized the construction of beautiful concrete thin shell structures, especially hyperbolic paraboloids. Los Manantiales Restaurant in Xochimilco, San Vicente de Paúl Chapel in Coyoacán, Chapel Lomas in Cuernavaca, all in Mexico are among his emblematic creations. As happens with other modern architecture archetypical projects, buildings inspired by Candela's principles keep being replicated. 1958s San Vicente de Paúl chapel by Enrique de la Mora y Palomar, Fernando López Carmona and Félix Candela in Coyoacán-Mexico City, has seen a handful of replicas in various countries, Ecuador included.
Ecuadorian engineer Luis Monsalve designed and built more than thirty double- curvature shells in the Andean south of the country. His accomplishments have just started being unearthed. One outstanding piece is Cristo del Consuelo church in Déleg. The roof of the temple starts from five supports in a pentagonal arrangement from which five spindly hypars rise. This work is inspired by the three-hypar temple in Coyoacán. Site surveying and interpretation of construction photos are used to reconstruct and understand the history of an engineering jewel that expresses the Ecuadorian 20th Century architectural Zeitgeist.

SESSION 6

Tue, 20 Sep.

Parallel Sessions,
16:45-18:15
(90 minutes)

Aluminum Alloy Structures - 1

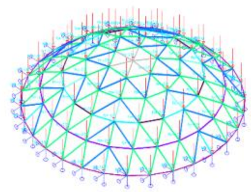
Chair(s): Huiyong Ban and Yuanwen Ouyang

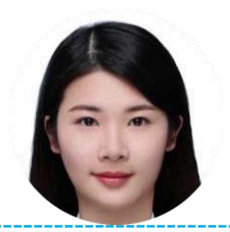
202

Application of 6A13-T6 high-strength aluminum alloy grid structure

Ruoqiang Feng. Southeast University. hitfeng@163.com

To solve the application problem of 6A13-T6 new high strength aluminum alloy in grid structure, experimental and numerical simulation studies were carried out. ABAQUS establishes the finite element model, and the compression performance of the member is studied after the test verification. The mechanical properties of the aluminum alloy grid structure were investigated by numerical simulation. The results show that the non-proportional yield strength of 6A13-T6 is f0.2 is 340 MPa, the ultimate strength is 352 MPa, and the elongation after fracture is 14.5%. The initial defects of the members have some influence on the bearing capacity of the members, but the overall and local defects have little effect. With the increase of member eccentricity, the bearing capacity of members will decrease significantly. The prediction of bearing capacity of 6A13-T6 high strength aluminum alloy axial compression members in Chinese code is conservative. The use of 6A13-T6 aluminum alloy can improve the grid structure's economic benefit and safety reserve.



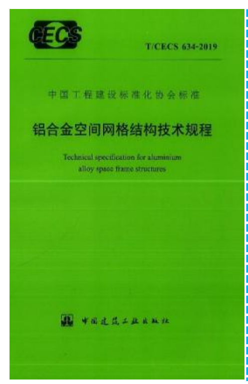


250

Preparation of technical specification for aluminum alloy space frame structures

Jiaojie Ying. Dept. of Civil Engineering, Tianjin University. jj_yingzzz@163.com

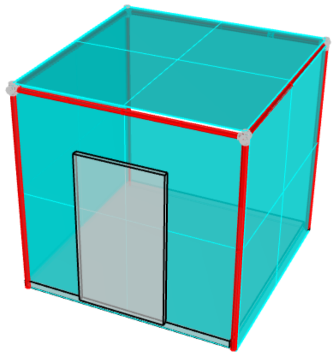
Aluminum alloy is widely used in space frame structures because of its low density, good corrosion resistance, high strength, excellent processing performance and cold environment adaptability. However, the existing design code of space frame structures are mainly for steel structures, while not suitable for aluminum alloy structures. In order to ensure the safety of the design and construction of aluminum alloy space frame structure and promote the further popularization and application, Technical Specification for Aluminum Alloy Space Frame Structures (T/CECS 634-2019) stipulates the design regulations, structural calculation, design and construction of members and joints, fabrication, installation, protection and acceptance. According to the characteristics of aluminum alloy space frame structures, this paper introduces the compilation of the code from the aspects of material properties, structural calculation and design of members and joints, and makes a comparative analysis with Technical Specification for Space Frame Structures (JGJ 7-2010).



345

Research status and prospect of modular rapid detachable biological detection aluminum alloy building structure system

Wenhao Shi. Department of Civil Engineering, Tianjin University. 3137250482@qq.com

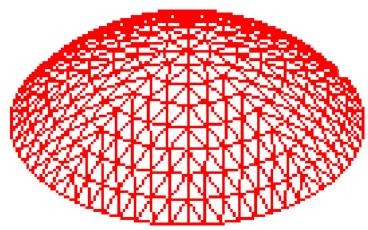


The rapid spread and frequent mutation of COVID-19 virus pose a serious threat to the lives and health of people around the world. It is urgent to rapidly build a large number of high-level biosafety laboratories around the world to obtain the genetic sequence information of the virus, develop detection reagents and vaccines. This paper introduces the concept, classification, architectural structure design and construction process of biosafety laboratory, but the traditional architectural structure and construction mode of biosafety laboratory cannot meet the needs of rapid construction, and cannot realize the assembly and disassembly. As the building structure form with the highest degree of integration, modular structure system provides an effective solution for the rapid and safe construction of biological laboratories. This paper summarizes the modular structure system, unit types and connection modes between units, etc. However, the existing modular structure is mainly steel structure, which is difficult to meet the high anticorrosion requirements of daily operations. Aluminum alloy has the advantages of light weight, high strength, low temperature resistance, good corrosion resistance, good modulability and so on. It is widely used in many engineering fields, especially in various special environments. The application status of modular aluminum structure and the prospect of modular rapid dismountable biological detection aluminum alloy building structure system are introduced, which can provide a reference for the future structural system research and development in response to emergencies including epidemic prevention and control.

523

Comparison of mechanical performance and stable capacity between aluminum alloy- and steel spatial grid structure in the process of fire

Fengjie Tan. Arcplus Group PLC. fengjie_tan@arcplus.com.cn



Spatial grid structures are getting prosperous as an architecture form in recent years, usually used in functional gymnasiums, convention and exhibition centers, museums, airports and other places. So far, the most commonly used materials for such kind of spatial structures are steel and aluminum alloy. Comparing to steel, the mechanical properties of aluminum alloy degrade greatly at high temperatures, the thermal conductivity of aluminum alloys is about three times that of steel, which indicated that the heating rate of aluminum alloys is faster than that of steel, and compared with steel, aluminum alloys have twice the thermal expansion coefficient. As a result, these properties would bring totally different performance characteristics at elevated temperatures for the spatial structure with these two materials. The analysis shows that under the same fire scene, the stable capacity of steel grid structure is less affected by temperature, however, it is maily affected by the increases span and decrease rise-span ratio. The stable capacity of aluminum alloy grid structure is greatly affected by boh of temperature, span, and rise-span ratio.

SESSION 7

Tue, 20 Sep.

Parallel Sessions,

20:00-21:30

(90 minutes)

Masts and Towers (WG4)

Chair(s): Bo Chen and Xudong Zhi

5

Castanea Sativa Reciprocal Frame, inspired by Friedrich Zollinger

Prof. Dr. Christopher Robeller. University of Applied Sciences Augsburg. cr@robeller.net

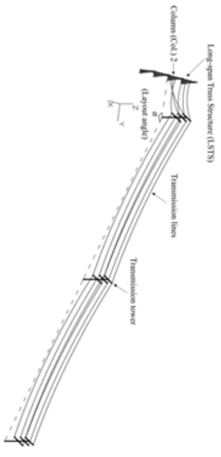
We present an assembly- and fabrication aware reciprocal frame construction system that exploits new possibilities of the latest generation of automatic joinery machines. Sweet chestnut wood (Castanea sativa), is a species that is currently not used for building construction in Germany. The wood of castanea sativa is highly durable and ideal for ext erior conditions, but it will corrode metal connectors unless they are stainless steel. Therefore, our system uses only digitally fabricated wood-wood dovetail joints. It was inspired by Friedrich Zollingers "Zollbauweise", in its geometry as well as its philosophy – while adding a second curvature to increase stability and considering assembly constraints of the dovetail joints.

51

Effect of fold-line transmission tower-line system on seismic responses of long-span truss structures in UHV substation

Jun Gong. School of Civil Engineering and Geomatics, Southwest Petroleum University. jun.gong@swpu.edu.cn

Earthquake damage data show that the long-span truss structures (LSTSs) in substations suffered serious damage and even collapsed under strong earthquakes, especially for those LSTSs coupled with transmission towers and lines outside the substation. This study numerically investigates the seismic responses of LSTS by considering the dynamic interaction in the fold-line transmission tower-line system. The fold-line LSTS-tower-line coupling system is modeled in the FE package ABAQUS. Seven far-field ground motions are selected as the excitations, and four layout angles (i.e., 90, 120, 150, and 180 degrees) are considered to investigate the seismic responses, failure modes, and bearing capacities of LSTS. The results indicate that the seismic responses are slightly affected by the layout angle, showing an average reduction of 6.4%, 4.3%, and 3.3% for 90°, 120°, and 150°, respectively, when compared with that conditioned on 180°. In addition, the layout angle has little effect on the failure mode of LSTS, and all LSTSs brittlely collapse out of plane caused by a local failure. The bearing capacity has a maximum difference of 14.2%, 19.6%, and 13.7% for 90°, 120°, and 150°, respectively, when compared with that corresponding to 180°, but the average differences are < 5.0% for the former three layout angles, illustrating that ignoring the layout angle influence on LSTS seismic design capacity is acceptable.



175

Topological optimization of lightweight tower systems for onshore wind turbines

Patrick Schäferling. TU Dresden, Faculty of Architecture, Chair of structural design
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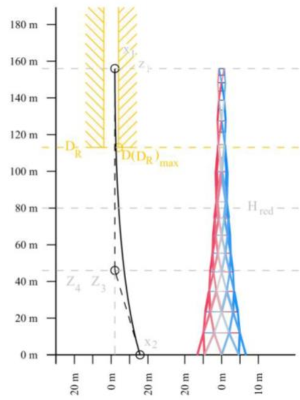
Wind speed increases significantly with height above the ground. This faster and more consistent wind at higher altitudes can be directly translated to an improved capacity of wind turbines. But material costs of the construction play an important role for tall towers. Especially at heights of 160m and above, rolled tubular steel towers reach their economical limits. To further improve the performance and economy of wind turbines, th e efficiency of the tower structure must be drastically increased. The paper presents the approach of a circular lattice structure as a tower for wind turbines. A first attempt is made to compare it with other common types under given boundary conditions. The objective of the study is to minimize the construction mass through a topological optimization process of the global shape and meshing of the steel structure.



SESSION 8

Tue, 20 Sep.

Parallel Sessions,

20:00-21:30

(90 minutes)

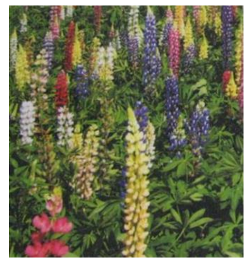
ETFE Film Applications (WG6-2)

Chair(s): Stefan Lehnert and Jianhui Hu

39

New ETFE film with a glass-like appearance for architectural applications

Hiroshi Aruga. AGC Inc. hirosi.aruga@agc.com



We made a prototype of transparent ETFE film. The transparency of the film can be expressed by the haze value. To obtain glass-like transparency, it is effective to change the resin sequence of ETFE. The haze of the prototype film is 2% at 250µm. This Type X has a stress of more than 25 MPa at 10% strain. In addition, the creep performance at 50°C is smaller than that of the conventional ETFE film (Type N). It also has high resistance to MIT bending tests and repeated tensile fatigue tests. So, we could improve both transparency and mechanical strength. In addition, the weather durability of Type X is evaluated by carbon arc (S.W.M.) and metal halide lamp (SUV). In the exposure test equivalent to 10 years outdoors, there was no change in optical characteristics and mechanical strength. And, printing films and colored films using Type X can be manufactured with the same weather durability as conventional Type N. In addition, the combustion characteristics of conventional ETFE are maintained.

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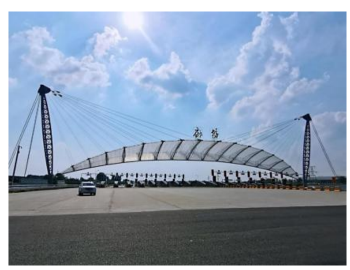
Design and construction of a large-span integrally tensioned structure with ETFE roof

Lemei Wang. Beijing N&L Fabric Technology Co., Ltd. 38518108@qq.com



This paper is based on the design and construction of a large-span integrally tensioned structure with a ETFE roof supported by bidirectional cable net. With its elegant architectural style, the project provides a landmark building of new concept for the field of public transportation. The maximum span is about 164.2m and the high transparent ETFE roof covers a area of 3840 m2. An equilibrium structural system with sufficient load-bearing capacity is obtained by tensioning the cables and the membrane surface. New approaches and new techniques have been used in the analysis, design, fabrication and construction of this project. Optimal design and reasonable construction scheme not only ensure the stability of the structure, but also shorten the construction period and reduce the cost. The determination of the prestress level if very important for a flexible structure and it is a crucial step in design optimization. High precision and high standards are required through the entire process.

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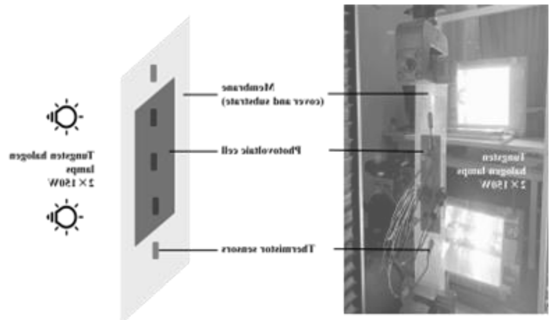
Experimental study on the photoelectric-photothermal-mechanical properties of new PV-ETFE foils

Yongsheng Yan. Space Structure Research Center, Shanghai Jiao Tong University. yys1217@sjtu.edu.cn

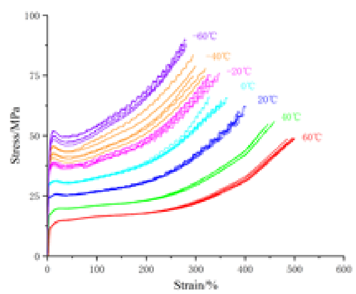


PV-ETFE structure combines ETFE foil and flexible photovoltaic panels(PV), making it possible to harvest electricity from solar energy and achieve flexible and lightweight building design simultaneously. However, solar energy conversion efficiency of PV and mechanical behaviors of ETFE foils are affected by high temperature resulting from photothermal effects. It is critical to understand the photothermal-photovoltaic-mechanical performance of PV-ETFE materials. Therefore, the development and evaluation of the new PV-ETFE materials are described in this paper. The developed PV-ETFE foils were tested to understand the relationship between conversion efficiency and temperature under different solar radiation conditions. Uniaxial tensile tests were carried out to understand the mechanical performance of the new material under solar radiation and to demonstrate the practical engineering applicability. The cell cracking and voltage variation during the stretching, as well as the breaking form of the materials, are obtained. It is found that the solar energy conversion efficiency of PV is mainly determined by temperature and solar radiation intensity. Before the material reaches the first yield point, the PV cell functions well and does not crack. The PV cracking is mainly caused by large deformation and the crack has less impact on the photovoltaic performance. These results prove that this new PV-ETFE material can be used in construction and provide reference for the design of ETFE structure integrated PVs.

249

Influence of high and low temperatures on tensile properties of ETFE film

Jinhe Chen. College of Civil Engineering, Tongji University jinhec@tongji.edu.cn

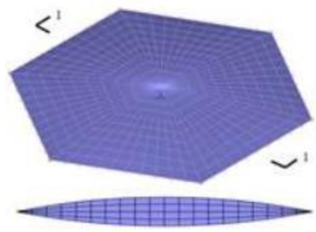


Uniaxial tensile tests at room temperature (23±2□) and from -60 □ to +60 □ were performed in order to investigate the mechanical properties of the traditional ETFE film and a new developed ETFE film with low haze and high strength. The yield stress, the yield strain, the tensile strength, the elongation at break and the elastic modulus of the two kinds of ETFE film were obtained and compared. It is found that compared with the traditional ETFE film, the strength of the new ETFE film is improved. Linear fitting formulas were also determined to show the influence of temperature on their mechanical properties.

268

Influence of wrinkling deformation on the bearing capacity of ETFE cushions

Xiaofeng Wang. School of Civil Engineering, Beijing Jiaotong University. wangxiaof@bjtu.edu.cn



ETFE cushions are a kind of flexible structure very sensitive to wind load. Wrinkling deformation changes the stress distribution of the enveloping membrane and then significantly affects the performance of an ETFE cushion under wind. This paper aims to study with the finite element method the effect of winkling deformation on the bearing capacity of ETFE cushions subjected to wind. The winkling model based on the stability theory of plates and shells is adopted to obtain the winkling deformation through the post-buckling analysis. The wind load is simplified as the uniformly-distributed load on the top membrane. The inflating air is treated as the linear potential-based fluid to consider the effect of air-membrane interaction. The finite element model of a hexagonal ETFE cushion is developed with the commercial finite element software ADINA and its bearing capacity under the influence of wrinkling deformation is numerically explored for different initial internal pressures, side lengths and rise-to-span ratios. The results show that (a) Wrinkling deformation will decrease the bearing capacity of an ETFE cushion with a transfer between the strength failure and instability failure; (b) Influence of the wrinkling deformation varies significantly when the parameters studied are within certain ranges. The present research is helpful to the understanding of the mechanical behavior of ETFE cushions for reliability in the design and engineering application.

392

Comparison of application of STFE and ETFE membrane material in roof structures

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ETFE membrane material is a kind of fluoropolymer film and it shows light architectural view and excellent transparency. However, the strength of the film is relatively weak because of its ultra-thin thickness. STFE membrane material is a new type of membrane structure material which is composed of high transparent fluoropolymer film and high strength polyarylate fabric grid. High strength ability would be afforded with the fabric grid, which greatly improves the crossing capacity of the skin. Comparison analysis are performed evaluate structural performance of roof structures between STFE and other materials such as ETFE. A roof structure of a dedicated soccer field is chosen for the objective of the study. To keep the lightness of the roof, the ETFE skin of the roof should be supported by a sub-structure with a cable-net system and then the sub-structure is installed on a main cable structure. The construction difficulties of the superimposed cable structure would be discussed. As an alternative way, the STFE skin is designed and the ease of construction is also compared with that of ETFE skin. By comparison between the two roof systems, the usage of new style STFE material is evaluated to widen the application of new membrane material, which also push the development of membrane structures in spatial structures.

SESSION 9

Tue, 20 Sep.

Parallel Sessions,

20:00-21:30

(90 minutes)

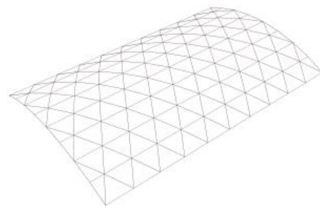
Buckling of Metal Spatial Structures - 1 (WG8-2)

Chair(s): Hua Deng and Xiongyan Li

134

Elastic buckling mode of cylindrical lattice shell roofs made of H-shaped steel

Midori Hashimoto. Kogakuin University. dm22055@g.kogakuin.jp



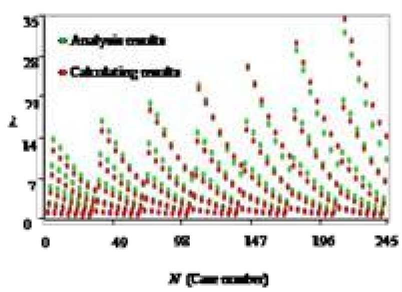
In designing a latticed shell structure, we should concern buckling. On steel triangularly-latticed shells, H-shaped section, which has strong and weak axes, are more preferably to be used. Since its bending stiffness on the strong axis is several times of that on the weak axis, it is expected that in-plane member buckling is more likely to occur than out-of-plane overall buckling.This study deals with the cylindrical latticed shells composed of triangle lattices. The latticed shells are subjected to static gravity load. We conducted geometric nonlinear analysis on the latticed shells in which member buckling appeared as the 1st eigenmode in linear buckling analysis. As a result, on the pin supported shells, overall buckling occurs when the ratio of the lowest linear buckling load of overall buckling to the 1st linear buckling load of member buckling, was smaller than 1.5. On the roller supported shells, overall buckling was observed in the models even though member buckling was found in the 1st eigenmode in the linear buckling analysis. The newly found buckling characteristics are compared to those found in the previous study on spherical latticed shells.

315

Approximate Equation for Evaluating Global Buckling Load of Single-Layer Cylindrical Space Frames with Crossing Pattern

Baoxin Liu. Kyusyu Institute of Technology. wuyezi894427800@gmail.com

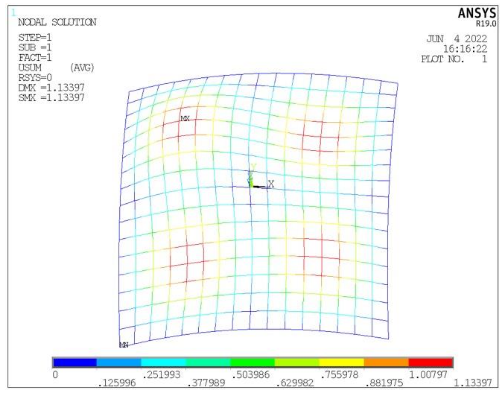
This study attempts to promote an approximate equation to evaluate the global buckling load for a single layer space frame without mechanical buckling analysis. Unlike the previous researches deriving the buckling evaluation equations by mechanical-analytical manners, this study attempts to fit the approximate equation through regression analysis based on the results gained from large amounts of linear buckling analysis with various geometric parameters. The accuracy of the proposed approximate equation is examined by comparing the results with linear buckling analysis, which show that the approximate equations can precisely evaluate the global buckling load of single-layer cylindrical space frames with crossing pattern.



330

Stability analysis of cable-stiffened latticed shells

Yang Zheng. School of Civil Engineering, Chongqing University. 373864308@qq.com



In order to improve the structural stiffness of an ordinary single-layer latticed shell, prestressed cables can be arranged in the shell grid to form a cable-stiffened latticed shell. The architectural aesthetics could not be affected by the prestressed cables, and the stability behaviour of the single-layer latticed shells can be enhanced by the cables. However, the research on the mechanical properties of cable-stiffened latticed shell is still not in-depth. To quantitatively verify the effect of prestressed cables in improving structural stiffness and stability behaviour, a series of research on cable-stiffened latticed shells was performed. The influences of different parameters such as the layout of cables, the initial prestress of cables, and the sectional area of cables on the stability behavior are investigated. According to the analysis in this work, it can be demonstrated that the prestressed cables could improve the ultimate capacity of single-layer latticed shells significantly.

333

Buckling characteristics of key parts of 1.5-layer space frames with lap-units

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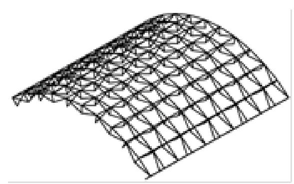

A 1.5-layer space frame with lap-units composed of key parts is a new structural system, which lacks lower chords compared with a double-layer space frame. This paper investigates the buckling characteristics and geometric imperfection sensitivity of the key part. An experimental and analytical comparative study was conducted, in which the experimental and analytical buckling characteristics, such as buckling modes and buckling loads, matched each other well as the depth-grid ratio (the ratio of web member length and upper chord length) is 0.36 and 0.84. The experimental and analytical results also show that the buckling characteristics changed with increasing depth-grid ratio. Besides, the influences of initial geometric imperfection on the buckling load were observed by nonlinear buckling analysis. The results show that the buckling load is not sensitive to the imperfection under the initial imperfection degree of 1/250.

SESSION 10

Tue, 20 Sep.

Parallel Sessions,

20:00-21:30

(90 minutes)

Concepts for Sustainable Innovation in Construction of Timber and Bio-based Spatial Structures -1 (WG 12-2)

Chair(s): Minjuan He and Yinlan Shen

142

Study on mechanical properties of reed and bending-active characteristics of reed-bundled column

Takuo Nagai. The University of Shiga Prefecture. nagai.t@ses.usp.ac.jp

Reed grows in wetlands and lakeshores around the world, and its culm is lightweight and has high tensile strength. Because of these benefits, it has been used as a building material from old days in wide areas. In these days, reed is attracting attention again as a sustainable material because it grows quickly and has abundant regenerative power. In this report, we investigated the geometries and the bending characteristics of a single-reed culm, and the bending characteristics of the reed-bundled column. First, it was found that the reed culm has a very rational shape and resistance characteristics against the bending moment. We also obtained a mathematical model that accurately represents the geometrical characteristics of the culm. Next, we discuss the mechanical characteristics of the reed-bundled column. It was found that the bending characteristics of the bundled column can be easily expressed by a simple linear combination of the geometric and mechanical models of the single reed, while they depend on the number of bundles and the binding force. Finally, for the bending-active element made by forcible bending of the reed-bundled column, the relationship between the introduced tension and the deformation, their changes over time and the restoring force characteristics subjected to cyclic axial loading were studied by experiments.

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Research Progress and Engineering Practice of Glulam Space Frame Structures

Jingxian Zhao. Tianjin University. jxzhao@tju.edu.cn

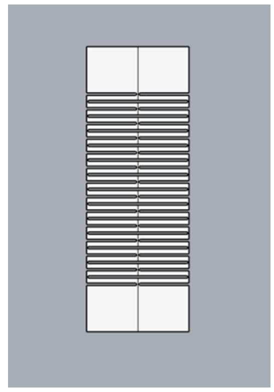
With the advantages of environmentally friendliness and high strength-to-weight ratio, glulam has been widely applied to modern structures. The glulam space frame structure is a representative large-span spatial structure, which can be categorized as glulam space grid structure, geodesic dome, post formed gridshell, and reciprocal structure. A comprehensive review of the main research advances of the glulam space frame structure is presented and mainly expounded from the aspects of mechanical performance of joints and overall structures. The main existing forms of joints applied in spatial structures were summarized and classified as dowel-type joint and glued-in rod joint. The behavior and innovation of the joints were systematically presented based on the latest research progress. Several issues that should be paid attention to the study of overall structures were proposed such as overall stability, seismic performance and creep characteristic. Finally, the further researches worth investigating were put forward. This paper has certain reference significance for the research and can also promote the development of relative engineering applications.

384

Physical to digital: Understanding the flexibility of engineered timber through kerfing

Ana Gatóo. University of Cambridge. ag773@cam.ac.uk

This paper explores the flexibility of engineered timber through kerfing with digital and physical studies. Using 6mm plywood, different parameters such as length of patterns, densities and scales are explored to understand the material´s behaviour. Digital simulations explored the correlation between the digital and the physical. Engineered timber is the most ecological of the major construction materials – it can readily replace steel and concrete in most buildings at significantly lower carbon intensity; moreover, timber buildings store carbon – we can extend their lifetimes significantly, acting as a carbon sink in our urban centres. However, engineered timber is a relatively new material and its full potential is yet to be understood. This study aims to explore the flexibility of engineered timber to promote spaces that can be sustainable, flexible, and adaptable for our future cities.



411

Terrene: Sustainable Shellular Structures

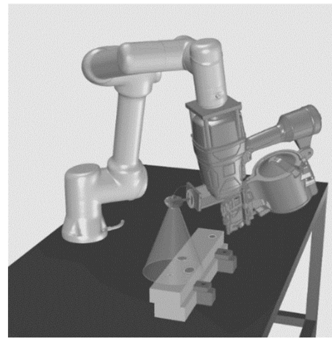
Liam Lasting. University of Pennsylvania. llasting@alumni.upenn.edu

With the construction industry being one of the leading contributors to annual carbon dioxide (CO2) emissions and to excess of waste, the utilization of sustainable materials is critical for the future of the built environment. Therefore, this research explores using the abundant resource of sand as a primary support by combining structural and material optimization methods. On one hand, to provide this compressive material with a tensile capacity, a composite is designed enhancing sand with natural fibers, plasticizers, and binding agents. This creates a biodegradable material system that can be reintegrated back into the environment without ecologically damaging effects. On the other hand, funicular form finding through polyhedral graphic statics is deployed to optimize the structural capacity, provide geometric efficiency, and use minimal material thickness in the designed geometry. Fabrication is executed via a networked enclosure that provides tensile capacity and contains pneumatic formwork as the foundation for a sand-based shell. The result of this research is a tension-compression system with performative geometry and material.

431

Deep Learning enhanced robotic fabrication of timber-to-timber connections with densified hardwood nails

Markus Hudert. Aarhus University. mhu@cae.au.dk



Using hardwood nails in timber construction could help reduce the amount of metal fasteners, the production of which is relatively energy intensive. Moreover, metallic fasteners are difficult to remove and reclaim at the end of a buil¬ding's service life: not only is their recycling challenging, but their presence also complicates the reuse and downcycling of the timber elements. In addition to making connections with hardwood nails more economical, automation promises to enable the use of lower grade, leftover, or reclaimed material. The challenge is to avoid the insertion of nails into knots or other defectuous areas. In order to achieve this objective, this paper proposes a novel combination of robotic fabrication with a pneumatic nail gun and Deep Learning for knot detection. In the following we introduce this novel approach, propose an experimental setup for an initial series of experimental tests, present first insights from training a network using YOLO-v5 with an existing data set, and outline potential applications as well as future challenges.

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Damaged timber dowel-type connections and the application of self-tapping screw reinforcement

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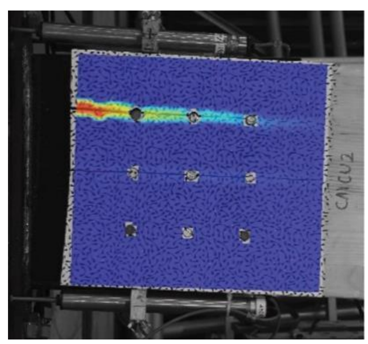


The swelling and shrinking process of the wood is often retrained around the connection area and lead to excessive stresses that could cause cracking of the structural member. The damaged timber connection will have a negative impact on the structural performance of timber spatial structures. An experimental program was conducted in this study to examine the effectiveness of screw reinforcement in improving the moment-resisting capacity of dowel-type connections with artificial cracks. The rotational capacity of reinforced connections without cracks is 45.6% higher than unreinforced connections, while the improvement in moment-resisting capacity is not significant. Overall, the reinforced groups showed a reduction in crack length by at least 37% when compared to the unreinforced groups.

SESSION 11

Tue, 20 Sep.

Parallel Sessions,

20:00-21:30

(90 minutes)

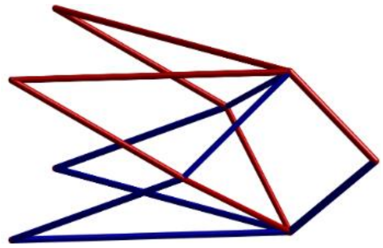
Optimisation Methods (WG 13-2)

Chair(s): Kai Bletzinger and Yao Chen

34

Finding diverse and competitive designs of truss structures

Ruoqiang Feng. Southeast University. hitfeng@163.com



Structural topology optimization plays an important role in obtaining conceptual designs in the preliminary design stage. However, traditional structural optimization methods can only generate one optimized design for the material distribution under certain constraints. However, this unique optimized structure could have some disadvantages, such as an unattractive appearance, difficulty in manufacturing, or high construction cost. Therefore, it is more practical to produce multiple designs that not only have high structural performance but also have substantially different forms from which the designer can choose. The penalizing length method (PLM) was explored in this study for generating diverse truss structures. Using the proposed PLM, it is possible to delete unneeded bars in the optimized structure, such as very slender bars, and the cross-sectional areas of the remaining bars will be automatically redistributed to ensure structural nodal stability. In addition, by generating overlapping potential bars in the ground structure, the structural instability problem caused by pin joints can be overcome. Two-dimensional and three-dimensional numerical examples were provided to indicate the effectiveness of the proposed methods. The numerical results showed that the proposed methodology can generate diverse structures while maintaining structural performance.

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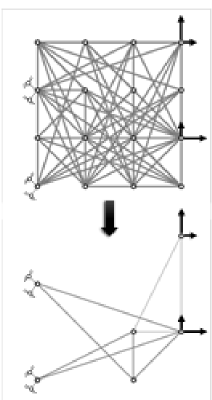
Generating kinematically-stable 2d trusses for topology optimization by reinforcement learning and graph-embedding

Shaojun Zhu. Tongji University, Tongji Lvjian Co., Ltd.. zhushaojun@tongji.edu.cn

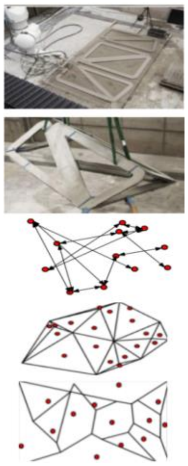


This study proposes a deep reinforcement learning-based framework for generating kinematically-stable 2D trusses for topology optimization. Unlike general ground structures with dense and regular connectivity, the generated trusses, defined as machine-specified ground structures, are sparse stable ground structures with a specified number of members designed by machines. Firstly, the generation process of machine-specified ground structures from a given node-set is formulated as a reinforcement learning task. Graph embedding integrates the structural information into a comprehensive feature matrix to describe the state. By establishing the policy network, the probability of each action, i.e., selecting each node in the node-set, is obtained based on the comprehensive feature matrix. The task is solved using a gradient-based algorithm called REINFORCE. A randomized 4×4 node-set is used to train the agent. The policy converges with a high average reward and generates different yet reasonable structures because a stochastic policy is employed. Besides, the agent can handle different-sized node-sets without re-training. Hence, the machine-specified ground structures generated by the trained agent can be utilized to assist the structural topology design. Subsequently, a method for a typical problem with singular optimal solutions, i.e., topology optimization of binary trusses with stress and displacement constraints, is proposed based on machine-specified ground structures. Finally, different numerical examples demonstrate that machine-specified ground structures can lead to various optimal solutions, and it is more likely to obtain the global optimum than fully-connected ground structures. It is worth noting that machine-specified ground structures can also be applied to other problems without re-training.

170

Application of the geometrical-based mathematical method for classification and investigation of two-dimensional structural elements toward using additive manufacturing

Abtin Baghdadi. Institute of Structural Design, Technical University of Braunschweig. a.baghdadi@tu-braunschweig.de



The development of manufacturing methods and the complexity of real structural problems indicate the necessity of new computational methods to design optimal building components. Nowadays, the technology utilizes the adaptation and integration between different scientific disciplines, including structural engineering, mathematics, and robotic techniques. This study investigates the two-dimensional patterns for the structural elements based on geometrical and mathematical definitions. In this regard, geometric-based methods, including Randomization, Voronoi, Delaunay, Graph and Triangulation, are used to form the composition of linear structural elements in 2D space. The structural performances of the designed layouts were analyzed while each line of the layout was assumed as in structural elements, e.g., a wall. Each designed layout has a unique stiffness matrix created by the accumulation of stiffness matrices of the member (frame-beam). The stiffness matrix components, Eigenvalue, and the cumulative length of the elements were selected as the objective criteria, coded entirely in MATLAB. Finally, the differences in stiffness and length of the elements designed by the selected geometrical calculation methods were compared. The results showed the prosperity of Voronoi and Delaunay configuration as the structural elements when ranges of dimensions and number of the nodes for comparison were selected.

253

Topology optimization of active structural systems

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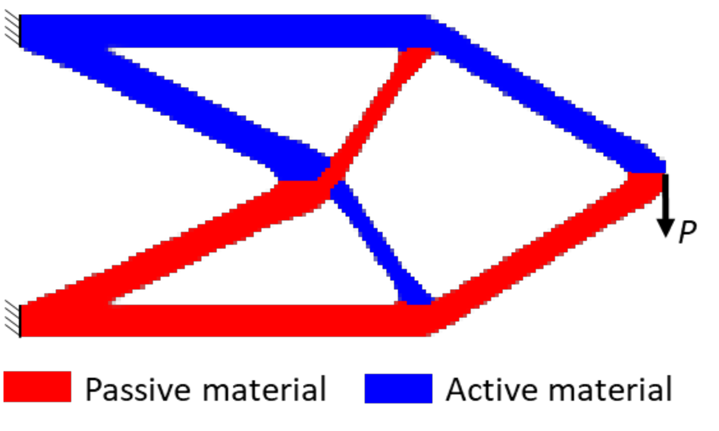
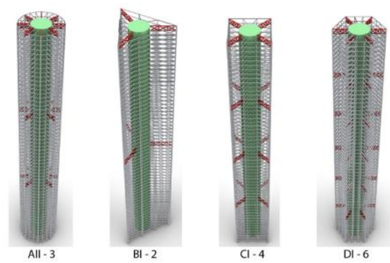


Active systems have been investigated to design lightweight systems to reduce material consumption and systems with the ability to “smartly” alter their shapes and/or internal forces. Recently, the potential of active structures to reduce energy consumption during their service life has also been investigated and sizing and shape optimization have been adopted to design such structures. In the passive structure design field, apart from sizing and shape optimization, topology optimization (TO) is a powerful technique for optimum structural design. This study aims to develop a general TO approach to design novel active structural systems with better performances. The approach is based on the density-based TO scheme. Passive and active materials are considered in the TO process. The structural weight is treated as the objective function to be minimized and the element stress, nodal displacements, and system buckling are introduced as design constraints. Typical examples are carried out to verify the developed approach. Results show that topology-optimized active structures could achieve significant mass savings compared to the equivalent topology-optimized passive structures, which indicates that the developed approach has the potential to be applied to design novel structural systems with lighter weight, larger span, and better mechanical performances compared to conventional passive structural systems.

300

Optimization of architectural and structural parameters of tall buildings in the early stage of design regarding along wind effect: considering outrigger structural system and architectural plan shapes

Vahid Koliyaee. Kent State University. v.koliyaee@gmail.com



Eliminating significant structural challenges from various tubular systems and growing architectural design flexibility has rendered the outrigger system one of the most prevalently used structural solutions for today's tall buildings. This study considers distinctive plan shapes and different outrigger numbers produced by parametric devices with respect to the architectural parameter and structural criteria. This research paper aims to demonstrate an innovative idea in the early stage of design to architects and designers who are mostly unfamiliar with structural and wind engineering. Besides, to manifest the belief that architectural geometry and the structural system can be considered simultaneously in the early stage of the tall-building design; consequently, this consideration can enhance the architectural decisions in the early stage of design. The objective of this study is to contemplate the impacts of the outrigger and the efficiency of each outrigger using one to six outriggers in the structure, which has placed on various plan shapes concerning one objective: total weight of the structural elements per unit area in respect of the maximum displacement. Ergo, 48 models placed on different plan shapes with fixed 240 m height are generated. The generated models are developed for 1, 2, 3, 4, 5, and 6 outriggers. To aimed that, Rhino programming and its plug-in Grasshopper are utilized for modeling, and Karamba3D (FEM) is utilized for structural examination. According to the weight of the structural per m² concerning maximum displacement in the eligible area of about 48 cm(H/500), in hexagon plan shape with two outriggers and circular plan shape with one outrigger, analyzes achieve more proper results.

396

A systematic mapping study of the optimization methods of structures in architectural design

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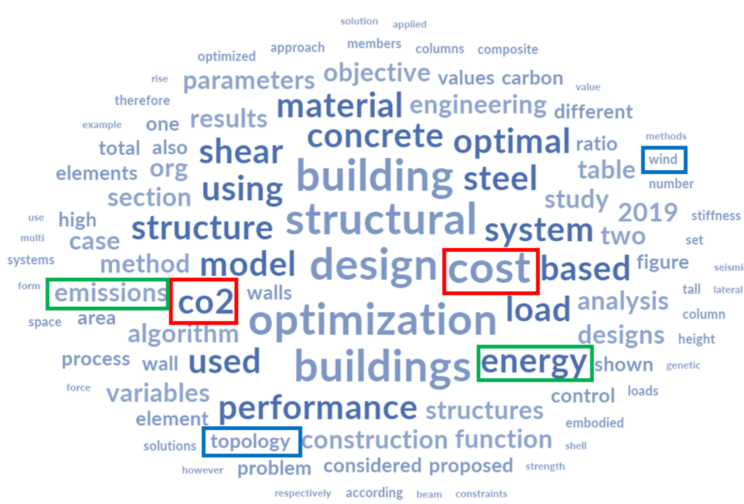


Structural optimization has been playing a key role in contemporary structural design. It helps reduce material consumption while maintaining the structural performance of buildings. The results of structural optimization also have an impact on how the architecture appears. The impact ranges at different levels from the sizing of cross-section, the structural form, and the structural members' layout. Structural optimization can be seen as a potential means for making architecture more attractive, beyond changes in the form as a by-product of minimizing materials or costs. However, numerous structural optimization methods have been proposed to date, and it is difficult to get an overview of them. A systematic mapping study has been therefore conducted on the structural optimization methods proposed in the last decade. Relevant journal articles are categorized according to the types of optimizations, kinds of material, typologies of structure, applied areas and optimization objectives. The result of this study serves not only as a useful overview of the structural optimization methods available for buildings in recent years but also as helpful information on in which areas there is a wealth of research and in which areas they are lacking. The types of structural optimization which are deemed relevant when actively applied as part of the architectural design process are discussed. It is recommended that future research should investigate where gaps need to be crossed in applying structural optimization to architectural design.

SESSION 12

Tue, 20 Sep.

Parallel Sessions,

20:00-21:30

(90 minutes)

Advanced Manufacturing and Materials, 3D-Printing and Molding-1 (WG21-1)

Chair(s): Jianguo Cai

61

A controlled shaping method through the shrinkage of clay

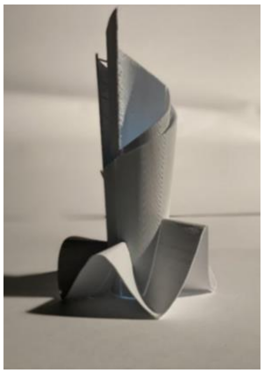
Lukas Gosch. Faculty of Architecture, Institute of Architecture and Media, Graz, University of Technology. lukas.gosch@tugraz.at

This research proposes a new controlled shaping method of thin-walled clay elements. A clay layer is applied to a carrier material, in order to use the shrinkage behaviour of clay as a shaping agent. This shaping process utilises the change of ratio of adhesion forces through the bond of a planar carrier material with a wet clay layer on its surface, and cohesion forces in clay, during the drying process. Afterwards, the geometry of clay ranges from single curved to double curved three-dimensional shapes that open up the possibility of using this method for creating spatial structures. The main advantage of the proposed method, as opposed to standard methods of shaping clay elements, is the use of van der Waals` attractive forces formation while drying, as active and controlled actors. This approach allows the production of three-dimensional forms without any kind of casting, formwork or elaborate scaffolding while using only secondary force formation during the drying process. The proposed method is corroborated by a sequence of experiments that evaluate the newly formed material and its reshaping process. According to the obtained results, the elements were shaped through the developed method and fired, while the carrier material was removed and reused once the clay elements were fully dried. The fired elements were assembled in a case study, in order to demonstrate the proposed method.

64

The Ice Torch

Arno Pronk. Department Built Environment, Unit Structural Design, Eindhoven University of Technology, The Netherlands. a.d.c.pronk@tue.nl



The Olympic flame histories from ancient Greece. The first Olympic torch was used at the1936 summer Olympics in Berlin, this was the start of the Olympic Torch Relay as we know it nowadays. The flame continues to burn till the Olympic closing ceremony at the end of the games. The Torch is built to resist the effects from wind and rain. The unique design of the torch represents the host country, China in our case, and the spirit of the Olympic Games. The first winter games were hosted in 1924 in Chamonix, France. Where only six sports were part of: skiing, hockey, speedskating, figure skating, bobsleigh and curling.[2] The inspiration for the torch of Beijing in 2022, with the name Flying, honors the Cauldron torch from the 2008 Olympic summer games. Beijing is the first city that will host both the summer and winter games. This is a historical event. The spiral design of the torch resembles the ribbon. The red line on the body resembles the great wall, which is iconic for China. It also resembles the skiing course at the games. The torch reflects the pursuit of light, peace and excellence where people strive for. For the torch of 2022 the same color combination is used as for the torch in 2008, red and silver, which is a metaphor for fire and ice. The torch will bring ‘light and warmth to the world of snow and ice.’[3] By choosing the design of the Flying torch of the Olympic winter games in 2022 as an inspiration for the ice sculpture, we want to honor this historic event which is going to take place in february of 2022.

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Optimization of building floor beam layout by optimization algorithms regarding the concrete printing techniques

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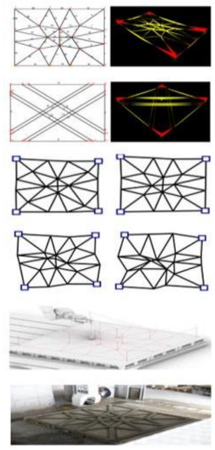


New manufacturing technologies, including robotic printing and robotic CNC, ease the construction of structural elements with unique optimum geometries. Robotic manufacturing technology, unlike classical methods, can be utilized to produce distinctive structural elements (e.g. unparalleled crossing beam layout) or change beams' sections (non-prismatic sections). On the other hand, the complicated analysis and design of distinctive elements with changing sections demand the development of a new optimized technique. To describe the potential and application of these techniques, the optimization of a building's floor's beam layout as the example was selected. The capabilities of the concrete printing technique as the optimization constraints were considered. This study designed and analyzed a wide range of layouts (No.61), respecting engineering judgment. Based on two of the superior layouts by, three optimization approaches were optimized, the coordinate of the nodes (Cx,y), the connectivity order (CO), the beams, and their combination were respectively regarded. Optimization and analysis tools were developed through an interface between analysis software and coding platforms to utilize the capability of the particle swarm optimization algorithm and valid analytical results for an adaptive optimization technique. This study, along with addressing optimum floor layouts and optimization techniques, displays the robotic concrete printing process by printing an optimum layout.

122

Ice composite research

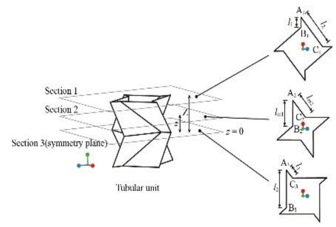
Arno Pronk. Department Built Environment, Unit Structural Design, Eindhoven University of Technology, The Netherlands. a.d.c.pronk@tue.nl

To gain insight into the influence of the composition of ice composites on the compressive strength of the ice composites cubes an experimental analysis have been done. Each ice composite cube consists of a material combination of different fractions of sand, water, Xanthan gum, Guar gum, regular cellulose and nano cellulose. The samples are subjected to a compression test to calculate the peak stresses and Young's modulus from a force-displacement diagram. To gain insight into the influence of the composition of ice composites on the compressive strength of the ice composites cubes, an experimental analysis have been done. The samples are subjected to a compression test to calculate the peak stresses and Young's modulus. From the compression test it can be concluded that there is no clear relation between the size of the grains of sand in comparison to the peak stresses and the young's modulus. On the other hand it can be concluded that the amount of cellulose increases the peak stresses or the young's modulus.

375

Practical calculation method for inertia moment of a curved Miura origami-patterned tube

Yangqing Liu. Chongqing Jiaotong University. lyq19@cqjtu.edu.cn

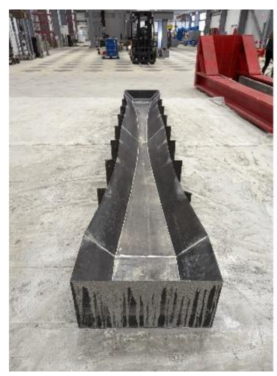


Flexural rigidity reflects the lateral deformation capacity of a structural member under bending, which is directly affected by the cross sectional inertia moment of the member. Origami-patterned tubes have intricate geometries and consequently varied cross-sections, thus making it difficult to calculate the inertia moment. As part of the endeavor to quantify the deformation capacity of a curved Miura origami-patterned tube, this manuscript develops a practical calculation method for inertia moment of the tube. Conducted on a basic tubular unit of the tube, the derivation adopts a simplified cross-section equivalent to the actual cross-section and follows the general theoretical formula for inertia moment. After substitutions and collections, a practical calculation formula expressed by six independent geometrical parameters is developed. The application of the developed formula on the tubes with different geometries reveals a zigzag distribution of the inertia moment along the tube length. By using the formula, the least inertia moment of the tube could be readily located and calculated.

467

Zip-formwork: Fabrication of shape-optimized concrete structures for the Global South

Mohamed A. Ismail. Massachusetts Institute of Technology. ismail@mit.edu



Building construction contributes to 11% of global carbon emissions, and that figure is only expected to rise due in large part to the high urbanization rates of the Global South. Global cement production has outpaced that of all other industrial construction materials since the Second World War, and production has increased exponentially in the decades since. It is undeniable that concrete is omnipresent and with projected demands for urban construction and new and restored infrastructure, concrete production shows no sign of slowing down. Consequently, we need design methods to reduce the environmental and economic costs of concrete in order to enable sustainable growth in developing regions. One pathway towards affordable and low-carbon concrete construction is to simply use less material. Shape optimization enables the design of materially efficient elements that meet the required structural demand while reducing the embodied carbon of concrete construction. Nonetheless, sape-optimized concrete construction is constrained by the viability of its formwork construction. This paper presents the results of a shape optimization method that enables the design of materially efficient concrete elements subject to structural and fabrication constraints of the Global South. This research combines a pre-existing shape optimization method with a novel method of steel formwork fabrication called Zip-form. In Zip-Form, analog fabrication techniques paired with computational design strategies make the construction of certain complex geometries easy and efficient. This allows for the fabrication of complex concrete forms using materials and methods that are readily available in the Global South. This paper presents the results of a full-scale (5m span) shape-optimized concrete beam built using the Zip-form system. The beam is designed to resist the ultimate and service loads of an equivalent prismatic beam while embodying 40% less carbon.

SESSION 13

Tue, 20 Sep.

Parallel Sessions,

21:45-23:15

(90 minutes)

Retractable and Other Tension Structures (WG6-3)

Chair(s): Sudarshan Krishnan, Hiroki Tamai and Jianhui Hu

48

Deployment analysis of a clustered hyperbolic paraboloid cable net

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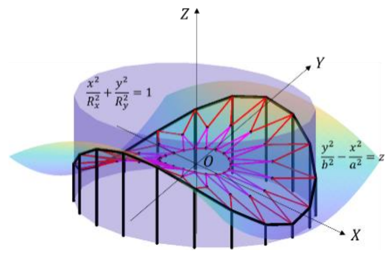
Cable nets are lightweight covers for large-span structures, such as roofs, patio shade frames, arenas, stadiums, and sports centers. After decades of study, a few research studies have been conducted but mainly focused on the static aspects, such as topology optimization, prestress design, and stability. This paper analytically and experimentally studies the deployment process of a clustered hyperbolic paraboloid cable net based on clustering actuation strategies. Firstly, the equilibrium equations of statics and dynamics for clustered tensegrity structures (CTS) are given. Then, we propose a deployable hyperbolic paraboloid cable net topology considering architectural aesthetics, lightweight, and easy control and assembly process. The deployability of the cable net is achieved by clustering the adjacent strings into one sliding cable, significantly reducing the number of actuators required for control. The deployment trajectory is selected based on the stiffness and stability requirements of the structure. That is, keeping the tension of the strings in the inner ring to be a constant value so that the structure can maintain specific stiffness during the unfolding and folding process. Then, we perform quasi-static and dynamic deployment analysis to validate the actuation strategy. Finally, a lab-scale model is constructed. We tested its static performance and conducted the experimental model's open- and closed-loop control. Results show that the closed-loop control approach is more stable and smoother than the open-loop one in keeping the stiffness during the deployment process. The approaches developed in this paper can also be used for various deployable tensegrity structures.



336

Experimental study of a new cable dome form with continuous cables

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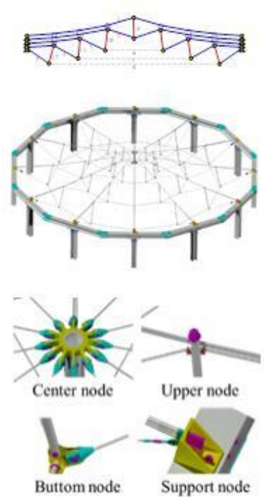
Cable domes have been widely used in the field of structural engineering for their lightweight and large span. Conventional cable domes are most built by using discontinuous cables. This paper conducts an experimental study of a new cable dome form with continuous cables. The main improvement of the new cable dome is to connect the adjacent diagonal and ridge cables of the conventional Geiger dome as continuous cables and allow overlaps between them. Compared to conventional forms of cable domes, the pre-stresses in the cables are more uniform, and the number and type of the cables are fewer. The span of the experimental model is 10 m, with 63 cables and 37 struts. The construction procedures, the pre-stress adjustment, as well as the static and dynamic properties of the new cable dome form are investigated. The use of continuous cables provides the following benefits. First, the tension process is much easier since all the ridge cables gather into the supported nodes. Second, the cable forces are more uniform since the continuous cables allow the force transfer between the continuous segments. Third, the sliding of the frictional nodes can absorb shock energy under the dynamic excitement. The results show that the new cable dome has good construction features and feasible mechanical properties, and is believed to have great potential for practical applications.



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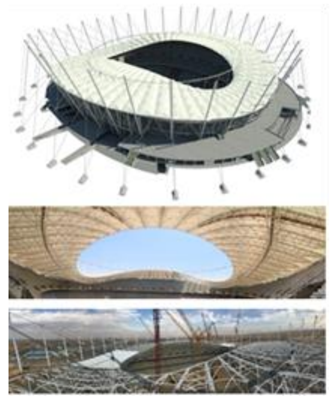
The new egyptian army stadium in Cairo: a cable suspended roof structure

Massimo Majowiecki. MJW Structures. info@mjwstructures.com



The New Egyptian Army Stadium is now under construction in the Egypt International Olympic City in Cairo, Egypt. Stadium capacity is of 93,000 covered seats with a roof surface of 45’000 m2. The building design fulfil the requirements necessary to host a FIFA World Championship final phase and there is also an athletics track meeting the IAAF standards for international competitions. The basic architectural concept is to create an iconic element that can characterize the skyline of the place that is a significant part of the overall development of this sports area. The structural solution has been reached with a tension circular ring supported by 32 pylons that hang the wave shaped roof composed by 64 lattice girders. That static scheme allows to merge efficiency with aesthetic value required by the client in agreement with the previous design experiences of the MJW Structures team. The structural concept has considered erection procedure since earlier phases; erection procedure has been performed with a big lift operation of the inner cable ring with 32 flying jacks and the aerodynamic behaviour of the roof and cables tested in RWDI wind tunnel in Milton Keynes (UK).

405

Micro-Operable ETFE Panels at SoFi Stadium

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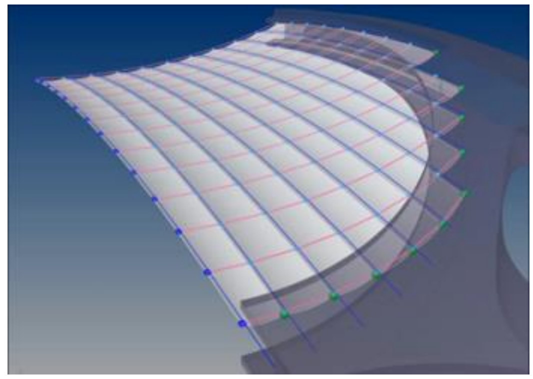
SoFi Stadium opened in 2020 as the new home as the Los Angeles Rams and Chargers. Uniquely designed to the favorable climate of Los Angeles, the SoFi Stadium roof extends 110,000 m2 over the stadium, adjacent plaza, and a 6,000-seat theater. The roof is open at its perimeter and spectator comfort is achieved by allowing the pleasant Southern California breezes to blow through the venue without need for conditioning. Thermal analysis of conditions under the stadium roof showed that under certain weather conditions heat build-up under the roof extends into the upper seating decks and could lead to unacceptable spectator conditions. To prevent such heat build-up forty-six “micro-operable” panels are strategically located on the roof surface to enable venting. In combination with the 73,000 m2 single-layer transparent ETFE roof cladding, the micro-operable panels at SoFi Stadium offer an alternative approach to connecting spectators with the outside environment versus past NFL stadiums with large-scale operable roof panels. The primary roof structure at SoFi Stadium consists of a curved steel shell structure that forms an inner compression ring boundary around the perimeter of the stadium seating. Inside the compression ring a two-layer orthogonal cablenet extends over the majority of the seating and field. The forty-six micro-operable panels are mounted to the cablenet through a series of specialized clamps and secondary framing members. Typical micro-operable panels are 9m by 18m and organized in bi-parting pairs so that the resulting opening is 18m by 18m. A series of irregularly shaped micro-operable panels exist at the east and west edges of the roof. The micro-operable panels are mechanized using a cable winch drive along each panel side. Accommodation of roof movements associated with the cablenet was a major challenge to the interfaces of the micro-operable panels with the supporting rail girders. Details of the mechanization system were validated through an extensive prototyping exercise. Consistent with the surrounding fixed roof panels, each micro-operable panel is clad with a single-layer ETFE system including reinforcing cables. Detailing of the ETFE system for drainage and sealing at operable roof joints was a major design consideration.

560

Use of lightweight technology for kinetic architecture

Igor G. Siotor. PFEIFER Structures North America. isiotor@pfeifer.us.com

The retractable roofs for large buildings, like big size stadiums, always create a lot of interest ever since they were re-introduced to construction industry. Although Sky Dome (now Roger's Centre) built in 1989 in Toronto, Canada is believed to be first large size stadium in the world with the permanent retractable roof, it is not the first sport facility with fully or partially moveable enclosures. Frei Otto started the experiments with the lightweight foldable membrane systems in the mid-60s. In early 70s retractable fabric roofs were built over a few functional swimming pools in France and Germany. In 1987 the roof of Montreal Olympic Stadium, designed by Roger Tallibert, was clad with a foldable tensile membrane roof. The history and lessons learned from the past, and the development of new materials and technologies, to include the testing methods, which become the international standards is the subject of my paper and my presentation.



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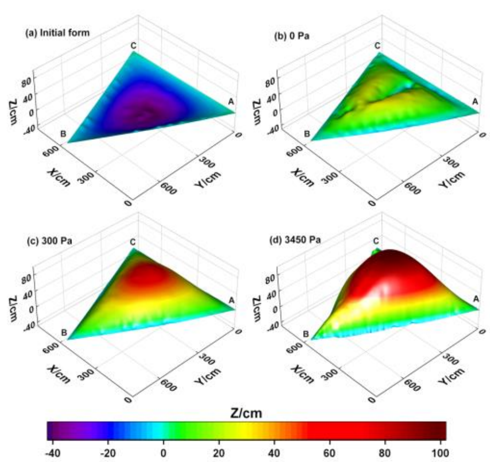
Configuration measurement and inflating failure analysis of full-scale four-layer ETFE cushion based on 3-D photogrammetry

Song Yinbo. Space Structures Research Center, Shanghai Jiao Tong University. songyb@sjtu.edu.cn

As a kind of typical air-inflated membrane structure, ethylene-tetrafluoroethylene (ETFE) cushion has become one of the most essential engineering structures in the field of large-span spatial structures. Up to now, most of the researches were still limited to scale structures or numerical models for two-layer ETFE cushion. Though multi-layer ETFE cushions have been widely used in engineering, which always follow the design method of two-layer ETFE cushion, or some empirical experience, lack of thoroughly detailed research. This study experimentally investigates the structural behaviors of a full-scale ETFE cushion with two chambers while inflating internal pressure until failure (3450 Pa). Firstly, the configuration of ETFE cushion during inflating can be measured by photogrammetry based on triangulation principle. Then, the configuration under the different internal pressures were used as a reference for discretized membrane link (abbreviated for mem-link) modeling, and the equivalent nodal loads were applied to the model to solve internal force distribution of the outmost membrane layer based on the force-finding with force-density. Finally, through the comparative analysis of failure position and force distribution, it can be determined that the welding seam and boundary constraints would cause significant stress concentration effect and may lead to overall failure of ETFE cushion.



SESSION 14

Tue, 20 Sep.

Parallel Sessions,
21:45-23:15
(90 minutes)

Connection Design of Metal Spatial Structures (WG8-3)

Chair(s): Kok Keong Choong and Guojun Sun

13

Connection detailing for scissor-type deployable structures

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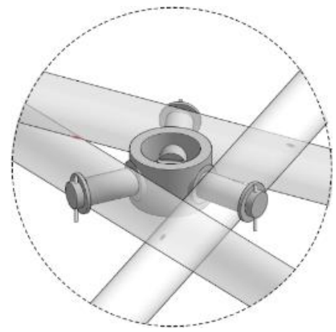
This paper presents the analysis and design of connections for scissor-joint deployable lattice structures that satisfy both kinematic and strength criteria. Two typical types of design, namely the scissor unit (SU) and tripod-scissor unit (TSU) are selected as examples for evaluation. The first part reviews the current research to catalog the structural and kinematic requirements for deployable lattice structures. Two structures, one made of SU and the other of TSU, are analyzed as examples to conclude the strength requirements for the connection design. The sample structures are examined for gravity loads for preliminary design. Section selection is based on the AISC steel manual. The stress distribution in the connections is simulated using ABAQUS to identify critical points of potential failure.



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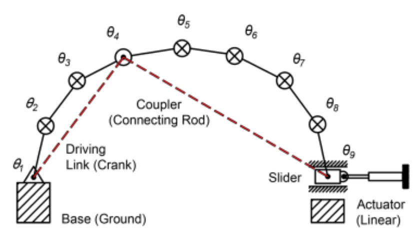
Comparative analysis of bar linkage systems based on the effective crank-slider method

Niki Georgiou, University of Cyprus, Department of Architecture. ngeorg25@ucy.ac.cy



Reconfigurable and deployable modular structures aim at minimum self-weight, simplicity and reduced energy consumption. The effective crank-slider (ECS) concept has applications in a wide spectrum of structures for transformability purposes. The paper presents the kinematics of an 8-bar linkage aluminum structure of different geometrical characteristics, i.e., of constant and variable bars length. The systems have an overall length of 12.0 m in their initial, almost flat configuration, and a respective span of 6.0 m in their specific arch-like target configuration. The planar linkage systems are reduced to an externally actuated 1-DOF mechanism through stepwise reconfigurations, in order to adjust the joint angles from the initial to the target values. Each linkage system is supported on a pivot joint on one end and a linear sliding block on the other end that is connected to a linear motion actuator. The comparative evaluation of the systems kinematics and structural behavior under self-weight are primarily based on the criteria of maximum brake torques on the joints and relative sliding distance of the rolling support during the system transformations. The analysis proves that the reconfigurability of linkage structures based on ECS is characterized by simple actuation requirements, controllability and flexibility.

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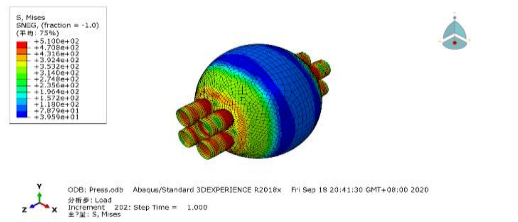
Study on mechanical behavior of welded hollow spheres joint with penetrated sleeves in truss string structure

Ji Ma. Beijing University of Technology, Faculty of Architecture, Civil and Transportation Engineering. 2279399945@qq.com



At both ends of the truss string, the welded spherical joints used to connect steel tube members and fixed cables will bear huge loads, so this joint is a critical part of the structural design of the truss string. Recently, two new types of domestic cables, Galfan cable and airtight cable, have been successfully developed and widely used in engineer practice. However, some problems are also exposed. For example, due to the diameter of Galfan cable and airtight cable are smaller than traditional PE cable, it has to use multiple cables in parallel to meet the bearing capacity requirements in the structure with large span.Therefore, this paper takes the string truss roof of Jakarta International Stadium (JIS) as an example, and proposes welded hollow spheres joint with penetrated sleeves (PS-WHSJ), a new type of joint is truss string structure. The PS-WHSJ is composed of sleeves and welded hollow spheres. The number of sleeves can be determined by the number of cables required. The sleeves penetrated through the welded hollow spheres and fixed by welding. In this paper, a numerical simulation analysis is carried out on the mechanical behavior of the PS-WHSJ, and the failure mode of the PS-WHSJ is obtained. The double polyline method is proposed to judge the yield strength of the PS-WHSJ. based on the above research, a large number of parametric analyses are carried out for the cable sleeve through ball joint. The double polyline method is used to obtain the designed strength of each PS-WHSJs, and compared with the designed strength of the welded hollow spheres joint under the same parameters to obtain the axial bearing capacity improvement coefficient, then the calculation formula of the axial bearing capacity of the PS-WHSJs is proposed.

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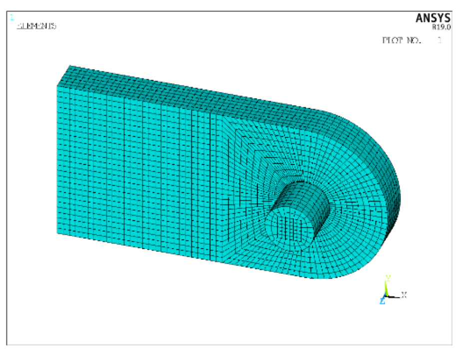
Study on the failure mechanism and design method of the ear-plate connection join

Xiaofei Gao. Beijing. 1453611719@qq.com



Pin shaft -plate connection is a common connection form of cable structure joints. The failure of cable joints will cause cable failure, and even the progressive collapse of the overall structure. However, at present, there are relatively few destructive test studies on pin-plate connections, and the failure mechanism is not yet clear. At present, there are great differences in the calculation of bearing capacity of pin plate joints. The design method given by Chinese code is not perfect, which refers to European and American codes. In this paper, a group of pin-ear plate connection specimens were subjected to uniaxial tensile destructive test, and the final failure mode and ultimate bearing capacity of pin-plate connection were obtained. Based on the finite element simulation results, the plastic development coefficient is introduced into the current ' steel structure design standard ' design formula, and the range of its value is analyzed. The design formula suitable for each failure mode of Pin shaft -plate connection is proposed.

317

Mechanical performances of single layer latticed domes with SLO nodes

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SLO node proposed by LANIK is widely used in single layer latticed dome. But the mechanical performances of single layer latticed domes with SLO nodes have not yet to be systematically studied. The FEA based on beam elements is an effective and efficient means to analyze the spatial structures. In the stability analysis of structures, the mechanical performances of nodes should be simulated accurately. A modeling method based on beam elements is proposed in the paper to model the SLO node, and the determination of the key parameters of the model is studied based on the relevant experiments. Based on the method above, the mechanical performances including static stabilities of single layer latticed domes with different typical geometrical parameters are systematically studied, and the instability mechanisms and modes are found. The stability capacities of the structures with SLO nodes are compared with those with rigid nodes.

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Proposal of arc- and spiral-shaped Miura-ori and its application to the design of large roof architecture

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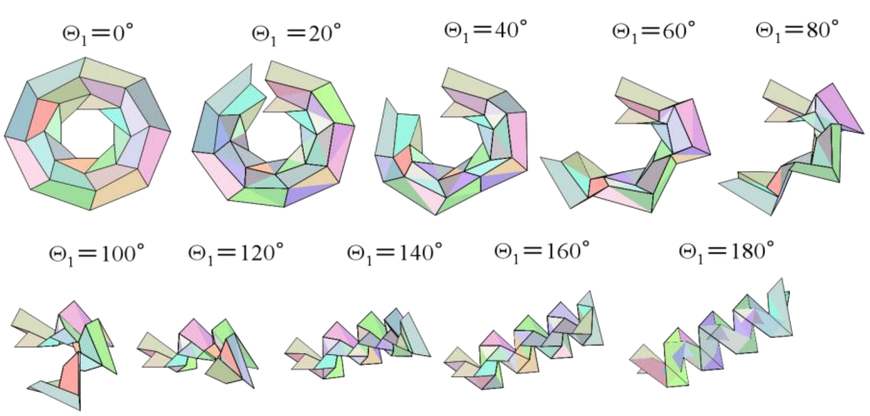
This study proposes an arc- and spiral-shaped Miura-ori, which is rigid-flat-foldable and one variational type of Miura-ori. The spiral-shaped Miura-ori is obtained by arraying quadrilaterals with identical internal angles in the same column. The rigid-flat-foldability of the spiral-shaped Miura-ori is verified through numerical simulations as well as by considering the deployment mechanism. The arc-shaped Miura-ori is obtained by setting equal edge lengths of the quadrilaterals in the radial direction. The numerical simulation of the rigid folding motion is demonstrated for the arc- and spiral-shaped Miura-ori. The large roof structure obtained by the proposed arc- and spiral-shaped Miura-ori has an elegant and natural shape with sharp mountain-valley fold lines. Examples of large roof architecture designed with arc- and spiral-shaped Miura-ori are presented.



SESSION 15

Tue, 20 Sep.

Parallel Sessions,

21:45-23:15

(90 minutes)

Concepts for Sustainable Innovation in Construction of Timber and Bio-based Spatial Structures -3 (WG12-3)

Chair(s): Minjuan He and Christopher Robeller

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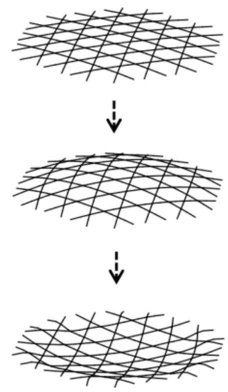
Formfinding and buckling analysis of three-way kagome timber latticed shells using general-purpose FE software

Kan Shiratori. Graduate Student of Kogakuin University. dm21034@ns.kogakuin.ac.jp



In this paper, a simple and practical method is proposed which enables formfinding analysis of a timber three-way latticed kagome shells and following buckling analysis, using general-purpose FE software without using specialized software for formfinding. In addition, the elastic buckling properties of the wooden latticed kagome shells formed by formfinding analysis are investigated. In most of construction of timber latticed shells, the central part of the lattice plate is lifted up to form a shell-like geometry by the inward forced displacement of the boundary. The in-plane shear stiffness of three-way kagome lattices is so high that fixing the intersections does not allow the lattice planes to deform significantly into a shell geometry. Therefore, the formfinding analysis is carried out with virtual slide mechanism at the intersections of the members that enables slide of the members along the shell-surface without additional axial stress. The slide mechanism allows the intersections of the lattice to move inducing out-of-plane bending stresses and forming a shell. After latticed shell is formed, this mechanism must be fixed to slip. So, this can be fixed by generating a new axial stiffness element and overlaying it on the bending stiffness element to share nodes. As a result, we completed a stressed latticed shell model and followed by buckling analysis.

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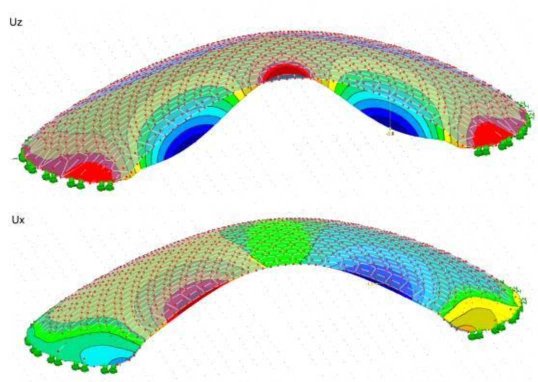
Structural performance of the grain-informed glued butt joint system for a large-span segmented CLT shell structure

Amin Adelzadeh*, Hamed Karimian-aliabadi, Marcel Muster, Christopher Robeller



This research is an extension of the work from our previous study on using digital technology to construct lightweight wood-only shell structures from Cross-Laminated Timber (CLT) production waste. In a previous paper, we developed an algorithm that turns CLT offcuts into efficient timber plates and uses them for the construction of a medium-scale compression-only shell demonstrator. Although the FEM analysis and experimental load tests proved the structural efficiency of wooden connectors, we found that realization of a significantly larger span requires a joint system with a higher tension resistance capacity. As a solution, this paper presents a custom adhesive joint system for reaching a higher load-bearing capacity of CLT plates for withstanding both compression and tension forces, enabling the construction of a larger shell structure completely without metal connectors. The joint system consists of an innovative gluing method without any additional bonding agent and wood grain direction optimization that increases the adhesive strength of butt joints where CLT plates are fastened together. The paper discusses the possible applications and limitations of the construction system while presenting the structural analyses for a load-bearing shell demonstrator with a column-free span of 35 meters. To validate the structural performance of the construction system, FEM analysis and MATLAB post-processing of the FEM results are presented.

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Assembly of lamella roof shell structures

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This paper continues the examination of segmentation and assembly strategies for prefabricated lamella roof structures. Based on previous theoretical work, full-scale prefabricated ReFlexRoof segments were built and assembled to erect barrel vault roof with a base area of approximately13m x 13m. Eighteen segments of various dimensions were then assembled in three production stages. While the first stage consisting of four segments served as a general proof of concept, the subsequent stages to complete the roof were utilized to test optimisations in the fabrication, as well as the assembly process. The theoretical model predicted an unproblematic alignment of the segments, but various aspects of real-world fabrication interfered with this procedure. The digital model neglects rotation and solely focuses on translation of the segments, while the real-world implementation may require a combination of rotation and translation. Estimated deflections and CNC-accuracy were in an acceptable millimetre range; however these estimations were based on a resting position and did not account for the deflection while the segments were crane mounted. Further deviations from the theoretical shape of the arc were caused by the elastic restoring force of the shell composed of cross laminated timber. This paper expands upon the previous theoretical model and strategy to mitigate the challenges of a real-world building environment.

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Structural design of CLT shells interconnected via multidirectional link elements

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This is a structural design proposal for cylindrical shells made by interconnecting CLT (Cross Laminated Timber) panels. As joining methods between CLTs, in-plane and out-of-plane shear joints using screws are commonly used. For a folded-plate structure composed of CLT panels, out-of-plane bending resistance is not required at the connections between CLTs. While for a CLT shell, especially for a shallow shell, it is required. Therefore, the authors proposed a joint using a box-shaped steel connector and LSBs (Lag Screw Bolts) to enable out-of-plane bending resistance. The joint is the bending resistance due to pushing and pulling by CLT for compressive stiffness and LSB for tensile stiffness. And its performance was validated by loading tests in this paper. Furthermore, to use a CLT shell to actual buildings under various load conditions, the joint arrangement with axial, in-plane shear, out-of-plane shear, and out-of-plane bending stiffness has to be carefully considered. The link elements containing these multiple stiffnesses require different stiffnesses at each position and at each stiffness, and each must be allocated appropriately. In this paper, the properties of the proposed bending moment resisting joint are presented, and a case study of its application to an actual building is presented.

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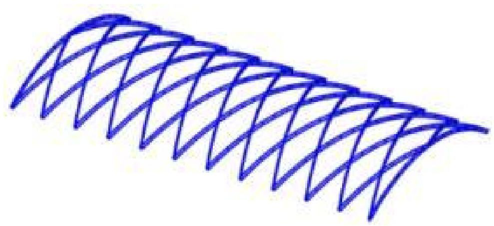
Static stability of single-layer cylindrical glued timber reticulated shells with X-shaped joints

Mingxi Xu. Sichuan University. xumingxi@stu.scu.edu.cn



This paper focuses on the static stability of single-layer cylindrical glued timber reticulated shells with X-shaped joints. The bending stiffness and failure modes of the X-shaped joints are first carefully investigated using the finite element method. The influence of the design parameters of the X-shaped joints on the bending performance is analyzed. Based on this, a single-layer cylindrical glued timber reticulated shell using X-shaped joints is selected and modelled to perform stability analysis. The load-displacement curves and the buckling modes of the whole reticulated shell are obtained. The conclusions are as follows, among the factors influencing the bending performance of the connection member, the influence of axial force is the most obvious. The ratio of the minor axial stiffness to the major axial stiffness of the joints has a more significant effect on the ultimate load-carrying capacity of the reticulated shell when the ratio increases from 1/8 to 1. In addition, the ultimate bearing capacity of fixed supported net shells without purlins is 1. 7 times of hinged supports.

360

Structural design of Suspension-Arch Structures with members cut from the CLT panels, and Development of its joint system

Eisuke Mitsuda. Kyoto Institute of Technology. mitsuda@kit.ac.jp

Recently, the technology to manufacture parts by linking digital data of complex shapes created computationally by 3D CAD such as “rhinoceros + grasshopper” directly with machines has been rapidly developing. Especially in the field of wood processing, it is now possible to NC-machine complex processes with high precision without relying on highly skilled carpenters. The ability to create large structures with flexible forms by efficiently sequencing members cut from CLT or plywood panels, which are made from scrap lumber, is expected to have implications for architecture in the age of decarbonization. In timber structures, joints are important for the continuity of cut members. The joints must satisfy all of the following requirements: structural performance, design, and constructability. However, plate-to-plate joints are not as common as historically accumulated beam and column joints, and in most cases, steel plates are used to join them. But if we continue to rely on using steel plates for joints, we will never be decarbonized. In this paper we presents a small challenge with such a perspective.

SESSION 16

Tue, 20 Sep.

Parallel Sessions,

21:45-23:15

(90 minutes)

Advanced Manufacturing and Materials, 3D-Printing and Molding-2 (WG21-2)

Chair(s): Yangqing Liu

65

Buoycrete, a light-weight concrete

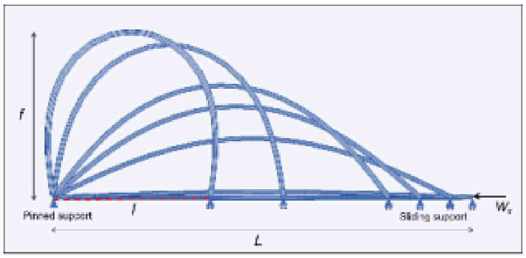
Arno Pronk. Department Built Environment, Unit Structural Design, Eindhoven University of Technology, The Netherlands. a.d.c.pronk@tue.nl

In this study, the authors present Buoycrete, a new material and work method invented by the company Boskalis. “Buoycrete” is a new cement mixture and work method. This mixture and the work method related to this material are developed by Boskalis and are patented in 2017[1]. The material is a lightweight concrete mixture that is ‘neutrally buoyant’ and non-dissolvable. The concrete is intended to be used under water. The neutral buoyancy makes that the concrete does not sink or float. In other words, within the cement mixture under water, right after application, there is no resultant vertical force apparent because of the neutral buoyancy. The cement slurry will be kept in place only by the internal cohesion of the Buoycrete slurry itself. This allows for fast and flexible adjusting of the concrete shape under water before the concrete cures. The unique cement-based grout opens up a wide array of possible application areas and markets, especially since application equipment, mixing equipment and curing characteristics are analogue to normal cement mixtures. Currently, there are no comparable light-weight cement mixtures available on the market. This paper will start with an overview of concrete structures in combination with fabrics and will present the structural behavior, construction methods and applications of Buoycrete. It demonstrates that Buoycrete combined with fabric formwork creates new possibilities for the realization of façade elements, shell structures and other free forms.

84

Use of fiber-polymer composites in bending-active structures

Tara Habibi. Doctoral assistant. tara.habibi@epfl.ch



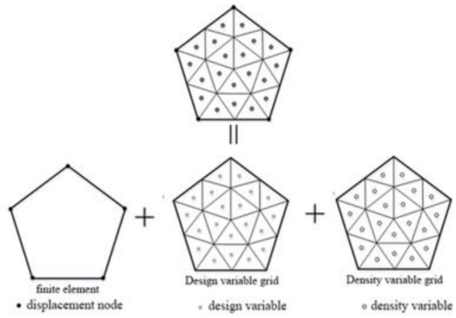
Fiber-polymer composites are currently used only for small-scale temporary bending-active structures. Bending-active represents a structural typology whose geometry is based on the elastic deformation of initially straight members that, in the case of beams, are known as elastica. As a result of the bending process, the desired structural form and a sustained residual stress state are imposed on the structure. This study explores the application limits of composites for permanent large-scale elastica beams. The factorial design method was applied for a systematic evaluation of the effects of the parameters and their interactions on the structural behavior. Analysis leads to the conclusion that increasing the material stiffness, creep-rupture stress limit and the bending degree allows the span, applicable live load and material use to be further increased. To obtain the highest applicable design live load and maximize material use, the bending degree should reach the creep-rupture stress limit. The study demonstrates the feasibility of using composites for permanent elastica beams and contributes to the transition from small-scale temporary to large-scale permanent composite bending-active structures.

179

Topology optimization of static stiffness for a multi-material structure using multi-revolution scheme

Xiaoyan Teng. Harbin Engineering University. tengxiaoyan@hrbeu.edu.cn

The static topology optimization method of multi-material structure is proposed by taking the minimization of flexibility as the goal and the volume proportion of multi-material as the constraint, and integrating the scheme of multi-resolution and polygon element. The multi-resolution scheme uses a coarse finite element mesh to perform the analysis, which is used to optimize the fine design variable mesh and the fine density variable mesh to represent the material distribution. The finite element discretization adopts uniform finite element mesh. Design variables and density discretization adopt matched or mismatched grids to provide more precise discretization for density and design variables. The results of typical numerical examples show that the combination of coarse finite element mesh with more refined design and density mesh can obtain higher quality optimization solutions and reduce computational cost. The optimization algorithm has certain robustness and has important theoretical significance for structural static stiffness design.

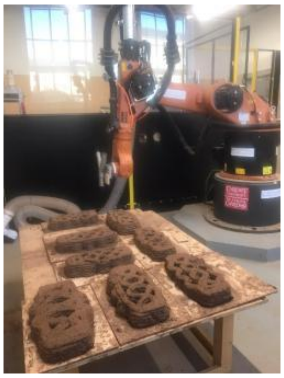


558

Robotic 3D printing with earth: A case study for optimisation of 3D printing building blocks

Yelda Gin. University of Cambridge. yg362@cam.ac.uk

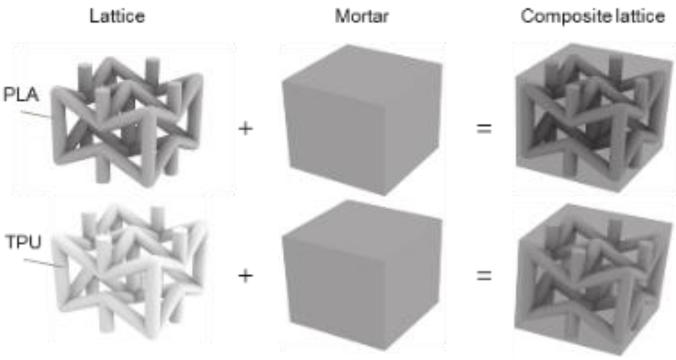
The interest in 3D printed earthen buildings in developed countries has increased due to the demand for healthy, comfortable and sustainable buildings constructed with low carbon materials and labour-saving methods. However, the amount of research about this field is still limited. Our research aims to contribute to this field by optimising the robotic 3D printing process by investigating issues such as buckling while printing, adequate soil mix recipe for printing, print and extrusion speed calibration. This paper illustrates the process and the results of the temporary research project and the Robotic Cob Printing Workshop with MSc Computational Methods in Architecture (CMA) students at the Welsh School of Architecture, Cardiff University, in March 2022. The project aims to achieve structural stability with less material by using the geometry and the infill of the building block while exploring the role of computational design, robotic extrusion and material understanding in robotic 3D printing with earth as a low-carbon novel building method.



362

Design, fabrication, and characterization of composite architected units with embedded 3D-printed lattice

Man Chen. South China University of Technology. ctcmcm288@mail.scut.edu.cn



We proposed a composite material design comprising 3D printed re-entrant lattice as core structures that are embedded to play a role of reinforcement for mortar. Our experimental and numerical results show that the composite unit has larger energy absorption properties and better ductility than the unit with pure mortar. To further improve the performance of the composite unit, we investigated key parameters associated with the 3D printing process to identify the effort of those parameters on the properties of composite units with re-entrant. We envision that our proposed composite design strategy can produce next-generation structural systems with higher performance, a lighter weight, and lower carbon footage toward a sustainable built environment.

231

Design for 3D printing models via layout and geometry optimization considering overhang constraints

Xiaoyang Lin. College of Civil Engineering and Architecture ,Zhejiang University. 22112260@zju.edu.cn

As engineering structures become increasingly complex, the demand for advanced design methods and 3D printing of sophisticated structures is growing. The layout optimization method based on the ground structure can lead to optimized designs, but the gravity-induced overhang effects require additional support materials during the printing process, resulting in a higher material cost or the need to remove supports, which severely limits the application of 3D printing. This paper presents a pilot line to obtain self-support layout optimized designs. Firstly, a self-support point-line structure is obtained via the layout and geometry optimization, considering overhang constraints. Secondly, the point-line structure is transformed into a physical model with nodal expansion considered (i.e., taking into account the overlapping of members at nodes). Thirdly, the physical model is sliced and printed using a plastic fused deposition modelling (FDM) printing machine. The results showed that the volume increase of the optimized structures obtained using the proposed method was less than 5% compared to the theoretical optimal solution without manufacturing constraints considered, which demonstrated the effectiveness of the optimization method.

SESSION 17

Tue, 20 Sep.

Parallel Sessions,
21:45-23:15
(90 minutes)

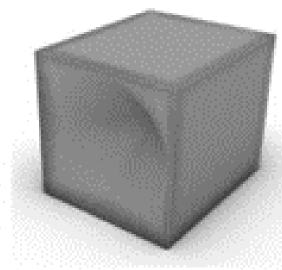
Innovation in New Concepts and Projects - 1

Chair(s): Minger Wu and Jinghai Gong

77

Conceptual Investigation on the Effectiveness of Hyperbolic Paraboloid Surfaces for Floating Breakwaters

Hamid Eldarwich. Princeton University. hse@princeton.edu



In the context of climate change, suitable breakwaters are needed to protect communities and infrastructure. Bottom-standing breakwaters design are only feasible in shallow to intermediate water and relatively not environmentally friendly due to the amount of carbon footprint during construction. Floating breakwaters provide a better alternative due to its deployment flexibility and smaller carbon footprint. Although gaining much attention, recent explorations on floating breakwater design focus only on bringing a bottom-standing type design, into a floating breakwater design, without taking full advantage of the modularity of a floating breakwater. Current research looked at the implementation of hyperbolic paraboloid (hypar) surfaces, which were popularized by Felix Candela, as floating breakwater. This thin shell configuration allows for low stress under applied load which further increases the cost-effectiveness of floating breakwaters. While the application of hypar as coastal defense structure is not new, its utilization as a breakwater has not been done before. The current study explores various warping values of the hypar to examine the best configuration to attenuate the wave. A 1:10 scale of a breakwater and bathymetry scenario is tested in a 2D numerical wave flume using Smoothed-Particle Hydrodynamics method. It is found that a hypar shape can reduce the wave transmission when compared with a simple rectangular counterpart.

228

A method of designing multi-compatibility induced multi-stable morphing structures

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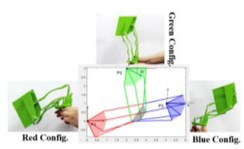

Fig 1. Design procedure and a simple example

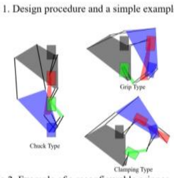
Fig 2. Example of a reconfigurable gripper

Multi-stable structures have the advantages of reconfigurability and requiring relatively simple actuation. This paper proposes a new method of constructing multi-compatible structures where kinematically determined truss-base structures are arranged in a manner to have several prescribed geometrically compatible configurations. As a consequence, the structures are globally stable in those prescribed states while unstable in other states as the truss-base has generically zero kinematic degree-of-freedom. The prescribed target configurations are represented by a set of reference points and angles. The truss structure is associated with them at nodes. The geometric parameters of the truss-base structure are the design variables, and its deformation such as rotation of joints are kinematic variables. We write rotational kinematic equations as constraint equations, describing the rotation motion of the structures to ensure they are compatible at target configurations and there are feasible transitions between them. The sum of bars' lengths is written as the target function to improve manufacturability. Then we use the build-in non-linear constrained optimization function called 'fmincon' in MATLAB to solve for those design and kinematic variables.We carried out a simple example in two-dimension (two rigid bodies with four trusses, prescribing the reference points P on rigid bodies) and made the corresponding physical model through 3D printing (Fig.1). Additionally, we designed and simulated an example of a reconfigurable gripper in two-dimension, which consists of four rigid bodies and ten trusses. As shown in Fig.2, grey (fixed on the ground), red, green, and blue plates denote four bodies while black lines denote trusses. We designed the reference points on rigid bodies to achieve three target configurations, namely chuck type, grip type, and clamping type (Fig.2). This method opens a novel path to designing multi-stable structures.

290

Topological stereotomic design of systems of interlocking stackable modular blocks for constructing multi-storey funicular masonry buildings

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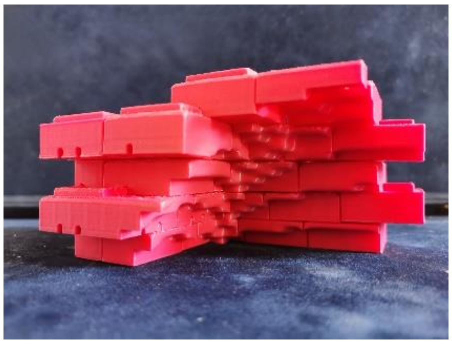


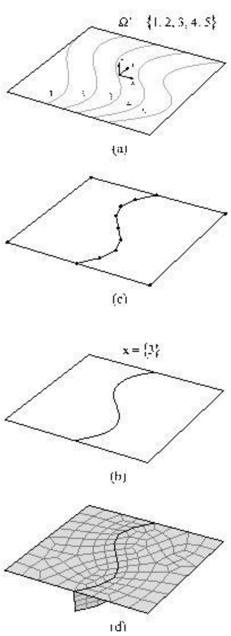
With the advent of Computer-Aided Design, the design and fabrication of complex free-form shells have become easier to achieve. However, this results in extensive usage of custom-made formworks for the production of shell components and falseworks which provide support for the shell during the construction process. Therefore, a modular design method is proposed for generating form-active spatial structures out of stackable blocks of a few types, having in mind its potential applications such as housing. Instead of shells, spatial masonry structures are thus the main consideration in the design process considering building on top of a vaulted ceiling. By designing a 3D interlocking grid and introducing a four-step topological design that is coupled with structural verification processes based on finite element modelling and discrete element modelling simulations, the geometry of interlocking stackable modular blocks can be automatically generated for constructing such spatial masonry structures. The proposed method ensures that the designed vaults are modular, reconfigurable, and self-supporting during construction, thus increasing the efficiency of mass production while allowing for combinatorial mass customization in designs.

303

Design of an adaptive rib-stiffened slab equipped with a variable post-tensioning system

Arka P. Reksowardojo. Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart, Germany. arka.reksowardojo@ilek.uni -stuttgart.de

Floor systems are typically designed to satisfy tight deflection limits under strong out-of-plane loading. While the use of prismatic slabs is common due to the ease of construction, the load-bearing performance is poor since the material is not optimally distributed within the cross-section to take the bending caused by external loads. This typically results in significant oversizing. Recent work has shown that rib-stiffened slabs offer significant potential for material savings compared to prismatic slabs. This work investigates the feasibility of adaptive rib-stiffened slabs equipped with a variable post-tensioning system. The post-tensioning system comprises high-strength cables embedded within the concrete rib through a duct that enables varying the cable tension as required. The cables are positioned following a parabolic profile so that the tension force is applied eccentrically to the neutral axis of the slab-ribs assembly. The resulting system of forces causes a bending moment and an uplift that counteracts the effect of the external load. A design of an 8 × 8 m adaptive rib-stiffened slab has been carried out to evaluate material savings potential. The rib placement is optimized through a greedy algorithm combined with a heuristic based on the direction of the principal stresses. The deflection of the slab is reduced by adjusting the cable tensile forces computed by a quasi-static controller. Results show that the adaptive slab solution can achieve up to 66% material savings compared to an equivalent passive prismatic slab.



306

Brick vaults for rural housing in Mexico

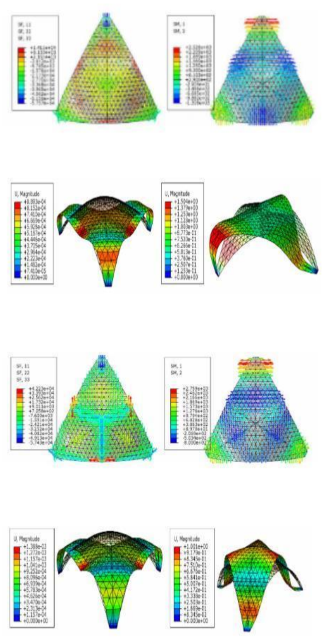
Juan G. Oliva. Lightweight Structures Laboratory-LEL, Faculty of Architecture, Universidad Nacional Autónoma de México-UNAM. jgos@unam.mx

The LEL research group of the Laboratory of Light Structures-LEL of the Faculty of Architecture of the UNAM is currently developing projects to provide solutions to the construction of sustainable rural housing in Mexico, where 21% of the population is rural and 79% urban. The objective of these projects is to offer affordable rural housing for the most disadvantaged social groups with the lowest incomes in Mexico. The house is built with sustainable regional materials and considers the traditions and customs of its inhabitants. It also has passive environmental adaptation systems and uses solar energy to heat water and generate electricity. The form of the developed projects has different geometries. The brick vaults discussed in this paper are revolution surfaces generated through the rotation of a catenary. Oliva et al.. The gridshells with bamboo bars are translation surfaces with catenaries. Oliva et al.. This guarantees that the mechanical behavior of both structural systems is exclusively in compression.The LEL research group presents prototypes of rural housing projects in Mexico covered with brick vaults in this paper. The use of annealed brick to construct brick vaults in many regions of Mexico is every day. Moreover, it is a technology typical of Mexico that allows covering spaces with irregular geometries in short periods without requiring any falsework. As a result, costs and execution times are reduced compared to other types of roofs, such as those made of reinforced concrete. In this article, the research group will present and describe three different projects for single-family housing.

557

Modular Textile Reinforced Concrete (TRC) shell structures: An exploration through geometrical and structural design

Arnaud De Coster. Department of Mechanics of Materials and Constructions (MeMC). arnaud.de.coster@vub.be



Curved thin-walled shell structures are very promising towards the future, as they possess the ability to carry their loads efficiently, resulting in very thin designs and therefore a reduced material consumption. Recent developments of new construction materials and innovative fabrication techniques have led to a resurgence in this research domain. Using Textile Reinforced Concrete (TRC) in the shell designs significantly reduces the required cross-sectional thickness, due to the use of fibres. On top that, these fibres are very flexible, making it possible to easily create nicely curved surfaces. Still, a major issue is the cost of the formworks, as they are in many cases project-specific and therefore not reusable.Fortunately, recent research towards a modular design approach may solve this problem. Several modular parts are already designed, which can be assembled in many ways to create a wide variety of shell configurations. As a result, only a few numbers of formworks need to be made that can serve for a vast amount of shell structures. The main objective of this research is to investigate the structural behaviour of these configurations and to evaluate their load bearing efficiency. A second objective is to evaluate the influence of considering different types of connections between the modules on the overall structural behaviour of the shells. The load bearing efficiency of the shells will be evaluated by considering both fully fixed and fully hinged connections between the modules. The results are very promising, as it is observed that some of the considered shell configurations possess a better load bearing behaviour than the form-found structure from which the modules are extracted.

SESSION 18

Tue, 20 Sep.

Parallel Sessions,

21:45-23:15

(90 minutes)

Disaster Prevention and Mitigation of Spatial Structures-1

Chair(s): Kiyoshi Shingu and Xiongyan Li

133

Seismic performance of an innovative cold-formed steel framed building

Yan Zhao. Beijing University of Technology. zyhbhj@126.com

Corrugated steel sheathing cold-formed steel (CFS) shear wall is an innovative lateral force resistant structural system with great development potential arising from the promotion of CFS structure from low-rise to multi-rise. However, dynamic tests of a CFS structure using corrugated steel sheathing have not previously been conducted, and its failure mechanism as well as seismic behavior under earthquake load are unclear. This study aims to increase the knowledge of the seismic performance of corrugated steel sheathed CFS framed buildings. The dynamic characteristics, seismic response and damage mechanism of the corrugated steel sheathing CFS house structure under horizontal earthquake were analyzed by shaking table test of full-scale model of two-story CFS house structure, and its seismic performance was evaluated. The test results show that the structure is damaged during vibration mainly in the connection damage of screws and the local damage of the inner wall panel, while the steel frame is basically intact. As the seismic intensity increases, damage occurs to the structure leading to an increase in its damping ratio. The acceleration response of the structure increase as the height increases. The acceleration response trend of the structure in two directions is different, and its acceleration change is mainly affected by the spectrum of seismic wave. In the 9-degree seismic fortification, the maximum elastic story drift ratio of the structure under both frequent earthquake and rare earthquake meets the relevant deformation limits in the seismic code. This research will provide a reference for the seismic design of the CFS structure with corrugated steel sheathed.

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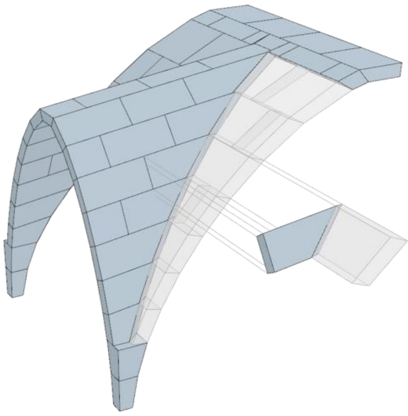
Geometry generation and modelling of non-standard cross vaults

Petra Gidak, Faculty of Civil Engineering University of Zagreb. Email 1: pgidak@grad.hr Email 2: pgidak@gmail.com

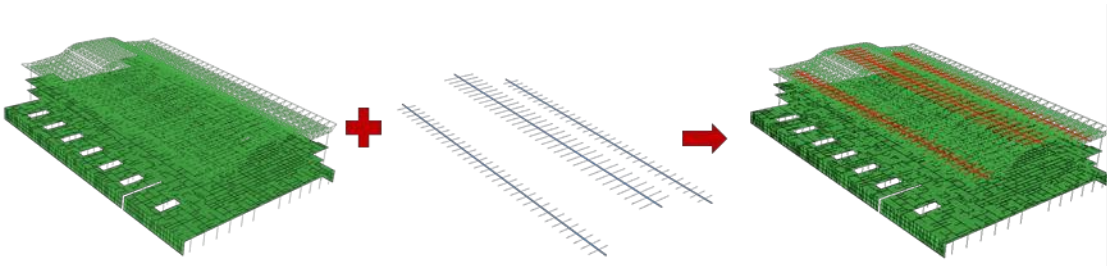


Zagreb Cathedral was severely damaged by the 5.4 magnitude earthquake on March 22, 2020. The church had already been hit by a severe earthquake in 1880 and was restored in the neo-Gothic style with cross vaults and arches supported by slender columns. In the restoration, the spatial connection between the load-bearing elements was poorly executed and the structural system for horizontal loads has not been significantly improved, which resulted in serious damage from the new earthquake. For the purposes of a new reconstruction, a structural analysis of the Cathedral is currently being done using the distinct element method (DEM). This paper focuses on the geometry of blocks that form a cross vault. The available solutions for the automatic generation of masonry geometries developed in Grasshopper are mostly focused on the generation of walls or barrel vaults. The vaults in Zagreb Cathedral are non-standard cross vaults that are not square in plan, but strongly rectangular. The crowns of orthogonal barrel vaults that form a cross vault are not at the same height and some are not horizontal. Since the block arrangement in vaults (stereotomy) is of great influence on the behavior of cross vaults (less depending on mechanical properties), this paper proposes a different definition of groins of untypical cross vaults. Finally, results (failure mechanism) of a numerical model for the cross vault after time history analysis obtained with 3DEC software are shown.

294

Seismic capacity and fragility of fire-fighting piping system of large-span transportation hub structure

Fengze Li. Harbin Institute of Technology. 837547369@qq.com

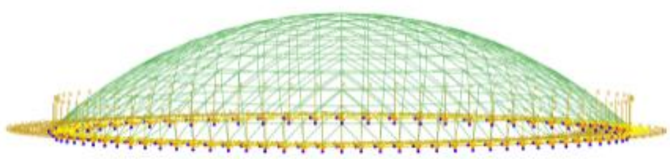


In recent years, earthquake disasters have seriously damaged nonstructural components, so it is necessary to study their seismic performance. As a common non-structural component in large-span space constructions, the seismic performance of the suspended fire-fighting piping system has been investigated in this work. Three failure modes of the piping system were offered as well as their accompanying calculation indications, based on static tests and other scholars' study results: axial failure of the connecting node, bending failure of the connecting node, and failure of the hanger. This paper chose Shenyang South Station as the research target which was modelled with the piping system. Seven ground motions corresponding to the specifications and seven most unfavorable ground motions were selected to develop the incremental dynamic analysis. Thereafter, the impact of the piping position distributions and types on the damage degree was investigated, and a fragility curve for the pipeline system was obtained. The results demonstrated that the pipeline system would be susceptible to damage even under small earthquakes, which had been neglected in prior studies.

298

Seismic behavior and failure mechanism of reticulated shells considering the influence of support members

Bo Huang. School of Civil Engineering, Harbin Institute of Technology. 837325847@qq.com



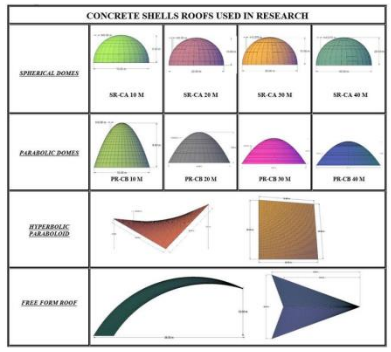
Due to the frequent occurrence of earthquakes, the reticulated shell structure which is commonly used as a landmark building, has suffered severe support damage in many earthquake events, causing the overall collapse of the structure and serious property damage. To explore the influence of support members on the seismic response and failure mechanism of reticulated shells, the support members of single-layer reticulated shell with different spans were designed and analyzed. A simplified mechanical model of the support was extracted. Then based on the integrated model, the influence of support stiffness on the natural vibration characteristics and the strong seismic response of reticulated shell structure was analyzed. After that, a method for judging the failure of the support members based on the vertical reaction force of the support members was proposed, the research on the response of the support failure to the strong earthquake of the reticulated shell when the support members are designed according to the rare earthquake, fortified earthquake and frequent earthquake is compared, and the effect of normal support variation is investigated. The results show that the design of the support members according to rare earthquakes can ensure the safety and reliability of the structure under rare earthquakes and even greater earthquakes and the variation coefficient of the construction quality of the supports should be reasonably controlled.

350

Nonlinear behavior of concrete shell roofs of different curvature under seismic loads using the finite element method (fem), located in mexico city.

Jesús Gerardo Pérez Vega. Instituto Politécnic Nacional (MEX). jess.arq77@gmail.com

This research presents the structural behavior of shell-type concrete roofs of different typology, curvature and support conditions, in which their structural performance is evaluated through the implementation of a numerical analysis (FEM) in different phases. The analyzes performed are; linear analysis that considers the methodology of the Construction Regulations for Mexico City, followed by a non-linear analysis that includes the buckling study based on the theory of large deformations under different load patterns and the time-history analysis with seismic accelerations, obtained from short period soil sites close to the fundamental periods of the structures, using a nonlinear material model for the behavior of the concrete and another for the steel of the reinforcing bars. When evaluating the behavior of shell-type concrete shells through nonlinear time-history analyzes under different load patterns, they reflect that the behavior of most roofs does not suffer structural damage since they do not exceed the allowable stresses of the concrete, unlike the rest of the roofs in which tension stresses predominate, where the increase in capacity due to reinforcement with steel bars is evaluated and compared.

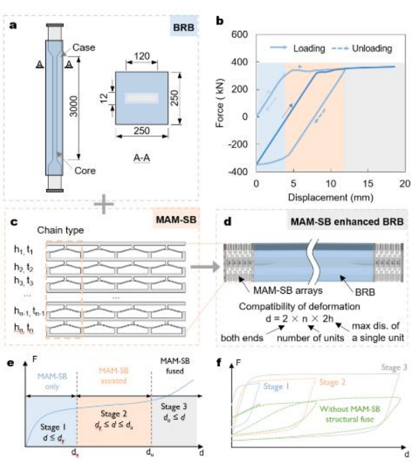


363

Gradient design and inelastic response of architected slender structures toward multi-stage energy dissipations

Xianhua Yao. South China University of Technology. 202110181407@mail.scut.edu.cn

We introduce architected slender structures comprising curved beams with energy absorption properties into the design of seismic resistance structural damping components, Buckling-Restrained Brace (BRB), aimed to develop novel energy absorption structural components with customizable properties and enhanced toughness and energy-absorbing properties. Besides, the plastic deformation of the curved beam unit is considered to improve its strength and energy dissipation ability, which also exhibits negative stiffness behavior. Based on numerical simulation analysis, this strategy can overcome the limitation of BRB that cannot contribute to energy dissipation in normal operation beyond seismic events. Moreover, the programmability of energy absorption of the bistable unit in the plastic range is realized by regulating its geometrical arrangement. Gradient design based on the pre-defined combinations of the bistable unit with various energy absorption capacities is proposed to enhance the adaptability of BRB under different levels of seismic action.



SESSION 19

Wed, 21 Sep.

Parallel Sessions,

8:30-10:00

(90 minutes)

Dynamic Performance and Seismic Response of Metal Spatial Structures - 1 (APCS, WG8-4)

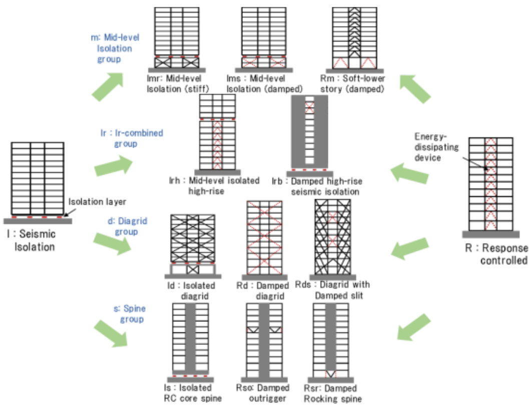
Chair(s): Jingyao Zhang and Guojun Sun

38

Borderless design between seismic isolation and response-controlled structures

Toru Takeuchi. Tokyo Institute of Technology. Takeuchi.t.ab@m.titech.ac.jp

In the past 30 years, seismic isolation and response-controlled structures with energy dissipation devices have been widely applied to numerous buildings in seismic areas, and they can no longer be called special structures. Consequently, a wider range of structural systems have been developed using these techniques, and the boundary between seismic isolation and damping structures is becoming ambiguous. In free-formed structures, the borders of building façades and roofs are becoming ambiguous, affecting the seismic design of spatial structures. In this paper, detailed application examples of these varied structural systems for multistory buildings are introduced, followed by the possibility of applying the algorithm to determine optimal design solutions, including spatial structures and gridshells.



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Research on the method of considering concrete substructures of suspen-dome prototype structure in shaking table test scale model

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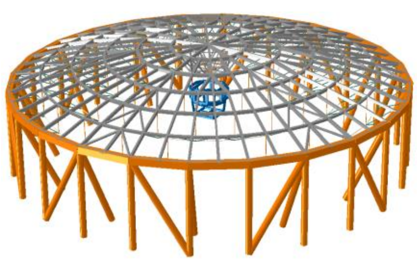
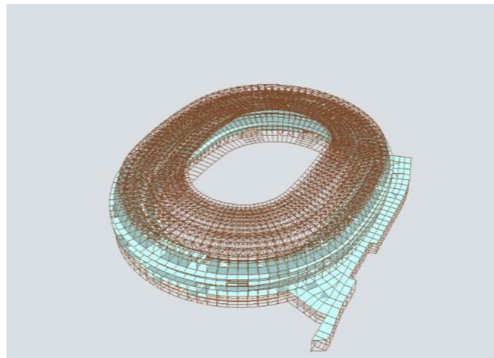


Due to most suspen-dome roof structures are built on complex concrete substructures, and the coupling effect between the two can not be ignored, the method of establishing a refined scale model of suspen-dome structure considering concrete substructures of the prototype structure in shaking table test needs to be further studied. In this paper, the suspen-dome roof structure of the Gymnasium of Lanzhou Olympic Sports Center was taken as the prototype, a method that replaces complex concrete substructures of the prototype structure with steel substructures and aims for the fundamental frequency of the test mode and the prototype structure considering the scale ratio to be equal in shaking table test was proposed and a scale model considering substructures was established. The natural frequencies of the model were obtained by white noise sweep test. The corresponding numerical scaled model was established by ABAQUS finite element software, and the numerical model of prototype structure was established by Midas/Gen software. The test results, the modal analysis results of the numerical scaled model and the modal analysis results of the prototype structure were compared. It is observed that the first three-order natural frequencies of the test model were very close to that of the prototype structure after considering the scale ratio, and the shape of the first two modes of the scaled model were consistent with that of the prototype structure, which proved that in shaking table test, the method of designing the integral scale model which replaces complex concrete substructures of the prototype structure with steel substructures and aims for the fundamental frequency of the test mode and the prototype structure considering the scale ratio to be equal is accurate and effective. The analysis results provides a reference for researchers and designers to build more accurate scale models of suspen-dome structures in shaking table tests.

132

Seismic response controlled structure based on soft-first-story theory for the new national stadium in Japan

Nobuyuki Yamato. Taisie corporation. ymtnby00@pub.taisei.co.jp



The New National Stadium is a facility that is also used as Tokyo Olympic Games and Paralympic Games in 2020. This stadium is hoped to become a place where all athletes can show their best performance, and to be loved and used frequently by people of future generations. Based on the concept of "Stadium in Forest", the new stadium is open to everyone. Becoming a part of the forest of Meiji Jingu, it will form a green network spreading from the Inner Garden of Meiji Jingu Shrine to the Imperial Palace, and become a "New center of sports cluster" where everyone can enjoy taking walks and various types of sports. In addition to the concept of "Stadium in Forest," the structural design was proceeded on the themes of Japanese-style and world-class stadium, the disaster-resilient stadium for improving the capacity of disaster prevention of the area, and so on. One of the central challenges in realizing them is how the 60 m long cantilever roof frame, which is applied for the stadium considering the efficiency of construction, achieves the high seismic performance against big earthquakes, despite its characteristic to vibrate-prone. In this paper, it will be reported the process of solving the issue above by applying the Soft-First-Story theory, known as a seismic control system, to the stadium in a unique way, through showing the analysis for seismic design.

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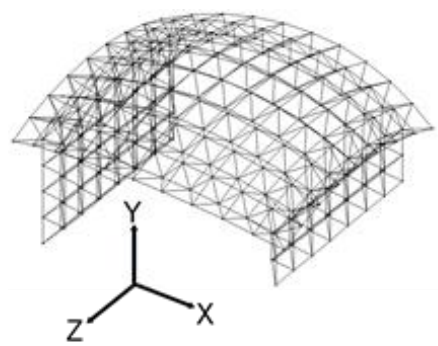
Seismic performance evaluation method of double layer spatial truss structures with truss walls subjected to earthquake motion

Zhiyuan Gao. University of Fukui. 1340086909@qq.com



This study deals with small and medium-sized three-dimensional spatial truss structures supported by truss wall structures. First, the equivalent static seismic force of the target structure is calculated by the response spectrum method, and the effect of eccentricity on the seismic response properties of this structure is clarified. In addition, accuracy verification will be performed by comparing the static analysis results based on the equivalent static seismic force with the elastic seismic response analysis results. The results show that the elastic seismic response characteristics considering the effect of the wall eccentricity can be calculated by static analyses. The purpose of this study is to elucidate the seismic response characteristics and propose a control method for the dynamic collapse mechanism for truss wall structures. For a truss roof structure, a method is proposed to use the equivalent static seismic force to determine the degree of snow load increase and the margin for the maintenance of member bearing capacity.

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Yield seismic intensity and seismic performance of pin supported arch structures

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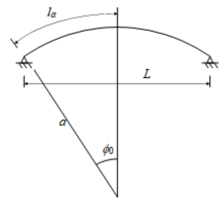
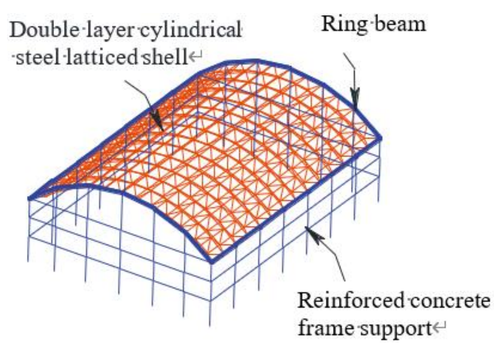


Spatial structures have served historically as evacuation facilities in earthquakes, and the study of seismic performance and the technology for retrofitting have accumulated. Arch structures are one of the fundamental and important structures for public use needing robustness against earthquakes. and several studies have investigated vibration characteristics and equivalent static seismic loads. Furthermore, in the previous studies, the critical seismic intensity was defined as an indicator of the seismic performance of arch structures, and it was proposed to express this value as the product of the static ductility index and the yield seismic intensity, which is the magnitude of the seismic load at which initial yielding occurs by buckling analysis. However, the evaluation of yield seismic intensity requires elasto-plastic buckling analysis, which is time-consuming in practice. In addition, the static ductility index estimation equation in the previous research is proposed based on the analysis of a limited number of analytical cases. It has not been fully analyzed using analytical parameters. The rapid calculation of the yield seismic intensity and static ductility index is beneficial in the evaluation of the seismic performance of arch structures.With the above backgrounds, this paper describes a method for estimating the yield seismic intensity of arch structures based on the continuum arch theory. First, the buckling behavior and the yield seismic intensity are investigated by elasto-plastic buckling analysis for equivalent static seismic loads. Through analysis of buckling behavior, the yield seismic intensity can be evaluated with high accuracy. Then, the static ductility index is analyzed by elasto-plastic response analysis, and an estimation equation for is proposed. The formulas for estimating yield seismic intensity and static ductility index are effective in assessing the critical seismic intensity based on response analysis.

340

Seismic responses of double-layer cylindrical reticulated shells under near-fault velocity pulse-like ground motions

Xuhai Li. Sichuan University. lixuhai2376100@163.com



In order to quantify the amplification effects of near-fault velocity pulse-like ground motions on seismic responses of reticulated structures, a representative double-layer cylindrical reticulated shell with reinforced concrete frame supporting structure was designed and used in this paper. A group of 22 near-fault ground motions each of which contains velocity pulses and the other group of 22 corresponding residual ground motions with removing velocity pulse components were used for IDAs. Then, statistical analyses on the seismic responses of the lower supporting structure and the upper reticulated shell were respectively conducted. The results show that, for the double-layer cylindrical steel reticulated shell with reinforced concrete frame supporting structure, the near-fault velocity pulse-like ground motions have significant amplification effects on the typical seismic responses; Specifically, for the lower supporting structure, the mean values of the amplification factors for maximum nodal displacements is about 1.6~2.1, for maximum inter-story drifts is about 1.6~2.0, for maximum axial forces of members is about 1.0~1.6, and for maximum base reaction forces is about 1.1~1.5; likewise, for the upper reticulated shell, the mean values of the amplification factors for maximum nodal displacements is about 1.6~2.0, for maximum axial forces of members is about 1.2~1.6, and for maximum reaction forces at the connections between upper and lower structure is about 0.8~1.1. The conclusions in this paper can provide technical guidance for the seismic design of the double-layer cylindrical steel reticulated shells with reinforced concrete frame supporting structures built in the near-fault high seismic intensity zones.

SESSION 20

Wed, 21 Sep.

Parallel Sessions,

8:30-10:00

(90 minutes)

Cable Structures (WG6-4)

Chair(s): Minger Wu

103

Error sensitivity analysis and multiple error coupling analysis for cable-supported grid structure with an internal compression ring

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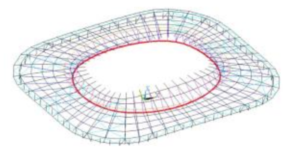

Cable supported grid with an internal compression ring is a new type of rigid and flexible structure. The compression ring is located inside the upper rigid grid, and the radial cable force is transmitted to the compression ring through the upper radial girders to form a prestress equilibrium system, which is innovative and first applied to Shanghai Pudong Football Stadium. The length of radial cables and hoop cables is fixed and not adjustable, which puts forward higher requirements for the production accuracy of the cable and the installation accuracy of the steel structure. By sensitivity analysis of cable length error and outer-linked-node coordinate error on the cable force, a reasonable error control index was determined to ensure that the cable force would not exceed the limit in the formed state. Both the cable length error distribution and outer-linked-node coordinate error distribution adopted the normal distribution model, and the Monte Carlo method was used to calculate and count cable force distribution under different error combinations. The results show that under the influence of independent error and coupling error, the cable stress obeys normal distribution. The radial cable force error plane distribution is uneven, and the cable force error of the radial cable at the corner of the structure is the smallest. The radial cable force is more sensitive to the errors of radial cable length and outer-linked-node coordinate, and the hoop cable force is more sensitive to the error of hoop cable length. To meet the requirement that the cable force error is not more than ±10%, the control indexes of the case project are determined as follows: the error of the radial cable and hoop cable length should not exceed ±0.02% and ±0.015% of their original lengths respectively, and the installation error of the peripheral steel structure should not exceed ±20mm. The analysis results provide significant guidance for the actual construction of the structure.

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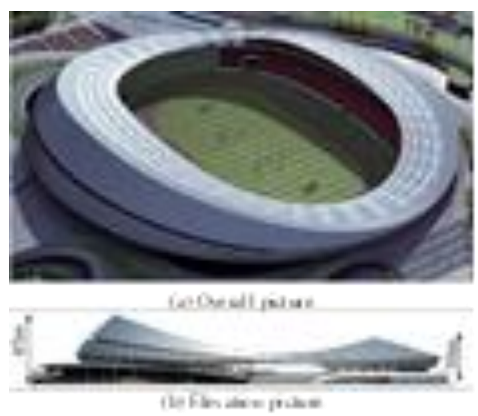
Research on mechanical property and construction technology of spoke tension structure with single-double-combined layer cable

Kun Zu. Key Laboratory of Concrete and Prestressed Concrete Structures of Ministry of Education, Southeast University. zuk1125@163.com



Aiming at the prestressed spatial structure system of large opening single-double-combined layer cable-bearing grid suitable for stadium buildings, the nonlinear dynamic finite element method for determining the static equilibrium state of the cable net system is used to study the mechanical properties of the hybrid cable-net structure. Performance and key construction technology, the construction scheme of the final anchorage in tension lifting in the double-layer cable net are simulated, analyzed and optimized in the whole construction process. The results show that the stress characteristics of the single-double-combined layer cable structure are quite different from that of the single layer or double layer cable structures. The balance force all appears at the junction of the single and double layers of the ring cable and the cable clamp. Considering the shape and stress characteristics of the cable net, as well as the controllability and economy of the construction process comprehensively, this structural system is suitable for the lower traction cable for the final anchoring of the double-layer cable net, the whole construction process analysis results provide a theoretical basis for the implementation of project.

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Tensioning simulation and experiment study of the upper-layer crossed wheel-spoke cable-strut structure

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This paper proposes a new cable-strut structural system, named as the single-layer oblique crossed wheel-spoke cable-strut structure, and the feasibility of tensioning is verified. In order to solve the difficulty of installing struts of this type of structure during tensioning construction, a numerical simulation method based on the relationship between the internal force of struts to be installed and the traction lengths of active cables was established by the theory of vector mechanics. Then, a tensioning experiment of the model with this new structural system was carried out. The experimental results indicate that the numerical simulation method is accurate and effective to guide the tensioning construction. The results also confirm that the single-layer oblique crossed wheel-spoke cable-strut structure can be formed successfully by whole tensioning and this structural system has great lateral stability in the process of tensioning.

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Research on multi-step form finding analysis method of single layer spoke cable structure

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In this paper, a multi-step iterative method for form-finding of single-layer spoke-type cable structures is presented, which takes into account the cooperative deformation of the supporting system, the pre-stress form of the spoke cable structure considering the cooperative deformation of the supporting system can be found. Firstly, the plane model is built in the projection plane, and the plane model is lifted by the support lifting method, and the coordinates are iterated to find the shape of the target, extract the stress distribution of the shape of the target and calculate the normalized vector of the cable force. Then, considering the influence of stiffness and gravity of the whole structure, given the magnifying coefficient of cable force, and applying the magnified prestress distribution, the shape of the cable net structure can meet the requirements of the target shape. Then, the initial deformation of the bearing system is calculated, and the deformation of the ear plate and the ring beam is controlled by applying the reverse displacement, and the ear plate is controlled by adjusting the temperature. Finally, based on the Ansys Software, the multi-step form-finding method proposed in this paper is used to obtain the pre-stressed form of the Suzhou Industrial Park Sports Center Stadium, and the node is compared with the given target shape. Through the contrast analysis, the prestress shape obtained by this method meets the actual engineering requirements.

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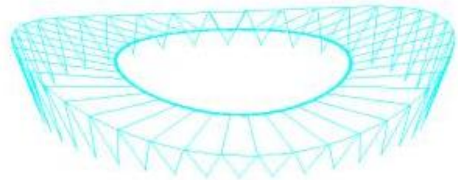
The influence of production and construction errors on single-layer spoke cable structure

Yurong Shao. Faculty of Architecture, Civil And Transportation Engineering in Beijing University of Technology. 1125046250@qq.com



The single-layer spoke cable structure has the advantage of light-weight, elegant appearance and has wide application prospects. In order to improve the understanding of the single-layer spoke cable net structure, this paper analyzes the influence of the production and construction error factors on the performance index of the cable net. Firstly, the single-layer spoke cable roof of Suzhou Industrial Park Stadium is introduced. Secondly, Numerical simulation was used to analyze the influence of three kinds of production and construction errors, such as cable length, sectional stiffness, and installation configuration of ring beam, on the performance indicators such as cable force, node configuration of loop cable, and ring beam stress. The sensitivity of the performance index deviation to the production and construction errors is also analyzed. Finally, the influence of errors above on the performance index of cable structure under different prestress levels is studied. The research results show that in the process of construction control, it is necessary to monitor the loop cable force, and the control of the length error of the loop cable should be stricter than that of the radial cable. The elastic modulus error of the loop cable at the lower part of the outer side of the cable clip also has an obvious influence on the performance index of the results. Properly increasing the prestress level of the structure can reduce the effect of production and construction errors.

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Experimental study on static performance of fully-assembly ridge-tube threading cable with annular-struts cable dome

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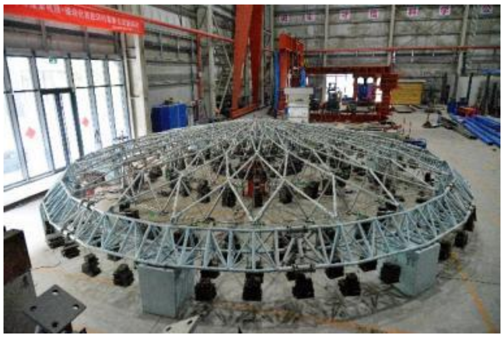

Based on the challenges of ridge cables easy to relax and large quantity of diagonal cables in the traditional cable dome, a fully-assembly ridge-tube threading cable with annular-struts cable dome structure is proposed. The structure ingeniously achieves the goal that the ridge tube is only compressed and the cable is tensioned, which can not only solve the problems that the traditional ridge cables exit work after relax, but also solve the problem of difficult assembly and construction between the ridge tube. A scaled cable dome model with a span of 10m and 24 equal parts in circumferential direction is designed and manufactured. The static performance under different vertical loads is studied by static loading test, and the various laws of internal force and node displacement of each member in the structural model are obtained. The research results to verify the rationality and feasibility of the fully-assembly ridge-tube threading cable with annular-struts cable dome, which can lay the foundations for future engineering application.

SESSION 21

Wed, 21 Sep.

Parallel Sessions,

8:30-10:00

(90 minutes)

Designing Structures with Computational Methods (WG13-3)

Chair(s): Anahita Khodadadi and Yao Chen

104

A Practical Method for Shape and Size Optimization of Space Arch Truss

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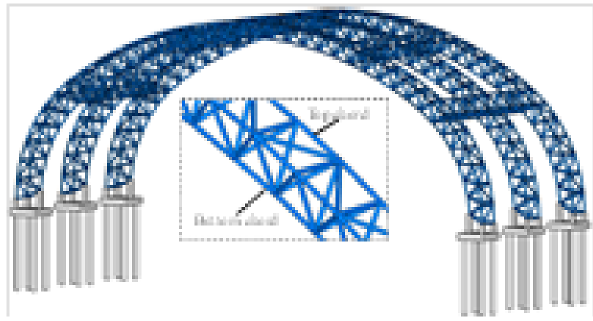

Space arch truss is a common form of space structure, which is widely used in industrial buildings and stadiums. Determining the shape of arch truss is a crucial step in the structural design process. Reasonable shape can not only improve the bearing performance of the structure, but also reduce the consumption of material. In the traditional design process, engineers usually determine the shape of arch truss artificially, which depends on the design experience. A practical optimization method is proposed, which takes the material consumption of steel and foundation pile as the objective function. The arch axis of truss is described by B-spline method, and control points of spline curve are taken as the variables to be optimized by genetic algorithm. Once the shape of the arch truss is determined, the fully stressed design method is used to optimize the member sections of the truss, so that the strength and stability bearing capacity of the members can meet the design requirements. Finally, a specific engineering example is selected to be optimized, which verifies the effectiveness of the method.

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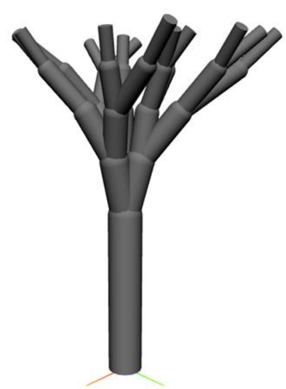
Creation method for tree-like pillar based on genetic algorithm

Hideyuki Takashima. Professor, Kanto Gakuin University. hide@kanto-gakuin.ac.jp



In order to create a space surrounded by pillars which look like natural trees, this study proposes the procedure based on genetic algorithm (GA) with L-System. As the former study, Frei Otto has introduced the tree type pillar and the consideration would be reached for Lindenmayer L-System. L-System is widely found in many books related to soft computing field. In the proposed creation method, optimal combinations for number of branches and their inclined angles will be selected through GA with float value chromosomes not binary ones. These pillar forms were found at each numbered generation under the fitness function where both the maximum bending stress and the supported areas at the tops of pillars were considered. In the present paper, further trials on the other estimation functions will be executed and the availabilities of the proposed procedure to generate architectural spaces composed of such natural tree-like pillars will be investigated.

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Link element arrangement for CLT shells

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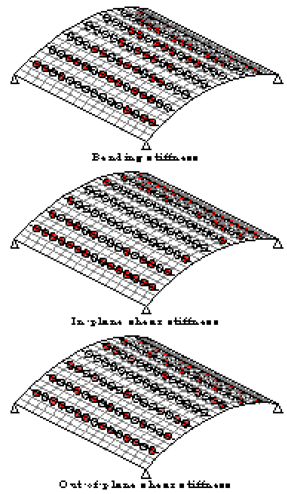
This paper presents an optimization method of the joint arrangement for shell structures composed of CLT (Cross Laminated Timber) panels. Because CLT shells, composed of interconnected discrete CLT panels, have different stress conditions compared to ordinary continuum shells, structural engineers should select several types of joints more carefully than conventional structures. The joining system is modeled as link elements with multidirectional stiffness. In this paper, independent weight parameters are introduced for each direction as design variables to optimize the joint layout. Their stiffnesses are computed by multiplying the weight parameters. Furthermore, the weight parameter is controlled by multiplying a power-law function to reduce the intermediate value of joint stiffness for ease of construction. An optimization problem is formulated to minimize the strain energy; the effectiveness of the proposed method is shown through numerical examples. It is confirmed that the joint arrangement in each direction is optimized, corresponding to the stress state.



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Prefabricated modular pavilion of architectural concrete

José Luis Encarnación Miranda, Facultad de Arquitectura Universidad Nacional Autónoma de México-UNAM. jlemiranda@comunidad.unam.mx

This document is part of a research project that analyses computing tools and digital manufacturing techniques in design processes, molds' elaboration, casting concrete and manufacturing of architectural precast concrete components using some manufacturing techniques. As an experimentation exercise it is proposed to design and build a prefabricated double-curved concrete modular pavilion of glass fiber reinforced concrete integrating both digital tools and digital manufacturing techniques combined with some industrialized architectural pre-manufacturing techniques used in Mexico. Using mineral aggregates in the concrete mixture that allow having color and texture on the surface of the pre-manufactured modules using the properties of the glass fiber reinforced concrete. This research project is part of a working group with the participation of UNAM labs and MODECO company which is a company dedicated to the architectural pre-manufacturing industry having construction sites in some cities in Mexico.

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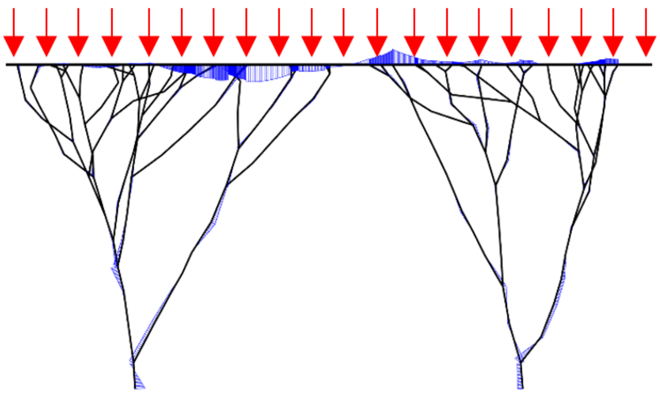
Structural morphology of 2D tree-like supporting structures

Jingyao Zhang. Kyoto University, Japan. zhang@archi.kyoto-u.ac.jp



Tree-like branching structures are aesthetically appealing and mechanically efficient in supporting architectural roofs for large space coverage. In particular, a branching structure provides ample space near the ground for human activities using a small number of columns, which is usually preferable in architectural design. For natural trees, phototropism and branches are biologically and mechanically essential: Trees absorb sunlight through their leaves as a source of energy, and branches provide physical support for leaves and transport water and nutrients to leaves. Inspired by natural trees, we first apply the L-system algorithm to generate a supporting structure with branches, according to the growth rule mimicking the phototropism of trees. Notably, the initial branches and their growth rule identified from a real tree are incorporated. We then slightly adjust the shape of the supporting structure to have a better structural performance by applying structural optimization. A numerical example demonstrates that the distribution of bending moments significantly reduces, while the appearance is not significantly changed.

SESSION 22

Wed, 21 Sep.

Parallel Sessions,

8:30-10:00

(90 minutes)

Form-Mobility Relationship: the Study of the Interdependency of Structural Geometry and Transformability (WG15-1)

Chair(s): Tomohiro Tachi and Jianguo Cai

55

Preliminary research on shape determination for curved crease origami using bending deformation

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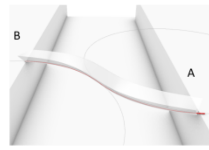

Curved origami attracts the attention of designers in recent years for the potential in the field of building structures for free form curved design. For practical use, the relationship between the mathematically obtained curved surface and the mechanical behavior needs to be revealed in the design process. In this paper, we propose a method to solve the shape determination problem by a sort of multi-objective optimization of shape and bending energy to find curved crease patterns. This method is based on an optimization method using a genetic algorithm (GA). It forms a shape close to a design by using Non-Uniform Rational B-Spline (NURBS) modelling techniques. Candidates of crease patterns can be obtained based on the target surface configuration defined by the designers. This research focuses on the application to structural engineering, aiming to determine the shape of curved origami using bending deformation to explore the possibility of applying curved origami to building structures.

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Form generation of rigid origami reflecting the mean curvature and feature lines of target surface

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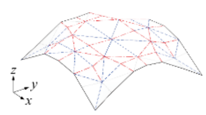

Form generation method of the rigid origami which approximates the geometric features of a target surface is proposed. The mean curvature vectors, the shape of the perimeter, and the feature lines of the target surface are approximated since they can represent the appearance of the surface. The target surface is discretized into the fine triangular mesh, and its mean curvature vector at each interior vertex is calculated by the cotangent formula used in the field of discrete differential geometry. Feature lines of the target surface are specified as the crest lines and determined by connecting points of local extrema of the principal curvatures along the corresponding curvature lines. Form generation is carried out by minimizing the approximation error function under the developability condition of the origami surface and the flatness condition of the origami faces with more than three edges. It starts from the coarse triangular mesh, and the crease lines are sequentially fixed (removed) to reduce the degrees of freedom of the mechanism of the rigid origami. Approximation error function is defined as the sum of the squared norm of the errors of the mean curvature vectors and the distances of the perimeter vertices between the target surface and the origami surface. The feature lines of the target surface are approximated by the crease lines by assigning the upper bounds of the Hausdorff distances between them.

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Deployability and structural performance of spatial scissor units made of zigzag bars

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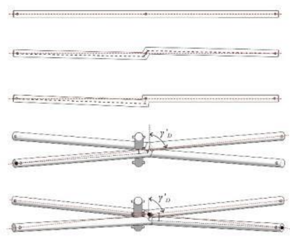

Structures using scissor-like elements (SLEs) consist of rigid bars connected by a hinge along the bar length. Depending on the number of rods used in a single unit, scissor units can be categorized into two groups: 1) planar units made of two members in the same plane, and 2) spatial units composed of multiple rods that are non-coplanar. The latter due the non-coplanarity usually conflict before full deployment is achieved. Earlier designs used two methods to improve deployability: 1) by decreasing member thickness, and 2) by increasing the eccentricity of the joints. However, the use of slender elements may cause buckling-related issues under high compression loads, and reduced compactness due to large joint eccentricity. In this paper, a modified zigzag member is used to improve the deployability of spatial scissor units to potentially overcome the drawbacks. Two units were developed using unilateral and bilateral zigzag members. The zigzag units showed better foldability and deployablility when compared to the conventional units.

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Continuous Approximation of Shellular Funicular Structures

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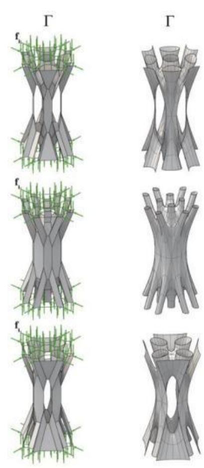

This paper introduces an interactive form finding technique to design and explore continuous Shellular Funicular Structures in the context of Polyhedral Graphic Statics (PGS). Shellular funicular forms are two-manifold shell-based geometries dividing the space into two interwoven sub-spaces, each of which can be represented by a 3D graph named labyrinth. Both form and force diagrams include labyrinths, and the form finding is achieved by an iterative subdivision of the force diagram across its labyrinths. But this iterative process is computationally very expensive, preventing interactive exploration of various forms for an initial force diagram. The methodology starts with identifying three sets of labyrinth graphs for the initial force diagram and immediately visualizing their form diagrams as smooth and continuous surfaces. Followed by exploring and finalizing the desired form, the force diagram will be subdivided across the desired labyrinth graph to result in a shellular funicular form diagram. The paper concludes by evaluating the mechanical performance of continuous shellular structures in comparison with their discrete counterparts.

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Zero Poisson's ratio origami structure inspired by Kresling tube

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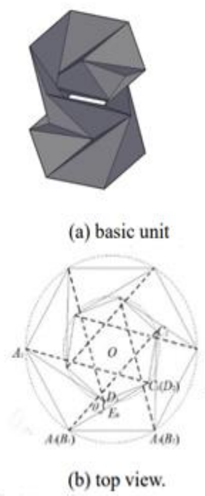
Thin-walled tubes have been widely used in engineering due to their lightweight and high efficiency under dynamic loading. For example, a variety of thin-walled tubes are commonly used as energy absorption components in manned tools such as automobiles, trains, and airplanes, where improving the energy absorption capacity has seen an urgent need nowadays. The traditional Kresling tube is modified to obtain a structure with variable section and zero Poisson's ratio, which shows great energy absorption properties and is more convenient for horizontal array arrangements. It is called the modified Kresling tube. Its basic tubular unit is shown in Fig. 1(a). Fig. 1(b) shows the top view of the modified Kresling tube, in which the bold dashed lines are valley creases, solid lines are mountain creases, and thin dashed lines are circumscribed circles of upper and lower regular polygons. Then, mechanics and energy dissipation analysis of the modified Kresling structures are conducted. The tube with modified Kresling pattern can gain an enhanced energy absorption capacity. The vertical array arrangements of the modified Kresling tube are similar to traditional Kresling tube, but more flexible. So, it is a suitable tubular structure as the buckling restrained brace. In addition, themodified Kresling tube performs better in both vertical and horizontal arrays, thus being more suitable for three-dimensional arrays. This capability could lead to broader applications in engineering problems of different nature.



(a) basic unit

(b) top view.

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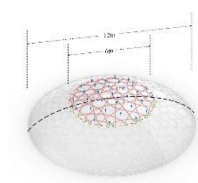
Effects of Singular Polygons on the Structural Performance of Irregular Kagome Gridshell with Continuous Rods

Jingyuan Hu. Graduate student, School of Architecture, Tsinghua University. hu-jy20@mails.tsinghua.edu.cn



In the design of gridshell structures, the topology of grid pattern is a fundamental factor. This study aims to analyze quantitatively the effect of singular polygons on structural performance of irregular kagome gridshells, mainly on the stiffness. Regular kagome is a triaxial grid pattern based on a hexagonal lattice, while in areas with large local double curvature, hexagons are replaced with alternative singular polygons (SP), creating an irregular kagome (IK). IK pattern can be generated on arbitrary triangular manifolds, so it can be used in various free-form gridshells effectively. Although researches have investigated the properties of regular kagome gridshell through simulations, and proposed the parametric generation process of IK pattern, the structural behavior of IK gridshell with a large number of SPs is currently unclear, which makes it difficult for designers to optimize. In this paper, the effect of SP on the stiffness of IK gridshell is discussed statistically. Three groups of IK gridshell samples in cylindrical, spherical, and hyperbolic shapes with different distribution of SP, are generated and simulated under uniform and concentrated load cases. Regression analysis of the number of SPs, and structural performance indicators, shows evidence negative effect of SP on the structural performance of IK gridshell, providing a theoretical basis for reducing SPs in design optimization.

SESSION 23

Wed, 21 Sep.

Parallel Sessions,

8:30-10:00

(90 minutes)

Life-Cycle Design and Assessment of Shell and Spatial Structures (WG18)

Chair(s): Kok Keong Choong and Yingying Zhaang

25

Expanding dynamic responses triggered by step excitations for spatial trusses

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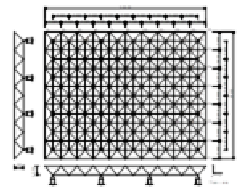

A method to expand dynamic responses of spatial trusses considering step excitations was proposed. For any moment during the time history, dynamic responses of a spatial truss triggered by step excitations can be approximately expressed by a linear combination of only a few contribution modes. Based on the simplified expression by contribution modes, the effective independence method was employed to determine optimal sensor locations, so that contribution mode coefficients (i.e., generalized coordinates) at each moment could be well estimated. Utilizing the estimates of contribution mode coefficients, the dynamic responses were expanded from finite sensor locations to other non-sensor locations. A correlation coefficient index was then put forward to determine non-sensor locations having high expansion precision. A flat spatial truss was taken as the numerical example. Analysis results show that it is effective for the proposed method to expand dynamic responses for spatial trusses, and many non-sensor locations with high expansion precision are reliably chosen by using the proposed correlation coefficient index. The work is conducive to increasing the quantity of high-quality test information during a dynamic test for a spatial truss, so that the dynamic test efficiency can be improved.

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The hanging model for the Mannheim Multihalle and its digital twin

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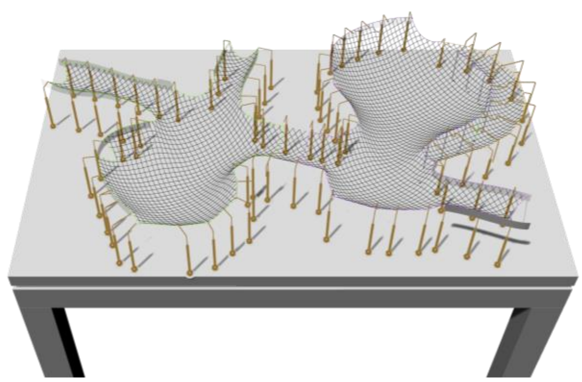

The Mannheim Multihalle, built for the 1975 Federal Horticultural Show, is an iconic construction and the largest free-span wooden grid shell listed as monument. This type of construction belongs to the category of lightweight structures, invented by Frei Otto at his Institute for Lightweight Structures (IL). To determine and optimize the geometry of the hall several physical models have been built but only one of them has been preserved at the Deutsches Architekturmuseum (DAM) in Frankfurt till today: the form-finding and measurement model at a scale of 1:98.5. The mesh of this hanging model was hand-knotted from wires with eyelets and rings and held in position on the marble base plate. The paper examines the influence physical models had on the construction of this exceptional grid shell structure. Recording and evaluating this last witness for designing the Multihalle – one of milestones of engineering history – shall help to develop concepts for the preservation of this outstanding object of construction history. For recording and further research on the behaviour of the cultural heritage itself, a digital twin was produced. This digital twin is reverse engineered purely by using digital tools. Besides photogrammetry, algorithms, and a particle-based form-finding process support the remodelling of this complex and filigree structure. It will serve to evaluate the construction in terms of today's boundary conditions and to provide access to the data in the long term in an open database format.

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Research on key technologies of intelligent monitoring and detection of operation and maintenance security of glass curtain wall

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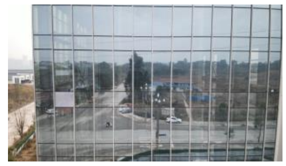

In recent years, falling accidents of glass curtain wall panels have occurred frequently, which has seriously damaged the safety of people's lives and property. By analyzing the multi-level safety risk sources of glass curtain wall, this paper puts forward a safety risk assessment and control methods. Based on UAV equipment monitoring, wireless transmission technology, data analysis and cloud technology, a new real-time monitoring technology is realized. An expert diagnosis system of glass curtain wall is developed to realize the comprehensive and efficient dynamic management of the data of glass curtain wall safety inspection. On this basis, a safety monitoring platform for operation and maintenance of glass curtain wall is established and applied to a demonstration project. The management and control method proposed in this paper adopts the comprehensive operation and maintenance method of "inspection (identification) - monitoring and early warning - operation and maintenance management and control". Its management ideas are clear, scientific, rigorous and reasonable. The research results of this paper can effectively improve the ability of safety risk monitoring, evaluation, early warning and control of glass curtain wall. This can effectively promote the prevention and control of urban public safety risks and prevent engineering accidents.

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Compressive sensing of wind speed data of large-span spatial structures using time-shift strategy

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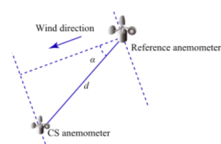
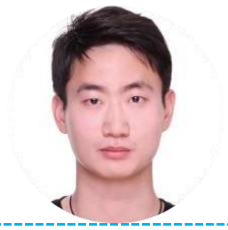


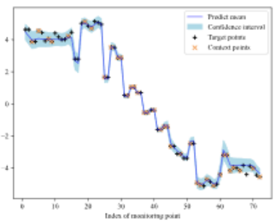
Large-span spatial structures are widely used as public buildings and the scales of them are getting more and more gigantic. To keep those structures safe and reliable, structural health monitoring (SHM) systems are widely used. The real-time measurement of wind is important for the SHM of large-span spatial structures that are naturally sensitive to the wind load, but the massive monitored data will bring difficulties to sensor energy, signal transmission, and data storage. Compressive sensing (CS) is a novel sampling technique that has great potential in solving those problem by combining the process of data sampling and compression based on the sparsity of the target signal. However, the wind speed data collected from the surface of the large-span spatial structures is often not naturally sparse on the traditional bases (e.g. Fourier basis). This paper proposed a novel method for constructing a dedicated dictionary for the wind speed signals using the time-shift strategy, and with this proposed dictionary, the signals can be compressed by random down-sampling and reconstructed by l1-norm regularized optimization. The performance of the proposed CS method is evaluated by using the wind speed data acquired from the roof of the Hangzhou East Railway Station. The target signals are successfully reconstructed with high compression ratios and acceptable error, and the wind characteristics of the reconstructed signals are well maintained.



387

Reconstruction of missing structural health monitoring data using attentive neural processes

Jingyu Zhao. College of Civil Engineering and Architecture, Zhejiang University. 11912071@zju.edu.cn



The reconstruction of structural health monitoring data is considered a challenging task of great importance for the complete understanding of structural performance and safety. For large-span spatial structures subjected to complex environmental and operational loads, the structural response evolution is a typical nonlinear dynamic process. This arouses a strong demand for developing a computationally efficient for reconstructing structural responses. In this paper, we develop a novel approach based on the attentive neural process (ANP) to reconstruct the missing data and give confidence intervals, which has considered the inherent spatial and temporal correlations in the monitoring data. The proposed method has the benefit of efficiently mapping observed discrete monitoring data of structural response to a generalized family conditional distribution, which fully exploits the linear complexity of the neural network. At the same time, the local and global relationship between different sensors is established by introducing an attention mechanism, which improves the accuracy of the reconstructed data. The ANP can be applied to both the recovery of missing data and the reconstruction of observational data, and its performance is verified with simulated data. Besides, the relative parameters of the algorithm (i.e. different attention mechanisms, model architectures) are fully investigated. Finally, the performance of the proposed ANP is demonstrated using the simulation data obtained from a surrogate model of a spatial structure named Xiongan Railway Station.

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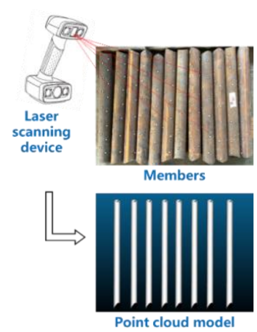
High-fidelity measurement and analysis of constructional errors of long-span spatial prestressed steel structures

Xi Zhao. Beijing University of Civil Engineering and Architecture. zhaoxi@bucea.edu.cn



Long-span prestressed steel structures, known for its light weight and good performance, are widely used and developed in the world. However, the construction errors of the structural system are non-negligible for the impacts on installation accuracy, shape formation, prestressing degree, and the global stability of the long-span prestress steel structures. The research conducts high-throughput and accurate measurements on a spatial prestressed steel structural prototype at different construction stages with the 3D laser scanning technology. A BIM model is established as the reference to the laser-measurement point cloud models where construction errors are achieved from the comparison between the BIM model and the point-cloud models. The construction errors accumulated at different stages are statistically studied. The probabilistic models of construction errors along the construction process thus are established. This research is an important step to the construction-error sensitivity study of the structural system to the global stability of a long-span spatial prestressed steel structure. It provides real-time high-fidelity data for the reliability study of the long-span spatial prestressed steel structures.

SESSION 24

Wed, 21 Sep.

Parallel Sessions,

10:30-12:00

(90 minutes)

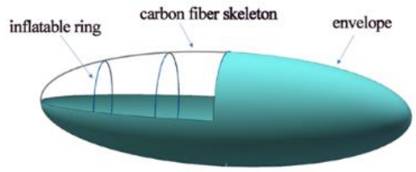
Pneumatic Structures-1 (APCS, WG6-5)

Chair(s): Ken'ichi Kawaguchi and Xiongyan Li

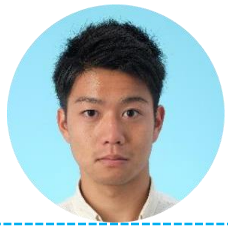
218

Force analysis of stratospheric airship with inflatable rings

Jiabao Li. Taiyuan University of Technology. smoothta11ker@163.com



Stratospheric airships have become a research hotspot in many countries. There have been growing research activities on various design strategies to improve the carrying capacity, cruise performance and stability of airships in recent years. Based on the background, many types of stratospheric airship structures were proposed. In this paper, the mechanical properties of stratospheric airship with carbon fiber skeletons and high-pressure inflatable rings were analyzed. Firstly, the properties of the airship membrane material were tested. Secondly, based on the comparative analysis of mechanical properties between traditional no-rigid stratospheric airship and the stratospheric airship with inflatable rings, the influence of carbon fiber skeleton, number of inflatable rings and internal pressure of inflatable rings were considered. The evaluation indexes and suggested values of the parameters of the inflatable rings were innovatively proposed. Finally, the mechanical properties of stratospheric airship with inflatable rings considering the overpressure load, gravity load and wind load were analyzed. The results indicate that the reasonable number of inflatable rings is 6, and the suggested internal pressure of the inflatable rings is about 200kPa. Carbon fiber skeletons and inflatable rings can effectively reduce the deformation of the airship, and improve the structural stiffness and the stress distribution. The research of this paper provides some technical support for the development of new stratospheric airship.



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Experimental research of axial elasticity and loading capacity of air-inflated tubes with low slenderness ratio

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The primary characteristic of air-inflated tubes is their low weight, and they are applied for various purpose. In the aerospace engineering, many works about air beams have been done mainly for space antenna since 1960's. For building structures, they are employed as beam elements and typically used to support temporary roofs or bridges. Muto and Kawaguchi proposed to apply air-inflated tubes as columns to support platforms. To realize it, mechanical properties of air tubes in the axial direction should be investigated. Numerical calculation and analytical solution about their buckling behavior have been revealed in the preceding research, but few experimental results are available. In addition, it has not been well investigated about the structural behavior of air tubes with low slenderness ratio. This paper reports about experimental study of cylindrical air tubes with low slenderness ratio through the loading test to reveal the elasticity and loading capacity in axial direction. The tension of membrane in the hoop direction is carried by the reinforcing net wounded around the membrane, while the tension of that in the axial direction is carried by membrane.

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Bending-wrinkling and reliability analysis of inflated beams

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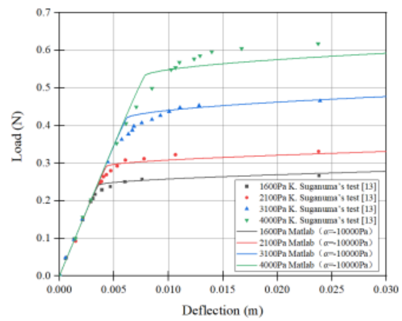
An inflatable tube membrane structure is a system formed by combining multiple inflated tubes. However, under the continuously increasing loads, the inflated tube will wrinkle and its stiffness drop significantly, which leads to failure. In this paper, it is assumed the membrane material can bear the compressive stress and the wrinkle occurs after the compressive stress reaches a certain value. The wrinkling bending moment model is established and the equations for calculating the flexural stiffness of beam elements is derived. At the same time, the critical wrinkling load of the inflated beam can be obtained. An iterative solving method is proposed and the corresponding program is created in MATLAB. Finally, considering the initial defects that exist in construction, the reliability of the inflated beam is analyzed based on the Quasi-Monte Carlo method and Multiple Linear Regression method.



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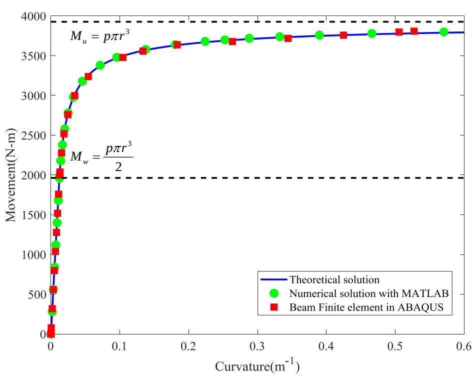
Beam finite element for nonlinear analysis of inflatable tubes

Fu Zhang. Department of Structural Engineering, Tongji University. fuzhang@tongji.edu.cn

For the inflatable membrane structure, the calculation of the wrinkle load, stiffness and ultimate bearing capacity of the inflatable tubes are very important for the design and construction. However, the beam finite element methods proposed at present are unable to obtain the forming state after inflation and are difficult to analyze the complicated 3D inflatable membrane structure.In order to solve these problems, a new computing method is proposed in this paper. Firstly, based on the assumption that the membrane is only in tension, the wrinkling angle is calculated according to equilibrium, and the expression of section flexural stiffness is deduced. Then, the PIPE31 element based on fiber beam model is used to analyze the spatial inflatable structure in ABAQUS. The numerical results are compared with the theoretical and full-scale experimental results to illustrate the effectiveness of the method. Finally, taking the semi-circular inflated arch as the discussing object, the parametric analysis is carried out to obtain the effects of sectional radius and internal pressure on the bearing performance of inflatable arch. The method proposed in this paper takes into account the effect of wrinkle and internal pressure, as well as the change of structural configuration after inflation. It can effectively analyze the bearing capability of spatial inflatable tubes and guide the preliminary design of inflatable membrane structure.



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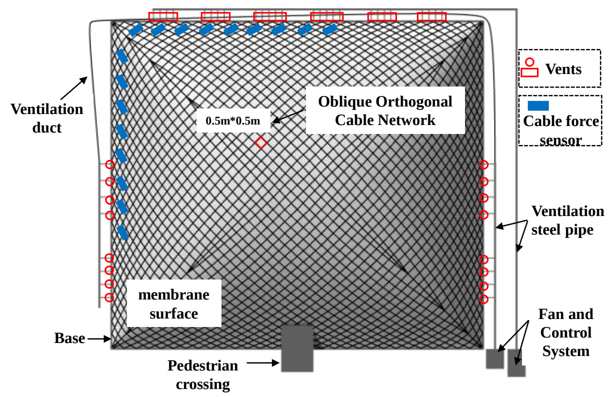
Initial shape analysis and experimental study of air-supported membrane structure considering cable-membrane contact

Zhen Zhang. Beijing University of Technology. 871279513@qq.com

The cable-membrane of the air-supported membrane structure transmits the load through mutual extrusion, and the contact interaction between the cable-membrane should be considered in the initial morphological analysis stage. Based on the 225m×198m×66m (length×width×height) large-span air-supported membrane structure project, this paper establishes a scaled model, conducts initial shape tests, and measures the shape of the membrane surface and the force characteristics of the cable net. At the same time, a finite element model of cable-membrane contact is established, and its interaction behavior is regarded as a combined contact state and sliding contact state. The results show that the influence of different contact state analysis on the prestress of the cable net is obvious, and the influence of the sliding contact between the cable and the membrane should be considered in the design of the membrane structure.



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Fabrication and loading tests of semi-rigid airmat beam structures

Yuki Ozawa. Shibaura Institute of Technology. y-ozawa@shibaura-it.ac.jp

Double-layer pneumatic structure does not require air to be introduced into the living space itself, it is easier to make air pressure management than with a single-layer system. This system can be generally classified into three types: cushion-type, tube-type, and tie-type. The tube- and the tie-types can span between two points like a simple beam without generating thrust forces at their supporting points. However, external forces acting vertically downward on the air beam causes a loss of tension due to the generation of the upper compressive force caused by bending. Wrinklings occur on the upper surface and the stiffness drops rapidly, and finally it leads to collapse. Therefore, these airmat beam-type structures require the introduction of much higher internal pressure than single air membrane or cushion-type formats. This study proposes a semi-rigid airmat beam structure, that can ensure rigidity under low internal pressure by utilizing low-rigidity board on top surface of the airmat. The board will be attached to the top surface enable to maintain stability for up to a certain level of compressive forces inside the plane. The purpose of this study is to clarify the effectiveness of this system through fabrication of full-scale test specimens and loading experiments. Generally, pneumatic systems are used to cover a site as the roof. However by using semi-rigid system as proposed in this paper for example, it could increase the possibility of pneumatic systems to be used as a temporary structures like floor or bridge.

SESSION 25

Wed, 21 Sep.

Parallel Sessions,

10:30-12:00

(90 minutes)

Mechanical Properties and Health Monitoring of Metal Strucures (WG8-5)

Chair(s): Tetsuo Yamashita and Bo Chen

23

An MPPCA approach for anomaly detection of a retractable roof structure

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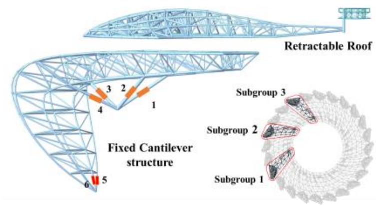

Structural anomaly detection based on the structural health monitoring (SHM) data has attracted significant attention owing to its important role in the early warning of structural damage to existing civil structures. This paper presents an anomaly detection method using a mixture of probabilistic principal component analysis (MPPCA) for a retractable roof structure with missing measurement data. First, the baseline MPPCA model was constructed for stress data collected under healthy conditions, where the estimation of the MPPCA parameters was reformulated for the missing data cases. Second, three anomaly statistics were presented for newly-monitored incomplete data to detect and localize structural anomalies. The probability distributions of the anomaly statistics were estimated to obtain thresholds for outlier detection. Finally, the effectiveness of the MPPCA-based method was investigated by applying the method to the anomaly detection of a retractable roof structure with real monitored stress data.

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Sensitive load areas in steel truss arches regarding geometrical and material nonlinearity

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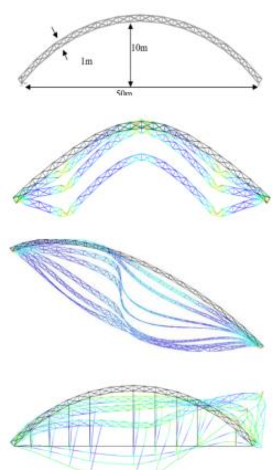

With the development of social economy, technology and the improvement of people's living standards, large-span buildings are increasingly demanded. The suspend-dome structure is suitable for building large space. Space sought the large-span suspend structure has excellent seismic performance, the project is still damaged in the case of rare earthquakes. This paper intends to study the mechanical response and failure mechanism of the suspended structure under an earthquake. The finite element numerical model of suspending structure is established with finite element software. The time history analysis of the suspended structure under earthquake action is carried out. The simulation results comprehensively reveal the failure mechanism of the suspend-dome under a strong earthquake. The results show that the suspended dome structure is always in the elastic stage under frequent and rare earthquakes. The suspend-dome develops rapidly in the plastic stage, and the structural failure caused by local failure is caused by the instability of struts and the buckling deformation of external members of the reticulated shell. Failure mode belongs to dynamic instability.

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Research on the design and construction technology of an aluminum alloy string spatial structure

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As an innovative structural system, the proposed aluminum alloy string spatial structure in this paper was suitable for arbitrary geometric boundaries, non-curvature flat roofs, special-shaped polygonal grids, etc. This new structure was composed of upper aluminum alloy latticed system and lower bidirectional cable-bar system. In order to improve the rigidity and bearing capacity of the aluminum alloy joints, a new type of gusset plate joint was suggested, with several important components involved, such as π-type rods, side web connectors, three-way reinforcer and gusset plates. This paper introduced the key technologies of design and construction of this new structural system in the practice of the Shanghai World Expo Greenhouse Project. Researches on structure system selection and shape determination, application of new "日" shaped extruded aluminum alloy members, FEM analysis and full-scale test on the new gusset plate joints, and construction simulation on the structure are presented. The integrated design technology of glass curtain wall and main structure, and the manufacturing and processing the super large "日" shaped aluminum alloy profile were described briefly, too.

415

Structural health monitoring of large-spatial structure based on unmanned aerial vehicle images

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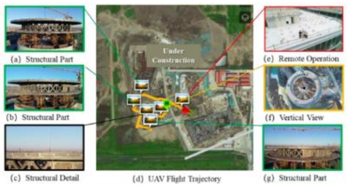

Corrosion and Cracks of large-spatial structure may cause failures that can adversely affect building performance, while which is not easy to be detected due the structural property. Aiming at the flexible and convenient monitoring method of unmanned aerial vehicle, an image-based detection and location method for the damage on the surface was proposed. Considering the compatibility between the detection of crack and corrosion, the method was composed of four steps: super-pixel segmentation, damage area primarily detection, pixel-level identification and crack location. Firstly, the UAV images were pre-segmented into suitable and universal size by simple linear iterative clustering. Then, different crack segmentation data sets were established for detection and pixel-level identification, on which YOLO V3 and DeepLab V3+ models were trained. Finally, combining images with UAV flight records, a panoramic crack location and presentation method was proposed. The method was verified by the case of Urban exhibition hall of Beijing-Tianjin Cooperation Demonstration Zone. The results showed only the close-range monitoring method could obtain the relative structure position of crack area and realization the monitoring of cracks.

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Experimental study on structural performance of innovative modular fully-assembly ring-truss steel structural system

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The fully-assembly long-span steel structural system is innovated to tackle the challenges such as redundant nodes, over welding, difficult construction, and high cost. Since the cable dome structure itself is a full-assembly long-span spatial flexible steel structural system, its supporting ring truss is still connected by traditional welding on site. Targeting at the full assembly and smart construction, an innovative modular fully-assembly long-span ring truss steel structural system is developed for cable dome structure. Experimental testing and numerical simulation are conducted where the structural system is under the static weights. The structural performance is carefully studied. The displacements and variations of stiffness at core joints are measured and analyzed. The strain variation of the joints is monitored for the stress state of the structural system. The research shows that the proposed new structural system functions well. The behaviors of connecting components are satisfactory in comparison with the welding connections. The fully-assembly property can significantly improve the constructional efficiency, minimizes the labor cost, reduce pollution to the environment, and promote the smart construction process of long-span steel structures.

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Study on bearing capacity performance of the new type of honeycomb plate hollow floor

Tengteng Zheng. School of Civil Engineering, Southeast University. 365768124@qq.com

As a common floor structure in high-rise beam-slab structure, the weight of concrete floor often accounts for about half of the total weight of the structure, and also affects the clearance of the floor to some extent. In order to improve the shortcomings of concrete floor, this paper proposed a new type of hollow floor, which is composed of lightweight and high strength aluminum alloy honeycomb plate and assembled into box type hollow floor by special connectors. The bearing capacity test of the new type of honeycomb plate hollow floor was carried out to study the bearing capacity performance and failure modes of the hollow floor. The results show that the connection effect of the hollow floor is good, and it has high bearing capacity. The failure mode of the hollow floor is mainly manifested as the compression-bending failure of the roof and the longitudinal side plate near the loading area. Through the comparative analysis of three finite element models, it is found that the error between the displacement values of the fully coordinated model and the experimental values is basically within 10 %, and the accuracy can meet the requirements of engineering design.

SESSION 26

Wed, 21 Sep.

Parallel Sessions,

10:30-12:00

(90 minutes)

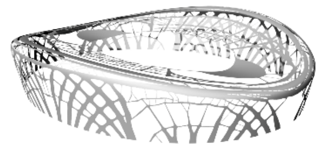
Optimisation, Form Finding and Parametric Design (WG15-2)

Chair(s): Hua Deng and Ruoqiang Feng

69

A high-resolution bi-directional evolutionary structural optimization method for gridshell structures

Yulin XIONG. RMIT University. s3826621@student.rmit.edu.au



Gridshell structures are widely used due to their attractive appearance and outstanding performance. However, designing an efficient gridshell structure to meet both engineering and architectural requirements can be quite challenging. To address this problem, we have developed a gridshell optimisation approach based on the bi-directional evolutionary structural optimisation method. In this approach, shell elements are used to discretise the free-form surface, and the element densities are regarded as the design variables. Additionally, a local volume control scheme is introduced to control the size and density of the gridshell members. A parallel computing scheme is developed to obtain high-resolution results efficiently. Several 2D and 3D examples are included to demonstrate the capability of the proposed approach. This approach opens a new path towards creating elegant and efficient gridshell structures.

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Fractal-Based Perforation Morphology and Structural Optimization of Perforated Steel Beams

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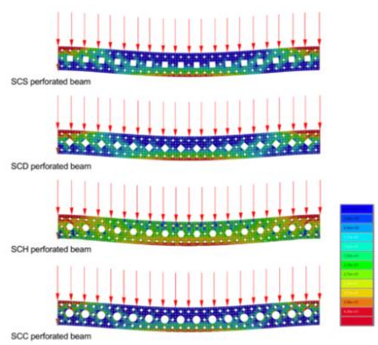
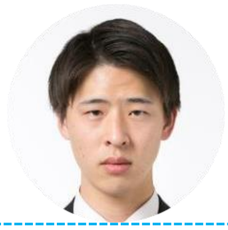
This paper applies the concept of fractal geometry, specifically the Sierpinski Carpet fractal, to develop different perforation morphologies of steel beams. The fractal-based approach creates a hierarchical tier of holes at different scales. This paper investigates the structural behavior and weight reduction of the fractal-based perforated beams compared to the simple perforated beams such as cellular and castellated beams, which have the same-scaled holes along the central axis. We have (a) analyzed the weight reductions and maximum displacements of same shaped holes with the increasing iterations of perforation, (b) analyzed the maximum displacements of different shaped fractal-based perforated beams having the same weight, and (c) optimized to find the designs with optimal strength-to-weight ratio.

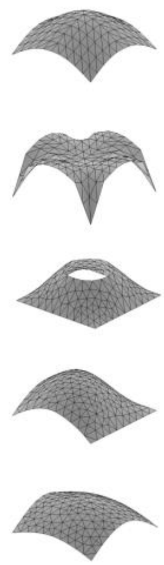




192

Form-finding analysis of funicular shells using eccentricity reduction method

Hiroyuki Shiomi. Tokai University. 1cckm018@mail.u-tokai.ac.jp



Various numerical methods have been proposed to find the funicular shell forms that are in equilibrium state only with membrane force without bending moment against its own weight. The dynamic relaxation method can be used to stably obtain large deflection shapes of membranes and cable-networks under their own weight, which are often unstable computationally. The force density method is another effective method to solve the equilibrium shape of cable-network. Shape optimization techniques are used to obtain shell forms with the lowest strain energy. Recently, the methods based on graphic statics and Airy stress function have received much attention to obtain the equilibrium shapes of membranes and cable-networks. These methods are not easy for structural engineers to code their own form-finding programs, as they require advanced mathematical knowledge.

In our study, we propose a simple novel method to obtain funicular shell forms. In this method, the eccentricity distance of each node is obtained by dividing the bending moment by the membrane force. Then, by moving the shell surface in the normal direction by the eccentric distance, the bending moment in the shell is reduced. By repeating this calculation, a funicular shell can be obtained. We call this method “the eccentricity reduction method.” First, the basic idea of the method is explained, dealing with the form-finding problem of arches. Next, the method is extended from two to three dimensions to find shell forms.

In the numerical examples, the bending moment almost disappeared in both the arch and shell examples, and the validity of the proposed method is confirmed. Since the method is extremely simple, if an engineer has a structural analysis program for shells, he can perform form-finding analysis by modifying the shell shape using a spreadsheet or other software and repeating the input and output.

292

Applications of graphic statics to the plastic design of reinforced concrete structures

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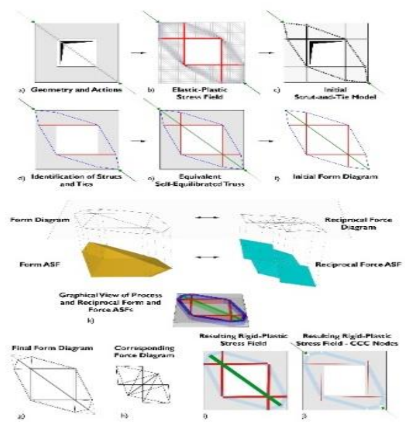

Graphic statics can be used as a design and analysis tool for the development of discrete rigid-plastic stress fields and their underlying strut-and-tie models in reinforced concrete structures. This approach relies on the construction of reciprocal Airy Stress Functions (ASF) to generate form and force diagrams; these diagrams are subsequently combined into Minkowski Sums (MS) from which discrete rigid-plastic stress fields are derived. This paper focuses on the creation of discrete stress fields for 2D practical case studies including typical reinforced concrete structural elements with various boundary conditions and loadings. To this end, a two-fold framework is introduced that comprises: a) the generation of an initial strut-and-tie model based on a stress field produced via an Elastic-Plastic Finite Element Analysis for given boundary and loading conditions on a reinforced concrete structural element; b) the transformation of such strut-and-tie model using non-linear optimisation methods in order to generate a geometrically and statically admissible discrete rigid-plastic stress fields. This approach provides structural engineers with a novel, visual and intuitive methods for the design and analysis of reinforced concrete structures.

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A review on the curvature and geometrical patterns of elastic gridshells: potentials for structural optimization and architecture

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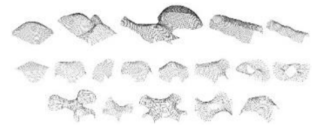

Elastic gridshells offer the possibility to create complex shapes with efficient structures in terms of structural performance and material consumption. The pattern of the spatial structure plays an important role in the overall aesthetics and structural performance of the structure. The curvature of the surface, the density of the grid, and their influence on the structural performance are important factors in the design or genesis of the used geometric strip patterns. In recent years, researchers have developed various methods for the generation of the pattern of the grid applied to a predefined overall shape of the gridshell. In general, however, it seems that the chosen pattern is mostly uniformly applied to the predefined shape, although the merging or transition of different patterns can significantly expand the design space and thus create new morphologies. We provide an overview and categorization of gridshells based on their overall shapes, Gaussian curvature, and applied patterns in order to identify previous logics in this regard and subsequently generate new morphologies. More specifically, this paper explores the reciprocity of geometrical strip patterns and the associated the surface curvature by means of eighteen built, elastic gridshell projects. In order to create a sufficiently large data set to serve as a representative basis for our categorization, our literature review is supported by the application of artificial intelligence. The provided overview and categorization of gridshells will then serve to further optimize the curvature-based structural performance of gridshells, but also enhance architectural aspects, create new morphologies, and moreover to improve the design solutions of elastic gridshells.

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Structural form-finding of multi-span undulating funicular beam structure

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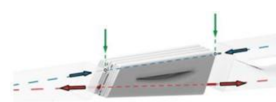

The recent innovation of building structure has been widely developed on generating funicular systems. The proposed strategy significantly reduces material usage compared to conventional concrete constructions. This paper presents a form-finding method that allows the user to design the integrated undulating beam system using graphic statics. By applying the method of the Geometric Degrees of Freedom, the modular units can span in multiple directions, iterating the boundary condition within the network to generate compression-only to compression-tension combined structures. It results in an undulating shape of the beam with various thicknesses that can integrate the necessary building services such as an energy heating – cooling system. The average thickness is significantly saved through the process. The preliminary structural analyses of a strip of the beam have shown the efficiency of the system compared with the traditional construction systems. Additionally, the post-tensioning cables are designed to be embedded within the structure to minimize the reinforcement.

SESSION 27

Wed, 21 Sep.

Parallel Sessions,
10:30-12:00
(90 minutes)

Snow and Ice Engineering (WG21-3)

Chair(s): Qingwen Zhang

66

Structural behavior and realization of a monumental ice structure in China for IASS/APCS2022

Arno Pronk. Department Built Environment, Unit Structural Design, Eindhoven University of Technology, The Netherlands. a.d.c.pronk@tue.nl

This paper will focus on the design and construction of a sculpture designed by American contemporary artist KAWS in collaboration with AllRightsReserved. The sculpture consists of two monumental characters. The inner structure is made with a steel frame. The steel frame was covered with a fiber reinforced polyester (FRP) composite. The surface has a layer of 5 cm reinforced ice and was realized in the winter of 2021-2022. The surface of the FRP was covered with a fabric to ensure a solid connection between the reinforced ice and the FRP. The sculpture is unique with regard to the application of ice composites in combination with FRP. In this paper there will be a special focus on the structural behavior of the sculpture. Ice can be reinforced by adding (cellulose) fibers such as wood and paper. These fibers make the ice up to three times stronger and increase the ductility, thus creating a reliable building material. This sustainable, fully recyclable building material might be a solution for temporary constructions in cold areas, ice events, the Olympic Winter Games or possibly even Mars missions. In this paper the latest developments will be described. The technique used might also be interesting for more architectural and sculptural structures.

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Design optimization of complex ice shell based on machine learning model driven by construction logic and performance simulation

Shuoyong Yang. Harbin Institute of Technology. 21B334002@stu.hit.edu.cn

Driven by the ice& snow industry and technology, modern ice-shell architecture, as a new type of ice and snow architecture, has great potential value in ice and snow tourism, cultural communication and other fields. Because of the particularity of ice, the ice-shell building is highly sensitive to the environment, and the climate adaptive optimization design is very important. However, due to the particularity of the construction logic, most of the ice shells are free-form surfaces, and the performance evaluation indicators are also relatively unique. The optimization process usually takes a long time. This paper presents a multi-objective optimization method and platform that introduces machine learning in the early stage of ice shell design, which effectively improves the speed of multi-objective optimization. Taking TRI-PAVILION, the work of the 2019 Harbin Institute of Technology International Ice& Snow Architecture Innovation Design and Construction Competition, as an example, the accuracy of the prediction within the scope of the target form is verified, and the feasibility of applying the method in practice is proved. At the same time, the reason for the large deviation of some predictions is analyzed, and future optimization directions, such as feature engineering and label data processing are put forward.

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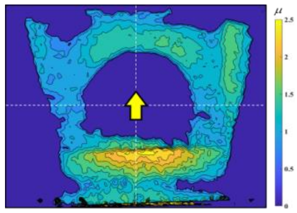
Experiment investigation of snow loads on Qiyang airport terminal roof based on a new similarity criterion

Rui Li. School of Civil Engineering, Harbin Institute of Technology, Harbin, 150090, China. lirui18846428089@163.com



Qiyang airport terminal is a typical long-span structure, which is light-weighted, complicated roof shape, and large roof area. It is more prone to collapse in extreme snow disasters because of the uneven snow distribution. This research investigated the snow distribution characteristics on the Qiyang airport terminal roof based on the snow-wind combined experiment facility and the new similarity criteria. Firstly, the setup of the experiment facility was introduced. Then, a new Froude number similarity, based on the modification of friction velocity ratio, was proposed, and its reliability and accuracy were verified by a group of scale model experiments. Finally, based on the new similarity criterion, snow-wind combined experiments on the Qiyang airport terminal roof model were carried out with different wind directions. The results showed that the new Froude number similarity criterion had higher accuracy in reproducing the snowdrift patterns on scale model experiments, and the maximum normalized snow depth on Qiyang airport terminal roof could reach 2.5.

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Probabilistic modeling of 10-min mean wind speed for the purpose of analytical simulation of snowdrift

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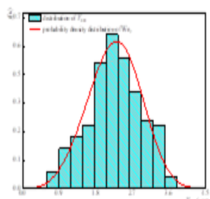

Long-term historical wind speed with high resolution is required for analytical simulation of roof snow distribution. However, the highest resolution for long-term historical climatological data in China is daily, which is too coarse for a sound analytical simulation of roof snow load. In this study, a statistical analysis method was utilized to model the 10-min mean wind speed, and the commonly used 2-parameter Weibull distribution was applied to fit the frequency distribution of 10-min mean wind speed in a full day. Meanwhile, a parameter estimation method, which combines the method of moment and cumulative probability, was proposed to estimate the parameters of Weibull distribution using very limited wind speed samples. Finally, validation of the probability model is carried out using high-resolution wind speed data. In the validation, the model is utilized to estimate the snow mass transported by the wind, and the result is compared with that obtained from actual high-resolution wind speed records. The comparison showed that the probability model proposed in this study has an excellent approximation of the wind speed from the snowdrift point of view.

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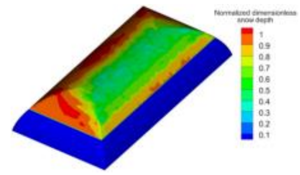
Wind tunnel test and CFD simulation of snowdrift on an air-supported membrane structure

Zou Jialin. Harbin Institute of technology. zerogress195217@163.com

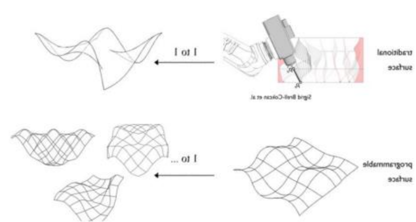


In snowy and windy regions, snowdrift may lead to uneven snow distribution on the roofs which can be much higher than average snowfall and ultimately collapse roofs. Although the membrane fabric structure has great advantages in rapid construction, it has deficiency in bearing the unbalanced snow loads. And climate-related disasters including heavy snow on membrane fabric structure have increased around the globe. Thus, it is indispensable to research snow distribution on the membrane fabric structure to ensure the safety of the structure.
In this paper, the snow distribution on the air-support membrane structure is investigated. Firstly, the wind tunnel tests of snowdrifts on a air-support membrane structure were conducted. Then, based on Euler-Euler method in multi-phase flow theory, the Mixture model using the secondary development method for Fluent software is adopted to simulate snow distribution on the air-support membrane structure. To verify the prediction accuracy of the simulation approach, we compared the simulated results with the wind tunnel test results.Thereafter, based on the this simulation approach, the snowdrift characteristics on the air-supported membrane structure under different wind velocity, wind direction, and structure span were studied.

420

Multistable grid shell as a flexible and reusable formwork for the sustainable construction of snow and iced structures

Haoming Huang. South China University of Technology. gybob62@163.com



Shell structures exemplify an integrated material-structure design approach, which exhibits the efficient flows of stress within and elegance of spatial configuration. Traditionally, double-curved geometry has minimized the shell thickness, but a tailorable shell geometry would significantly increase costs, limiting the creativity of architects and engineers. However, recent advances in digital fabrication, structural mechanics, and material science provide new perspectives on shell design. In this work, we leverage a novel concept of bistability to develop grid shell formworks with programmable surfaces. To achieve the multi-form iced structure, we first designed a bistable unit that is made of GFRP strips. With the understanding of the behavior of a single strip, we assembled six strips to form a grid unit. To design a multistable formwork for the iced shell, we eventually develop a 3x3 grid surface that can have 512 configurations due to the combination of nine bistable units. After trial simulations and physical models, we selected three representative grid designs to showcase the programmability of our formwork design. We built the geometric model of the iced structure using Rhino and then import it to the commercial finite element software Abaqus. Conceptually, we will switch the shape to another stable state and repeat the process to form another shell. Later, our design was built by a practical company in late December 2021 in the city of Harbin. The proposed strategy opens a new avenue to develop reusable formwork with high shape-tuning ability.

SESSION 28

Wed, 21 Sep.

Parallel Sessions,
10:30-12:00
(90 minutes)

Aluminum Alloy Structures - 2

Chair(s): Hongbo Liu and Ruoqiang Feng

195

Study on out-of-plane flexural behavior of aluminum alloy gusset joints after fire

Shaozhen Chen. Tongji University. chenshaozhen@tongji.edu.cn

The gusset joints are widely used in aluminum alloy latticed shells. Due to the damage of the aluminum alloy latticed shells under fire, the residual bearing capacity of aluminum alloy gusset (AAG) joints has to be investigated during the evaluation of the structural integrity. Hence, this paper studied the out-of-plane flexural behavior of AAG joints after fire. Firstly, twelve AAG joints were heated to preset temperatures and air-cooled to room temperature. Subsequently, bending tests on these twelve joints were carried out. The failure modes, ultimate flexural bearing capacity, bending stiffness, and post-fire reduction factors of these joints were obtained. The test results indicated that the failure modes of the thin-plate joints were the local buckling and block tearing of gusset plates, and the failure modes of the thick-plate joints were the buckling of members. The initial stiffness of joints approximately remained constant, while there was a trilinear relation between the ultimate flexural bearing capacity and the maximum post-fire temperature. Before the bolt slipped, the post-fire reduction factors of the flexural bearing capacity and bending stiffness remained constant. After the bolt slipped, the post-fire reduction factors of the flexural bearing capacity and bending stiffness presented a trilinear trend with the rise of the post-fire temperature.

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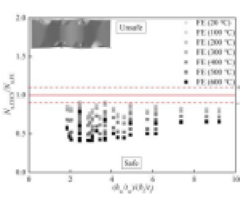
Buckling behaviour and design of aluminium alloy I-sections in fire

Zhongxing Wang. Tianjin University. zhongxing_wang@tju.edu.cn



Aluminium alloys have gained increasing use in shell and spatial structures over the past few decades, owing to their high strength-to-weight ratio, excellent durability, aesthetic appearance and good recyclability, a selection of which is shown in Figure 1. Despite the above merits, the mechanical properties of aluminium alloys degrade fast at elevated temperatures, leading to substantially reduced cross-section resistances of aluminium alloy members. I-sections are currently the most commonly used cross sections in aluminium alloy spatial structures, however, limited research has been conducted into the behaviour and design of them in fire conditions. This research gap may pose a great threat to the structural fire safety and hence is the focus of the present study.
The structural behaviour and design of aluminium alloy I-sections under axial compression at elevated temperatures are investigated in the current paper. First, the two-stage Ramberg-Osgood model is developed to well describe the nonlinear stress-strain behaviour of aluminium alloys in fire conditions. Numerical models are then established and validated, followed by extensive parametric studies using the proposed constitutive model and covering a broad range of material and geometric parameters. Finally, a new design method for the cross-section resistances of aluminium alloy I-sections in fire is proposed. The new proposal takes due consideration of three key aspects which have not been accounted for in any current codified design approach; they are (1) the different deterioration rates of the yield strength (fy) and the Young's modulus (E) of aluminium alloys at elevated temperatures, (2) the more curved nature of the stress-strain behaviour of the material in fire conditions, and (3) the element interaction between the adjoined flange and web plates in I-sections. The proposed method is shown to provide more accurate and consistent resistance predictions than the existing design provisions.

349

Tensile tests on high-strength aluminum alloy at elevated temperatures

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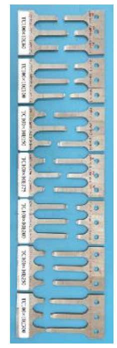

Aluminum alloy has light weight and high corrosion resistance, which can realize the convenient construction of transmission towers in mountain areas. However, the traditional aluminum alloy has low strength and cannot meet the demand of high bearing capacity of large transmission towers. This paper adopts a new type of high-strength aluminum alloy named XL703-T6, which is expected to be used for large transmission towers in mountain area. To deal with the adverse situation of possible fire in mountain areas, it is necessary to investigate the mechanical properties of this new material at elevated temperatures. Accordingly, standard tensile coupon tests on such high-strength aluminum alloy were carried out at ambient and elevated temperatures, ranging from 20 ºC to 300 ºC. Their mechanical properties at different temperatures, including modulus of elasticity, 0.2% proof strength and ultimate tensile strength, were obtained. The test results show that the 0.2% proof strength of this material can reach 450 MPa at 20 ºC, which is much higher than other common aluminum alloys. When the temperature rises to 300 ºC, the 0.2% proof strength decreases to about 60 MPa. The reduction factor at elevated temperature could be obtained by dividing the mechanical properties at elevated temperature from those at 20 ºC, and were compared with those in the standards of various countries. It was indicated that at elevated temperatures, the reduction degree of this aluminum alloy is close to those with similar strength in the standards. Among them, the test value of this material is closest to the requirements in the GB 50429 for 6061-T6 aluminum alloy. The research outcomes may provide valuable reference for further research on the fire resistance of high strength aluminum alloy structures.

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Structural behaviour of 7A04-T6 high-strength aluminium alloy CHS stub columns under axial compression

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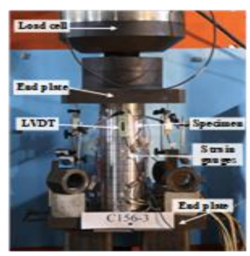


The structural performance of 7A04-T6 high-strength aluminium alloy circular hollow section (CHS) stub columns were presented in this paper. Four CHS stub columns, including two Class 3 and two Class 4 cross-sections according to EC9, were tested under axial compression. The material properties, failure modes, axial compression resistances and axial load versus end shortening curves were analysed. The numerical modelling programme were then carried out in which the finite element models were established and validated against the test data, and parametric studies over 26 cross-sections with three different local geometric imperfection amplitudes were conducted. The axial compression resistances of stub column tests and parametric analysis were compared with predictions by Chinese, European and American standards. The assessment results indicated that the limit value of the diameter-to-thickness ratio specified in Chinese standard was appropriate for the 7A04-T6 CHS stub columns. The effective thickness method given in European standard was accurate in general but a little unsafe for CHS members of local geometric imperfection tolerance Class 1. The American standard totally overestimated the axial compression resistances of 7A04-T6 CHS stub columns by about 23%.

SESSION 29

Wed, 21 Sep.

Parallel Sessions,
16:15-17:45
(90 minutes)

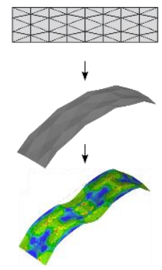
Future Challenges in the Design and Construction of Shell Structures for Low or Zero Carbon - 1 (WG5-1)

Chair(s): Stefano Gabriele and Joshua Schultz

82

Stress redistribution capacity of textile-reinforced concrete shells folded utilizing parameterized waterbomb patterns

Homam Spartali. Institute of Structural Concrete, RWTH Aachen University, Aachen, Germany. hspartali@imb.rwth-aachen.de

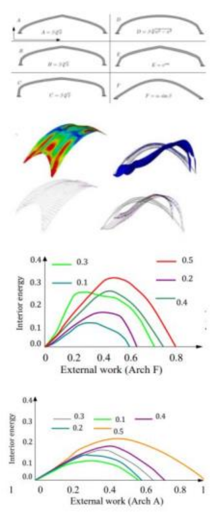


The development of lightweight, high-performance cementitious composite materials such as carbon concrete has triggered the need for innovative design and construction methods for thin-walled structural elements with an optimal material utilization. Combining the material efficiency of carbon concrete with the form flexibility provided by parameterized origami patterns, such as a waterbomb tessellation opens up new options for innovative design of high-performance light-weight shell structures. Indeed, the possibility to fold concrete shells in a fresh state of concrete matrix from a planar configuration to a spatial form can be exploited to develop an efficient and customizable construction method that eliminates an expensive, single-use spatial formwork. A crucial question posed in this context is, how to achieve ductile structural behavior with a composite material consisting solely of brittle and quasi-brittle components, i.e. carbon, glass, basalt reinforcement and concrete matrix. Since these materials do not provide any source of ductility on their own, substantially different design approaches compared to traditional steel-reinforced concrete are required, that exploit the stress redistribution effects at the structural level due to debonding and multiple cracking of the composite. To contribute to the understanding of these stress redistribution effects in the context of folded thin-walled spatial shell structures, this paper presents preliminary numerical and experimental studies investigating the structural behavior of shells folded using waterbomb tessellations with varied geometrical parameters. The conducted experiments on folded waterbomb shells made of carbon concrete and produced using the fold-in-fresh method are presented showing the potential of this structural concept with a maximum ultimate load 45 times larger than the self-weight of the shell. This development serves the aim to optimize thin-walled geometrical forms to reach a high-performance carbon concrete elements with high material utilization in service state, high ductility before failure and high load-to-weight ratio.

90

Application of energy method to investigate the stability of structural shells and arches with the threshold capacity

Abtin Baghdadi. Institute of Structural Design (ITE), TU Braunschweig. a.baghdadi@tu-braunschweig.de



This paper studies the stability of nine arches selected from different structures and five shells designed by Heinz Isler under vertical load, discussing their failure trend. The selected arches and shells are mainly supposed to resist under in-plane (axial) loads, exposed to probabilities of buckling failure. In addition, to obtain the buckling factors and stiffness of the structure, the energy method calculates the absorbed energy throughout the collapsing process. In this study, utilizing energy assessments, the external works demanded during the failure were documented. Some parameters for more evaluation of arches were extracted, while the height to span ratio of the arches as the variables changed. The accumulative performances of the arches (used in the shells) influence the shells' resistances. The influences seen in the shells' force-displacement diagrams are the main criteria in the shell's seismic performance. In this regard, some of the Heinz Isler shells were additionally studied, looking for optimum arches. The shell geometries and probable relation between the failure of shells and arches used in shells were also considered. The studies using energy methods concluded that 0.35 as the optimum height to span ratio, forming plastic hinges. This plastic performance in some of the Isler's shells, like Coop Distribution Center, was not observed. In other words, the capability of making plastic zones in the structures for more energy absorption was not regarded in some Isler shells.

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Form finding for free-curved RC shell using multi-objective optimization considering structural performance and formwork manufacturability

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This study proposes a form-finding method for free-curved RC shells using multi-objective optimization, considering the structural performance and wooden formwork manufacturability. The shape of the curved surface is represented by using the B-spline function (NURBS) and discretized into triangular elements for the FE Analysis. Additionally, the quad meshes are introduced to represent the plywood form board (PFB) shape in the formwork system. The coordinates of the PFB are described using the NURBS surface. For evaluating the manufacturability of PFB, the curvature of the surface is computed at each corner of the PFB. A design problem is formulated to minimize strain energy and optimize the PFB's curvatures. The z-coordinates of the NURBS control points are adopted as the design variables. The form-finding process is conducted using Rhinoceros+Grasshopper. Numerical examples are represented to demonstrate the effectiveness of the proposed method. Furthermore, a practical formwork design of the optimal solution is conducted to validate the constructability of the whole formwork system.

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Digital construction technology of double helix spatial free-form concrete thick shell of Shanghai Grand Opera House

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Shanghai Grand Opera House will have an appearance of a Chinese fan when completed. The fan axial, which is named as zone B, is a non-accessible roof structure that consists of a double helix concrete thick shell and a steel reinforced concrete column. This paper comprehensively introduces the main technical solutions formed during the planning and construction of the zone B of Shanghai Grand Opera House. First, by analyzing the shape and law of the zone B in the software Rhinoceros, the overall construction process of the Zone B is determined; Then through parametric modeling, optimize the original free-form surface into a helical surface with stronger regularity, and based on the optimized surface, formwork system combining wood formwork and customize GFRP (Glass Fiber Reinforced Polymer) formwork is adopted as the curved surface formwork; Through performing nonlinear staged construction analysis, a combination of temporary steel frame and fastener steel tube frame is applied to support the huge self-weight of 1210mm-thick curved surface concrete shell. The adopted construction technologies break through the technical barriers, guarantee the practical construction feasibility, save construction costs, and improve construction efficiency under the premise of safety and quality.

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Practice and research of complex concrete reticulated shell structure in high speed railway station

Chuanping Liu. Architectural Design & Research Institute of Tongji University (Group) Co. Ltd. liuchuanping@126.com

The platform canopy of Zhengzhounan Station adopts fair-faced concrete reticulated shell structure. The paper studies the deformation characteristics of the continuous reticulated shell structure under various working conditions. Such conditions as temperature effect, earthquake action, and the progressive collapse resistance performance under the train impact are calculated and analyzed. The double-columns scheme is put forward to resist lateral thrust in side span of the shell structure, and the health monitoring is used to monitor the stress state during construction and application. The results show that the reticulated shell structure is reasonable, has good mechanical performance and lateral stiffness, it has good economy and aesthetics.

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Felix Candela's architectural heritage at the intersection of sustainable development

Marisela Mendoza. Senior Lecturer School of Architecture Design and the Built Environment, Nottingham Trent University.

The historic concrete shells built by the architect Felix Candela in Mexico during the mid-1950s represent an important legacy to the 20th Century Architecture. His work was pioneering in the development of ingenious construction strategies which made possible some of the most elegant and daring concrete shells built during that period. The concrete shells that Candela built in Mexico City addressed specific structural challenges due to Mexico City's poor soil conditions, earthquakes, and their iconic architectural design also responded to the socio-cultural, political, and economic contexts and challenges that Mexico was experiencing during the post-revolution period. The devastating earthquakes that have shook Mexico City (19 September 1985 and 19 September 2017) have indeed been a threat to the structural integrity of Candela's shells. In 1985 one of the two rows of umbrella's sheltering the Jamaica Market toppled due to the seismic force and sadly, all the market umbrellas were demolished a few days after the earthquake. Thirty years later, on 19 September 2017 another earthquake shook the city and produced substantial damages to Los Manantiales Restaurant shell also located in Mexico City. However, it is not only natural disasters that pose a threat to the shell's structural integrity but in fact poor maintenance, inadequate use, and adaptations are factors that can gradually threaten buildings' structural integrity. This paper will focus on specific case studies built by Felix Candela in Mexico City: Los Manantiales Restaurant, Cosmic Rays Pavilion, and the High Life Factory to analyse the challenges and opportunities to preserve Candela's historic concrete shells and at the intersection of sustainable development.

SESSION 30

Wed, 21 Sep.

Parallel Sessions,

16:15-17:45

(90 minutes)

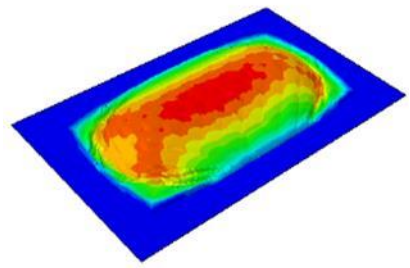
Pneumatic Structures-2 (WG6-6)

Chair(s): Ken'ichi Kawaguchi and Yingying Zhang

110

Collapse property of Air-supported structures

Fei Yan. Beiijng University of Technology. yan.fei@emails.bjut.edu.cn

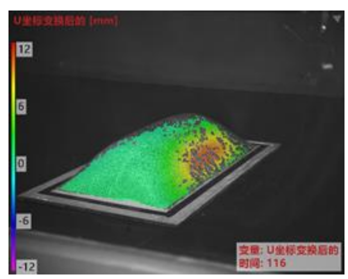


Air-supported membrane structures are widely used in stadiums, malls and museums. The stiffness and shape of such structures are dependent on the pressure difference between the indoor and outdoor environments. As the leakage of indoor air may lead to the collapse of the structure, it is necessary to study the deflation deformation process, including the properties that can cause air-supported membrane structures to collapse. In this study, a rectangular air-supported membrane structure is fabricated using a PVC-coated polyester fabric membrane with dimensions of 38 m × 20 m × 7 m, and a leakage experiment is performed. The relationship between the initial leakage area and the pressure difference is obtained, and a new algorithm to determine the equivalent initial leakage rate is proposed. A collapse test is then conducted, with results illustrating that there are two distinct phases of collapse. There is a quick drop in the pressure difference in the first phase, whereas the pressure difference declines rather slowly in the second phase. A new theoretical method of the two phrases was proposed in this paper. Computational formulae for collapse and escape times are established, and finally, a quasi-equilibrium status-based algorithm to determine the collapse time of air-supported structures is proposed. The time-displacement curves obtained by the new theoretical model and status-based algorithm are similar to the existing experimental results.

126

Research on the wind-induced failure mechanism of an inflatable membrane structure

Junbin Zhao. Northeast Electric Power University. zhaojunbin2021@163.com



To investigate the mechanism of wind-induced failure of an inflatable membrane structure in Russia under low wind speed, a series of aero-elastic model wind tunnel tests and rigid model wind tunnel tests were carried out. The full-field dynamic displacement and strain of the aero-elastic model at 0°, 45° and 90° wind angles under different wind speeds were measured by noncontact displacement and strain measurement method based on DIC (Digital Image Correlation) technology. The positions of the maximum displacement, maximum main strain and overall vibration law of the aero-elastic model at different wind angles are discussed. Damping ratios of the measuring points with maximum displacement of the aero-elastic model at different wind speeds are calculated by Random Decrement Technique, and the possibility of aero-elastic instability of the structure is discussed. Nonlinear dynamic time history analysis method is used to study the variation laws of the maximum displacement and maximum principal stress at higher wind speed. The possibility of strength failure for the membrane is discussed. The results show that the average deformation of the structure shows a trend of depression on the windward side, uplift on the top and outward bulge in the transverse direction. Under the same wind speed, the maximum principal stress of the model at 45° wind direction angle is significantly greater than that at the other two wind directions, and the stress form of the membrane at this wind direction is significantly different from that at the other two wind directions. As a result, the sudden failure of the structure was not caused by the aero-elastic instability, but by strength failure. The study reveals the specific reasons of the wind-induced failure of an inflatable membrane structure in practical project, and gives some useful suggestions for designer to reference, which has obvious positive significance for preventing wind-induced failure of strip-shaped inflatable membrane structure with rectangular plane.

277

Simulation deployment behavior of air-inflated fabric arches based on modified Control Volume method

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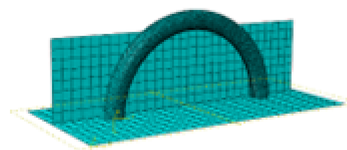

Air-inflated fabric arch structure has obvious advantage of being light-weight, able to accommodate large spans, low cost, easy mobilization and reusable. It has been widely applied to military and aerospace structures. However, there are few studies on its dynamic deployment behavior and self-erection feasibility during the construction phase, which restricts the breakthrough of its span and its development in civil buildings. In this study, the effects of considering heat exchange with the environment and the traditional adiabatic assumption of Control Volume method（CV Method）on deployment pressure were analysed and compared. Comparing the simulation with the experimental data, the feasibility of the ABAQUS fluid cavity in simulating the dynamic deployment behavior of Air-inflated fabric arch structure was verified. The traditional Control Volume Method were modified by including a heat exchange, and the feasibility of this method was verified. Next, the modified Control Volume method was employed to evaluate the factors influencing the deployment pressure of air-inflated fabric arch structure. Research was conducted on influence of deployment time, span to height ratio, and arch length to diameter. The reasonable design parameters for span to height ratio and arch length to diameter ratio of air-inflated fabric arch structure are given. Thus, this study serves as a reference for deployment behavior in engineering applications.

335

Experimental study on aeroelastic response of air-supported membrane structures

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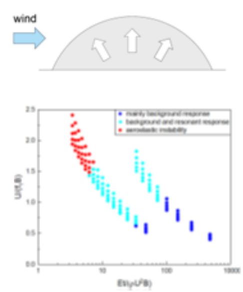
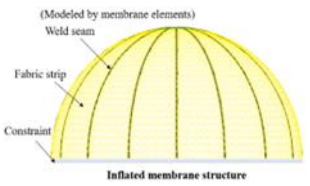


Aeroelastic responses of air-supported membrane structure were investigated by wind tunnel tests in this paper. Two aeroelastic models of air-supported membrane structure with different membrane materials, latex and TPU, were fabricated, and wind-induced deformations were measured during wind tunnel tests with different inner pressures and wind velocities. Mean and dynamic wind responses of the two models generally increased with lower inner pressures and higher wind velocities. Aeroelastic instability was observed under high wind speeds for the latex model, while the TPU model remained aeroelastic stable under all conditions. When the ratio of inner pressure to wind pressure was low enough, dynamic wind responses of the structure increased abruptly. From results of wind tunnel tests, it can be concluded that dynamic wind-induced deformation of air-supported membrane structures are dominated by the background response with high membrane stiffness and low wind velocity, while the resonant response would appear when the membrane is flexible and wind speed is high.

524

A simulation method of weld seams for precise forming of inflated membrane structure

Yan Pang. Shanghai Jiao Tong University. pangyan2018@163.com



Inflated membrane structures are displacement-sensitive structures. The change of shape can greatly change preset stress distribution of membrane structure and mechanical performance. The material properties of weld seams differ from those of single-layer fabric, which results in actual stress state of membrane surface being different from ideal stress state derived from membrane theory. In this paper, a simulation method of weld seams for precise forming of inflated membrane structure is proposed, which uses membrane element to simulate weld seam and adopts a biaxial material model, to consider the influence of the stress-strain state in width direction of weld seams on the strain in length direction. The material modulus is modified to simulate the effect of fabric overlap at weld area. The proposed method is used in analyzing a hemisphere inflated ball with a diameter of 4 m through cutting analysis and forming analysis. The real stress distribution and deformation of the inflated structure is therefore obtained and compared with the results predicted by an existing cable-based method to verify the rationality and effectiveness of the proposed approach.

SESSION 31

Wed, 21 Sep.

Parallel Sessions,
16:15-17:45
(90 minutes)

Buckling of Metal Spatial Structures - 2 (WG8-6)

Chair(s): Huiyong Ban and Xudong Zhi

32

Local buckling strength of high-strength aluminum alloy H-sections under combined compression and major-axis bending

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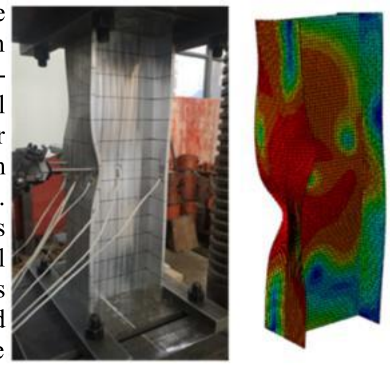

High-strength aluminum alloy sections are often subjected to local buckling. Extensive experimental and analytical studies on stiffened and unstiffened elements have been carried out and have led to well-established equations for the estimation of the post-buckling strength of such elements in uniform compression. In comparison, experimental investigations on elements under stress gradients are quite limited. Therefore, this paper aims to enlarge the available experimental and numerical database of high-strength aluminum alloy H-sections subjected to local buckling under non-uniform compression. The paper first deals with an experimental investigation on slender H-section stub columns under combined compression and major-axis bending moment. Then a numerical model was developed and validated against the experimental data, after which parametric studies were performed to generate data over a wide range of cross-sectional geometries and eccentricities. The obtained experimental and numerical results were used to assess the applicability of the interaction curves between compression force and bending moment set out in EN 1999-1-1 and Aluminum Design Manual. Comparison results have revealed that both the interaction curves yield conservative capacity predictions for non-slender cross-sections and the latter gives accurate failure load predictions for slender cross-sections.

137

Arranging active bars to improve stability of loaded pin-bar mechanisms

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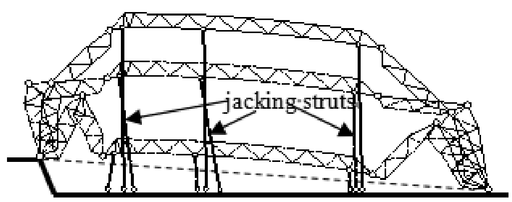

The rapid deformation or erection of some pin-bar assemblies can be realized using rigid-body displacements in construction engineering, e.g., Pantadome. It is crucial to maintain the stability of these loaded pin-bar mechanisms during deformation (erection) in their design. The layout of active bars which drive the motion of the system is discussed from the viewpoint of enhancing the structural stability. Mathematically, the participation of active members is interpreted as the positive perturbation to the zero eigenvalues corresponding to the modes of inextensional mechanism of the system. If the active members are arranged to maximize the perturbation, the geometrical stability of the system can be enhanced as much as possible. The validity of the proposed method is verified by the layout of jacking struts for an illustrative double-layer reticulated Pantadome.

177

Evaluation on plastic buckling load of axially compressed latticed cylinders

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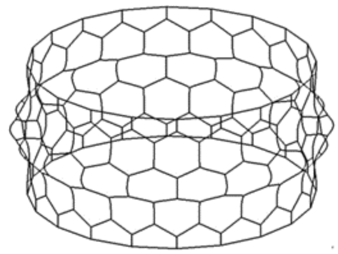

Latticed cylinders have been used as roof structures in the field of architecture, but in recent years, they have also been used as tower structures. In order to study inelastic stability of such tower-like latticed cylinders, the authors have conducted axial compression tests of small scaled latticed cylinders made of aluminum formed by 3D printer. In this study, by performing parametric FE analysis of the models of the same size as those in the experiment, applicability of the tangent modulus theory to the axially symmetric buckling, the so-called 'elephant leg' buckling often observed in plastic region. The tangent modulus theory was used by Timoshenko to evaluate the plastic buckling of continuum aluminum cylinders. The plastic buckling load of a latticed cylinders using the tangent modulus theory is calculated by assuming that the elastic buckling load is a linear buckling load and considering the decrease in stiffness in the plastic region from the load-deformation curve obtained by Pushover analysis that considers only material nonlinearities. It has the advantage that it can be obtained by linear buckling analysis and Pushover analysis without elasto-plastic buckling analysis that considers material nonlinearity and geometric nonlinearity, which cannot be performed by general analysis software.

In earthquake-prone regions such as Japan and China, the deformation performance after plastic buckling is required for tower structures. By using the tangent modulus theory, the plastic deformation performance can be estimated approximately.

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Structural stability analysis of eye of the yellow sea, a large-span arched pedestrian bridge

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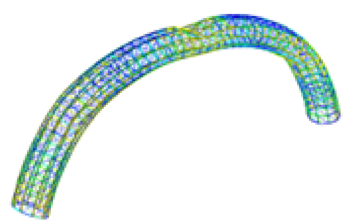

To date, scholars' research on the stability behavior of the arch structure mainly focuses on solid–web section arches, steel tubular truss arches and concrete-filled steel tubular arches, but the stability behavior of the novel spatial grid arch structure, which integrates the characteristics of grid structure and arch structure, is not yet clear. Based on the Eye of the Yellow Sea pedestrian bridge project in Rizhao, China, the stability behavior of this large-span spatial grid arch structure was studied, in this paper, by the project's structure design team. The project is a glass covered steel arch pedestrian bridge with a span of 177 m, a height of 63.5 m, an elliptical section with a long axis of 18 m, and a short axis of 13.5 m. The elastic and the nonlinear elasto-plastic stability behavior considering different initial geometric imperfections, was analyzed by the ABAQUS finite element model. The buckling modes and the full-range load-displacement curve of the structure were analyzed, and the stress distribution, deformation mode and overall structural performance during the whole loading process were analyzed. The effects of initial imperfections, geometric nonlinearity and material nonlinearity on the ultimate load-carrying capacity of the structure were studied. The stability behavior of large-span spatial grid arch structure was studied in this paper, which provides an important reference for the design and analysis of such structures.

SESSION 32

Wed, 21 Sep.

Parallel Sessions,

16:15-17:45

(90 minutes)

Computational Methods for Additive Manufacturing and Origami (WG13-4)

Chair(s): Makoto Ohsaki and Ruoqiang Feng

108

Exploring the potential of equilibrium-based methods in additive manufacturing: the Digital Bamboo pavilion

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Additive manufacturing allows the use of naturally grown structural elements in combination with 3D printed components, aiming to foster a more sustainable building culture. From a structural perspective, the combined use of natural and artificial materials introduces new uncertainties and challenges in relation to the design and analysis of the global load-bearing behavior of structures, as well as their local connections. In this context, equilibrium-based methods derived from the lower bound theorem of the theory of plasticity are particularly effective since they are not restricted to a specific structural typology, material, or scale. This paper illustrates the application of equilibrium-based methods such as strut-and-tie modeling and graphic statics to the structural design and analysis of a full-scale demonstrator, the Digital Bamboo pavilion. The load-bearing system of the pavilion is a bamboo space frame reinforced by post-tensioned cables. The bamboo elements are connected via bespoke 3D printed nylon and steel connections. Thanks to the combination of natural and artificial materials, the Digital Bamboo exhibits a filigree high-performance geometry that goes beyond the ordinary space frame architecture.

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Prototyping parametrically designed fiber-reinforced concrete façade elements using 3D printed formwork

Deyan Quan. Xi'an Jiaotong-Liverpool University. Deyan.Quan20@student.xjtlu.edu.cn

This paper documents the initial stage of a study investigating the interrelations between façade geometry design, material and fabrication constraints, and focuses on incorporating structural and fabrication constraints into parametric façade design. It presents the initial phase of the prototyping process for intricate façade elements employing robotically 3D printed formwork in combination with ultra-high-performance fiber reinforced concrete. Following a review of precedent research related to digitally designed and fabricated concrete elements, experimental results derived from compression load testing of high-performance fiber-reinforced concrete using 3D printed formwork are discussed and compared to structural performance of the same material cast in conventional formwork. The prototyping process and structural analysis of the prototypes demonstrate the feasibility of a design approach that facilitates parametric geometry design and resource-efficient small-scale production of façade prototypes.

125

Free-form folded shell structure inspired by no-crease origami

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Free-form shell structure has always been an attraction to architects due to its attractive appearance. Origami, on the other hand, as the exemplary ancient art of paper folding has increasingly large appeal due to its astonishing formal richness and variability. Lately, the recognition of folding features in increasing the structural stiffness further pique the interest of the researchers for advance development and application of origami to structures. Among the numerous origami patterns, no-crease origami, possesses the potential to be further explored in designing free-form shell structure due to its intriguing surface feature. Complexity of modelling technique and construction process are among major issues to be overcome towards realization of no-crease origami-inspired structure. This research focuses on the surface geometry generation, structural behaviour and the constructability of no-crease origami-inspired structure. Paper modelling is adopted in initial stage to study the stability of the physical model. Wet folding, Spine and Tripoint Principle were adopted in the paper modelling process. Subsequently, Rhino3D was utilized to implement the parametric modelling for the geometrical models. Numerical analysis was performed using SOFiSTiK to study the structural behaviour of the no-crease origami-inspired structures. Construction of laboratory scale model by concrete cloth was carried out to investigate the constructability of the structure. Result shows that the stability of the structure was greatly affected by the break point position and spine orientation. The higher the break point position, the more stable the structural model. Locating the break point at the mid-width of the model can further enhance the stability. Numerical analysis also shows that stress and displacement decrease with the mid-width location of break point and higher position of the break point. By adopting the developable surface feature, falsework that renders the desired shape can be realized and thus demonstrates that the construction of no-crease origami-inspired structure is feasible. Application of concrete cloth also presents the possibility of alternative ways for free-form shell structure's construction.

147

Design and fatigue life prediction of origami creases

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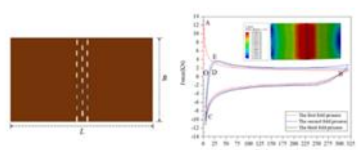

Design of origami creases is widely applied in origami structures with non-zero thickness such as opening, laser cutting and pre-bending. In this study, we have proposed structural design scheme of 10 basic origami creases (such as oblong hole, rectangular hole, moon hole, single-side or double-side cutting). The corresponding basic origami crease elements are designed. Through ABAQUS, folding and unfolding process of each origami crease has been studied. During the process, its mechanical properties are evaluated by the stress and deformation characteristics. It has a stable stress deformation process. The force-displacement curves are closed hysteresis loops. The force in the folding process is greater than that in the unfolding process. Moreover, finite element models are imported into the FEsafe software to predict its fatigue life. The ones are consistent with the theoretical fatigue life calculation results used by E-N method. The origami creases formed by three rows of oblong hole have high energy absorption and high fatigue life with satisfactory stiffness. Certain engineering materials and geometric design parameters (thickness t, hole width w, hole length l, hole spacing b, row spacing d) are studied for extensive engineering applications. The material Al is proved to be a good choice. Origami crease with Al has better energy absorption characteristic and enough stiffness. Its fatigue life is relatively higher than other materials. The thickness t, hole width w and hole length l have a great impact on its mechanical properties and fatigue life. A better origami crease can be designed by adjusting these parameters reasonably.

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Stretch responses of kirigami inspired metamaterials based on rotating units

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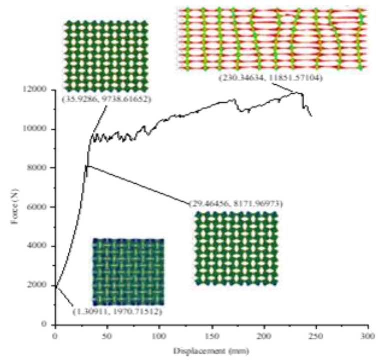
Two dimensional auxetic metamaterials based on kirigami techniques exhibit exceptional mechanical responses. The stretching behavior of kirigami metamaterials highly depends on the kirigami pattern scheme and the corresponding geometric parameters. Fractal kirigami achieves a large elongation and auxetic response through the rotation of the cut units within the smallest unit cell. The stretching behavior of 12 kinds of rotating quadrilaterals is investigated. The geometric models are established respectively, and the analytical expressions of elongation and Poisson's ratio of each model are derived. These analytical equations are the theoretical basis for compiling the unit cell side length on demand. Certain influencing factors have been studied, such as the width of the hinges, the elasticity and plasticity of the materials, and the pattern geometry. Studies have shown that the width of hinges affects the elongation rate of the metamaterial when it reaches its limit state.



550
A structure- and fabrication-informed strategy for the design of lattice structures with Injection 3D Concrete Printing

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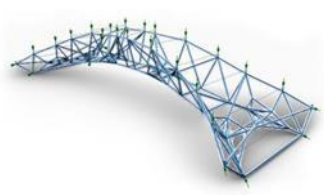
This paper presents a design strategy that aims to integrate structural and manufacturing considerations in the conceptual design of three-dimensional lattice structures for Injection 3D Concrete Printing (I3DCP). Early experiments with I3DCP showed that multiple structural and fabrication constraints need to be taken into consideration in terms of node design. To address these constraints, a procedure for optimizing the geometry of the nodes of the designed lattice structures is introduced. Combined with 3D vector-based graphic statics, this approach provides intuitive visual information of the structural behavior both locally and globally. It allows controlling the internal forces within the target geometry. A case study of a pedestrian bridge is presented to test the proposed approach.



SESSION 33

Wed, 21 Sep.

Parallel Sessions,

16:15-17:45

(90 minutes)

Prototyping: Physical and Virtual Model Making and Fabrication (WG15-3)

Chair(s): Hiroki Tamai and Rupert Maleczek

276

Micro-structural biomimetic: new perspective of shell structural morphology innovation

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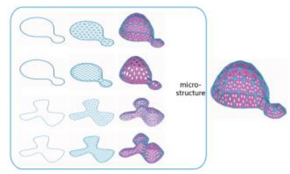
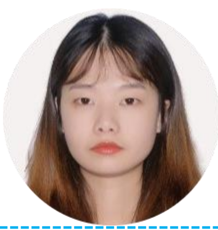


In the long history of the theory development of shell structures, the research and engineering of shells focus on the ideal form finding and optimization of the shell's surface and structural grid, breaking through the balance of force flow and form beauty. However, with the cross application of new computing technologies, new materials, and new aesthetics, a series of pioneering shell experiments are emerging. Based on complexity science, a new perspective of micro-structural biomimetic of shell structure is proposed, to break through theoretical boundaries of shell morphology innovation. Firstly, it interprets and hierarchically reconstructs the shell form system from two dimensions of complexity science and digital technology. Then, bionics was introduced into the hierarchy of microstructures, and the bionic design process of microstructures was constructed from the aspects of emergence, generation logic and environmental response. Finally, the paper puts forward the future development approach of shell architectures and tries to achieve the integration of the performance-oriented, sustainable, and cross-innovative in the new era.



364

Design and assembly of origami-inspired modular adaptive flow regulations

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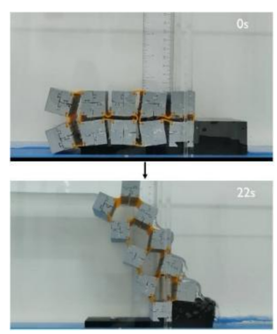

The emergence of origami-inspired architected materials and structures has provided new avenues to design adaptive devices and structures at various length scales, but their post-fabricated geometries usually remain unchangeable, showing low reconfigurability and poor adaptability toward multiple functionalities. In this work, we introduce a new class of modular structural designs, that is inspired by the game of jigsaw puzzle. Guided by experiments on dual-material 3D-printed specimens and simulations, we demonstrate high programmability in structural design with the proposed modular architected material units. Their versatility is demonstrated by an easy-to-assemble routine to form geometric designs with desirable properties for a specific function. As a proof-of-concept, we utilize this strategy to design adaptive flow regulators featuring tailorable stiffness and programmable reconfigurations. Our numerical and experimental results showed that by programming cell geometry, unit distributions, and the spatial arrangement of joints, a series of linear and planar flow regulators were designed and built. The structural units can be assembled in a variety of forms with tailorable stiffness and controllable reconfigurations, leading to a multi-functional flow regulator. We envision the proposed integrated material-structural design concept can be expanded to realize adaptive flow regulations over a wide range of scales, from microfluidic devices to large-scale weirs.

400

Programmable origami bolt tightening robot

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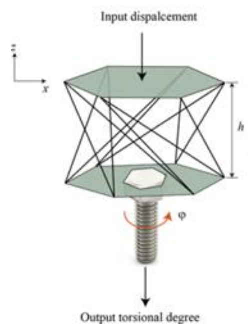

Origami-based robotics is a popular research field in recent years, including origami grippers, deformable origami wheels and bionic-inspired robots. We proposed a novel origami-based bolt tightening robot, utilizing the Kresling unit to fabricate the robot. Applying downward displacement to the upper facet of the Kresling unit while limiting its torsion, and the lower facet will be twisted to realize screwing bolts. Numerical simulation was conducted to study the relationship among compression displacement, pressure and torque when the upper and lower working facet of a single Kresling unit is restricted. By programming the geometric parameters of the Kresling pattern, bolt tightening robots with different tightening ranges can be designed for tightening different types of bolts. Then, the relationship between the input downward displacement and the output torsion degree was studied by numerical simulation, thus the geometric design of the bolt tightening robot was conducted. The number and angle of the brace between the upper and lower facets can be programmatically adjusted to achieve the design goal of the bolt tightening robot. The bolt tightening robot proposed in this paper can tighten the bolts only by pressing and can realize controllable installation by preset the maximum torsion angle, which simplifies the installation process of industrial bolts.

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Conceptual design and fabrication of modular deployable origami structures for architectural-scale applications

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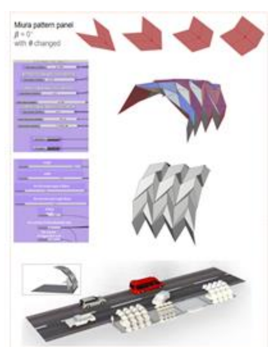

Increasing amounts of extreme events and harsh environmental conditions have challenged the architecture and construction industry toward the development of adaptive structural systems. One of the major routes of research is to enable the shape-changing and reconfiguration of structures. Recently, deployable structures inspired by the Asian art of origami are receiving enthusiasm from both academia and practice. Examples such as rapidly deployable bridges and canopies have been proposed and built. Compared to small-scaled origami-inspired devices, there are a quite number of challenges for building origami-inspired structures at a large scale such as folding thicker panels with higher compactness and selecting appropriate joints to connect numerous panels. In this work, we exploit the design, manufacturing, and parametric modeling of a deployable structure based on Miura-origami patterns. Guided by the geometric analysis, we create large-scale origami prototypes constructed by thickened panels that are actuated by mechanical forces. Numerical simulations are carried out to evaluate the unique mechanical properties of the deployable structures and to perform parametric analyses of the geometry unit of the deployable structures. A meter-scale prototype was built with cardboard paper which is an initial step for full-scale construction. We envision that the proposed deployable structure can be used for sun-shading, sound barriers, and other purposes.

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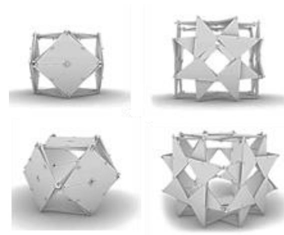
Expandable cube: A reciprocal reconfigurable structure for the activation of public spaces

Katherine A. Liapi. University of Patras, Greece. kliapi@upatras.gr



In this paper a temporary and transformable structure of cubic shape that can be placed in a public space to host or provoke cultural events and to function as a landmark is presented. The expandable cube can be transformed from a compact configuration to an expanded one with minimum human effort, and can be easily stored and moved to various locations in a city. The expandable cube's kinematic conception is based on the double layer reciprocal frame method with planar surfaces that is applied to all its six faces. At the early stages of this study, an investigation of reconfigurable polygonal surfaces and reconfigurable polyhedral forms of regular geometry, such as the Platonic and Archimedean solids, which can change configuration by following the principle of reciprocity, was conducted and is presented in the paper. Initial design issues, such as the position and type of joints that allow the cubic structure to expand or contract, as well as the kinematic performance of the developed cubic structure, have been tested with small scale physical models and with kinematic simulation studies. Finally, a discussion on fabrication methods, material choices, and processes that would facilitate the customization and assembly of the expandable cube are also discussed.

SESSION 34

Wed, 21 Sep.

Parallel Sessions,

16:15-17:45

(90 minutes)

Teaching of Shell and Spatial Structures facilitating Innovation, Sustainability and Legacy (WG20)

Chair(s): Alireza Behnejad, Juan Gerardo Oliva Salinas and Koichiro Ishikawa

114

Open educational resources in structural engineering education

Anahita Khodadadi. State University of New York at Buffalo. akhodada@buffalo.edu

Twenty years have passed since UNESCO launched a forum on Open Education Resources (OER) for Higher Education in Developing Countries to reduce educational barriers by providing students and informal learners with free information resources. Despite the support of many institutes and governmental agencies, awareness of OER is still low across different disciplines. Particularly, established open-access educational resources on architectural technology and structural engineering seem scattered and sometimes underrepresented.
This study has two parts. The first part analyzes the existing OERs developed for architecture and structural engineering students to identify the OER gaps within the discipline. The second part of the paper presents the features of an open-educational multi-modal textbook on "Basic Concepts of Structural Design for Architecture Students,". This study examines the success of designing this textbook in improving community access to technical information. Accordingly, students' experiences and learning outcomes, captured through a survey, can inform the designers of the textbook and other institutions seeking equitable access, affordability, and student success through open education and open textbooks.

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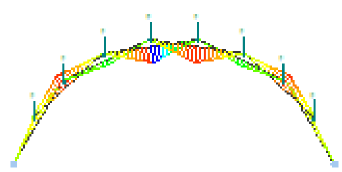
The mechanical properties of bamboo arched reciprocal structure based on parameters of configurations

Yi Lin Lee. University of Fukui, Faculty of Engineering, 3-9-1 Bunkyo, Fukui-shi, Fukui 910-8507. Japan yilinlee0102@gmailcom



Reciprocal Structure consisted of mutually supporting beams that can achieve stability by their own weight and allow spans greater than material length. The ideology of a reciprocal structure has been studied by many researchers and is adopted in constructing long-span structures. It is found that the properties of the elements significantly affect the shape and size of the reciprocal structure. Each structure is positively defined through its 3 components, "Flow of Forces", "Geometry" and "Material". Hence, it is essential to clarify how the parameters of an element could affect the geometrical composition and structural principle of a reciprocal system. Long-span wooden structures often adopt bamboo as a building material due to its flexibility and durability characteristics. In addition, bamboo comes with varieties of parameters such as length and diameter that can contribute to parameters studies of an Arched Reciprocal (AR) structure. Therefore, this research aims to explore the mechanical properties of AR structures made of bamboo with various parameters. The structural performance is evaluated through the rise-span ratio (RSR) and strain energy of the structure that is affected by a few main parameters, number of elements, length (l), diameter (D), and engagement ratio (λ). At the end of the research, we will be able to identify the structural properties of an AR structure and discover the parameters that will lead to a structure with higher structural performance.

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Timber 1/10 scaled model of Yakushiji's West Tower built by Mamoru Kawaguchi Laboratory

Chie Matsuo. Meisei University. chie.matsuo@meisei-u.ac.jp

On some occasions, structural engineers attempt to build physical models of existing buildings for the purpose to deepen their understanding of those structural mechanisms. In Japan, many historical timber towers still exist today preserving their elegant forms for more than thousand years. Those forms are multi-storied high towers in triples and quintuples characterized by symmetrical geometry with deep projection of eaves (noki-no-de). In order to interpret those special qualities, the relationships between their unique morphology and their structures were investigated by the laboratory of Mamoru Kawaguchi at Hosei University around the late 1970s. In the process of their research, they built a wooden partial structural model of Yakushiji's West Tower in scale of 1/10 in 1979. The model was exhibited at the University, however after the retirement of Mamoru Kawaguchi in 2003 the model was disassembled and kept in a storage to date. After 18 years of time, the model was taken out and reassembled. Only few information was left over, therefore it started from finding clues to build. This paper focuses on the procedure and clues the reassembly was based on. The findings gained through the experience is shared, in order to succeed this model to the future generations as legacy.

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Tradition and heritage on teaching of shell and spatial structures in Mexico

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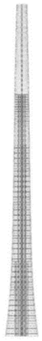
Architects and engineers contributed during the 1950s and the 1960s to the design and construction of reinforced concrete shells in Mexico. As a result, Mexico was worldwide recognized and influenced the design and construction of reinforced concrete surfaces beyond the borders of our country. Today, the teaching of shell and spatial structures in Mexico continues with the school left by prominent structural designers, including Félix Candela, Enrique de la Mora, Fernando López Carmona, Juan Antonio Tonda, José Luis Rincón, Alberto González Pozo, and Porfirio Ballesteros. Mexico City preserves many shells from those golden years. Today, the teaching of shell and spatial structures incorporates modern digital tools and cutting-edge knowledge of materials and technologies. Structural designers look for the same targets that the above-mentioned structural designers did: maximum efficiency with a minimum of materials, low costs, and time reduction—in other words, looking for sustainable architecture. In the first part of this manuscript, the authors of this paper will describe memories of the school of reinforced concrete shells in Mexico, and in the second part, they will present the Specialization in the Design of Lightweight Structures at the Faculty of Architecture - FA of the Universidad Nacional Autónoma de México - UNAM.

397

What is the legacy of structural design expertise? The parametric design approach to high-rise buildings.

Denis Zastavni. SST/LAB – Louvain research institute for Landscape, Architecture, Built environment [LAB], UCLouvain – Faculty of Architecture, Architectural engineering and Urbanism [LOCI], Place du Levant 1 (L5.05.02) - B 1348 Louvain-la-Neuve (Belgium). denis.zastavni@uclouvain.be

Some structures from the past such as large bridges constructed during the industrial revolution demonstrated rare qualities of efficiency and aesthetic character. These bridges were designed based on the fundamentals of engineering, where mistakes or inefficiency was irrelevant in the structural design. Today, high-rise buildings have similar structural challenges and potential opportunities of expression. Some of these buildings are among the most complex in the field of structural engineering and required fully integrated design approaches. Particularly with a height of 500m or more, designers face challenges in developing the most efficient solutions for these complex structures. For the student or junior engineer, a design exercise has been created and experimented considering full sets of sequential operations to complete the design. After reviewing the development of engineering sciences and engineering education, the paper presents a design exercise based on parametric design, interactive numerical analysis, comparative design and environmental assessment to provide architecture-engineering students with a complete design expertise, with the main benefits that can be gained.

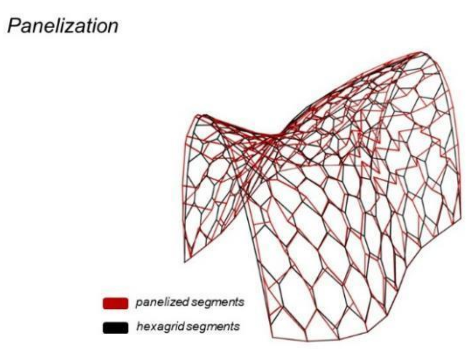


421

Design-Translate-Manufacture-Assemble framework for designing and building a segmented plywood shell

Thian-Siong Choo. Singapore Polytechnic. choo_thian_siong@sp.edu.sg

In the current architectural design coursework for the Diploma in Architecture at Singapore Polytechnic, digital design tools have predominated the way we teach our architectural students, and in the process, disengaged our students from the physical world and the reality of construction. This concern with the discrepancies that exist between the virtual space of the design and the physical reality of construction led to the development of a computational design course with an educational design-build pedagogy. A segmented plywood shell as a design case study was used to facilitate the design-build process via a Design-Translate-Manufacture-Assemble (DTMA) framework. This paper will present the work done by students during the course and discuss the impact that the DTMA framework had on student learning.



SESSION 35

Wed, 21 Sep.

Parallel Sessions,
20:00-21:30
(90 minutes)

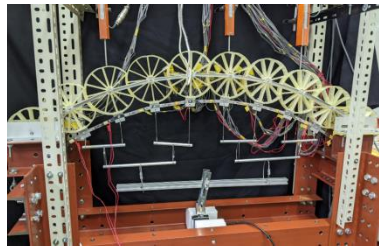
Mechanical Behavior of Tension Structures (WG6-7)

Chair(s): Massimo Majowiecki and Wujun Chen

40

The effect of changing boundary conditions at the arch End on the structural behavior of String Crescent Structure

Akira Tanaka. Tsukuba University of Technology. akira@a.tsukuba-tech.ac.jp



String Crescent Structure (Abbreviated name: SCS) is a stable structure based on a backbone-like kinetic structure. This is formed by the assemblies that were designed to be reusable into structures of various shapes. This structure is a unique structure proposed by the author. For this reason, some of these structural properties have not been clarified. Previous load experiments and analyses have verified the structural properties, but these are not considered the effects of Cyclic Load and different boundary conditions: pin-pin, pin-roller. To investigate this issue, the following study was conducted on SCS without prestress. *Comparison of structural properties between two kinds of models with different boundary conditions under Cyclic Load. *An analytical model with boundary spring will be created and the nonlinear analysis will be done to verify the effect of boundary spring stiffness on the structural properties. As a result, the pin-pin support has less maximum stress and less residual stress, etc. under Cyclic Load. etc. Therefore, it was found that the SCS with pin-pin support has more mechanical advantage than that with pin-roller support.

60

Study on the basic structural characteristics of hp type cable-net structure consisting of hexagonal mesh

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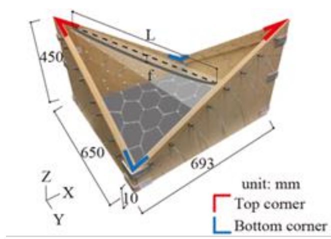

Hyperbolic Paraboloid (HP) type cable-net structure is characterized by the form resistance of the axial force resistance system and is excellent in structural rationality. Most of the existing cases of this structure are composed of two-way cables, and most of the meshes form a square mesh. In this case, when a vertically downward load is applied, the stress on the bracing cable decreases or disappears, and the stress on the suspension cable increases to resist the load. On the other hand, the HP type cable-net structure consisting of hexagonal mesh proposed in this report has a Poisson's ratio of 1. Therefore, it is easy to form a uniform stress surface. In addition, with an applied load, all cable tension increases and resists without loss of cable tension. Hexagonal mesh has unclear criteria for setting initial tension due to the fact that tension does not disappear. Based on the above, a comparative study of the structural characteristics was conducted in order to adopt the cable net structure in Japan. In the case of hexagonal mesh, the results show that it is necessary to set the PS (initial tension) while considering the roof shape and cable cross section from the viewpoint of suppressing deformation.

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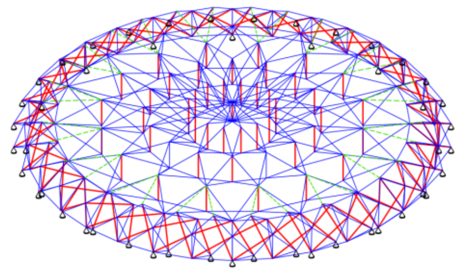
A parametric study on the instability behavior of a new hybrid cable dome

Karim Abedi. Professor of Structural Engineering, Sahand University of Technology. Tabriz-Iran; k_abedi@sut.ac.ir



Cable domes are one of the most efficient types of long-span structures designed using the concept of tensegrity structures. They maintain the stability by being attached to compression concrete ring at the boundaries which contradicts the free-standing principal of tensegrities. In the present paper, the combination of a Levy-type cable dome with a tensegrity ring created by semi-regular modules is considered. Form-finding of the studied structures is carried out using the force density method together with linear programming. Instability behavior of these structures is evaluated by the static and dynamic collapse analyses under two symmetric and asymmetric loading cases considering various geometrical and mechanical parameters. Results indicated that presence of a tensegrity ring around the cable dome increases slackening load level and total load carrying capacity of a cable dome in both loading cases and leads to change of collapse mechanism from “overall collapse” to “local collapse with snap-through”. Angle of modules of tensegrity ring relative to horizon plane plays leading role in the behavior of these structures. The influences of changes in prestress level, effective length of struts and various rise and depth to span ratios were examined on the collapse behavior of studied structures.

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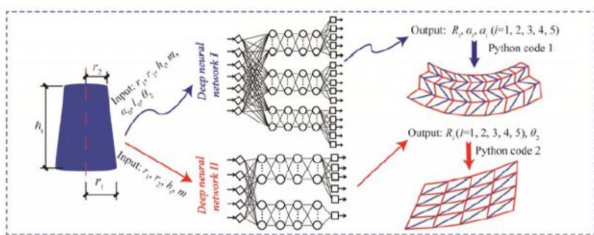
Automatic design of origami patterns for deployable conical structures using deep neural network

Yao Chen. Southeast University. chenyao@seu.edu.cn



Deployable mast is a basic component for most deployable assemblies. Compared with cylindrical masts, conical masts are easier to enhance structural performance by increasing their bending stiffness to weight ratio. Here, deep neural networks are introduced to automatically design origami patterns for deployable conical structures. The capacity of the datasets used are 120,000, and the division ratio of training set and test set is 7:3. Deep neural networks are trained with the Adam optimizer, to predict the key parameters of the origami patterns rapidly and accurately. First, geometric parameters for a deployable conical structure would be given for the trained deep neural network. Then, the key parameters of the origami pattern can be effectively obtained. Moreover, the origami patterns can be displayed through the written Python code. Relative error of the key parameters obtained by this method is less than 1%. This study has established deep neural networks for deployable conical structures with both four-fold and six-fold origami patterns. The unfolding and folding performances of origami patterns are verified by numerical tools and physical models. The results show that the established deep neural networks can neatly design origami patterns for both deployable conical structures and cylindrical structures.

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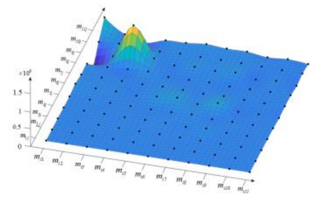
Influence study of members' area-loss in cable-strut structures

Manyu Deng. College of Civil Engineering and Architecture, Zhejiang University. manyudeng@zju.edu.cn

Many factors, especially corrosion, will lead to the area-loss of cable-strut structures. The damages will commonly shorten the service life of structures, and seriously affect their safety performance. In this paper, three failure modes of cable-strut structures caused by area loss are established based on reliability theory, and the coefficient inequality matrices of member's force as well as the nodal displacement are deduced. By introducing the corrosion model and combining with mathematical programming, a complete solution method for the area-loss limit of members is proposed. Compared with the calculated results under different failure modes, the most unfavorable area-loss limit of members will be selected. The result can be used to control the corrosion degree and the method can provide a theoretical basis for the corresponding specification design and structural health monitoring.



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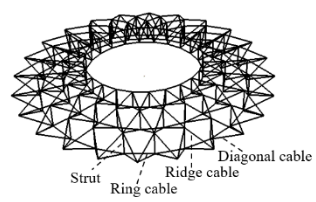
Progressive collapse analysis of Levy type open cable domes

Weijing Zhang. Beijing University of Technology. zhangweijing@bjut.edu.cn

In order to investigate the progressive collapse resistance of Levy open cable dome structure, the progressive collapse analysis of Levy open cable dome structure with span of 120m was carried out by using the alternate path method. Based on the vertical displacement and collapse area of joints as the criterion, the collapse resistance of the structure after removal of single cable is studied, and the effects of initial prestress, rise-span ratio and opening diameter on the collapse of structures are studied, which can provide reference for the collapse resistance design of such structures. The results show that the outer ring cable is the key member of the open cable dome structure to resist progressive collapse. When a single outer ring cable is broken, the maximum vertical displacement of the joint is about 1/14 of the structural span, and the roof structure has a large range of local collapse. With the increase of initial prestress or opening diameter, the collapse area of roof structure decreases, but it has no effect on whether the whole progressive collapse occurs. The collapse area of roof structure increases with the increase of rise-span ratio, and the small variation of rise-span ratio will lead to a large change of collapse area of structure. Reducing the rise-span ratio can reduce the risk of collapse of structure.



SESSION 36

Wed, 21 Sep.

Parallel Sessions,

20:00-21:30

(90 minutes)

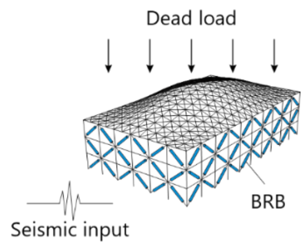
Dynamic Performance and Seismic Response of Metal Spatial Structures -2 (WG8-7)

Chair(s): Toru Takeuchi and Xian Xu

20

Computational morphogenesis based on generalized response spectrum analysis considering both dead load and seismic response of metal gridshell with buckling-restrained braces

Yuki Terazawa. Tokyo Institute of Technology. terazawa.y.aa@m.titech.ac.jp

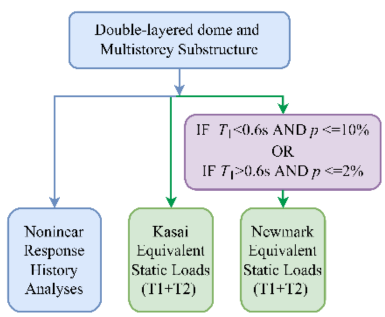


Structural morphogenesis is widely being used as a parametric tool to find an optimal structural shape of shell structures for a prescribed objective function and a given design loading. However, as the seismic response nonlinear history analyses are time-consuming, the current methods available in literature and commercial software are limited to finding an optimal geometry under only a specific static load like the dead load or an equivalent static seismic load for predefined geometrical shapes. This poses a challenge to achieving an efficient free-form shell structure in severe earthquake areas. Therefore, this paper presents generalized response spectrum analysis (GRSA) based computational morphogenesis considering their complex seismic response characteristics, and the response reduction effects using energy-dissipation devices to obtain form-found shell structures. The obtained results are summarized as follows: (a) the proposed method found an efficient geometry of metal gridshell roofs as well as an efficient damper layout, (b) BRBs are recommended to be placed in the (relatively heavy) supporting structure than the light roof, (c) a flattened but locally bulged roof shape proved to be the most efficient shape for mitigating the seismic response, and (d) while GRSA evaluates the displacement response with sufficient practical accuracy, it may underestimate the acceleration response. Therefore, NLRHA is recommended to be performed for only the final design check.

26

Preliminary seismic design of double-layered domes with nonlinear multistorey substructures

Deepshikha Nair. Graduate Student, Tokyo Institute of Technology. nair.d.aa@m.titech.ac.jp



This paper presents a novel approach to designing double-layered domes supported by (nonlinear) substructures using horizontal and vertical equivalent static seismic loads for considering their coupled horizontal-vertical response, closely spaced modes and substructure-roof interaction. These are determined from the input horizontal acceleration at the substructure's roof level, an assumed acceleration distribution, nodal roof masses and (horizontal and vertical) amplification factors derived from the dynamic characteristics of the dome and substructure. The proposal is also extended to nonlinear multistorey structures (that can be represented by an elastoplastic or bilinear relationship) by computing the peak horizontal acceleration in each participating mode of the substructure using the inelastic response spectrum computed from ductility-based reduction factors (as well as an alternative equivalent linearization approach). The proposed static approaches are compared and validated against the (time-consuming) nonlinear response history analyses (currently used for design) and are confirmed as simple and efficient alternatives for estimating the peak roof response at the preliminary design stage.

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Seismic behavior of a single-layer spherical lattice shell structure with superelastic-friction pendulum bearings

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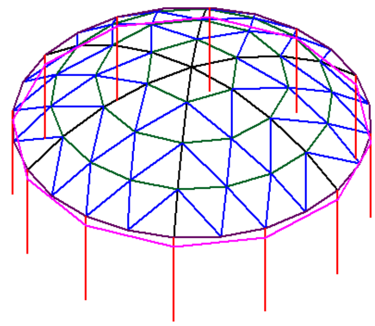

Friction pendulum bearings (FPBs) are mature seismic isolation devices for engineering structures. These bearings have been extensively studied and successfully applied to multistory buildings, bridges and industrial facilities over the past decades. However, FPBs may undergo large horizontal displacements under strong seismic ground motions, implying potential impacts between components in the isolation system. This issue is urgent be addressed, especially in the research field of high-position isolated structures (e.g., high-position isolated spatial lattice shell structures). To achieve improved performance, various tension-resistant FPBs using steel components have been developed by several researchers. Nevertheless, the control devices utilized in these improved FPBs limit the displacement produced only when the specified free stroke of the isolator is attained. Hence, further research is required to achieve the adaptive control of FPBs during strong earthquakes. To this end, a superelastic-friction pendulum bearing (SFPB) is proposed to achieve adaptive control of friction pendulum bearings (FPBs) during strong earthquakes. The SFPB consists of an FPB and superelastic shape memory alloy (SMA) wires. Moreover, additional SMA-based devices are arranged uniformly around the interior slider of the FPB. In this study, the configuration and operating principle of the SFPB were evaluated in detail. Quasi-static tests were conducted on SFPB specimens to examine the cyclic responses of prototype isolators. Numerical modeling of the SFPB was implemented using the OpenSees platform. Subsequently, the accuracy of the simulation method was validated through comparison with experimental results. Finally, SFPBs were used to evaluate the high-position isolation performance of a single-layer spherical lattice shell with surrounding columns. The seismic control effects of the SFPB system in the lattice shell structure were analyzed using nonlinear time-history calculations.

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Numerical simulation on seismic performance of suspen-dome structure

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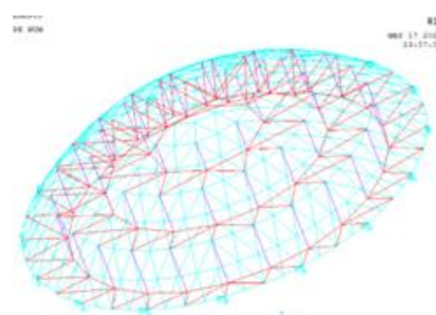

With the development of social economy and technology and the improvement of people's. living standards, large-span buildings are increasingly demanded. The suspen-dome structure which is suitable for building large space. Although the large-span suspen-dome structure has excellent seismic performance, the project is still damaged in the case of rare earthquake. This paper intends to study the mechanical response and failure mechanism of the suspen-dome structure under earthquake. The finite element numerical model of suspen-dome structure is established with finite element software. The time history analysis of the suspen-dome structure under earthquake action is carried out. The simulation results to comprehensively reveal the failure mechanism of suspen-dome under the strong earthquake. The results show that the suspen-dome structure is always in elastic stage under frequent and rare earthquakes. The suspen-dome develops rapidly in the plastic stage, and the structural failure caused by local failure is caused by the instability of struts and the buckling deformation of external members of reticulated shell. Failure mode belongs to dynamic instability.

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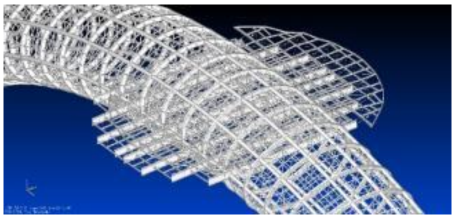
Vibration control of large-span arch structure, Eye of the yellow sea, by Houde damper system using mass of double floor

Susumu Yoshinaka. WASEDA University. syoshinaka@waseda.jp

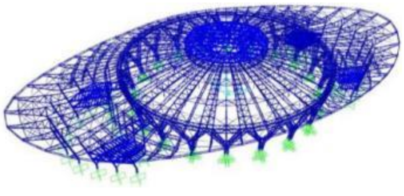


The Eye of the yellow sea pedestrian bridge is an ongoing project in Rizhao, China. It is a large-span arch structure and its structural system comprises a single layer braced steel frame with full glass coverage. The arch's span and rise are 177m and 63.5m, and its cross section is elliptical, 18m×13.5m. There is an observation platform at its center. In order to control vibration response caused by earthquake load, wind load and human walking, we propose a vibration control method using the Houde damper system. The Houde damper consists of a mass and a damper, but there is no spring as in a TMD. We isolate the observation platform and adopt it as the mass of the Houde damper. In this paper, we first describe the application method of the Houde damper system using the mass of the bridge's double floor. Next, we describe analytical results of a seismic response analysis. We thus confirm that the response of the Eye of the yellow sea pedestrian bridge under earthquake loading is effectively controlled.

500

Static and seismic performance analysis of the long-span full-steel structure of a gymnasium

Yang LI. Beijing University of Technology. 1770571182@qq.com



With the rapid economic development of China, many large-span spatial structures have been built in the past two decades. The static and seismic performance analysis and construction simulation of a full- steel gymnasium structure is introduced in this paper. The steel structure can be divided into three parts,i.e. the central main hall and two auxiliary halls, as shown in Figure 1. The whole steel structure of the main hall is unique. Its roof is a 110m-diameter suspen-dome composed of 20 radial trusses, which is quite different with a traditional suspen-dome composed of single-layer shell and struts and cables. The radial trusses are supported directly by 20 Y-shaped latticed columns, and they work together. The static behavior under dead, live, prestress and wind loads are studied, and the results show that the roof structure and the columns work well together, and the cables and their pretention increase the stiffness of the structure significantly. Modal analysis shows that the directions of the first three mode shapes are transversal, longitudinal and vertical, with the period of 0.84s, 0.83 and 0.76s respectively. The displacement, member forces are calculated under frequent and rare earthquakes. The anti-collapse capacity of the structure under severe earthquakes are analyzed. The plastic hinges distribution and the collapse process under different earthquakes are studied. The results indicate the seismic performance of the structure is quite good.

SESSION 37

Wed, 21 Sep.

Parallel Sessions,

20:00-21:30

(90 minutes)

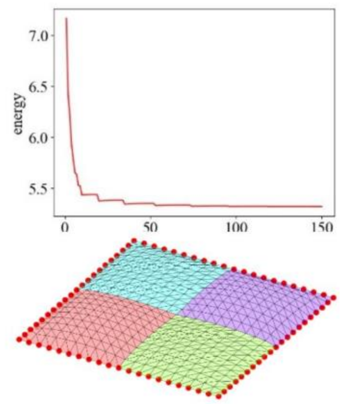
Computional Methods for Shell Design and Geometrical Methods (WG13-5)

Chair(s): Anahita Khodadadi and Ruoqiang Feng

28

Gaussian curvature flow for constant Gaussian curvature surface with triangular mesh

Makoto Ohsaki. Kyoto University. ohsaki@archi.kyoto-u.ac.jp



Numerous methods utilizing parametric surfaces have been proposed, e.g., using Bézier surfaces and non-uniform rational B-spline (NURBS) surfaces, to express the shape of shell roof structures. Even if the architectural geometry is defined by smooth surfaces, it is necessary to discretize them into meshes to apply finite element analysis for simulating its structural performance. Therefore, it is beneficial to directly design non-parametric form of discrete (polyhedral) surfaces consisting of a set of planar surfaces. In this study, the gradient of integral of mean curvature of a surface, called as Gaussian curvature flow, is utilized to generate a triangular mesh with constant Gaussian curvature (CGC) surfaces, which include the developable surface with zero Gaussian curvature. The energy functional is first formulated for the linear Weingarten (LW) surface, which has a property such that the weighted sum of mean and Gaussian curvatures is constant. The CGC surface is regarded as a special type of the LW surface, and it can be obtained using the Gaussian curvature flow derived from the first variation of the energy functional and moving the vertex in the normal direction of the surface in accordance with the Gaussian curvature flow. The discretized form of Gaussian curvature flow is obtained using the angle defect at each vertex of the triangular mesh. In the numerical examples, CGC surfaces with various boundary shapes are generated. It is shown that piecewise CGC surfaces with discontinuity of the Gaussian curvature along the internal boundary are naturally generated by assigning different parameter values for scaling or delaying the update of the vertices along the internal boundaries. Convergence properties are discussed in view of the sign of Gaussian curvature, boundary shape and initial shape.

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Initial numerical development of design procedures for TRC bioinspired shells

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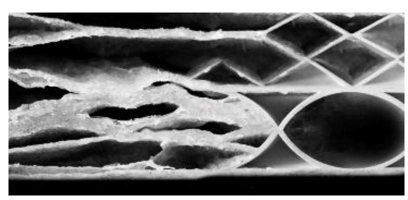

Nature, one of the biggest sources of inspiration for civil engineering design, exhibits thin-walled shell structures among a wide range of organisms. Due to membrane stresses that ideally prevail in such thin-walled structures, shells have an extremely favourable span-to-material ratio that in turn means excellent structural performance. The approach of looking towards nature for inspiration can be simplified by considering crystallographic symmetries, which also appear in nature and give rise to a method for creating shell structures carrying an additional topological interlocking property. The aim of the joint research project CRC/TRR 280 [1] is to achieve equivalent performance in shell structures made of textile reinforced concrete (TRC). Figure 1 illustrates the project's main concept, by showing how similar, after appropriate processing, the TRC structures can be to naturally occurring shell structures. Consequently, processing in all generality is the main focus of the project. The way how to design, optimize, and, of course, how to produce such bioinspired structures from TRC with the appropriate accuracy to match required design properties gives rise to many challenges to be overcome within the duration of the project. For the purpose of design and optimization of the structures mentioned above, it was necessary to establish a reliable data flow for the realization and generation of the geometrical data. Multiple software environments were used as a platform for the creation and assembly of the computational routines that, using principles and methods of generative design, aim to find an efficient TRC shell solution according to the required architectural and structural constraints.

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Discrete surface control using amount of change in surface gradient

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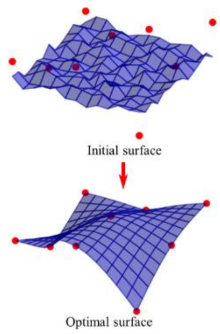
In this paper, we propose a new method to handle the geometry of discrete surfaces composed of quadrilateral elements directly, without using parametric surfaces, and to generate the required shape and construction-friendly geometry of the design, assuming that it will be applied to the geometry design of a lattice shell consisting of a quadrilateral grid in the future. In this study, a new control functional which can treat the surface as discrete surface while free-formability and smoothness of the surface is highly maintained using amount of change in surface gradient. Furthermore, multi-objective optimization of the proposed functional, surface area, and stiffness is carried out and the effectivity of the proposed functional is considered through the optimization results.



210

Creating novel dynamic architectural forms from kinetic elastica-ruled surfaces

Minghao Bi. RMIT University and minghao. bi@rmit.edu.au

Dynamic architectural forms are studied for many novel applications, as they can reconfigure their shapes to generate striking visual effects and obtain improved structural performance to respond to environmental changes. Such architectural forms may be created using the elastic-kinetic approach to achieve complex elastic deformations without mechanically complex systems. In this paper, we propose a new dynamic architectural form based on the concept of "kinetic elastica-ruled surface," which can rationalize dynamic curved surfaces using a series of non-interacting elastic strips bent to their minimum energy states. We classify the formed surfaces into two categories based on their motion behavior: "distanced-based" and "rotation-based" kinetic elastica-ruled surfaces. We demonstrate that distanced-based kinetic elastica-ruled surfaces can achieve interesting wave effects simply by controlling the support distances of parallel elastic strips. Moreover, we show that rotation-based kinetic elastica-ruled surfaces can alter their shapes by controlling the radial motion of the boundaries using non-parallel elastic strips. A full-scale rotation-based kinetic elastica-ruled surface is built to demonstrate its capability to realize a lightweight, high-speed, and cost-effective construction.

357

Free-form deformation based isogeometric shape optimisation of thin-shell structures

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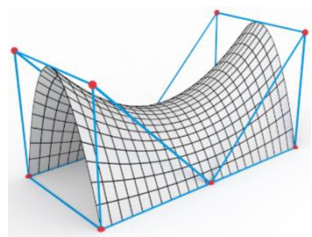

We introduce the isogeometric shape optimisation of thin-shells using free-form deformation (FFD) technique. The thin-shell mid-surface is modelled with a Catmull-Clark subdivision surface, and the Kirchhoff-Love thin-shell model discretised with subdivision basis functions is considered in the structural analysis. For shape optimisation, the thin-shell is immersed in a control prism and parameterised with free-form deformation technique, such that the thin-shell shape is controlled by the control prism coordinates. The control prism is defined in terms of trivariate Bernstein basis functions. The optimisation objective is to minimise compliance, i.e. maximise stiffness, with a constant volume constraint. By updating the control prism with a gradient-based optimisation algorithm, the immersed thin-shell shape is optimised accordingly. During optimisation the connection between the physical domain and the control domain of the thin-shell is taken into account in sensitivity analysis. The effectiveness of the proposed optimisation method is demonstrated with shape optimisation of a square thin-shell and a parabolic thin-shell. Compared with shape optimisation based on finite element mesh, the FFD optimisation scheme exhibits the capability to produce smooth and well-shaped results. The influence of the control prism on shape optimisation is also studied.

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Trans-topological learning and optimisation of reticulated equilibrium shell structures with Automatic Differentiation and CW Complexes Message Passing

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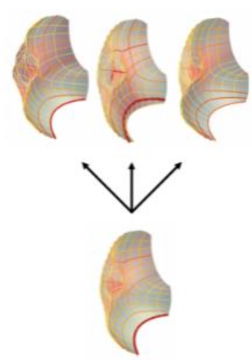

Reticulated equilibrium shell structures (RESS) are expressive structures governed primarily by efficient axial structural action; they are also hierarchical assemblies of joints, bars, and faces with constrained configurations of pattern, force distribution and equilibrium geometries. Translating performance goals into feasible RESS designs is a difficult task that typically requires supporting optimisation and learning applications. This paper proposes a framework combining recent advances from Geometric Deep Learning based on CW Complexes Geometric Message Passing (CWCGMP) with Automatic Differentiation to support both applications. At the core of CWCGMP is a principled and efficient framework for formulating differentiable functions over higher-dimensional hierarchical assemblies like meshes representing RESSs. This expressivity is exploited here to enrich the structural and design properties—related to vertices, edges, faces, or entire designs—that can be considered in both applications, and to develop powerful learnable architecture that can flexibly incorporate any combination of these properties, overcoming limitations in conventional graph-based approaches. Specifically, the proposed framework is applied to tackle the classic inverse RESS form-finding problem of closest geometry fitting, which—given an input pattern—aims to find a feasible configuration of vertices' positions and edges' forces resulting in a valid equilibrium force network with geometry that is optimally close to an input target geometry. Firstly, this research develops an inverse surrogate model to provide approximate closest-fit solutions given pattern and target geometry provided as inputs. Next, the framework is deployed as a modular optimisation system to discover a varied solution space of closest-fit solutions in less tightly constrained problems. The two design scenarios respectively demonstrate the opportunity for the framework to model the constrained RESS design space to directly support performance-explicit design, and to enhance the control available for designers to steer design optimisation. More broadly speaking, this research aims to augment the capacity of developers of optimisation and learning applications to support performance-informed structural design exploration.

SESSION 38

Wed, 21 Sep.

Parallel Sessions,

20:00-21:30

(90 minutes)

Geometry: Describing and Controlling (complex) Geometry, Including Parametric Design (WG15-4)

Chair(s): Niels De Temmerman and Jinghai Gong

74

Design of N-fold-symmetric multi-layered hinge frame deployable from bundle to surface of revolution

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A systematic method is proposed to obtain new horn-shaped, dome-shaped or other structures which have dihedral symmetry and can be folded into a straightly bundled shape. The proposed structure, which we call N-MLHF, contains some layers stacked vertically and connected by horizontal hinges. Each layer consists of 2N bars and 2N inclined hinges, which can be deformed from a regular 2N-gonal frame into an entirely straight rod shape. For the case N is smaller than 4, the proposed structure has single degree of freedom, and is movable only along the desired single motion path. If N is greater than or equal to 4, we can efficiently control its motion by introducing some mechanical devices or supports like actuators. For an application to shape design, a method is also introduced which enables us to generate the structure expanded on a target surface of revolution. Additionally, the formula considering hinge offsets are derived to realize the detailed design of hinge joints which have finite volume. The proposed method is applied for a horn-shaped structure, a ball-shaped structure and a dome-shaped structure as its numerical examples.

81

Rapid prototyping for non-developable discrete and semi-discrete surfaces with an overconstrained mobility

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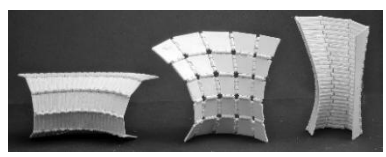
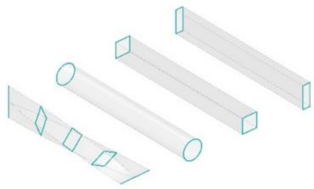


In recent years, technical folding, also known as structural origami, has been developed and implemented in many fields and applications to a wide range of materials. As many techniques are inspired by computational origami, their output is in most cases a three-dimensional mesh that can be developed without stretching or tearing in a planar mesh that represents a planar sheet of material. This is not only helpful in the fabrication of large spatial structures, but also in the design and development phase where the models can easily be built from planar sheets of paper. For geometries that cannot be folded from a single sheet, an assembly strategy is needed that allows for a high accuracy of the final model.
We present a solution for the model making in the design phase, that uses 3D printing of a hinge that can be assembled with a simple snapping mechanism to facilitate the model making process. Based on the special class of T-hedral surfaces, the authors will show examples and methods for discrete and semi-discrete models with an overconstrained mobility. Therefore, the strategy will be shown and explained for straight- and curved foldlines, respectively. Although STL printers are becoming more popular, the focus lies on FDM printers as they are currently more commonly used in design and engineering offices, as well as by design- and architectural students.

158

The structural geometry of a beam element from 4 torqued strips: A comparison to standardized profiles and applications

Serenay Elmas. Aalto University. serenay.elmas@aalto.fi



The shape of a structure and its members does play a significant role in structural and architectural questions, especially in the design of lightweight structures. Starting from this point, this paper provides a comparison of a torque-generated structural element to standardized profiles, namely circular, square, and rectangular profiles regarding their structural performance. For the comparison, the shape of the cross-section is set as the only variable to highlight the effects of the elements' geometry on their structural performance. The comparative study includes standard applications including the elements' use as a cantilever beam, a simply supported beam, and a pin-joined column. Numerical and analytical methods as well as graphic statics were employed to evaluate the behavior of the elements under certain loading scenarios. Accordingly, we present the distribution of stresses, displacements, buckling loads, and the utilization of the material.

394

A polyhedral approach for the design of a compression-dominant, double-layered, reciprocal frame, multi-species timber shell

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With the advent of polyhedral 3D graphic statics, form-finding processes for multi-layered funicular shells can be attained with considerable ease by leveraging polyhedral reciprocal diagrams. Yet, the resulting space-frame structure consists of multiple structs converging at a single point, and demands a high degree of customization for the connecting node. This poses design, fabrication, and assembly challenges. Reciprocal frame (RF) offers an alternative connection logic with added structural stiffness and aesthetic benefits. We present the design process of a timber frame prototype - a double layered, RF, compression-dominant, funicular shell. The paper, for the first time to our knowledge, applies the polyhedral form-finding method for a compression-only turned compression-dominant shell with RF. The prototype is designed with PolyFrame for Rhinoceros, fabricated by a 3-axis CNC machine and assembled with a 1-axis stacking logic. The optimal performative relationship between structural load, strut geometry, and principle axial stress of multiple wood species are investigated for the final prototype's material specification. The known complex RF geometric vs structural challenges found in free-form RF are addressed in relation to the funicular shell geometry given the varying strut lengths per node. The structural performance of the RF compressional-dominant shell prototype is numerically tested and compared with a conventional space-framed, compression-only shell of the same form. The workflow presented shows potential for application in multi-layered, structurally efficient, spatial structures with simplified fabrication and assembly process with locally sourced timber materials

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Research on the parametric design and optimization of the hexagon-cell shell structure

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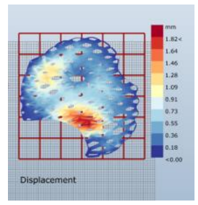

The shell structure of hexagonal sea urchin cell bionic cells has been partially studied and practiced, but detailed studies of the bionic structure have not yet been carried out. This study sought to investigate the effect of the density of the bionic cells (1untis/m2 - 9 cells/m2), the height of the cell projections (0-600mm),and the porosity of the cells (10%-200%) on the mechanical properties of the shell using parametric tools. Firstly, a parametric model of the bionic shell was built using the Rhino-Grasshopper platform, and then the shape of the bionic shell was completed using the Kangaroo plug-in. Finally, the strain energy of the bionic shell under self-weight loading was simulated using the Karamba3d plug-in. The results show that the strain energy of the bionic shell is lowest when the porosity is approximately 10%-70% and the shell unit's bulge height and porosity are kept constant; the strain energy is lowest when the density is approximately 1-4 units/m2 , the shell unit's density and porosity are kept constant, and the strain energy is lowest when the bulge height of the shell unit is between 0-0.500m and the strain energy is minimal when the other two parameters remain stable. Last but not least, this study uses the evolutionary algorithm Galapagos plug-in to determine the shell parameters with the lowest strain energy, which are 2 units/m2, 0.138m height of augmentation, and 51.39% unit porosity.

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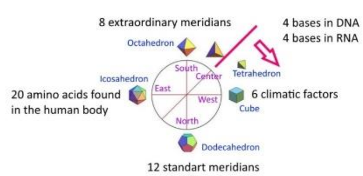
5 Platonic bodies, 5 Chinese elements: two isomorphic expressions of the same general system?

Serge Monnot. UMR 5600 Environnement Ville Société (EVS) - CNRS Laboratory of Lyon Architecture Urbanism REsearch (LAURE). serge.monnot@lyon.archi.fr



Previous studies have shown that it is possible to match two traditional cosmogonies: the 5 Chinese elements - wuxing - and the 5 Platonic solids, the basis of structural morphology. The objective here is to place this rapprochement in the context of the systemic theory. The wuxing applying to various registers, do they constitute a general system? Can we consider Plato's model as a minimal system? Does this rapprochement meet the desired objectives of the General Systems Theory? Several arguments seem to strengthen this hypothesis. The GST is rooted in the rapprochement between biology and mathematics: in the same way, our study puts in correspondence the wuxing of Traditional Chinese Medicine with a geometric system. The hypothesis of an isomorphism between these 2 systems makes it possible to integrate the polyhedrons in the wuxing summary tables and reciprocally to consider Plato's system as a mapping of the relationships between the different TCM subsystems. The issues are many and complex: to restore meaning to the Timaeus, a new reading of TCM from geometry, to update the general systemology. Finally, our study, if it is approved, gives structural morphology a central role in spatial planning and more broadly in understanding living organizations.

SESSION 39

Wed, 21 Sep.

Parallel Sessions,

20:00-21:30

(90 minutes)

Sustainable Heritage: Challenges and Strategies in the Preservation and Conservation of 20th Century Historic Concrete Shells-2 (WG17/WG5-2)

Chair(s): Marisela Mendoza and Atsushi Mutoh

33

Structural muqarnas: Reconstructing muqarnas using graphic statics

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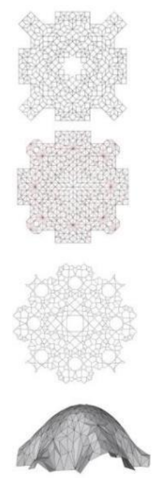

Muqarnas is an aesthetic spatial element in Islamic architecture with stalactite-like complex geometry. While it has the potential to be structural,it is mostly considered an ornamental element. Due to its geometric complexity, it was difficult for architects and masons to consider muqarnas as a structural element in the past, using their basic tools. This research will use graphic statics to contemporize and regenerate muqarnas as a structural element by maintaining its aesthetic while being an efficient compression-only structure that can be fabricated using advanced manufacturing techniques in a timely manner. Muqarnas is divided into two main types according to their 2D pattern: radial and tessellation ones. Two prominent examples of these muqarnas in Iran, Hasht Behesht (radial), and Natanz (tessellation) have been studied here. To reproduce the patterns, the graphic static methodology (using thrust network analysis) is implemented. The 2D pattern of muqarnas is considered as an initial form diagram to find the reciprocal force diagram. In almost every case, the primal form diagram cannot be used directly and needs some modifications according to the principles of graphic statics. By finding the horizontal and vertical equilibrium, the thrust lines that follow the pattern of muqarnas are generated. After the form-finding, different methods of materializations are performed to find a similar shape to the original muqarnas while considering efficiency, fabrication limitations, and construction time. Structural analysis of the found muqarnas showed very small deflection and stress because of that they are lightweight and designed in compression.

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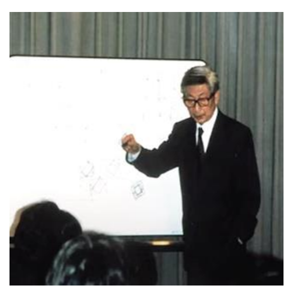
Gengo Matsui: the contribution of a structural engineer to post-war Japanese architecture

Federico Bertagna. ETH Zurich, Dept. of Architecture, Chair of Structural Design. +41 76 813 36 27



In Western practice, building design often results from a process of sequential involvement of an architect and a structural engineer. As such, the collaboration becomes a negotiation between pre-conceived spatial qualities and structural requirements, in which the input of the engineer is confined within the dimensioning of a structural system retrofitted within an already projected spatial construct. Although efficient, this repartition of tasks greatly limits the potential of structural design. An alternative to this sequential approach is provided by the Japanese building culture, in which collaborations between architects and structural engineers led to the development of innovative solutions, merging the border between the two disciplines. The present paper aims at investigating this alternative design approach through the key figure of the Japanese structural engineer Gengo Matsui (1920-1996), one of the protagonists in the evolution of Japanese architecture during the 20th century. In particular, the paper discusses the genesis and the early developments of the void slab system as a tangible result of the collaboration with the architect Kiyonori Kikutake (1928-2011). Through a detailed analysis of existing literature and exemplary projects, the current research seeks to illustrate Matsui's contribution as a structural engineer to the creation of elegant structural systems in which the pragmatic needs for load bearing capacity are seamlessly integrated within ambitious architectural visions.

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Dynamic characteristics and shaking table tests on suspend-dome structure with the center-hung scoreboard

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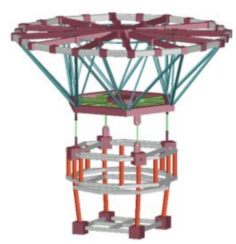

The LED display, i.e., center-hung scoreboard, has become an indispensable electronic device in modern stadiums. To investigate the seismic performance of suspend-dome structure with the center-hung scoreboard, based on a prototype scale model of the Lanzhou Olympic Sports Complex, a dynamic scaled model with a geometrical 1:20 was designed. The dynamic characteristics test and shaking table test were carried out for structure with a sling length of 200mm. The dynamic characteristic parameters such as natural frequencies and damping ratios was obtained by the Hilbert-Huang Transformation method for modal identification and the transfer function method for checking. The responses and change rules of acceleration, displacement and internal force of the structure under three-dimensional seismic were obtained. The test values were compared with simulation results of Abaqus. The results show that the test values of the scaled model are essentially consistent with the simulation results. The model has closely distributed modes and more vertical modes. The structure has good seismic performance under the actions of 8 degree rare earthquake.

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Why collapsed ancient hellenic temples? the case study: athena pronaia tholos at delphi.

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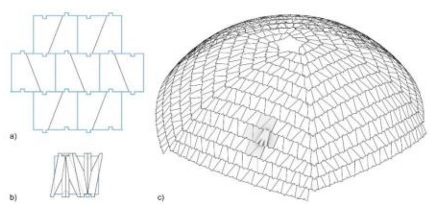

The hypothesis that the stone roof of Delphic Tholos has been vaulted has been already stated in a previous article by the same authors, The Stone Roof, cited in the references. Such thesis is coherent with the finds of the stone tiles preserved in the Archaeological Museum of Delphi. Within this document, the structural state has been examined at two different scales (local equilibrium and global equilibrium). The relevance of the stereotomy in achieving the balance is highlighted by studying the aggregations of a few tiles (local equilibrium) using a Non-Smooth Contact Dynamic Formulation. The study shows that any kinematics mechanism is avoided due to the tiles' geometry. The overall state of the Delphic Tholos has been estimated (global equilibrium) through a Graphic Static method, the Graphic static tool of the Modified Thrust Line Method. The analyses show how the masses of the acroteria and entablature (geisons, or cornice, frieze and architrave) provide the contrast needed to achieve the balanced state. In particular, the remotion of acroteria, connected with the frieze by the cornice, could be the reason for the collapse of the entire structure.

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A continuum between sculptural and structural form in the sutjeska memorial

Jelena Milošević. University of Belgrade – Faculty of Architecture. jelena@arh.bg.ac.rs

The Monument on the Battle of Sutjeska (1965-71), Tjentište, BiH, is an exceptional contemporary artwork in the former Yugoslavia. The monument was designed by sculptor Milorad Živković, while the structural design was developed by the engineer Đorđe Zloković. It represents a monumental sculpture/structure consisting of two symmetrically placed reinforced concrete boulders, 19m heigh, and penetration. In its symbolic, conceptual, and formal sense, the sculpture is related to the battle of World War II and inspired by the spirit of high modernism and the aesthetic of the so-called freeform. This paper analyses the relation between sculptural and structural forms in this work of memorial architecture. The study results from a literature review, a review of the original design documents (including project elaborate, models, and photo materials); a site visit; and an interview with the sculptor. The paper contributes to the discipline of structural critique by highlighting the lesson learned from the specific design and construction processes, such as the importance of cross-disciplinary collaboration to solve the challenges that art posed; the value of integrating rational reasoning based on technological requirements with creativity to achieve design excellence; and the relevance of simple formulas for structural estimation and learning from experimental models.

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Measuring and comparing digital images of a historical Japanese reinforced concrete dome obtained by using LiDAR and SfM

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Before the 1920s when reinforced concrete shells are said to have emerged in Europe, there already had been attempts of building reinforced concrete domes in the world. This paper focuses on the “Imabari Radium Hot Spring” which is one of the few existing early reinforced concrete domes in Japan. This facility is a complex located in Imabari, Ehime, said to have been constructed around 1919-1927 and registered as a Tangible Cultural Property of Japan in 2016. In Japan, which is prone to earthquakes, seismic retrofitting of this aged building is an urgent task, but it is difficult due to the high renovation cost. In this study, we conducted a series of the three-dimensional survey of the building by laser scanning using LiDAR (Light Detection And Ranging) and photogrammetry using SfM (Structure from Motion) technology. These data are utilized to preserve the building in a digital space. LiDAR is a method of measuring three-dimensional shapes by irradiating a laser beam on an object. On the other hand, SfM is a method to generate the three-dimensional shape of an object in an image by analyzing multiple images taken by a digital camera. In this paper, we present a basic study on the detailed shape of the dome of Imabari Radium Hot Spring based on the three-dimensional model obtained from the survey. We also report the principle differences between the two methods, the procedure for creating 3D models, and a comparison of the accuracy of the 3D models.

SESSION 40

Wed, 21 Sep.

Parallel Sessions,
20:00-21:30
(90 minutes)

Innovation in New Concepts and Projects - 2

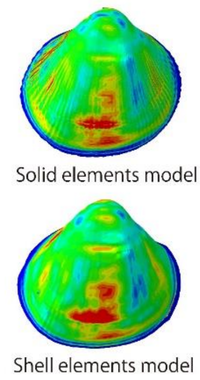
Chair(s): Juan Gerardo Oliva Salinas and Jianhui Hu

62

Finite element analysis of the bi-valve shell based on solid and shell elements

Minori Ogoshi. Niigata University. f21n004h@mail.cc.niigata-u.ac.jp

Biomimetics has recently been applied to the field of architecture. In this context, the properties of natural shells and their potential applications in structures have been examined. Moreover, stress and eigenvalue analyses of bi-valve shells have been performed. Notably, for the application of such shells in building structures, it is necessary to investigate the mechanical behavior of bi-valve shell in response to vibrations caused by earthquakes. In our previous work, solid elements have been used for static analyses whose calculation cost was considerably high because of huge degrees of freedom for solid elements. From the perspective of calculation cost, shell elements are effective in large scale analysis because their calculation cost is relatively lower than those of solid elements. Considering these aspects, this study examines that shell elements can be used instead of solid elements in the static analysis of bi-valve shell, where the image-based finite elements analysis are conducted by using X-ray CT images to consider the real shaped bi-valve shell. Fig. 1(a) and (b) compare the von Mises stress seq distribution on the surface and AA' vertical cross section between solid and shell elements. These results show that the numerical results with shell elements are agreed well with those with solid elements in this static analysis, along with about 90 % reduction in calculation time.



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Model Selection for Super-Long Span Suspension Mega-Latticed Structures

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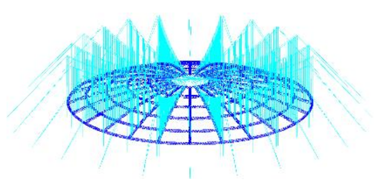

Combining super-large span suspension bridge with the traditional large span structure forms, suspension mega-latticed structure makes it possible to realize the super-large span structure with kilometric scale, and its mechanical and economic performance deserves further exploring. Five kinds of suspension mega-latticed structure models with the span of 1000 meters, including one Ribbed type, two Schweidler type, one Kewitt type and one Three-dimensional grid type, were established by ANSYS. The initial shape of main cables and the internal prestressing force of slings were obtained after the initial form analysis. And then the static analysis and stability analysis were carried out. The results showed that the wind load has a significant effect on the suspension mega-latticed structure. Through the whole procedure of load-displacement analysis of the structure, it indicated that there is no destabilization problem in the structure, and the failure mode of the structure is strength failure of the members in the trusses without slings. At last, different kinds of suspension mega-latticed structures with large span were studied and their optimal span ranges were summarized.

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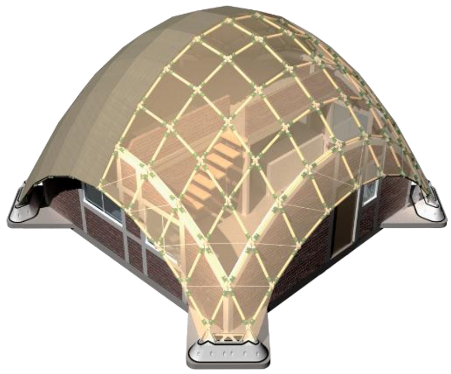
Bamboo gridshells for rural housing in Mexico

Juan G. Oliva. Lightweight Structures Laboratory-LEL, Faculty of Architecture, Universidad Nacional Autónoma de México-UNAM. jgos@unam.mx

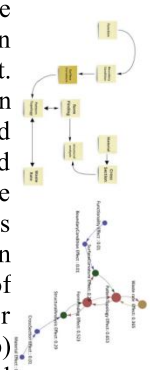


The LEL-Research group at the Faculty of Architecture of the UNAM is currently developing projects to provide solutions to constructing sustainable rural housing in Mexico, where 21% of the population is rural and 79% urban. The objective is to offer affordable rural housing for the most disadvantaged social groups with the lowest incomes in Mexico. The house is built with sustainable regional materials and considers the traditions and customs of its inhabitants. It also has passive environmental adaptation systems and uses solar energy to heat water and generate electricity. The form of the developed projects is based on two different geometries. The form of bamboos gridshells obeys to translation surfaces whose directrix and generatrix curves are catenaries. Oliva et al.. The brick vaults discussed in a second paper start from surfaces of revolution generated through the rotation of a catenary. This guarantees that the mechanical behavior of both structural systems is exclusively in compression.
The LEL-Research Group presents in this paper prototypes of rural housing constructed with bamboo gridshells covered with plasticized jute membranes. The gridshells are assembled using the kit for nods and bars previously developed by the LEL research group. Oliva et al.. The nodes manufacturing recyclable materials are Celanese's Frianyl. Three different projects intended for single-family housing are described.

456

Parametric thinking for decision-making in elastic gridshell design

Mohammad Hassan Saleh Tabari. University of Innsbruck. Mohammad.saleh-tabari@uibk.ac.at



Even in the field of lightweight structures, where structural, material-related, and design aspects must be considered simultaneously, mostly a serial and top-down process can be identified in the design and realization of projects. Typically, designers specify a geometric shape, and engineers then try to find a method to realize it. In the design of elastic gridshells, the architectural functionality is usually to span a wide-open space with a thin lattice of flexible material. The geometries of these shells are very often similar as we can learn from the realized projects and literature respectively. The geometry of the desired gridshell targeted by designers has direct and indirect effects on the design, structural stability, and architectural functionality. But how can we evaluate the design process in relating these various aforementioned issues? Defining a metric that can measure the success of the end result in relation to the various goals can be helpful for decision-making throughout the design process. Parametric design thinking thus expands the possible design solutions and achieves a broader range of forms. Using a mixed-method of literature review and experiments, this paper aims to provide a method for measuring the network of key design parameters for both, shape-first (top-down) and pattern-first (bottom-up) approaches. From literature we identified eight most essential design parameters such as functionality and surface curvature and explored their correlation by use of directed graphs and centrality theory. Finally, we show that these parameters can be complemented, changed or deleted, resulting in new, parametrically driven and dynamically responding graphs, improving the design process of elastic gridshells with the prospect of architectural, structural and environmental impact.

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Coreless filament-wound structures: toward performative long-span and sustainable building systems

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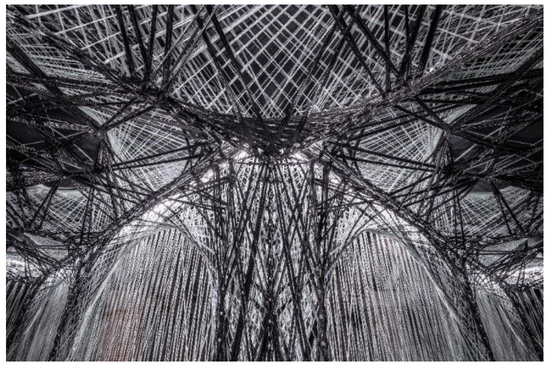

Coreless filament winding (CFW) was developed in 2012 at the University of Stuttgart to reduce material waste during the fabrication of composite parts. This was achieved by diminishing the required formwork of state-of-the-art filament winding to discrete boundary frames. Then, impregnated fibers are wound between them, forming lightweight lattice structures. A series of pavilions at the University demonstrated the system's potential and enabled the transfer of CFW into practice, bringing along other engineering challenges, such as the requirement to prove structural integrity and safety. The BUGA Fibre Pavilion was the first long-span application using CFW. In this project, a series of full-scale structural tests successfully proved the structural capacity of the composite components. Maison Fibre expanded the research toward multi-story building systems and explored the combination of CFW components with timber plates as hybrid slabs. To improve the sustainability aspects of the system, the LivMatS Pavilion replaced the previously used carbon and glass fibers with natural fibers. This pavilion achieved different materiality, showing the potential of bio-composite filament wound structures. This paper describes and compares the design and engineering process in each system: long-span, hybrid slab, and natural fiber components, and reveals the potential and future research goals to achieve more sustainable building systems using CFW structures.

21

Study on shear strength of partially connected steel plate shear wall

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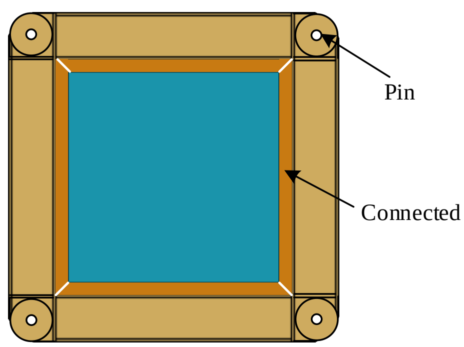


The paper proposed a new form of connection between steel plate shear walls and frames, by using discretely distributed fish plates to connect the infill plate and frame at the corners and centers, namely the partially connected steel plate shear wall (PC-SPSW). The high lateral resistance of SPSW has led to its widespread use in the design of structural shear resistance. In this paper, a finite element model of the PC-SPSW was established by ABAQUS, and the effect of the different partial connections on the shear strength was firstly investigated. Moreover, the variation of the structural shear strength with the plate-to-frame connectivity ratio is analyzed numerically, and the effect of the connectivity ratio on the development of the tensile field is studied. Based on the numerical analysis results, the effect of the connectivity ratio on shear strength is evident at low levels. When the connectivity ratio is over 80%, the shear strength of the PC-SPSW can reach 95% of that of the fully connected SPSW. Partial connection at the centers is more important on the shear strength of the PC-SPSW than that at the corners. Therefore, when the connectivity ratio is at a low level, the shear strength of the SPSW with the partial connection at the centers is high. Furthermore, the fitting formula for the PC-SPSW is obtained by changing the connectivity ratio and width-to-height ratio of the examples, which can predict the shear capacity of the PC-SPSW with different partial connections.

SESSION 41

Wed, 21 Sep.

Parallel Sessions,
21:45-23:15
(90 minutes)

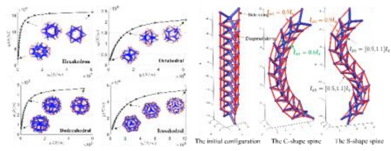
Tensegrity Structures (WG6-8)

Chair(s): Sudarshan Krishnan and Renjie Liu

49

Statics of tensegrity systems with arbitrary rigid bodies

Shuo Ma. Zhejiang University of Technology. mashuo@zju.edu.cn

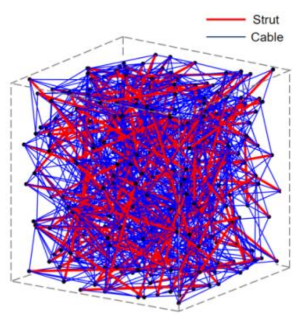


The first attempts in building tensegrity sculptures by Ioganson (1921) and Snelon (1948) never assumed there were no rigid bodies other than rods in the structures. However, it is probably because bars and strings are more efficient in taking compression and tension. And it is complicated to model the irregular shape of the rigid bodies. Most of the literature focus on bar-string networks. But for many engineering structures, we must include the rigid bodies, i.e., the deck of the bridges, the roof of the shelters, the shell of cable domes, and the shield of space structures.To embrace a much more general problem of system design, we develop an approach to study the equilibrium, stability, and form-finding of any tensegrity systems with rigid bodies. The governing equations are derived based on the Lagrangian method and given in an explicit form. The proposed method allows one to do the following studies, but not limited to the listed items. 1). Conducting structure equilibrium configuration, prestress design, and stiffness studies. 2). Performing prestress and mechanism modes analysis. 3). Checking stiffness, stability, and robustness in terms of prestress, materials, and geometric information of the structure. 4). Conducting studies on form-finding of rigid body tensegrity systems. 5). Simulating the forced motion of structures. 6) Studying the feasibility of pseudo-static deployment trajectories. It is also shown that without rigid bodies, the governing equations of the rigid body tensegrity system yields to the pure string-bar tensegrity. Numerical examples are given to demonstrate the capability of the developed method, and some results are shown in the figure below.

211

Stress to stiffness response of tensegrity structure networks

Shaoxiong Huang. Space Structure Research Center, College of Civil Engineering and Architecture, Zhejiang University. 22012282@zju.edu.cn

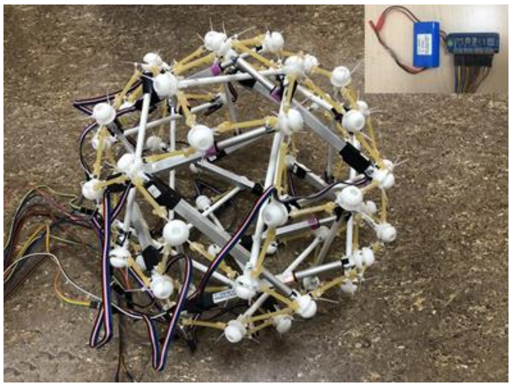


Tensegrity structures have been used as conceptual mechanical models for cell cytoskeleton and cellular organization. To explore quantitative tensegrity-based models for actin networks, this paper proposes a large-scale tensegrity structure network which is generated in a given three-dimensional space by a topology optimization method based on mixed integer programming. The member lengths of the tensegrity system are constrained within the length range of the actin filaments. The postbuckling of struts and the initial slack of cables are considered in the numerical study of tensegrity structure networks. It is found that the proposed tensegrity-based model for actin networks exhibits three distinct regimes of elasticity: linear regime, stress stiffening and stress softening, and the range of the three regimes is basically consistent with the experimental result reported in literature.

265

30-strut locomotive tensegrity robot

Meijia Wang. Zhejiang University. 229150@zju.edu.cn



Tensegrity structure is a prestressed self-equilibrated system consisting of compressed struts and tensioned cables. Locomotive tensegrity robot is a new type of tensegrity structure which is capable to perform locomotion by changing the length of actuated members. The robot is flexible, lightweight and highly-redundant, making it adaptive to unconstrained environments and ideal for various co-robotic scenarios such as space exploration, emergency rescue and so on. Previous researches on tensegrity robot are mainly based on the 3-strut, 4-strut prismatic tensegrity and 6-strut spherical tensegrity. A 12-strut spherical tensegrity robot is also studied.

This paper develops a locomotive robot based on 30-strut tensegrity with 90 tendons. The 30-strut tensegrity robot has more controllable degrees of freedom and is much more flexible than previous tensegrity-based robots. As a result, it possesses more various motion behaviors as well as gait primitives. Using an optimization approach based on dynamic relaxation method and genetic algorithm, the gait primitives of the 30-strut tensegrity robot and the corresponding control strategies are obtained in this paper. The motion behavior of the gait is discussed and a prototype with 15 strut-actuators is manufactured and tested to verify the found gaits.

355

Form-finding of hybrid tensile structures with active bending using finite element technique assuming nodal coordinates

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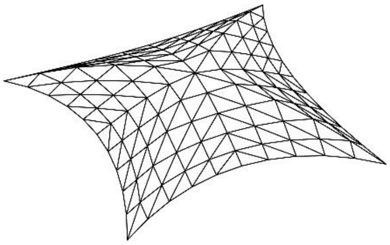

This paper presents form-finding problem using beam elements of finite element technique assuming nodal coordinates, and demonstrates to apply elements to hybrid bending-active structures with beam, membrane and cable elements. The finite element technique assuming nodal coordinate is one of a useful method for form-finding analysis of tensile structures, which does not require coordinates transformation and is described by a simple formulation. Furthermore, bending-active structures in which active bending is acting to beam elements is known as a form-finding problem for hybrid tensile structures. It is possible to realize lightweight structures with self-equilibrium by the prestressing tension of the membrane and cables or the temporary external force during construction. In this paper, we derive the discrete formulation of beam elements with the finite element technique assuming coordinate values, and apply the method to hybrid bending-active structures.

Firstly, we derive analytical solution of 2-dimensional Euler buckling forms with rigorous definition of curvature, and compare analytical results and numerical solution. Secondly, we propose the hybrid tensile structure with Active bending, and conclude importance of inheritance of bending moment from form-finding to stress-displacement analysis with vertical or horizontal load.

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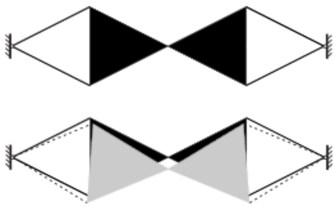
Equilibrium and stability of general tensegrity structures with rigid bodies

Yafeng Wang. Zhejiang University. yafengwang1239@gmail.com



Most existing tensegrity applications are based on classic tensegrity systems (i.e., tensegrities that only consist of members carrying axial forces). Another category of tensegrity, referred to as general tensegrity systems, that also contains rigid bodies aside from axially loaded members, is promising to be applied in some specified scenarios. However, existing analysis methods for tensegrity structures mostly focus on classic tensegrity systems, which limits further and wide applications of general tensegrity structures. Recently, general tensegrity systems with disconnecting rigid bodies have been investigated; the equilibrium and stability conditions are derived, and a topology design approach is proposed. However, it is assumed in the study that there is no connection between rigid bodies in a general tensegrity. From a practical application point of view, different rigid bodies in a general tensegrity could be connected; for this case, the analysis method proposed in the previous study will become inapplicable. This work further proposes a comprehensive analysis method in terms of equilibrium and stability for general tensegrity structures in which the connections between rigid bodies are allowed. The generalized inverse theory is employed to derive the equilibrium and compatibility equations and the product force method, as well as the reduced geometric stiffness matrix method, are employed to derive the stability condition. This study completes the analysis theory of general tensegrity, which provides a fundamental analysis method for further studies and wide applications of general tensegrity structures.

SESSION 42

Wed, 21 Sep.

Parallel Sessions,

21:45-23:15

(90 minutes)

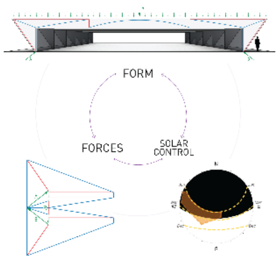
Graphical Methods and Funicular Structural Design (WG 13-6)

Chair(s): Juan Gerardo Oliva Salinas and Kazuki Hayashi

73

Graphical methods as the key to holistic design: bringing together structural design and solar control strategies

Federico Bertagna. ETH Zurich, Dept. of Architecture, Chair of Structural Design. bertagna@arch.ethz.ch



Building design is a complex, open-ended task that involves diverse disciplines and professionals. Architects and engineers are challenged with solving a variety of often-conflicting issues related to various aspects, such as space making, structural performance, energy consumption, and user comfort. Holistic design approaches allow for addressing all these requirements jointly from the conceptual design stage. However, it is necessary to use appropriate tools to enable effective relationships between different disciplines. The objective of this research is to introduce a new holistic framework in which structural design and solar control strategies are addressed simultaneously thanks to the use of geometry-based graphical methods. Within the framework, graphic statics serves in solving structural design aspects, while graphical methods for solar control are used to tackle solar design aspects. The results obtained show how geometry-based graphical methods lead to a concise and intuitive formulation of the problem without curtailing the precision of the results. On the contrary, the use of such methods represents a crucial advantage for designers as it fosters a thorough understanding of the underlying design principles, thus enhancing the ability of the designer of controlling the design process as a whole.

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A historical graphical analysis method for rigid frames

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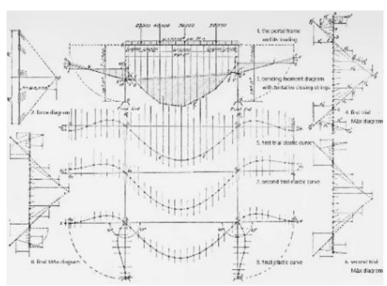

This research reviews a historical graphical method for the analysis of rigid frames. As the basis of this method, the graphical analysis methods for statically indeterminate beams, as well as determinate ones, were also reviewed. This method for rigid frames was presented by William Wolfe in 1921. Although somewhat rudimentary and almost forgotten, it possesses a special cognitive value comparing to the analytical and numerical methods. The current mainstream of the study on graphic statics pays limited attention on the application of graphic statics to rigid frames, as well as to hyperstatic beams. However, exploration on the analysis methods of these structure types was an important part of the history of graphic statics. Such explorations have occupied a large portion of some of the classic works of graphic statics. After the introduction, this paper reviews the origin and basis of the graphical method for rigid frames, revealing the history and system of the technique behind the graphical method for rigid frames. The methods for beams will be explained in more technical details in the following section, enabling readers to readily comprehend the explanation of the method for rigid frames in the next part. After the technical account, the advantages and disadvantages of this method for rigid frames are discussed. The author argues that this graphical method for rigid frames, notwithstanding its present limitation, is potential to be developed into a design method for architects to explore the form of rigid frames perceptively.

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On the thrust line of piecewise-linear-elastic continuous funicular structures

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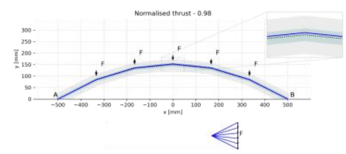

Thrust Line Analysis (TLA) is a powerful graphical method for the assessment of the stability of compression-only structural systems. TLA can also be used for the design of two-dimensional funicular structures by aligning the centreline of the structure to the trust line of the given loads. Structures designed in such a way are in a state of uniform compressive stresses under the given loads, making full use of the section's capacity, and therefore very efficient. Nevertheless, TLA only provides the correct solution for structures made of multiple discrete elements (e.g., voussoirs) or for continuous but statically determinate systems. When a continuous structure is statically indeterminate (such as a two-hinged arch, for example made of concrete), the actual thrust line, sometimes called True Thrust Line and in this paper referred to as Elastic Thrust Line (ETL), deviates from the structure's centreline, generating bending moments that induce tension and could potentially lead to unwanted cracks. This paper discusses the derivation of the ETL of generic continuous statically indeterminate elastic systems and presents an extension of the traditional TLA method to piecewise-linear-elastic continuous structures. By combining elastic theory and graphic statics, it provides an easy, fast, and insightful method for the design of new funicular structures. Examples of applications to the design of funicular structures are also presented and discussed.

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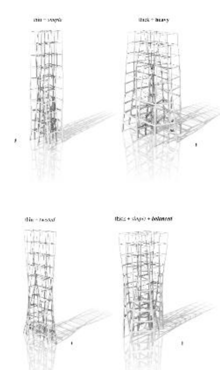
Enhancing structural form-finding through a text-based AI engine coupled with computational graphic statics

Zifeng Guo. University of Florida. guo.zifeng@ufl.edu

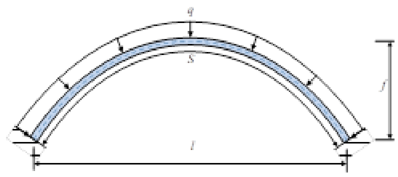


This paper introduces Text2Form3D, a machine-learning-based design framework to explore the embedded descriptive representation of structural forms. Text2Form3D relies on a deep neural network algorithm that joins word embeddings, a natural language processing (NLP) technique, with the Combinatorial Equilibrium Modeling (CEM), a form-finding method based on graphic statics. Text2Form3D is trained with a dataset containing structural design options generated via the CEM and labeled with vocabularies acquired from architectural and structural competition reports. For the labeling process, an unsupervised clustering algorithm Self Organizing Maps (SOM) is used to cluster the machine-generated design options by quantitative criteria. The clusters are then labeled by designers using descriptive text. After training, Text2From3D can autonomously generate new structural solutions in static equilibrium from a user-defined descriptive query. The generated structural solutions can be further evaluated by various quantitative and qualitative criteria to constrain the design space towards a solution that fits the designer's preferences.

320

Exact solutions for out-of-plane buckling of funicular arches considering warping deformations

Chuanhao Zhao. College of Civil Engineering and Architecture, and Center for Balance Architecture, Zhejiang University, Hangzhou, China. zhaochuanhao@zju.edu.cn



The out-of-plane buckling behavior of arches is closely related to the element torsional behavior. The traditional 12-degree-of-freedom second-order element stiffness matrix which uses a simplified element torsional stiffness GJ/L (where G is the shear modulus, J the St. Venant torsion constant, L the element length) may significantly underestimate the out-of-plane buckling loads of funicular arches. This paper presents a simple and effective exact matrix stiffness method (MSM) for the out-of-plane buckling analysis of funicular arches. The developed MSM uses a 14-degree-of-freedom second-order element stiffness matrix of three-dimensional beam-columns considering both torsion and warping deformations. The out-of-plane buckling analysis of funicular arches is performed by using the global structural stability stiffness matrix which combines the transformed second-order element stiffness matrices. The proposed MSM with the exact 14-degree-of-freedom second-order element stiffness matrix for the out-of-plane buckling analysis is verified by comparing with some classical solutions of funicular circular arches with I-sections.

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Performance-informed pattern modification of reticulated equilibrium shell structures using rules-based Graphic Statics, CW Networks and Reinforcement Learning

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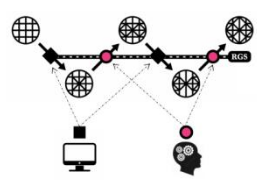

Reticulated equilibrium shell structures (RESS) designs are efficient axial-dominant structures: they are also constrained combination of three design aspects—structural pattern, force distribution and geometry—that prescribe one another's feasible explorable design space and cannot be modified independently. Research supporting performance-informed pattern design exploration are rare, and often entail closed and end-to-end processes that cannot flexibly accommodate bespoke designs under development by designers, and may require extensive pre- and post-processing of design inputs and outputs. Consequently, the modification of structural patterns according to performance goals during iterative conceptual design development remains a challenging task for which there are few effective methods for achieving.

In response, this paper proposes a framework combining Reinforcement Learning and Geometric Deep Learning based on CW Network to support the modification of the connectivity of RESS designs according to structural performances using Rules-based Graphic Statics (RGS). The combination of data-driven methodologies enables the learning of an expressive structural design decision space encompassing trans-topological designs of variable sizes and connectivity, and pattern editing operations that may involve the vertices, edges, or faces of RESS designs. Importantly, the equilibrium constraint of RESS is preserved by RGS in all generated and modified designs. In this paper, the proposed framework is applied to learn recommendations for improving the general stiffness of RESS designs against unanticipated structural loads, in the process addressing a well-known limitation in standard RESS design workflows, which typically consider only a single dominant load-case. Conceptually, the presented work is formulated to seamlessly integrate with the iterative design development stage to suggest recommendations at any step of the process: it offers a promising step towards learning a reusable model to tackle the combinatorially complex structural design task of performance-informed pattern modification in a manner conducive to iterative design exploration.

SESSION 43

Wed, 21 Sep.

Parallel Sessions,

21:45-23:15

(90 minutes)

Form-Force Relationship: The Study of the Interdependency of Structural Geometry and Mechanical or Kinetic Behaviour (WG15-5)

Chair(s): Rupert Maleczek and Marina Konstantatou

85

Semi-symmetric origami waterbomb cell kinematics and tessellation for the design of thin-walled folded shells

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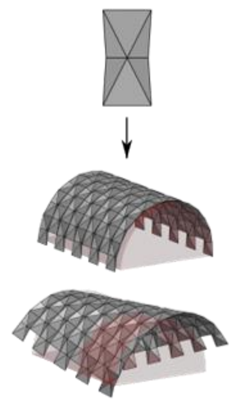
The art of origami proved to be a remarkably useful technique for technical applications in many fields such as architecture, engineering, medicine and aerospace. Even though existing numerical methods of rigid-origami can be used to describe the geometrical forms, algebraic solutions of the waterbomb folding kinematics and tessellations reduce the algorithmic complexity and determine the range of admissible configurations exactly. In this paper, a previously presented analytical solution for a symmetrically folded waterbomb cell and tessellation is extended to the case of a cell folded semi-symmetrically. The algebraic derivation is presented, which provide instant solutions for the entire folding process. The resulting functional relationship between the design parameters and the 3D cell geometry of the folded waterbomb cell enables efficient studies of achievable shell geometries. This development facilitates a deeper understanding of the correspondence between the geometrical parameters of a single waterbomb cell and the statically relevant geometric properties, i.e. the shell curvature and the effective cross-sectional height. The systematic description of this correspondence provides the basis for innovative design concepts using modern cementitious composites, e.g. textile-reinforced concrete, to produce thin-walled, high-performance, light-weight shells.



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Growth deformation of surface with constant negative curvature by bending-active scissors structure

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Ruffled surfaces that appear in biological forms such as coral and lettuce are a great source of inspiration for architectural and furniture design. Such surfaces are produced by differential growth in which the growth rate increases from the center to the edge of the surface. We propose a mechanism based on bending-active scissors that effectively reproduce the process of differential growth through the incompatibility of in-plane shear deformation produced by scissor units. The structure can deform between a linearly folded state with rotational symmetry and a buckled surface of constant negative Gaussian curvature without rotational symmetry. First, we propose a design method for the mechanism computed from the surface of constant negative Gaussian curvature. Then, we show how to analyze the mechanism through geometric methods and elastic simulation. Then, we analyze the process of the curvature change and optimize the design variables to obtain the desired deformation process. Finally, we show the comparison between the simulated model and the physical prototypes.

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A study of form creation and structural performance verification of a large-scale wood masonry structures

Daiki Iwamoto. Tokyo Denki University. iwa.reon@gmail.com

In a library renovation project, four structures called "Mirika no Ki" were designed, which are based on a tree of the city symbol. The structures were designed as uniquely shaped bookshelves. The installation designer, structural engineer, contractor, and material supplier were involved from the early stage including form study and decision making. A process of form determination flow chart was created. Multiple morphogenesis algorithms were created that enable to satisfy those conditions such as height, width, etc. The models created from the algorithms were compared in terms of aesthetic perspective, buildability, and rationality. The variables were adjusted to complete the process after an algorithm was decided. The decision on the design and construction aspects was discussed with architects and builders. The safety performance verification of the form is shown below. Wireframe analysis approach was adopted for this wood masonry structure. The structured calculation was based on elastic assumption. Gravity and seismic studies were carried out, and it was determined that a building has sufficient performance if it is within the design capacity. The structures are able to resist 0.5g horizontally force. However, there is not enough data to determine whether the actual joint's structural to perform can resist this design criteria. Therefore, full-scale bending tests on the full thread screws used in the structures were conducted to confirm that the joint evaluations made in the analysis were appropriate. The experimental results showed that the stresses exceeded those assumed in the analysis and calculation.

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Preliminary research of low-cost hysteresis seismic damper using thin steel plate with folding crease for wooden houses

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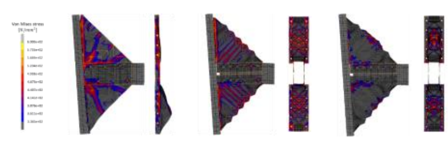

A series of low-cost seismic dampers using folded normal steel sheet, instead of expensive low yield point steel, is proposed and developed. Stiffness and energy absorption performance against cyclic load of it are numerically investigated by finite element analysis. When the shape of the steel plate is limited to flat, large out-of-plane deformation with a hinge line occurred. A crease called rib, intersecting the hinge line, greatly increase the damper stiffness. In the origami crease shapes, it was confirmed that the slip properties included in the hysteresis curves of previous models could be reduced and the energy absorption level could be further increased. These results shows that it is possible to increase the energy absorption and stiffness by making simple creases on the steel plate. It also suggests that more energy absorption during earthquake can be expected with Origami crease pattern.

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Paper Study on a loop-free crossed cable net evolved from the spoke-wheel cable net

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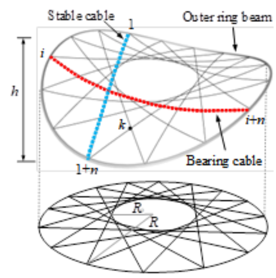
A novel loop-free crossed cable net evolved from the spoke-wheel cable net is investigated in this paper. Combined with the mathematical expression of the saddle surface, a form finding method based on space coordinate transformation is proposed to determine the initial equilibrium state of the new structure. The structural stiffness and bearing capacity of both the new structure and the spoke-wheel cable net are compared quantitatively by using the load path criterion. A new concept, named the load path factor, is proposed to quantitatively evaluate the structural vulnerability of the cable-net. The results show that the new structure is superior to the spoke-wheel cable net in structural behavior, is more economical, and has development potential.

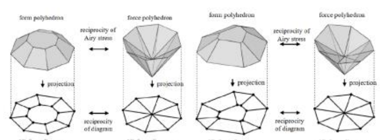


365

The extended affine method for form finding of a spoke wheel system in light of graphic statics

Hiroki Tamai. Nikken Sekkei. tamai.hiroki@nikken.jp

This paper revisits the extended-affine concept for determining equilibrium forms of spoke wheel roof systems in light of the graphic statics. The extended affine concept allows a designer to choose a more arbitrary compression ring shape for covering an asymmetrical plan shape with a spoke wheel system, as well as to determine the self-equilibrium prestresses without resorting to sophisticated nonlinear calculations. By this, the forces in the compression and tension rings can be made uniform, and those in the radial cables are also all equal. This means that the force diagram is unique, though scalable, for all feasible geometry with the same topology. This paper illustrates such form and force relations in light of Airy stress polyhedra, and is part of the authors' effort to give a more comprehensive explanation about the remarkable properties of the equilibrium geometry of spoke wheel structures in the extended-affine concept, which include the evolute and involute relation between two compression polygonal curves: one with the minimum sum of the squares of the segments and the other with the minimum variance of the segment, and the fact that the limit curve of the evolute polyline is a cycloid.



SESSION 44

Wed, 21 Sep.

Parallel Sessions,
21:45-23:15
(90 minutes)

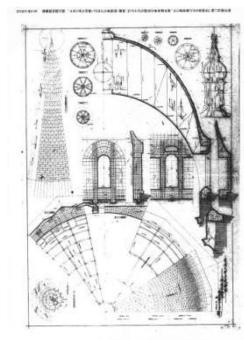
Sustainable Heritage: Challenges and Strategies in the Preservation and Conservation of 20th Century Historic Concrete Shells-3 (WG17/WG5-3)

Chair(s): Stefano Gabriele and Mohammad Bolhassani

233

Preliminary Investigations of Early Reinforced Concrete Shells in Japan

Kazutaka Uemura. Ken Nagasaka Engineering Network Co.Ltd. kuemura@nagasaka.com



The history of Reinforced Concrete shell structure is documented with the development of Dywidag company around 1920, but there had been various attempts before that The first RC structure in Japan was built in 1905, and many RC structures have been constructed since then. In the 1950s, after the end of World War II, various RC shell structures were constructed, led by Yoshikatsu TSUBOI, and received international acclaim. On the other hand, there are few reports on cases of RC shell structures in Japan before the 1950s. In this report, design details based on the membrane theory are reported along with examples of RC shell structures in Japan constructed in the early 20th century.
Several pre-Zeiss-Dywidag RC shell structures are known in Europe, while smaller RC shell structures were built in Far Eastern Japan at a slightly later date. By reporting that early RC shell structures have been constructed not only in Europe but also in Asia, this paper will help to understand the global spread of RC shell structures in the early 20th century.

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Searching for the engineering optimum: evolution of the topology of the triangulated rebar grid of the Zeiss-Dywidag domes

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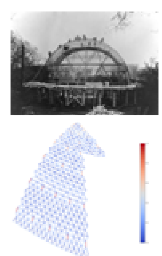

This paper investigates the evolution of the triangulated reinforcement grid of the early Zeiss-Dywidag domes. The originally geodesic grid was replaced by a lamella-dome-type topology. Both designs originate from Walther Bauersfeld, a chief engineer of the Zeiss company. Bauersfeld assumed that the gridshell's internal force distribution would be well approximated by the membrane shell model (i.e., equivalent shell) if the triangulation was 'uniform enough'. There are two main questions investigated in this paper: (a) In what regard (if any) is the lamella-dome-type topology superior to the original, geodesic triangulation? Constructional and structural-geometrical aspects are investigated. (b) Could any of the geometric benchmarking parameters studied by Bauersfeld suggest an engineering optimum? The benchmarking parameters considered are the ratio of longest and shortest edges (lmax/lmin) in the grid and the bar-density (D, fraction of the half-perimeter and the area of a triangle). The presented results are based on the study of Bauersfeld's original manuscripts and the analytical and numerical analysis (FEM) of reconstructed structural models (in the Rhino-Grasshopper environment). The study's conclusion goes beyond the historical context, as it illustrates the difference between the (optimal) behavior of gridshells and continuous membrane shells.

269

Structural characteristics of the central dome of hagia sophia : focused on during reconstruction after the first collapse

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St. Hagia Sophia is one of historical masonry structures in Istanbul, Turkey. The construction began in 532, and it was completed in 537. Hagia Sophia has undergone three collapses of the central dome and its supporting structure, and has been reconstructed each time. After the first collapse in 558, the height of the dome was increased by about 6 meters due to the reconstruction in 562. The structure of the central dome was not significantly changed in the reconstruction after the two subsequent collapses. Therefore, investigation of the structural characteristics of the dome at the time of its 562's reconstruction would provide valuable insights for repairing and strengthening the present Hagia Sophia in order to prevent the collapse of the central dome and its surroundings. The purpose of this paper is to clarify the structural characteristics of the dome at the first reconstruction in 562 by conducting structural analysis with the finite element method, focusing on the dome before and after the first collapse.

280

Demolition of heinz isler's free-form shell in sargans

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Heinz Isler is one of the most prominent figures in reinforced concrete shell design. Thanks to form-finding approaches based on the use of physical models, he pioneered original ways to control "new shapes for shells". The paper examines Isler's shell project for the architectural office Grob in Sargans (1968) in Switzerland, comparing archival documents stored at the Heinz Isler Archive at ETH Zürich with the traces revealed by the full-scale shell after its demolition, that took place in 2021. On the one hand, through original materials, Isler's methodology can be followed step by step. On the other hand, through on-site observations, the shell's structural behavior can be explored as a 1:1 physical model, until collapse. This sad event for the history of engineering asks for a broader reflection on the preservation of 20th-century iconic shell structures in reinforced concrete.

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The Mitchell Park Horticultural Conservatory in Milwaukee, Wisconsin

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The Mitchell Park Horticultural Conservatory consists in part, of three conoid structures, referred to as domes. Each of the domes contains a different climate. The Conservatory has a unique variety of plants not found in other conservatories. The domes attract about 250,000 visitors annually. Each dome is 26 m tall and has a 43 m base diameter. The main structure for each dome is a precast concrete frame, supporting an aluminum framed wire glass cladding and a steel framed apex. The precast concrete frame is a series of hexagons, diamonds, and triangles which make up the conoid shape. The individual concrete sections were formed on site and erected over a temporary steel scaffold. Each dome is glazed with approximately 3,150 triangular shaped glass plates. The glazing system sits outside of the concrete frame and is connected to the concrete with steel plates, tubes and hubs. The hubs were also designed to collect and drain condensation water. The domes were designed between 1955 and 1962 by Charles Whitney (of "Whitney Stress block" fame in plastic analysis of concrete). These domes were developed concurrently with other famous projects including collaborations with Eero Saarinen on early thin-shell concrete structures such as Kresge Auditorium (1955), TWA Flight Center (1962), and Dulles International Airport (1962). Construction of the Mitchell Park Horticultural Conservatory began in 1959 and proceeded in stages until 1967 with the opening of the arid-climate dome.

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Cylinder, arch, double curved shell—a history of shell structure in chinese buildings around 1960

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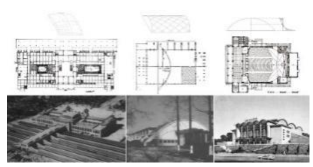

This paper illustrates the innovative design, calculation and construction process of three types of shell contructions: Chongqing Mountain City Cinema, Peking Railway Station, Tongji Auditorium. Based on field investigations, detailed analysis of original drawings, calculation method comparison, interviews with relevant architects and engineers. This paper discusses three different shell structures through an interdisciplinary approach, figure out how architects handled the spacial shell in building's plane, section and facade design, and how structural engineers calculated these three shell structures. Furthermore, it points out the architect and engineer's very positive contribution to the forms and mechanics of shell, depicting the trajectory of the development of reinforced concrete shell structure in China to launch the construction history research in the early PRC.

SESSION 45

Wed, 21 Sep.

Parallel Sessions,

21:45-23:15

(90 minutes)

Disaster Prevention and Mitigation of Spatial Structures-2

Chair(s): Yue Wu and Christopher Robeller

251

Equivalent static wind loads of long-span roofs and application in Chinese building code

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Long-span space roofs usually have dense distributed natural frequencies, and the calculation of their wind-induced response usually has to consider multiple vibration modes. Such multiple vibration effects make it difficult to reach the maximum response for multiple largest load effects under one equivalent static wind loads (ESWL) obtained by traditional methods. In order to overcome this shortcoming, the authors proposed one new method to calculate the universal ESWL, where dominant eigenmodes of wind loads and dominant vibration modes of structures are chosen as fundamental vectors to construct the universal ESWL that would simultaneously reproduce multiple largest load effects. And the least-squares approximation method is employed to calculate the combination factors of these fundamental vectors. Furthermore, parametric studies are conducted to investigate the influences of wind loading and structural parameters on the wind-induced response and the universal ESWL of four commonly-used kinds of long span roofs, including flat-roof spatial grid structures, the single-layer cylindrical shells, single-layer saddle shells and the single-layer reticular dome shells, where the effects of the structural span, rise-span ratio, roof mass and the mean wind velocity on the universal ESWL are investigated. Simplified expressions of universal ESWL are proposed for engineering design, which are expressed as a function of the reduced frequency of the structures. Using these expressions, it becomes very convenient for the structural engineers to calculate the design wind loads for the main loading-bearing structural systems without wind tunnel tests and complex random analysis. These simplified expressions of universal ESWL for these typical kinds of long-span roofs have been introduced into the Standard for Wind Loads on Roof Structures in China (JGJ/T481-2019).

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The latest status of research on damping characteristics of shell and spatial structures in Japan

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Damping is one of the important parameters about vibration phenomena of shell and spatial structures. However, damping of the structures is not as clear as stiffness and mass of the structures. It is impossible to evaluate damping ratios by theory or to know ones in advance from the structural system because there are so many factors around the structures and in the structures, for example, those are the shapes, materials, sizes, ground conditions, support condition of the structures, and by the seismic forces or wind forces and so on. The study of damping ratio evaluation of shell and spatial structures has been conducted by Professor Tatemichi at Meisei University and members of Shingu Laboratory at Nihon University until now. In this paper, damping ratios and characteristics of shell and spatial structures have been analyzed using 55 data of damping ratios of the structures built in Japan. We tried to search data in another countries, but to our regret, we could not find the data of damping ratios of shell and spatial structures in another countries. Therefore, the data of damping ratios of shell and spatial structures results to only the data in Japan.Conclusions Two kinds of evaluation of damping ratio of shell and spatial structures have been proposed in Equation (a) as the parameter of the spans of the structures, and similarly, as the parameter of the rises of the structures in Equation (b). ・Proposed damping ratio (parameter: span(m)) : $h1=0.01L+1.67$ (a) ・Proposed damping ratio (parameter: rise(m)): $h1=0.025H+1.75$ (b) There is damping ratio's dependency by the scale of the structure. There is damping ratio's dependency by amplitude of vibration. There is damping ratio's dependency by frequency.Effect of damping ratio by nonstructural elements is very large.As the constitution number of the database of shell and spatial structures is not so large, accurate correlation equations are not obtained yet. It is urgent work to grasp damping characteristic of the structure correctly as shell and spatial structures are often used for evacuation facilities in the case of disasters. In near future, the database is expected to be enlarged.

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Considering cable and membrane collaborative work - influence of friction coefficient between cable and membrane on wind-induced response of air supported membrane structures

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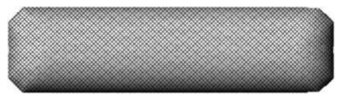

Cable and membrane structures usually produce large displacement and deformation under load action, and the cable and membrane contact and produce relative sliding. At present, in the form-finding and load analysis of cable and membrane structures, the collaborative work between membrane elements and cable elements is generally simplified as a shared node. In this paper, for the form-finding and load analysis of air supported membrane structures, the interaction force between cable and membrane is transmitted through friction contact action, owing to considering the influence of friction between cable and membrane, the friction coefficient must be needed to consider. In view of the lack of corresponding data of the friction coefficient between cable and membrane, some representative membrane materials were selected to test the friction coefficient between cable and membrane according to the application of cable and membrane materials in the engineering practice of air supported membrane structures, and the friction coefficient between different membrane and cable materials are obtained; then utilizing ANSYS software, the friction and slide between cable and membrane of air supported membrane structures is considered as a contact problem, and the contact model is established, initial form analysis and wind load response analysis are also carried out, and the effects of different coefficients of friction on form-finding and wind-induced vibration response of air supported membrane structures are emphatically compared.

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Experimental investigation of mechanical properties of steel cable at and after elevated temperatures

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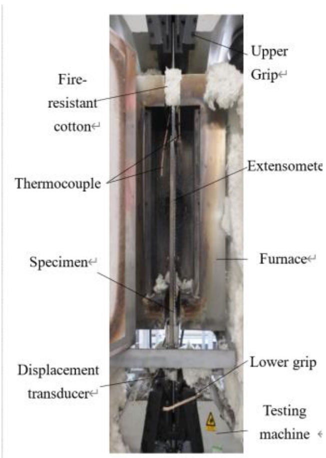

With the rapid development of urban modernization, the pre-stressed space structure has been widely used in large-span space structures. Thus, it is necessary to study the safety of space structures, and the fire resistance of pre-stressed space structures has become a popular topic. As a necessary component of space structure, the high-temperature performance of cable directly determines the fire resistance of space structure. Based on this, the mechanical properties tests of different specifications of cables were carried out under normal temperatures and elevated temperatures. The high-temperature mechanical properties of zinc-5% aluminum-mixed mischmetal alloy-coated steel (M-C steel) with round and Z-shape cross-section shapes were studied in the temperature range of 30–800 °C. The mechanical properties of stainless-steel cable and Galfan cable were tested at and after elevated temperatures. The equations for nominal yield strength, elastic modulus, ultimate strength, and ultimate strain for two steel cables at and after elevated temperatures are proposed. Furthermore, a modified two-stage Ramberg-Osgood model for cables at ambient and elevated temperatures is proposed. The thermal-mechanical deformation of the cable at elevated temperature and after elevated temperature is obtained. The collaborative working mechanism of cables affected by temperature was fully revealed.

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Research on the dynamic response and tension loss for cable-net supported glass facade systems under wind-seismic coupling excitations

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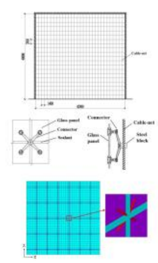

The cable-net supported glass facades are widely used in large public buildings. Due to its low damping, low stiffness, and strong non-linearity, the façade system is subject to sudden changes in tension, excessive deformation, and panel damage under strong wind and seismic excitations. In this research, a refined numerical model of a cable-net supported glass facade system containing pre-stressed cable nets, connectors, glass panels, and sealants is used to study the dynamic responses of the façade system under coupled wind and seismic excitation by simulating wind pressure periods of 10, 50 and 100 years based on the AR linear filtering method. The results show that for wind or seismic single action, the tension and deflection responses of the cable-net supported glass facade system under wind excitation are severer than that of the single seismic excitation, and the structural responses are dominated by wind load. For wind and seismic coupled excitations, the dynamic deflections of the cable net vary less compared to the tension, and tension responses are more sensitive to external excitations. Also, the effect of tension loss on the dynamic performance of this facade system cannot be ignored. More importantly, the stress variation of the glass panel in the middle and end of the facade is larger, which should be paid more attention to in daily operation and maintenance.

SESSION 46

Thu, 22 Sep.

Parallel Sessions,

14:30-15:30

(60 minutes)

Future Challenges in the Design and Construction of Shell Structures for Low or Zero Carbon - 2 (WG5-2)

Chair(s): Stefano Gabriele and Wujun Chen

151

Development of structural elements for thin flat plates and shells using high-performance mortar

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In this study, technical consideration for realizing thin concrete plates and shells is shown by the new concept of using high-performance mortar by member tests.In recent instances of two representative big reinforced concrete shell constructions in Japan, thickness greater than 250 mm and double reinforcement is required to resist extra bending after a Level-2 earthquake. Thin and single reinforcement shells, on the other hand, are perfect for axial force management, and weight reduction is also useful for seismic force.In this paper, we present the concept for thin continuous plates and shells using high-performance mortar developed in Japan and stainless mesh. The mortar utilized in the experiment is made from PVA fiber and has a high-strength of around Fc150, as well as great fluidity and self-filling capabilities. These properties permit the use of multi-layered mesh reinforcements in thin plates and shell components.In the experiments, bending tests of beams and thin flat plates were performed, high-strength and ductility were confirmed. Furthermore, the air permeability and water permeability coefficients are quite low, and it has outstanding durability when combined with stainless steel mesh. Through these efforts, we shall seek to apply it to the modern-day by industrializing Nervi's Ferro-cement idea based on superior handcrafted techniques.

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Different uses of the generalized eccentricity for shells' shape optimization: a comparison

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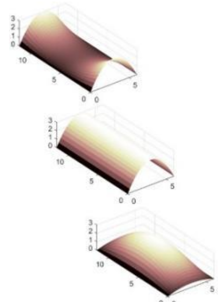

The aim of this work is to define a variety of objective functions based on the generalized eccentricity, a parameter that quantifies the funicular behavior of shells, and to test their performance for shells' shape optimization. The efficiency of shell structures is influenced by the relationship between geometry and load to support. For this reason, their design is usually approached by means of shape optimization procedures. Here we perform a shells' shape optimization procedure by minimizing, one at a time, the defined objective functions. The goal of the proposed shape optimization is to obtain a shell that is as much as possible R-Funicular by modifying a few parameters that define its geometry. The results are compared each other in order to test and discuss the performances of each objective function. We present significant numerical examples where the shape of a bi-parabolic concrete roof is optimized.

430

Parameter sensitivity analysis of hybrid gridshells with bending-active formwork

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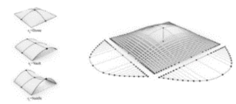

Thin concrete shells can efficiently span over large distances with very little amount of material. However, their construction requires the planning and assembly of complex, material-inefficient, and labor-intensive formwork. To overcome these challenges, promising experiments have been made to use flexible formwork techniques and, in particular, bending-active structures as a lightweight alternative for casting concrete shells and lattice-like hybrid gridshells. Yet these studies have also shown that the geometric properties of shells and hybrid gridshells play a crucial role in their performance, such as their structural stability and material utilization. To better understand the effects of different geometric settings on the structural performance and material efficiency of hybrid gridshells in particular, this study aims to perform a multiparametric sensitivity analysis. Among the parameters used to generate the gridshells on different target surfaces are the span-to-rise ratio, the support conditions, and the grid density pattern. The shapes created in this way are then loaded and evaluated according to their global stiffness, maximum deflection, and maximum utilization. Based on this analysis, the authors summarize their findings and provide recommendations for the development of future gridshells.

470

Adoption of air-supported forms for thin-shell concrete structures: understanding uses, benefits, and barriers to scale

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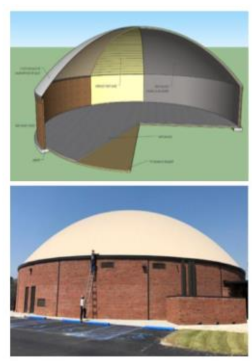

Air-supported fabric forms for the construction of thin-shell concrete structures are a demonstrated option for efficiently scaling thin-shell structural geometries in the built environment. With an almost 100-year history of development, it is estimated that the air-supported forming processes has been used to construct over 10,000+ structures, 2,500-3,000 structures across the globe in the last 40 years. Although significant, this number remains proportionately small compared to other structure types. With exception of limited niche industries, concrete thin-shell structures have not achieved wide market adoption despite a range of purported advantages. Drawing from a database of over 1,000 structures, this paper outlines a research agenda of continued practical inquiry.

SESSION 47

Thu, 22 Sep.

Parallel Sessions,

14:30-15:30

(60 minutes)

Dynamic Behavior of Tension & Membrane Structures
(WG6-9)

Chair(s): Susumu Yoshinaka and Xiaofeng Wang

102

Study on static and dynamic behavior of roof Structures consisting of radially arranged cables under strong winds

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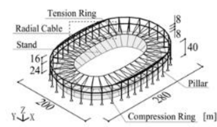
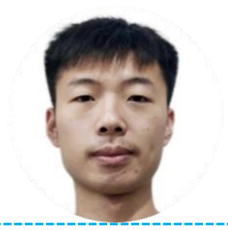


In Japan, it is assumed that there will be many new constructions of stadiums with roofs and expansions and renovations of stadium roofs in the future. In this paper, the authors focused on a roof structure consisting of radially arranged cables in which cables are radially arranged between the inner tension ring and the outer compression ring. This structure has been adopted extensively both for new and renovated roofs on the stadiums outside of Japan, but there are no cases of it being adopted in Japan. One of the factors is wind load. Since this structure is a lightweight structure, the wind load is generally dominant. In the case of Japan, wind load is larger than in many places in the world due to the influence of typhoons. Deformation and stress are also considered to be larger than in many places in the world. Various studies on this structure have been reported in the past, but there have been few reports of detailed investigations of structural behavior under strong winds. In this paper, with a view to adopt this structure in Japan, the authors consider the structural characteristics under wind load. The authors conducted wind tunnel tests using scale models, studied static and dynamic behavior by numerical analysis, and analyzed the structural behavior in strong winds for structural design.



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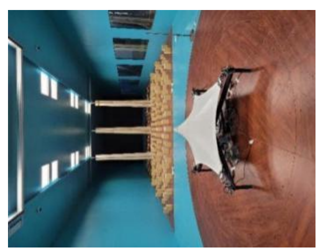
Aerodynamic characteristics of an umbrella-shaped membrane structure in high turbulence flow

Zhou Zhang. Fuzhou University. 757983298@qq.com



Membrane structures are susceptible to wind load, especially high turbulence flow. To investigate the effects of high turbulence flow on the aerodynamic characteristics of membrane structure, wind tunnel tests of an umbrella-shaped tensioned membrane structure were carried out in both low turbulence flow (Iu=14%) and high turbulence flow (Iu=20.5%). Aerodynamic characteristics of the three dimensional membrane structure in these two wind fields are discussed in terms of displacement, frequency, and damping ratio et al. Results show that the influences of high turbulence flow are (i) the increasing damping ratio results in the reduction of displacement response; (ii) the non-Gaussian distribution of displacement appears more obvious with larger skewness and kurtosis, which should be considered in reliability design of membrane structure; (iii) the added mass over membrane surface can be obtained, even up to 8 times as structural mass, which can not be ignored in dynamic analysis. This study can address the deficiency of current studies for aerodynamic characteristics of membrane structure in high turbulence flow.

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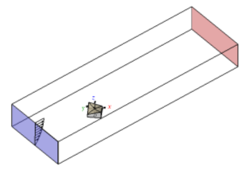
Nonlinear motion-induced aerodynamic forces on large-scale membrane roofs

Tengfei Wang. Chongqing University. wangtengfei@cqu.edu.cn



In this study, the nonlinear motion-induced aerodynamic forces on the large-scale membrane roofs are numerically investigated using large-eddy simulation with the forced excitation approach. The mean and standard deviation of wind pressure coefficients on the rigid membrane roofs in the turbulent boundary layer are first simulated to validate the numerical models. Then the large-scale membrane roofs under forced excitation with different oscillation amplitudes and frequencies are simulated, and the motion-induced aerodynamic forces, which include the aerodynamic stiffness force and aerodynamic damping force, are investigated. The findings show that the aerodynamic stiffness force is linearly proportional to the oscillation amplitude, while the aerodynamic damping force is nonlinearly dependent on the oscillation amplitude. Moreover, the models of linear aerodynamic stiffness force and nonlinear aerodynamic damping force are presented based on the numerical results.

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Effect of the mass-damping ratio on the wind-induced response of a tension membrane structure based on FSI simulations

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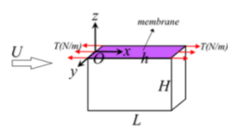

This study mainly investigates the effects of mass-damping ratio on the wind induced response of a flexible, tension membrane structure considering fluid-structure interaction (FSI) effects with numerical simulation. Loose coupling simulations, in which finite element method (FEM) and large eddy simulation (LES) method are used on the structure field and flow field respectively, are performed on a one way, close type tension membrane with different mass-damping ratios. Firstly, the numerical simulation are validated against the reference aero-elastic experiments. And then, characteristics of the wind-induced responses of the one-way tension membrane structures with different mass damping ratios are elucidated in both time and frequency domain. Finally, the underlying mechanism of the wind-induced vibration of the membrane with different mass damping ratios is revealed by spectral analysis. It is found that typical vortex-induced resonant vibration (VIV) phenonmenan could be observed for the tension membrane structure. With the damping ratio of membrane increases from ξ_"1" =4% to ξ_"1" =8%, the reduced critical wind velocty at which the resonant vibration starts delays from 1.20 to 1.60, and the velocity range of the resonant regime would also be decreased. Additionally, no obvious resonant vibration could be found for the tension membrane with smaller mass ratio, i.e., m^*=0.87. The outcomes of this study facilitate our understanding of the FSI effects in flexible membrane structures and the wind-resistant design of such structures on the practical engineering.

SESSION 48

Thu, 22 Sep.

Parallel Sessions,

14:30-15:30

(60 minutes)

Dynamic Performance and Seismic Response of Metal Spatial Structures -3 (WG8-8)

Chair(s): Koichiro Ishikawa and Zhi Ma

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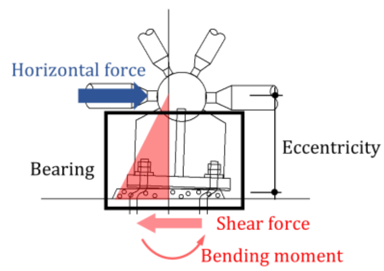
Nonlinear restoring force characteristics of conventional roof bearings subjected to moment and shear

Hiroyuki Ogata. Graduate Student of Kogakuin University. dm21008@ns.kogakuin.ac.jp



In 2011, the Pacific coast of Tohoku earthquake destroyed many roof bearings which support steel truss roofs on lower RC structures. Some of them were designed as slide bearings to release the thrust caused by the weight of the roof. In this study, we analyzed the observed behavior in the cyclic loading tests on conventional roof bearings to figure out the damage mechanism. In ball-jointed system truss roofs, bearings are subjected horizontal move and rotation when horizontal earthquake force acts since the roof structure has insufficient rotational stiffness. We assumed that anchor bolt's stress and friction force resist the move and rotation and developed equations which express horizontal force in relation to the horizontal displacement and rotation angle. From the geometry anchor bolt's elongation and bend angle are expressed by the horizontal displacement and rotation angle of the bearing. After the stress of tensioned anchor bolt is on the M-N yield surface, the bending moment and axial force are calculated by using the law of plastic flow. We also conducted two experiments where the mortar thickness was 30mm and 70mm. Comparing the skeleton curves obtained in the tests with the calculation. it is found that the calculated skeleton curve well approximates the 30mm-mortar test results, but the estimation is lower than the 70mm-mortar test results.

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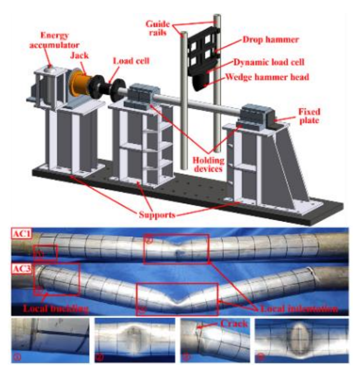
Dynamic response research on axially preloaded aluminum alloy circular tubes under lateral impact loadings

Lingzhao Meng. Harbin Institute of Technology. 19B933045@stu.hit.edu.cn



Aluminum alloy has been widely used in the spatial structures for its advantages of high strength–mass ratio, excellent corrosion resistance, and great durability. However, these aluminum alloy spatial structures are usually regarded as landmark buildings, which are at a high risk of terrorist attacks. Therefore, the dynamic response of the aluminum alloy component utilized in the field of structures subjected to lateral impact loadings attracts more attentions of scholars. In this study, lateral impact tests on 6082-T6 aluminum alloy tubes with circular hollow sections were carried out by employing a drop hammer test system. Especially, the effect of axial force (both axial compression and axial tension) on the dynamic response of the aluminum component was considered. To achieve the stable axial force during the impact process, a system using airbag was proposed. The impact force histories, displacement histories, permanent deformation, and failure modes were obtained from the experimental study. Moreover, the energy transformation between the hammer and the aluminum tube was also obtained and discussed in detail. The test results showed that axial compression is unfavorable to the impact resistance of the aluminum tube.

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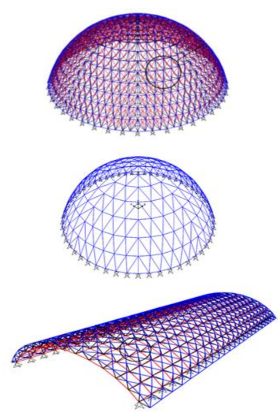
Investigation into the seismic behavior of space structures and extraction of modification factor of seismic responses

Mehdi Poursha. Associate Professor of Structural Engineering, Sahand University of Technology, Tabriz-Iran. poursha@sut.ac.ir

The experience of Kobe earthquake in Japan revealed that the assumption of invulnerability of space structures despite their lightweight, high redundancy and reserve strength, is incorrect. Therefore, particular attention should be paid to analysis and design of this type of structures in seismic zones. For the design aim, due to the nonlinear deformation of structures during an earthquake, calculating the actual displacements of structures and the response modification factor, which shows the inelastic performance of structures, is of special importance. Nevertheless, none of the existing seismic codes provides guidelines for the seismic design of space structures. The objective of this paper is to evaluate and calculate the seismic response modification factors of space structures. For this purpose, the seismic behavior of three types of space structures called single-layer diamatic dome, double-layer diamatic dome, and double-layer barrel vault with different rise-to-span ratios, are investigated. Finally, by extracting the capacity curve of structures with various rise-to-span ratios, the seismic response modification factors are obtained.



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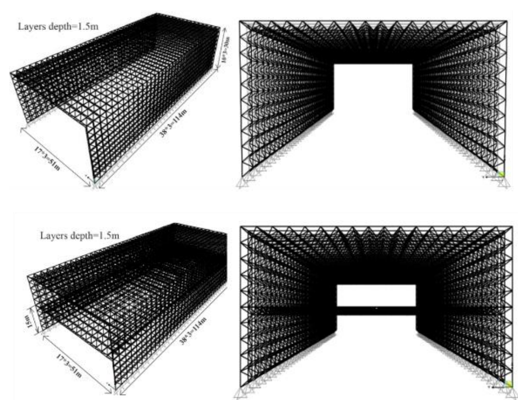
Dynamic instability analysis of industrial buildings with flat double layer grid floors and walls under impact loading

Javad. Shaki Masouleha. Sahand University of Technology. J_shaki97@sut.ac.ir



Space structural systems are suitable option for construction of industrial buildings due to their ability of creating large spaces and also due to their lightness and ease of erection. Flat double layer grids are the most widely used space structural systems for the construction of these buildings. Choosing this type of spatial structures will affect the static and dynamic performance of the building. On the other hand, in most cases, industrial buildings are exposed to impact loads (caused by cranes and industrial machines) and should be analyzed in terms of stability by considering the mass distribution and damping. Therefore, special design criteria should be considered for these structures. In this research, two industrial structures are considered; The first structure has no middle floor and its dynamic stability has been investigated under impact load of the overhead crane. The second structure has been considered under impact load of industrial machines located on its middle floor. Both structures have roof, floors and walls of flat double layer space grids. Static and dynamic nonlinear analysis performed on FEM models of mentioned structures using Abaqus/CAE Software in order to find their static and dynamic critical loads caused by overhead crane and industrial machines. The Budiansky-Roth criteria is considered for detecting unstable state. In various regulations for applying dynamic effects of such impact loads, design recommendations have been proposed in the form of applying dynamic load conversion coefficients to equivalent static loads. According to the results of study for crane loads, the ratios of static to dynamic critical load are different from regulations conversion coefficients. Also, for the load of industrial machinery, the regulations consider a constant coefficient to obtain the static load equivalent to the machinery, but these coefficients are not different by type of impact loads. According to the results of the analysis of this study, the ratios of static to dynamic critical load are different for stepped, rectangular, triangular and sinusoidal loads.

SESSION 49

Thu, 22 Sep.

Parallel Sessions,

14:30-15:30

(60 minutes)

Concepts for Sustainable Innovation in Construction of Timber and Bio-based Spatial Structures -4 (WG12-4)

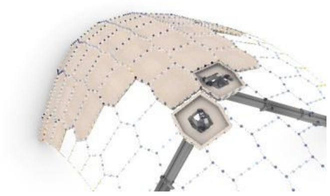
Chair(s): Minjuan He and Cong Zhang

78

Assembly-Oriented Design Methodology for Segmented Timber Shells

Anand Shah. ITECH Master's program. University of Stuttgart.

This research demonstrates a structurally-informed assembly method for the construction process of modular timber structures. Within the context of modular timber structures, segmented timber shells are of great interest for large span applications. These structures predominantly confront external loads through membrane action and therefore have reduced bending moments. During erection of these structures, assembly stages with unfavorable spanning conditions and high bending moments occur. In traditional construction methods, scaffolding is built below the shell structure to stabilize the assembly steps. This temporary reinforcement results in uneconomical, time-consuming and labor-intensive construction. Moreover, they create a congested working space which sometimes results in unsafe working conditions for laborers. The research proposes a design method which reimagines the reciprocity between the design, the on-site robotics and the coordination of the on-site equipment as a structurally-informed design for assembly methodology for segmented timber shell structures. It brings the possibility of supportless assembly and automated erection, while opening up unexplored design possibilities for segmented timber shells.



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Cable-driven self-assembly of elastic grid formworks toward sustainable shell constructions

Lu Xiong. School of Architecture, South China University of Technology.
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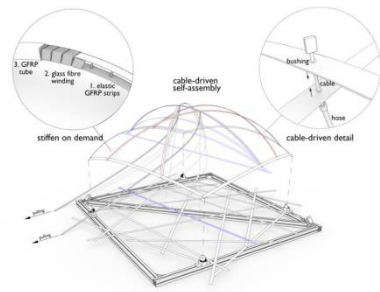
The high cost of the manufacturing of the formworks and scaffolding has burdened the construction of shell structures for years. However, recent advances in digital technology have revolutionized the emerging studies on the elastic geodesic grid shell which traditionally requires lifting equipment and large quantities of scaffolding for erection. Motivated by this concept, we propose an integrated approach toward the design and fabrication of shells along with their formworks. This integration is driven by a two-stage self-assembly procedure of a cable-pulling geodesic grid shell, which could significantly reduce the cost of freeform formworks manufacturing and scaffolding. In the first stage, the weaving strips are placed on the ground in a pre-defined configuration before the erection, with cables going through and connecting corresponding holes. In the second stage, the weaving strips are gradually lifted to the target form by pulling the cable system and eventually stable when the gaps between strips are closed. To avoid unpredictable stress distribution and concentration that occurred in the forming process, we adopt proper layout and pulling order of the strips with synchronized control of the cables. Further, by using a tunable stiffness mechanism with GFRP tubes on-site forming craft involved, we can achieve both the flexible form-finding process and the stiffening of the structure as formworks for a diverse range of shapes and stability of the fabrication process. The approach might offer a new perspective on automation in the construction of shell structures.



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Parametric waffle slabs: Optimal geometry materialized with additive construction

Alexander Curth. Massachusetts Institute of Technology. curth@mit.edu

Many researchers have leveraged digital fabrication to reduce the climate impact of high embodied carbon material use. However, horizontal spanning structures (e.g. roofs and floors) remain challenging with respect to energy intensity and structural mass quantity, and existing low-mass construction systems, such as ribbed or waffle slabs, either require proprietary formwork or are particularly labor/cost intensive. Recent advances in mass customization through digital fabrication have enabled efficient, formwork free methods for concrete construction. This work presents a hybrid design methodology using FEA simulation and closed-form approaches that allow for the shape optimization of two-way ribbed spanning systems in response to spatially varied structural demands. We utilize a LSAM (Large Scale Additive Manufacturing) system paired with a nonplanar toolpath optimization workflow to 3D print lost concrete formwork for a cast-in-place, shape optimized waffle slab. The geometric freedom of additive manufacturing allows for the wide range of void sizes specified by the optimization to be printed without significant increase in labor and material costs. With the simulation approaches outlined here and tests printed with an industry partner (TAM) we show a flexible methodology for widely customizable cast-in-place waffle slabs. This novel construction automation approach is promising for a wide range of construction applications, broadening the scope of what can be printed on site.

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Development of an active bending formwork based on bamboo mortar shells: preliminary results

Qiu Zhang. Zhejiang University - University of Illinois at Urbana Champaign Institute, Zhejiang University, Haining. Zhejiang, PR China. qiu.20@intl.zju.edu.cn

This study sets up to demonstrate the potential of using easy-available Moso bamboo strips to create an active bending spatial concrete shell structure to use as a building roof. The core concept of bending-active structures is to use large elastic deformations of initially straight or planar elements for the construction of complex curved geometries and load-bearing systems. In this study, planar bamboo grids are used to make bamboo grid shell structure systems that are actively bent and used as a framework for a mortar shell. Tensile tests of bamboo strips and compression tests of mortar were performed to evaluate mechanical properties of materials. Four scaled prototypes of the structure were realized to investigate the feasibility of the proposed structural systems, where the mortar was used to replace concrete as roof cover in this preliminary study. Each prototype is obtained by active bending of the gridshell of bamboo strips, covering with a PP geofabric and casting a mortar layer on the top of the PP geofabric layer. The four scaled prototypes are characterized by different spans and by the presence or not of the mortar. Then load-displacement tests on the bamboo grid spatial shells are performed. The span of the shell influences the strength, shorter spans are characterized by higher strength and stronger lateral stiffness. On conclusion, the proposed active-bending structural systems integrate geometry, design, and engineering, it can successfully employ large elastic deformations to achieve curve configuration.

SESSION 50

Thu, 22 Sep.

Parallel Sessions,

14:30-15:30

(60 minutes)

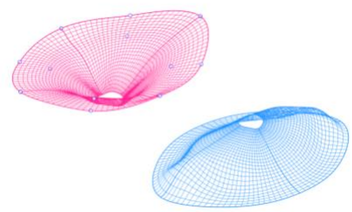
Computational Methods for Membranes and Tensegrity (WG13-7)

Chair(s): Jingyao Zhang and Xian Xu

11

Solving bilinear tensor least squares problems and its application to tension-compression mixed form-finding of membrane shells

Masaaki Miki. the University of Tokyo. masaakim@g.ecc.u-tokyo.ac.jp



Tension-compression mixed shells deserve more attention. In the history of construction, a consistent attention has been paid on optimal forms that stand against gravity by in-plane stresses streaming along the form. Regardless of it was physically found or numerically found, such forms are usually either in pure-compression or in pure-tension. However, there is no fundamental theory contrary to mixing tension and compression in a membrane shell. The bilinear tensor least squares problem is a special type of nonlinear least squares problems. Although it does not seem relevant to architectural design in the first place, the tension-compression mixed formfinding is one of its major applications. This paper overviews the major difficulties one may face when attempting tension-compression mixed form-finding of membrane shells and points out that the difficulty can be avoided by solving the bilinear tensor least squares problem. The computational methods to solve this type of nonlinear least squares problem has been well studied and established already . Among them, the variable projection method is recognized as by-far the best method. The author has developed an interactive user-interface runs on Grasshopper and Rhinoceros, to allow for the user to manipulate a couple of point constraints placed on the shell surface during the optimization process. A couple of simple example problems are introduced and discussed to evaluate the applicability of the method and the user interface to the realistic scenarios in the architectural design.

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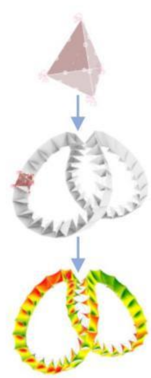
Computational form-finding of a biotensegrity hybrid textile structure

Gabriela Gonzales Allende. College of Architecture and Environment Design, Kent State University. ggonzal6@kent.edu



Hybrid structural systems constitute a broad field that expands design explorations toward non-euclidean geometries with double curved surfaces and lightweight components. The BeTA pavilion is a structural assembly integrating biotensegrity principles with bending-active components. It constitutes a complex hybrid system due to the high interdependence between its components to assemble and achieve the desired force equilibrium and structural stiffness. Thus, textiles are employed as an active structural component rather than a skin, challenging the effective control and prediction of the pavilion's structural behavior and final geometry. This study developed an integrated platform to efficiently approach the design and predict the structural behavior of hybrid textile systems in the BeTA Pavilion. The study concludes that it is feasible to control the global geometry of the structure through the proposed workflow. Also, It has been observed that each new configuration of the knitting influences the elastic properties of the knitted textile from a linear to a nonlinear elasticity behavior parallel and perpendicular to the stitch pattern. Thus, precisely predicting the final global geometry of the structure is still challenging.

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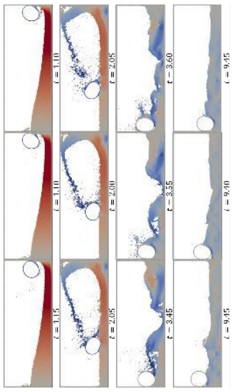
Numerical analysis of interaction between air-inflated membrane and water using MPS method for simulation of an inflatable personal shelter in water disaster

Yota Ohtsuka. The Univ. of Tokyo. yota-otsuka@g.ecc.u-tokyo.ac.jp



This paper reports a numerical analysis model for interaction between air-supported membrane structure and water by MPS method. Under the condition of water disaster, quick evacuation to high places is required. However, considering the difficulty for the vulnerable people, such as elder people, babies and hospitalized patients, to evacuate such places immediately, evacuation destination other than higher places is needed. Kawaguchi et al has been presented a preliminary model of personal tsunami shelter with air-supported inflatable membrane. The shelter has six air tubes in spherical outer membrane, and could be expanded with inflate to the air tubes. When used as a shelter, this shelter will withstand by largely deforming from external force such as water pressure and collision forces, and the deformation causes increasing in internal pressure. Considering it is difficult to prepare an experimental environment of water disaster, numerical approach is efficient for safety confirmation. Numerical methods are needed to calculate considerable fluid-structure interaction and changes of inner pressure of membrane structure caused by large deformation. The MPS (Moving Particle Semi-implicit) method is one of the numerical particle method of incompressible fluid. Because dominant equation is discretized on Lagrange coordinate system, the MPS could solve free surface flow easier than other mesh method in Eulerian coordinate. It has been applied for some Fluid-Structure interaction (FSI) problems such as dambreak problem with elastic wall. In this paper, new MPS model that can take into account the changes in internal air pressure caused by deformation and resulting stress in tension is presented and validated with simple benchmark test. The FSI simulation result of the personal shelter loaded by water pressure and collision forces by the assuming actual water disaster is also reported.

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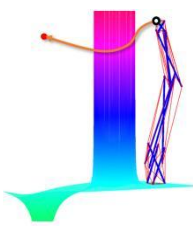
Shape control of tensegrity model mimicking human spine by the potential method

Ikuto Hukumori. Kanazawa Institute of Technology. b1805864@planet.kanazawa-it.ac.jp



In the biomechanics field, tensegrity structures are considered to be similar to the human skeleton and the joint. Therefore, the structures have the potential for flexible shape control like the human body. Oh proposed a bio-tensegrity model that mimics the human spine. This model maintains self-stability and simulates postural changes with muscle and tendon movements. Oh, et al. presented a shape control strategy, which leads to the optimization problem with the lengths of the tensile members corresponding to the muscle and tendon as design variables. This study extends previous shape control methods by incorporating strategies to avoid obstacles. As the methodology, the potential method, which has been applied in robotic engineering, is adopted. This method derives an appropriate path in which the function called potential field finally proceeds towards negative infinity. We analyzed a spinal tensegrity model to consider the mechanism of flexible movement that avoids obstacles like the human body. As a result, it was confirmed that due to the joint deformation and twisting motion, the model could be shifted to the target position without interference from the obstacles and without causing relaxation or yielding of the members.

SESSION 51

Thu, 22 Sep.

Parallel Sessions,

14:30-15:30

(60 minutes)

Innovation in New Concepts and Projects - 3

Chair(s): Jianguo Cai and Yan Lu

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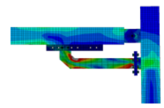
Research on the seismic performance of beam-column joints of a prefabricated steel structure with additional replaceable energy-dissipating elements

Binhui Huang. Department of Structural Engineering, College of Civil Engineering, Tongji University. keyhbh@163.com



In this research, an innovative fabricated steel beam-column joint with energy dissipation elements was proposed. The steel beam was hinged to the steel column by a pin and a connecting plate. An L-shaped steel plate energy dissipation element was installed underneath. One side of the energy dissipation element was rigidly connected to the steel column by a short beam and high-strength bolts, while the other end was connected to the steel beam by a connecting plate and high-strength bolts. The energy dissipation elements and the others exerted yielding strength of 345Mpa. The vertical net distance between the energy dissipating element and the steel beam was constant at 200mm, and the beam and column remained consistent. By altering the thickness and horizontal length of the energy dissipating element, 6 different experimental frameworks were created. Through experimental research and numerical simulations of 6 groups of frames, the strength, stiffness, ductility, hysteresis curve, energy dissipation coefficient, equivalent viscous damping coefficient, and failure mechanisms of the joints were obtained. The results were compared with those of traditional rigid connection beam-column joints. An analysis was also performed of the influence of the ratio of the horizontal length of the energy dissipating element to the span of the beam, and the ratio of linear stiffness between the energy dissipating element and the steel beam on the load-bearing performance of the joint. The results indicated that when the ratio of the linear stiffness of the energy dissipating element to the steel beam was approximately 0.7, the joint conformed to the seismic performance concept in which the energy dissipating element was destroyed first and was thus replaceable. When the ratio of the horizontal length of the energy dissipating element to the span was approximately 0.225, and the ratio of the linear stiffness to the steel beam was approximately 0.7, the load-bearing performance of the joint was close to that of the traditional rigid joint, which was equivalent to the rigid joint of the steel frame.

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Self-stress distribution in large-scale cylindrical tensegrity structure

Tara Habibi. Doctoral assistant. tara.habibi@epfl.ch

Tensegrity structures are spatial, reticulated, and lightweight structures that are composed of struts and cables. Stability is provided by the self-stress state between tensioned and compressed elements. Pure tensegrity structures are composed of straight compression struts only linked with cables. However, there are tensegrity systems that also include struts that are interconnected. Although the form finding of tensegrity structures has attracted a lot of attention, few studies have focused on the implementation of the concept especially on large-scale complex systems. This study explores the design and the self-stress distribution in a large-scale suspended tensegrity structure with interconnected struts. The structure is 6.2m tall and consists of stainless-steel cables and carbon fiber composite tubes. Different stress levels were introduced through cable tensioners integrated into the system and the self-stress distributions were investigated experimentally. The study revealed that the effective prestress levels were different from the nominal prestress levels since the cable-by-cable prestressing process had only local effects on the structure, i.e., the changes in the stress distribution were limited to the prestressed cable in question and cables above and below that.

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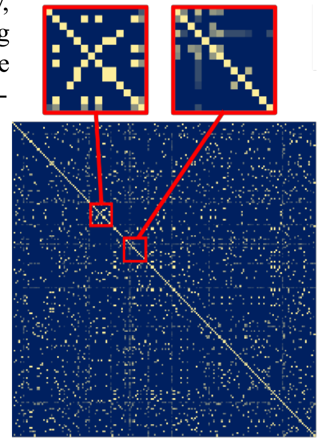
Bridging scientific and artistic thinking through an algorithmic eulogy of Heinz Isler

Vincent Kuo. Aalto University. vincent.kuo@aalto.fi



Combining “scientific” and “artistic” modes of thinking can stimulate multidisciplinary creativity, with compelling evidence from psychology, cognitive and social sciences. Building on our existing research on artificial intelligence in civil engineering, this project aims to computationally generate a “eulogy” of Heinz Isler, as an emotive expression that can appeal to the intuition of the non-specialist. To do so, natural language processing and graphing algorithms are applied to the article abstract texts of the IASS journal special issue on Heinz Isler (2011, vol. 52, no. 3 September n.169). We observe that, without any predefined keywords or ontologies, our method can effectively distil the important topics and their relationships describing Isler’s legacy. For instance, the algorithm can readily identify links between Isler and "natural laws", "form-finding", "concrete shells", forming a semantic network. Based on the data outputs, a variety of data visualizations are generated, with varying levels of insight and aesthetics. We discuss the importance of knowledge representations intuitive to non-specialists, the roles that “art” can play, and the far-reaching implications of multidisciplinary thinking within IASS and beyond.

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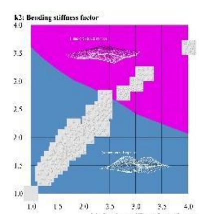
Deployable Polyhedral Structure with Snap-through Behavior Induced by Dimples on Metal Panels

Hirotaka Ujioka. Graph Studio Inc. hirotakaujioka@gmail.com



Non-rigid-foldable structures, such as closed polyhedra, could potentially offer more versatile usage than the rigid-foldable ones. Specific non-rigid-foldable structures require snap-through phenomena for their expanding and folding performance. Snap-through type deployable structures (snapping-structures) are multi-stable. They lock in place after deployment and their expanded form achieves state equilibrium. Conventional design approach utilizes smooth flat plates. In this paper, we found that we can induce the snap-through behavior of deployable structures by embossing patterns on metal sheets that we call “dimples" on the panels. Conducting structural analysis of snapping-structures, there are two domain buckling modes -snap-through mode and Euler’s buckling-like bifurcation mode. In the case of increase of size of the structure and decrease of panels thickness, the bifurcation buckling mode tends to become dominant. Snap-through mode is mainly dependent on in-plane stiffness of panels, which decreases with introduction of dimples, while bifurcation mode is mainly dependent on bending stiffness of panels, which increases due to the dimples. As a result, the effect of the dimples makes snap-through behavior dominant buckling mode. This means that dimples have the effect of inducing snap-through behavior. It is expected that the results of this research will be applied to the design of large-scale snap-through type deployable structures consisting of lightweight panels.

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Xiaoqun Luo
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Minger Wu
Yue Wu
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10 Organizers and Sponsors

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Faculty of Architecture, Civil and Transportation Engineering, Beijing university of technology

In April 2020, the Faculty of Architecture, Civil and Transportation Engineering (FACTE) was put into operation. FACTE offers three first-level PhD programs in civil engineering, transportation engineering, and urban and rural planning, and two first-level graduate programs in water engineering and architecture. The Discipline of Civil Engineering, the Discipline of Transportation Engineering, and the Discipline of Urban and Rural Planning were established in 1960, 1979, and 2002, respectively. In 2017, the discipline groups of Modern Urban Construction and Environmental Engineering, with Civil Engineering and Transportation Engineering as the core disciplines, officially made it onto the list of national first-class disciplines.

There are 328 full-time faculty members in FACTE, including 109 full-time professors. Among them, there are three full-time academicians of the Chinese Academy of Engineering, one academician of an overseas engineering academy, seven high-end national talent including winners of the National Outstanding Youth Fund, thirteen national outstanding young talent, three Beijing scholars, two recipients of the Beijing Youth Medal, seven from the New Century Hundred-Thousand-Ten Thousand Talents Project, four prominent Beijing teachers (including one outstanding young teacher), etc. In addition, FACTE has one innovative research group under the National Natural Science Foundation of China, two innovation teams under the Ministry of Education and eleven academic innovation teams in Beijing.

There are three colleges, six departments, 14 research institutes and 3 lab centers under FACTE. In addition, it has two state-level teaching bases, one state key laboratory training base jointly built by the Beijing municipal government and the Ministry of Education, one key laboratory of the Ministry of Education, four Beijing key laboratories, one Beijing collaborative innovation center, three Beijing engineering research centers, two Beijing international science and technology cooperation bases, and one industry key laboratory. Over the past ten years, FACTE has completed or is undertaking more than 40 major and key national projects and more than 210 national projects, such as the General Program of the National Natural Science Foundation of China, with an average annual funding of more than 100 million yuan. It has been granted six national science and technology progress awards for its research achievements over the past decade. FACTE offers nine undergraduate programs, namely Civil Engineering, Intelligent Construction, Water Supply and Drainage Science and Engineering, Building Environment and Energy Application Engineering, Traffic Engineering, Transportation Equipment and Control Engineering, Architecture, Urban and Rural Planning, and Landscape Architecture. Since the Ministry of Education launched the "Double Ten Thousand Plan" for the establishment of first-class undergraduate programs in 2019, five programs (Civil Engineering, Traffic Engineering, Architecture, Building Environment and Energy Application Engineering, Water Supply and Drainage) in FACTE have been approved as national first-class undergraduate programs, and one program (Urban and Rural Planning) has been approved as a first-class undergraduate program in Beijing. FACTE's Civil Engineering undergraduate program has been selected as a key first-class program among Beijing universities, and its Architecture program has been listed as a featured program by the Ministry of Education. In the past ten years, FACTE has turned out more than 2,500 graduates, 500 PhDs and 3,500 undergraduates.

Association for Spatial Structures of China Steel Construction Society

China Association for Spatial Structures (CASS) of China Steel Construction Society was established in November 1993 as a national professional society in the spatial structure industry. Currently, it contains more than 550 company members, including the production and installation companies of grid structures, cable structures and membrane structures, as well as relevant companies, institutes and colleges engaged in the design and analysis of spatial structures.

CASS has been developing continuously since its establishment and has become a social organization in the Chinese spatial structure industry, and many of us are experts, university professors, senior engineers, senior managers and technicians.

With the sole purpose of serving its members, CASS actively carries out the following works:

(1) Organize technical exchange conferences. Based on the needs of industrial development, CASS holds technical exchange conferences and technical seminars on grid structures, membrane structures, and cable structures biannually to share scientific and technological achievements and advanced experience in design, production and scientific research. It also actively carries out international exchange activities and invites renowned scholars as keynote speakers at international conferences.

(2) Manage and promote the technological progress of the industry. CASS has organized the compilation of industry standards, i.e. “Technical specification for space frame structures”, “Technical specification for membrane structures”, and “Coated fabrics for membrane structures”. CASS actively carries out the development, research, extension and training of new products and technologies for spatial structures. At the same time, it also organizes the evaluation and training of workers to strengthen their professional skills.

(3) Carry out the evaluation and nomination of the “Spatial Structure Award” and the publication of “Compilation of excellent large span spatial structure engineering”, which has established excellent samples of engineering and improved the design and construction of spatial structures.

(4) Strengthens communication and coordination with relevant government departments, provides technical consultation and helps its members to solve practical problems.

(5) Promote the application of spatial structures through the China Association on Spatial Structure website (www.cncscs.org/kjjg) and publishes a “Newsletter of Spatial Structure” with the Association for Bridge and structures engineering.

(6) Build and expand the network through the construction industry and attract related companies and institutions to join our membership.

China Academy of Building Research

Founded in 1953, China Academy of Building Research (CABR) used to be affiliated to the Ministry of Construction. Since the year 2000, it has transferred from a public research institution into a technology-based enterprise, affiliated to the State-owned Assets Supervision and Administration Commission of the State Council (SASAC). CABR is now the largest comprehensive R&D institution in the building industry of China.

● Achievements of R&D

CABR has always taken it as its own task to promote the scientific and technological progress of China's building industry and actively carried out many national key projects, including "973" and "863" Hi-tech projects, science and technology support programs and international cooperation projects, as well as other scientific research programs assigned to it by Ministry of Housing and Urban-Rural Development, Beijing Municipality and other municipalities and provinces.

● Standards and Codes

CABR has been responsible for the development of total 900 plus plus construction standards and codes relating to building structure, foundation, engineering disaster prevention, building environment and energy efficiency, building material, and construction machinery and equipment. In recent years, CABR has also taken charge of the formulation of many standards and codes in the emerging fields such as green building, building information model and building industrialization.

● Major Laboratories

(1) Building environment and energy efficiency
(2) Engineering disaster prevention and mitigation
(3) Engineering structure
(4) Soil & foundation
(5) Construction machinery
(6) Building material

● Lines of Business

/Quality supervision and Inspection of Projects and Products
/Building Environment and Energy Efficiency
/Engineering Disaster Prevention/Engineering Structures
/Soil & Foundation /Engineering Software Technology /Construction Machinery
/Building Materials /Building Design, Planning and Survey /General Contracting of Projects /Special Contracting of Projects
......

School of Civil Engineering (SCE) at Chongqing University

The school of Civil Engineering (SCE) at Chongqing University, ranked top 4 in the subject Civil Engineering in mainland China in 2022 evaluated by ARWU, and was elected as the first-rate subject of the “Double First-rate” Project in 2021, academician Xuhong ZHOU, academician Yeong-Bin YANG, and academician Yukio TAMURA are the academic leaders. SCE is one of the largest and most nationwide recognized schools of Chongqing University.

SCE consists of 4 advisory & decision-making organizations, 8 teaching & research institutions, 9 Research institution, 1 self-organizing body (the Research Center), 2 support & service organizations. Up to September 2022, SCE has 283 faculty and staff; 214 among them are taking teaching positions, including 84 professors, 76 associate professors, and so forth. There are 43 national-level talents such as CAE academicians and 60 provincial and ministerial talents in the faculty formation. SCE offers 5 undergraduate programs, 2 master’s programs, and 2 doctoral programs with 7 sub-disciplines. There are more than 3,500 SCE students on campus, including undergraduates, post-graduates, and doctoral candidates.

SCE offers five undergraduate programs, including Civil Engineering, Building Environment & Energy Application Engineering, Urban Underground Space Engineering, Surveying & Mapping Engineering, and Intelligent Construction. It has first-level disciplines doctoral and master's programs in Civil Engineering; a doctoral program in Civil & Hydraulic Engineering (Energy & Environmental Protection, and Advanced Manufacturing); a master’s program in Civil & Hydraulic Engineering (Architectural & Civil Engineering); and it has seven sub-disciplines - Geotechnical Engineering, Structural Engineering, Heating, Gas Supply, Ventilation, and Air Conditioning Engineering, Disaster Prevention and Reduction Engineering and Protection Engineering, Road and Bridge Engineering, Engineering Construction and Management, and Intelligent Geomatics of Civil Engineering. Currently, SCE has more than 3,500 students on campus, including undergraduates, post-graduates, and doctoral candidates.

Introduction of HIT

Harbin Institute of Technology (HIT) was established in 1920 in Harbin, Heilongjiang, China. In 1954, HIT became one of China's first six leading universities. Presently HIT is a member of China's top nine University Union (C9). It is a National Key University with science and engineering as its core and has developed with management, liberal arts, economy, law and other disciplines. Renowned as "the cradle of engineers," the university has many firsts. HIT established the first School of Astronautics in China. It was the first Chinese university to independently develop and enter small satellites (smallsats and microsats) into the moon's orbit. HIT was also the first to achieve satellite ground laser communication link communications. Additionally, HIT developed the first computer to play chess and talk with people and it is the first university to produce arc- and spot welding robots. HIT was the first university to reveal the virulent factor of the HIV virus. It was also the first university to achieve a major breakthrough in supporting structure development for the largest radio telescopes. The first human–machine in orbit maintenance experiments on a space operator was also developed by HIT.

At HIT, there are 23 schools, 86 undergraduate programs, 9 National Key Disciplines, 7 National Key Labs, and 39 members of the prestigious Chinese Academy of Sciences and Chinese Academy of Engineering. Eleven disciplines of HIT are ranked among the top 1% on the Essential Science Indicators (ESI) lists. The material science and computer science of HIT in particular are ranked among the top 1‰, and engineering discipline ranked among the top 1‱. In 2020, HIT ranked 6th on the list of the best global universities for engineering announced by the U.S. News & World Report. Since its beginning, HIT has always had a strong international environment. Now HIT has signed academic cooperation agreements with 278 universities in 39 countries. These collaborations include student and faculty exchange programs, joint academic conferences, and scientific research cooperation. Together with Weihai campus and Shenzhen campus, HIT forms the pattern of "One University, Three Campuses." HIT is steadily moving towards the goal of becoming a world-class university.

The School of Civil Engineering was one of the earliest established disciplines in HIT. In 1950, the first batch of programs of Industry and Civil Architecture in China was established. In 1952, postgraduate students entered the contemporary leading programs in Structural Engineering. The school was authorized to grant doctoral degree in Engineering Mechanics and Structural Engineering in 1981 and 1986 respectively. The two primary disciplines, Civil Engineering and Mechanics, enjoy great reputation across the country and respective post-doctoral research stations. In 2001, the discipline of Structural Engineering became the national key discipline. In 2002, the discipline of Engineering Mechanics became the national defense key discipline. As a whole, the programs of civil engineering and mechanics are ranked the third in both research progress and graduate education in China. Currently, there are 160 faculty members. In particular, there are four academicians of the Chinese Academy of Engineering. At present, a total of 1,630 students are enrolled in the school, including 920 undergraduate students, 420 master students, 290 doctoral students, 90 international students and 120 post-doctoral fellows.

Tianjin University

Tianjin University, founded on October 2nd, 1895, is a national key university under the Ministry of Education of China and the first modern university of China. School of Civil Engineering has three first-level programs: civil engineering, hydraulic engineering, and marine and ocean engineering. All three programs have a long history of education and a profound academic heritage. They have owned a high academic reputation at home and abroad. They are among the top national disciplines of China and the traditional superiority disciplines of Tianjin University.

The Department of Civil Engineering of Tianjin University is one of four founding departments of Peiyang University (predecessor of Tianjin University). It has a long history of education and profound academic accumulation. It has always won a high international academic reputation. The civil engineering program of Tianjin University has been supported by many governmental projects, such as a key construction discipline under the national "985 project" and "211 project", a key discipline of the Ministry of Education of China, a key discipline and brand major of Tianjin. It is in the first group of doctoral and master's degree-granting units of the State Council Academic Degrees Committee. The program has a post-doctoral research station of civil engineering. Under the first-level discipline of civil engineering of Tianjin University, there are four second-level disciplines including structural engineering program, geotechnical engineering program, disaster prevention and mitigation and protection engineering program, and bridge and tunnel engineering program. The four programs develop synergistically. The Program has a group of excellent faculty. There are 95 full-time academic staffs in the program.

The Civil Engineering Program has 12 research platforms, such as National Facility for Earthquake Engineering Simulation (NFEES), the Key Laboratory of Coastal Civil Engineering Structure Safety of Ministry of Education of China, and Overseas Expertise Introduction Project for Discipline Innovation of Earthquake Engineering Comprehensive Simulation. In the past five years, the department has received 100 plus national-level scientific research projects, more than 100 provincial-level scientific research projects and more than 400 major projects. The department published more than 600 journal articles and participated in the compilation of more than 20 standards. The department also was awarded with one national first prize for scientific and technological progress, and 10 plus provincial and ministerial scientific and technological progress awards.

Focusing on the major strategic needs of national, industry and regional developments, the program closely focuses on the economic and social development of the Bohai Rim region and the major needs of the development and opening up of the Binhai New District. The Program takes the advantages of the Program, strengthens basic research in civil engineering and cross-disciplinary fields, and pays attention to the fundamental research. Theoretical research and applied technology research are combined and distinctive innovations are conducted in the frontier direction of high-performance civil engineering structural disaster-resistance system and seismic and anti-explosion safety, advanced construction and safety of geotechnical and underground engineering, and high-performance materials and structural systems. The research achievements are incorporated into the main standards of the country and industry, and they are widely used in major projects, key projects and infrastructure constructions such as large-span stadiums, transportation hub facilities, exhibition and people's livelihood projects.

Tongji University

Tongji University, one of China's earliest national key universities, is a prestigious institution of higher education which is directly under the Ministry of Education (MOE) and is supported by the Shanghai Municipality. Already in its second centenary, the University has grown into a comprehensive and research-intensive university with distinctive features and an international reputation. The University was among the 36 Class A universities in the list of Double First Class University Plan released by the central government of China in 2017. According to 2019 Global Universities Rankings by US News & World Report, Tongji University ranks 11th in Country Rank of China and 35th in Best Global Universities in Asia.

The University has always placed nurturing talents of the highest quality as its fundamental responsibility. The three-dimensional KAP educational principles of "Knowledge, Ability, and Personality" are deeply rooted in the undergraduate education and reinforced at the graduate level of education, aiming to ensure that every student has "a solid foundation, practical ability, creativity, global vision, and a sense of social responsibility" in order to become "the top talent who will lead sustainable development and act as the backbone of society." Among over 300,000 graduates of the University since its founding, many are extraordinary political leaders, scientists, educators, social activists, business leaders, medical specialists, and engineering experts. Over 150 alumni are members of the Chinese Academy of Sciences and the Chinese Academy of Engineering.

The University has provided strong technical support to some significant national strategies, including but not restrict to the Belt and Road Initiative, the fields of bridges and tunnels, railway and urban traffic, urban sewage treatment, earthquake relief work. The economic development initiative around Tongji Campus launched jointly by the local government and Tongji proved a tremendous success.

The University has always taken an active role in expanding international cooperation. With close historical ties with Germany, it partners mainly with European universities, but is also actively expanding its influence to North America, Asia and Africa. So far, it has established 11 international cooperation platforms in partnership with Germany, France, Italy, Finland, Spain and United Nations agencies. The University has also signed memorandum of understanding with over 200 international universities and co-founded research centers with Volkswagen, Siemens, Bayer, IBM and many other multinational enterprises.

Over the years, the people of Tongji have adhered to its aspirations of "serving the people and the world with one heart, on the same boat, and with the responsibility of rejuvenating the Chinese nation." With full enthusiasm, Tongji University will continue to develop and work together to create a world-class university.

Space Structures Research Center of Zhejiang University

The Space Structures Research Center of Zhejiang University is one of the earliest research institutions for space structures in China. The founding director of the center is prof. Shilin Dong who is a fellow of Chinese Academy of Engineering. The current director of the center is prof. Yaozhi Luo who was granted the Chinese National Natural Science Fund for Distinguished Young Scholars and won the first prize of Chinese National Science and Technology Progress Award. The center has 14 faculties which includes 7 full professors, 4 associate professors and 3 assistant professors. All the faculties of the center have oversea study/research experience and they have cooperated with a number of research teams from world-class universities such as Harvard University, Oxford University, Cambridge University, University of Illinois at Urbana-Champ, Georgia Institute of Technology, University of Maryland, North Carolina State University and so on.

The researches of the center mainly focus on new systems and new methods in space structures, structural health monitoring and control, and deployable/retractable structures. The center has produced a large number of postgraduates in the area of space structures. At present there are more than 80 postgraduate students studying in the center. The center is the founder of the Chinese academic journal "Spatial Structures", and is also the host of the "National & Local Joint Engineering Research Center for Design & Construction Technology of Advanced Structures" and the "Key laboratory of Space Structures of Zhejiang Province". In the last decade, the faculties have received more than 60 national or provincial research grants which include National Natural Science Fund, National Science and Technology Research and Support Program, National Key R&D Program of China, and so on.

The center also emphasizes on technology development and practical application, and has provided solutions for a number of engineering problems raised in the design, construction and operation of large-scale space structures. The research results of the center and the technologies developed by the center have applied to hundreds of large-scale and complex buildings which include National Theatre, National Aquatics Center, National Stadium, Terminal 3 of Beijing International Airport, Axis of World Expo 2010 Shanghai, UK Pavilion of World Expo 2010 Shanghai, Ji'nan Olympic Sports Center Stadium, Beijing North Train Station, New Shengzhen North Train Station, Tianjing West Train Station, Xiamen West Train Station, Hangzhou East Train Station, Hanghzhou Olympic Center and so on. Due to its distinguished contributions in science and technology of space structures, the center has received 19 scientific and technological awards which include National Scientific and Technological Progress Awards, Provincial Scientific and Technological Progress Awards, Engineering Science and Technology Innovation Award of Beijing Olympic Games, Zhejiang Province Science and Technology Major Contribution Award, Zhan Tianyou Civil Engineering Award et al.

Introduction to the Journal of *Building Structure*

Founded in 1971, *Building Structure* is jointly sponsored by China Construction Technology Consulting Co., Ltd. Yatai Construction Science & Technology Consulting Institute Co., Ltd., (Former Ministry of Construction Science and Technology Information Research Institute) and China Civil Engineering Society. The reporting content is characterized by scientific, practical, systematic, oriented and informative. *Building Structure* always sticks to the original intention of establishing a journal of "facing national economic construction, flourishing construction science and technology, promoting the progress of Chinese building technology". It will continue to focus on the frontier of science and technology, the main battlefield of the economy, major national needs, and the safety of people's lives. It will give priority to the quality of content, and take it as the duty to disseminate advanced architectural structure technology. With the support and love of colleagues in the industry, through the continuous efforts of several generations, *Building Structure* has gradually built a platform integrating science and technology communication and media, which integrates journals, new media matrix, brand activities and industry research, and constantly contributes its own strength to the development of the industry.

Building Structure has been ranked among the top The Core Journal of China, and its circulation has always been among the top of similar journals. Nearly 140 experts, including 16 Academicians of Chinese Academy of Engineering and 22 National Masters of Engineering Survey and Design, constitute the editorial board team with careful guidance and care, which provides strong support for the improvement of the academic level of *Building Structure*. A team of more than 300 experts in the industry strictly reviewed and supported the publication, providing a strong guarantee for the high-quality publication of *Building Structure*.

Building Structure actively responds to the call of the government, closely conforms to the needs of the Ministry of Housing and Urban-Rural Development and the industry in its content publication, theme planning and invitation for manuscripts, and pays close attention to the hot and difficult issues in the industry, editing and publishing technical topics and major engineering projects, such as subjects of 70 years of development achievements in building structure industry, prefabricated building structure, seismic isolation and energy-dissipated technology, reinforcement and reconstruction, Beijing World Horticultural Expo theme, Beijing New Airport theme, Shanghai Center theme, Xiong'an Railway Station theme, etc., to report advanced engineering technology and excellent engineering experience and promote the high-quality development of engineering construction industry.

Building Structure sponsors or organizes more than 10 high-end academic activities nationwide, aiming at the hot issues concerned by the majority of engineers and researchers. Among them, the " National Building Structure Technology Exchange Conference" has been held for the eighth time, with more than 1,000 participants. Online live streaming platforms - "Structural Engineers Voice" and "Youth Structural Engineer Voice" have held nearly 40 consecutive events since their launch in 2020. In particular, international conferences have been held successively in recent years, such as the 15th International Conference on Wind Engineering (ICWE15) and the 14th International Symposium on Structural Engineering (ISSE14), which have promoted international technical exchanges. High-quality offline and online academic activities build a platform for technical exchange, which is conducive to promoting technological progress.

The 8th National Building Structure Technology Exchange Conference

The 15th International Conference on Wind Engineering (ICWE15)

In addition to traditional paper media and professional and technical exchange forums, *building structure* keeps pace with the times, and the new media matrix has also formed brand influence. Since the beginning of 2011, *building structure* has opened a micro blog to closely follow the development of the industry and release one piece of professional information every day. now *building structure* has nearly 70,000 fans. Opened in january 2013, the *building structure* WeChat (WeChat id: buildingstructure) has nearly 370,000 + followers and 3 to 4 professional information every day. *Building structure* has also opened several short video and information websites, such as douyin (chinese version of tik tok), wechat video, weibo video and toutiao.com, to present professional contents in different ways.

Building Structure WeChat

Tongzheng Aluminium Structure Construction Technology (Shanghai) Co,.LTD

Shanghai Tongzheng Committed to providing customers with one step solution in new form of large-span structures and complex façade system. We offer full-industry chain services through R&D, design, manufacturing, construction and installation, together with full-life cycle operation and maintenance. Our global headquarters located at Hongqiao CBD, also set up regional branch of the Guangdong, Hong Kong and Macao Greater Bay Area at Guangdong. In Kunshan, Jiangsu, the fully digitalized and intelligent manufacturing center, continuously producing aluminium structure and complex façade, with the support of our R&D testing center of advanced material and new structure form.

After more than ten years of innovation and development, Shanghai Tongzheng has formed three major brands as Tongzheng Aluminum Structure, Tongzheng Complex Façade System, and Tongzheng New Structure under three high-tech enterprises. As a pioneer of the industry, we keep emphasizing product R&D and technological innovations. More than 100 invention and patents has been obtained through the practice. It also has participated in more than 30 provincial and ministerial scientific research projects, joined in the compilation of 19 national, local and industry standards, published more than 100 papers, and won the provincial and ministerial level scientific and technological progress awards and dozens of other awards at all levels. And constructed of 2 provincial and ministerial level technology centers.

The company has the first-class qualification for steel structure and the first-class curtain wall design, first-class curtain wall and general contracting qualification issued by the Ministry of Construction. Adhering to the concept of "Transforming Product & Technology into artwork", the company actively promotes the global development of digital construction technology and low-carbon energy-saving buildings under the guidance of the values of professionalism, innovation and excellence.

The company's aluminum structure, complex façade system, and new large-span structure products have been widely used in national landmark construction projects, for example, Beijing Daxing International Airport Terminal, Nanjing Usnisa Palace, Shanghai G60 Science and Technology Cloud Gallery, Nanjing Garden Expo – Future Garden, Shanghai World Expo Park - Botanic Gardens, WLF permanent site and other numbers of major civic projects with success award of the Luban Award, the Zhan Tianyou Award, the Golden Steel Award and other awards .

About Jinda

Jinda was founded in 1981. In the past four decades, we are dedicated to the manufacture and innovations of technical tech-textiles. Jinda always stands at the forefront of the coating fabric industry in China.

Jinda knife coated fabrics are widely used in membrane-structured construction materials, tents, side curtain, inflation formation materials, truck covers, advertising materials and marine development. These fabrics are featured with high-strength, bacteria-resistant, flame resistance, environmental-friendly, aging-resistant performance, that meeting international standards.

Jinda has set up “Jinda High-Tech Research and Development Center for High-performance Textile Coated Composite Material”, which has a professional R & D team and a complete set of supporting experimental testing equipment. Jinda has invested 20 million yuan in research and equipment development successively. Meanwhile, the long-term and stable research cooperation with industry-university ensures the improvement and innovation of the new products.

Jinda always stands at the forefront of the industry. The advanced woven machines and coating machines are imported much earlier than the other counterparts. The skillful and superior coating technology ensures the stable and valuable product for our customers.

PVC architecture membrane, as an important element of membrane structure, is widely used as a kind of the flexible construction materials. Jinda imports the fluorine polymers lacquer from Germany to make the fabrics in achieving excellent weather-ability and fouling resistance, blocking the migration of plasticizer effectively and anti-UV, thus greatly extending the durability of membrane material. It is mainly used in stadium, exhibition, shopping center, airport and another large public facilities.

HONTEX
浙江宏泰

HONTEX Profile

Zhejiang Hontex New Materials Co., Ltd. since its establishment in 2014, has firmly taken science technology as the primary productivity, talents as the innovation driving force, products as the core competitiveness, services as the brand influence. Adhering to the concept of "Quality casts Hontex , Service wins the market", we provide membrane solutions to more than 100 clients from more than 20 countries around the world.

In 2015, Hontex invested Ten millions of USD introduced full set of Knife Over Roll Coating production lines and industrial computer servers from Europe, creatively developed advanced biaxial PRESET technology to set up the world's most advanced and intelligent membrane coating processing facility. In the process of production, the coating line can control and adjust the tension in the direction of 0 and 90 degree in live time, which greatly improves the mechanical properties of the membrane.

A sound quality traceability system ensures the quality of products and continuously expands Hontex brand influence. Once the production process standards are set, Hontex Staff will spare no effort to adhere to them.

Provide global customers with high quality, professional and efficient segmentation solutions, double win with customers and create maximum value for clients. This is who we are, this is Hontex Corporation.

Zhejiang Hontex New Materials Co., Ltd. Add: No.56, Fenghuang Road,
Dingqiao Haining, Zhejiang 314413, China

GUIZHOU WIRE ROPE COMPANY PROFILE

Guizhou Wire Rope Incorporated Company is one of the largest enterprises specialized in producing steel wire rope in China. It is located in Zunyi city. It was in the shanghai stock exchange market. The main machines were imported from Germany, Japan and Italy. And the main products are steel wire rope, PC strand and steel wire. The capacity is 350,000 metric tons every year.

With more than 40 years' producing and technique experience, the enterprise has excellent production machine, advanced production technique and perfect Quality control system. The enterprise can all kinds of structure wire rope, PC strand, sales steel wire and pre-stressed wire rope, PVC coated wire rope and wire rope sling. The enterprise has superiority in production for the extra diameter, extra length, special structure and special use wire rope. The "JULONG" brand round strand, shaped strand, linear contact and facial contact etc bright and galvanized steel wire rope, galvanized spiral strand, PC strand, Bead wire, spring wire and ACSR wire etc. products has been used widely in Mining, oil, transport, bridge, Oceanographic engineering, port machine and military etc. Some high difficulty products has been used in Ge Zhou Dam hydro-junction project, Three Gorges power plant, Bao steel, Guangzhou humen bridge, Baling river bridge, Huatianlong large-scale fishing crane ship, Antaibao mining, Guangzhou international convention center, Space engineering, Marine oil drilling and Famous tourist area manned rope way etc. The products has been exported to USA, UK, Canada, Australia, Demark, Netherlands, Singapore and Middle East etc. countries and area according to the advanced international standard.

"Quality is life" is the policy of the enterprise. With technique development, the enterprise improves the quality and meets the requirement of the customer. The customers satisfy the quality of the products for many years. The "JULONG" brand is Chinese National Famous Brand. The "JULONG" brand steel wire rope is Chinese top brand products and has become customer satisfied products for 5 times. The enterprise has got certificated by quality associations such as CCS, LR, DNV, BV, GL, KR, API, ISO9001, ISO10012, ISO14001 and GB/T28001.

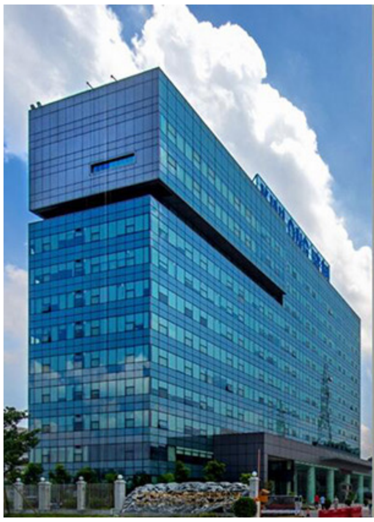
The promise of all the employees of the enterprise is that we will make our best to meet the customer's requirement and get the development during the cooperation with the customer

GUANGDONG KIN LONG HARDWARE PRODUCTS CO., LTD.

Kinlong was established in 2003 and is a company offering services in terms of design and research, manufacturing and sales of construction and building accessories products. We are committed to provide high-quality products and services. After years of development, Kinlong has become a reputable brand in the construction industry.

Kinlong focuses on providing supply of integrated construction and building accessories and diversified products. In addition to the one stop service model, the demand of customers can be fully satisfied. Kinlong embraces the philosophy of “Unique value is created by professionalism, but no future shall be created by speculation”. This has made Kinlong standing on the leading position in construction hardware market.

Kinlong has honorably contributed its excellence in the construction of many famous buildings and benchmark projects. These achievements bring encouragement and pride to everyone in Kinlong .To every designer, engineer and company committed in construction industry, Kinlong is always the most trustworthy and reliable partner.



Vector Foiltec

Vector Foiltec designed, manufactured and installed the first ETFE cladding system in 1982 and has retained the position as world market leader in this field.

We are Worldmarket Leader

We currently manufacture our product under the trademark of Texlon® and operate two high capacity production facilities in Germany and China. Vector Foiltec holds the world’s most comprehensive body of ETFE related research data and continues to bring new and innovative products to the market. We are proud of our consistent track record in the delivery of elegant and cost **effective engineering solutions to meet our client’s many varied and often complex needs.**

We are Setting Standards in Industry

We have eighteen offices around the world and have to date delivered successful projects in over one hundred different countries. Vector Foiltec continues to maintain and develop an in-house multidisciplinary team, which is the key factor to our success, enabling us to resolve complex integrated design problems quickly and efficiently and deliver a specialised production, installation and after sales service.

Serge Ferrari
group

Serge Ferrari Group designs, develops and manufactures innovative composite materials for lightweight architecture and outdoor equipment applications.

www.sergeferrari.com

Info@sergeferrari.com.cn

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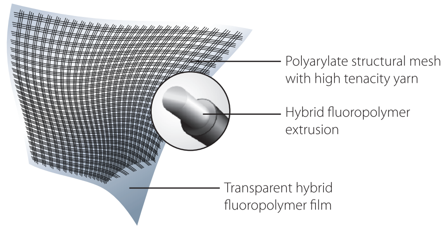

INDOOR PROTECTION

OUTDOOR FEELING

11 Photo Album of Participants

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