Proceedings of the

24th Young Researchers Conference

15 March 2022

The Institution of
StructuralEngineers

Contents

Synopses

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Conference Programme 2022

Time	Activity	Persons
13:00	Institution Welcome	Leroy Gardner, Chair of the Research Panel, Imperial College London
13:05	Keynote address	Dr Mariapia Angelino, WSP
Session 1		
13:35	*Research presentation 1 - Mechanical performance of composite column connections with extended blind-bolt under shear loads*	Partha Pratim Debnath, The Hong Kong Polytechnic University
13:50	*Research presentation 2 – Rework and Its Impact on Engineering Productivity in Building Design: A Design Research Analysis*	Yvonne Y.B Wong, Singapore University of Technology and Design
14:05	*Research presentation 3 – Strategies for low carbon data-driven structural design*	Sandie Kate Fenton, Cergy Paris University/Vrij Universiteit Brussel
14:20	Research presentation 4 - Structural behaviour and design criteria of segmental high-speed railway bridges	Javier Cañada Pérez-Sala, Imperial College London
14:35	Break	
Session 2		
14:45	*Research presentation 5 – Behaviour of the Masonry Arch Bridge Under Foundation Movement*	Ahmed Naggasa, University of Salford
15:00	*Research presentation 6 – Enhancing the robustness of PBBS precast concrete systems*	Kamil Riedel, Imperial College London
15:15	*Research presentation 7 - Smart Net-Zero Energy Structural Control*	Lefteris Koutsoulakas, University of Leeds
15:30	Research presentation 8 - Additively manufactured stainless steel corrugated shells: shape optimisation and experimental validation	Ruizhi Zhang, Imperial College London
15:45	Research into Practice Case Study Competition winner – Presentation	Dr Smail Kechidi
16:00	Certificates, prize giving	
16:15	Networking	

To note: each presentation is 10 minutes with a 5 minute Q&A

Poster presentations

Structural-acoustic optimization of concrete floors (Synopsis no. 2)
Jonathan Broyles – The Pennsylvania State University

Fire Analysis of Cross-Laminated Timber (CLT) Wall Panels (Synopsis no. 3)
Muhammad Yasir – Munster Technological University

Experimental Analysis of Blind Bolted Connections in Concrete-filled Tubular Columns (Synopsis no. 4)
Manuela Cabrera – University of Nottingham

Experimental investigation on axial compressive behaviour of novel FRP-ECC-HSC composite stub column (Synopsis no. 5)
Shuai Li – The Hong Kong Polytechnic University

The role of vertical extensions in decarbonising the built environment (Synopsis no. 10)
Charles Gillott – University of Sheffield

Bipedal inverted pendulum for modelling vertical pedestrian-structure interaction on footbridges (Synopsis no. 13)
Bintian Lin – University of Exeter

Investigating the effects of freeze-thaw cycles on the bond behaviour of lime-based TRM composites (Synopsis no. 14)
Ali Dalalbashi – University of Minho

Testing and analysis of wire arc additively manufactured steel single lap shear bolted connections (Synopsis no. 17)
Xi Guo – Imperial College London

Appraisal of traditional structural systems and development of system-specific assessment guidelines: A case study of unreinforced masonry buildings in southern India (Synopsis no. 18)
Krishnachandran S – Indian Institute of Technology Madras

Web Crippling Strength and Behaviour of Cold-Formed Thin-Walled Channels with Web Openings (Synopsis no. 20)
Hasini Weerasinghe – University of Sri Jayewardenepura/ Northumbria University

Development of Innovative Modular Connection and Bracing System (Synopsis no. 22)
Heshachanaa Rajanayagam – Northumbria University

Potential of low-grade kaolinitic clay as a cement substitution in concrete (Synopsis no. 24)
Kwabena Boakye – Coventry University

Development of modular wall panel with improved fire, energy and structural performances (Synopsis no. 25)
Dilini Perera – Northumbria University

Enhancement of modular building system in terms of sustainable performances (Synopsis no. 28)
Elilarasi Kanthasamy – Northumbria University

Human jumping on slender flexible structures (Synopsis no. 30)
Nimmy Mariam Abraham – University of Exeter

Structural response and design recommendations for aluminium alloy structural elements (Synopsis no. 32)
Evangelia Georgantzia – Liverpool John Moores University

Pressurized sand damper as a sustainable solution for the response modification of structures (Synopsis no. 33)
Kostas Kalfas – Southern Methodist University

Keynote Speaker

Dr Mariapia Angelino

MEng(Hons) PGDip(Hons) EngD CEng MICE

Infrastructure Strategic Consultant, WSP / Golder

Mariapia is an Infrastructure Strategic Consultant in WSP Golder Italy, formerly Associate in WSP UK in the Civil and Bridge Engineering department. She is a chartered civil and structural engineer providing technical consultancy and research services. Mariapia holds two engineering degrees and an engineering doctorate at the University of Bristol sponsored by WSP on excellence in design standards for the construction sector. She formerly worked as a forensic engineer on structural collapses.

Over the last ten years, Mariapia has combined her award-winning doctorate research with work on WSP projects. She is a trusted advisor for her clients, including CEN, BSI, National Highways, National Grid and HS2. She has been technical lead and project manager on the refresh of the entire Design Manual for Roads and Bridges and more recently on the Manual for Contract Documents for Highways Works (over 500 standards), which are cornerstones for the design, construction, maintenance and disposal of the UK strategic road network.

Mariapia invests significant time and energy in standards and policy development activities in the UK and globally. Heavily involved with the activities of CEN/TC 250 (the European committee responsible for the Eurocodes, structural and geotechnical design standards used worldwide) since 2013, Mariapia helped build international consensus on the strategy to enhance the usability of the second generation of the Eurocodes. She is currently the sole technical reviewer for all Eurocodes, enhancing the quality of documents used by over 500,000 engineers in Europe alone, with expecting savings of hundreds of millions of euros in the European construction market.

Research Panel

The Institution of Structural Engineers' Research Panel comprises members from both industry and academia, and has the primary role of supporting, facilitating and directing research in Structural Engineering. The Research Panel, through its members and sponsors, as well as through its links with the local regional groups of the Institution and Institution Liaison Officers in Universities, aims to promote the effective dissemination and application of research, attract young people to research careers and liaise with other organisations with an interest in research. The Research Panel also engages with 'Structures', the Research Journal of the Institution of Structural Engineers, by judging papers for awards.

Through its Research Fund, the Panel are responsible for several research grant, award scheme and competitions, including the assessment of applications, the assignment of funds, the judging of deliverables and the award of prizes. The research grant and award schemes are as follows:

- Undergraduate Research Grant scheme
- MSc Research Grant scheme
- Research Award scheme
- Research into Practice Case Study Competition

The Research Panel has introduced the Industry Focussed Research Challenge which means that research funding, available through the Institution's established schemes, can be focussed on research that is well aligned with the current challenges faced by the profession. Applications through the established schemes that address the priorities of the industry focussed research challenge receive additional credit in the initial selection of grant winners. However, grants can still be awarded to high quality applications on other topics.

The challenge is built around research themes that aim to encourage and facilitate collaboration between industry and researchers and are designed to better align research with the needs of industry and should be considered in the broader context of the climate emergency. Full details of current themes are available here and are given below:

- Construction materials
- Loading on buildings
- Global Solutions
- Systems and resilience thinking
- Digital engineering

The Research Panel also suggests to review the climate emergency research and development priorities outlined in Structural engineering innovation for a zero-carbon world: an R&D agenda to match the carbon budget, by Winslow et al.

More information on the Research Fund can be found at: Research Fund - The Institution of Structural Engineers (istructe.org)

The Young Researchers' Conference was instigated by the Research Panel to provide PhD students and young researchers with an opportunity to present their work to an audience of peers and industry professionals, and to exchange ideas and experiences with fellow researchers. The Panel assesses the applications submitted to the conference and judge the presentations on the day.

Professor Leroy Gardner
Research Panel Chair

Conference Team

Presentation Selection Panel:

Chris Iliffe – *SHED Structural Engineers*
Steve Matthews – *WSP*
Jason Ingram – *University of Auckland*
Mithila Achintha – *University of Manchester*

Judging Panel:

The judging panels are formed from eligible members of the Research Panel and invited industry guests.

Pete Winslow – *Expedition Engineering*
Steve Matthews – *WSP*
Philip Pearson – *Cavendish Nuclear (Babcock International)*
Zhenjun Yang – *Wuhan University*
Andrew Foster – *COWI*
Pete Gates – *Giraffe Engineering*
Chris Iliffe – *Avie Consulting*
Fernando Madrazo-Aguirre – *COWI*
Kamel Bilal – *Stantec*
John Forth – *University of Leeds*

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Research into Practice Case Study Competition winner

Dr Smail Kechidi

University of Leeds & ilke Homes Ltd

Smail Kechidi (born, 1986) is a KTP Associate at the University of Leeds and ilke Homes Ltd., UK. He received his Ph.D. from jointly the University of Porto (Portugal) and the University of Blida (Algeria) in 2018 with a focus on earthquake engineering applied to cold-formed steel structures. His research over the last 10 years has focused mostly on experimental testing and numerical modelling of CFS shear walls and, more recently, on integrated seismic risk assessment and loss estimation. He is author of several articles in top scientific journals. He has recently won the research into practice case study competition organised by IStructE.

Research Panel members

Professor Leroy Gardner (Chair)

PhD, CEng, FICE, FIStructE

Leroy is engaged in teaching at both undergraduate and postgraduate level at Imperial College London, including specialist advisory work and leading an active research group in the area of steel structures. His principal research interests lie in the areas of structural testing, numerical modelling and the development of design guidance for steel structures and has co-authored four textbooks and some 300 papers. Leroy is a member of the European and BSI Committees responsible for Eurocode 3 and Editor-in-Chief of the new Research Journal of the Institution of Structural Engineers - Structures. In 2017, Leroy was awarded the prestigious IABSE Prize.

Dr Mithila Achintha PhD

PhD, MIStructE, CEng, FHEA

Mithila is a Senior Lecturer in Sustainable Infrastructure Materials at the University of Manchester where he leads Construction Materials research. Mithila is a Chartered Structural Engineer (MIStructE) and a Fellow (FHEA) of the Advanced HE, UK. Mithila's current research focuses on experimental, theoretical and computational investigation of novel and efficient use of a range of constructions materials and composites such as concrete, fibre reinforced polymer (FRP) and glass and sustainable construction technologies, including digital design and construction. As a research investigator, he has been awarded and managed a total research funding /contracts approaching £1M. Mithila is an experienced doctoral and post-doctoral supervisor with a track record of successfully guiding early career researchers. He has authored/co-authored over 70 peer-reviewed journal and conference publications.

Martin Henry Asare

MSc, PhD, MASCE, GMIStrucE

Martin is a Structural Engineer at G2 Energy based in Olney. He obtained both his MSc and PhD from South China University of Technology (SCUT) in Guangzhou, China with distinction and received SCUT excellent research award in both degrees. His research was in the structural equation modelling of risk assessment in international construction. He also holds a Diploma in Project Management and is a Certified Oracle Database Administration Professional. He is a member of the American Society of Civil Engineers (ASCE) and served as the first Practitioner Advisor for the ASCE in the southern chapter of the Guangdong Province in China. He is currently a graduate member of the Institution of Structural Engineers and has published several journals. He is also a reviewer for various journals including the Journal of Engineering (JOE).

Pete Gates

BEng (Hons), PhD, CEng, MICE, MIStructE

Pete moved into engineering from a background in carpentry and general building, including experience as an oak frame carpenter, and on sustainable building projects in Central America. Pete worked for Atkins Middle East in Dubai before completing his degree, undertook his PhD with ARUP on an EPSRC case award at the University of Bath, and worked for Buro Happold in Bath (and briefly Qatar) following completion of his doctoral research. Pete was job leader for the 'Icons at the O2' retail development inside the O2 dome. More recently Peter has worked for a smaller company in Poole, Smith Foster, and now works with two colleagues from his alma mata (Bath), at Giraffe Engineering. He has recently delivered stage 4 design for the UK's first purpose built climbing centre. Pete is a reviewer for ICE proceedings journals, and continues to supervise research dissertations as industry partner.

Professor John Forth (Vice-Chairman)

PhD, CEng, MIStructE

John is the Chair of Concrete Engineering and Structures in the School of Civil Engineering at the University of Leeds and Director of the Neville Centre of Excellence in Cement and Concrete Engineering. He was awarded his first degree, a BEng (Hons) in Civil and Structural Engineering from the University of Sheffield and received his PhD from the University of Leeds. As a Chartered Member of the Institution of Structural Engineers, he is on several Technical Committees (i.e. Eurocodes, fib, RILEM) in the European Union. His research interests include serviceability, durability and the dynamic performance of reinforced concrete and masonry structures.

Christopher Iliffe

MEng, PhD, CEng, MIStructE

Christopher completed his PhD, "An Inverse Predictive Model for the Design of Functional Textiles", at Newcastle University in 2015 and has since worked at consulting practices across the north of England, currently working for Avie Consulting. His research focussed on producing an analytical method for the design of architectural fabric properties for specific response criteria and analysing the reliability of the resulting composite. Since working in industry Chris has worked on a number of large and small projects in the UK and further afield including sports venues, museums, art installations, accommodation, and bespoke housing in steel, concrete, structural glass, structural fabrics, timber, and aluminium. Chris is currently largely focussed on Modular construction, and improving the efficiency of modular design.

Dr Jason Ingham

BE(Hons), ME(Dist), PhD, MBA, F.EngENZ

Jason obtained his doctorate from the University of California San Diego in 1995 and is a Professor of Structural Engineering and Head of the Department of Civil and Environmental Engineering at the University of Auckland. His research interests are primarily focused on the seismic behaviour of existing masonry and concrete buildings. Jason led the collection of data related to the performance of masonry buildings following the Canterbury earthquakes and has also undertaken post-earthquake building inspections in Sumatra (Indonesia) and in Nepal. He is a past president of the Structural Engineering Society of NZ (SESOC), a past president of the NZ Concrete Society (NZCS), a past member of the management committee of the NZ Society for Earthquake Engineering (NZSEE) and is a Fellow of Engineering New Zealand. Research led by Jason contributed significantly to the development of the New Zealand methodology for detailed seismic assessment of unreinforced masonry buildings.

Professor Dennis Lam

BEng, MPhil, PhD, CEng, FIStructE, MICE, MASCE

Professor Dennis Lam is the Chair of Structural Engineering and the Director of Bradford Centre for Sustainable Environments at the University of Bradford, UK. He was also formerly Chief Structural Engineer for the City of Wakefield, UK and has more than ten years' experience in engineering practice. Dennis is a Chartered Engineer, Fellow of the Institution of Structural Engineers and Member of the Institution of Civil Engineers. He is currently a Distinguished Chair Professor at the Tsinghua University, China and the President of Association of Steel – Concrete Composite Structures (ASCCS). He is the European Editor-in-Chief for the Journal of Steel & Composite Structures and a member of the European Committee on Standardization (CEN) responsible for the Eurocode 4.

Fernando Madrazo-Aguirre

PhD, DIC, CEng, MICE

Fernando is a Principal Engineer in COWI's London office working in the design and assessment of bridges and special structures. He has contributed to infrastructure projects including the maintenance of West Gate Bridge in Australia and the 1915 Çanakkale Bridge (the new world record suspension bridge with a main span of 2023m) in Turkey, as well as to smaller scale footbridge competitions, and has led engineering teams in projects like High Speed 2. He completed his PhD on under-deck cable-stayed bridges at Imperial College London, where he currently holds the role of Visiting Design Fellow and is involved in undergraduate teaching.

Steve Matthews
MSc, DIC, CEng, FIStructE, MICE

Steve is Senior Technical Director at WSP UK and has over 40 years' experience with consulting engineers, steelwork fabricators and research organisations. He specialised in steelwork and composite construction bridges. Steve was responsible for strategic business planning and technical overview of the UK Bridges teams. He has led research frameworks for DFT and Highways England, working with Academia, SMEs and consultants delivering £100M of projects. He contributes to industry seminars and seeks to improve industry/academic collaboration ensuring mutual benefit through more focused research. Steve is a Lean and PRINCE2 practitioner with an engineer's "drive" for ingenuity, innovation and making things work more efficiently and effectively.

Emily Roberts
MEng, CEng, MIStructE

Emily graduated from the University of Cambridge in 2008 and has been a Chartered Member of the IStructE since 2012. She is an Associate with Arup and has worked on transport projects such as Abu Dhabi airport, King's Cross Station redevelopment and Riyadh Metro. She worked for three years in Hong Kong on the MTR Shatin to Central Link Exhibition Centre station and is now working in Boston, MA. Emily is the global research manager for Arup's Structural Skills Network which involves taking an overview of structural engineering research projects, shaping research priorities, and promoting Arup research.

Martin Simpson
CEng, MIStructE, MICE

Martin is a Reader in Structural Engineering at the University of Liverpool and Director of the Centre for the Digital Built Environment. He has spent most of his 20-year career with Arup working on stadium projects like the Beijing National Stadium and most recently Singapore Sports Hub. The highly multi-disciplinary Centre for the Digital Built Environment supports the construction industry in its digital transformation through research and education to solve industry challenges. His personal research interests are parametric and generative design, multi-disciplinary optimisation, digital workflows, digital competence, digital fabrication and closing the loop between the real-as-built-world and the virtual world.

Dr Eleni Toumpanaki
MEng, MSc, DIC, PhD

Eleni Toumpanaki is a Lecturer in Civil Engineering at the University of Bristol. She received her PhD from the University of Cambridge and worked as a Structural Engineer at Foster + Partners in an interdisciplinary design environment. She joined the CNMI group at the University of Cambridge in 2017-2019 researching timber. Her research focuses on structural materials such as timber, concrete and composites (FRPs) with an approach that ranges from nano- to building scale. Her research interests lie in the optimised use of structural materials and material substitution strategies to reduce the carbon footprint of infrastructure considering sustainability, durability and resilience criteria.

Professor Ahmer Wadee
PhD, ACGI, DIC, CMath, CSci, FIMA, MASCE

Ahmer is Professor of Nonlinear Mechanics at Imperial College London. He is an internationally-leading expert on structural instability and has published over 160 articles in the scientific literature. In 2014, he was listed as one of the UK's top 100 practising scientists by The Science Council. He is an Associate Editor of the international journal "Thin-Walled Structures" and also serves on the editorial board of the institution's research journal "Structures". He is a Fellow of the Institute of Mathematics and its Applications, a Chartered Mathematician, a Chartered Scientist, a Member of the American Society of Civil Engineers (ASCE), and served as Chair of the ASCE Engineering Mechanics Institute Stability Committee from 2017-19.

Dr Pete Winslow
PhD, CEng, MIStructE

Pete obtained his PhD from the University of Cambridge in 2009 and is now a practicing structural engineer and R&D lead, sitting on the executive board of Expedition Engineering and the Useful Simple Trust. He played key roles in designing the pioneering ferrocement solar canopy for the Stavros Niarchos Cultural Centre in Athens and the Stockton Infinity footbridge. He was in the engineering team for the award-winning London 2012 Velodrome and has experience across a range of unusual and special structures: from the acoustically-sculpted Soundforms shells to HS2 Old Oak Station Roof design. Pete is actively involved in a portfolio of R&D programs and innovation consultancy, working with universities, industry and several major infrastructure clients to bring research into practice: seeking to deliver tangible benefits with a particular focus on the climate emergency and carbon reduction.

Yancheng CAI
BEng, MEng, PhD, CEng, MASCE, MHKIE, MICE

Dr. Yancheng CAI currently held the Research Assistant Professor position in Department of Civil and Environmental Engineering at The Hong Kong Polytechnic University. He received his PhD degree from The University of Hong Kong in 2013. He then worked in the engineering industry for a few years before he returned to the university in 2016. He is a Chartered Engineer and a Member of the Institution of Civil Engineers (ICE), UK, a member of Hong Kong Institution of Engineers (HKIE) and a member of American Society of Civil Engineers (ASCE). He is also a member of the Editorial Board for the ICE --- Civil Engineering Journal, and a member of Sustainability Panel and Research Panel of the IStructE, UK. He received the Grand Prize of the HKIE Innovation Awards for Young Members in 2018 and, the "Commendation Merit --- R&D Award by Joint Structural Division of Structural Division of HKIE and the IStructE in 2017. His main research areas include steel structures, structural stability, connections and joints, structural fire resistance and composite structures.

Philip F. Pearson
BSc (Hons), C.Eng. F.I.Struct.E.

Philip is a Principal Structural Engineer currently with Cavendish Nuclear (Babcock International), involved for approximately 38 years within the civil nuclear industry on the design and build of Nuclear Structures, Operational Reactors and finally Reactor Building Decommissioning. His interest in the long-term integrity of civil structures, whilst responsible for reactor pre-stressed concrete pressure vessels (PCPV), lead him to develop a national (UK) structural integrity strategy for nuclear safety related structures (nuclear site license condition 28). Interest in improving structural investigations, led to joining a Nuclear Utilities civil engineering working group (HSE chaired), proposing research (nuclear industry funded) into various structural integrity issues. Some 20 years later providing technical expertise for Cavendish Nuclear to fund university research benefiting structural integrity. Currently technically involved with Bristol University research using Muon Scattering Tomography (MST), and developing site trails, as an NDT in heavy civil engineering structures appertaining initially for the nuclear industry, but potential wider benefits.

Professor P.A. Muhammed Basheer, FREng
PhD, DSc, FIAE, FICE, FIStructE, FACI, FICT, FIAAM, CEng

Basheer, as he is known, is Chair in Structural Engineering and former Head of School of Civil Engineering at University of Leeds, UK. Currently, he is also the President of the Institute of Concrete Technology and will serve until April 2023. He has been an educationalist and researcher in the field of civil (structural) engineering for nearly 40 years. Basheer has secured research income in excess of £19 million, supervised more than 30 PhDs to successful completion and published nearly 400 refereed technical publications. He has received numerous awards/prizes for his contributions to research, including a lifetime achievement award from the Civil Engineering Research Association of Ireland, CANMET/ACI award for his sustained contributions to the field of concrete technology and the Callendar prize from the Institute of Measurements and Control for developing test apparatus for the construction industry. In 2012, he was elected to be a Fellow of the Irish Academy of Engineering and in 2014 he was elected to be a Fellow of the Royal Academy of Engineering. He is also a Fellow of the Institution of Civil Engineers, Institution of Structural Engineers, American Concrete Institute, Institute of Concrete Technology, and International Association of Advanced Materials.

Eva Gaal
MBA, MSc, CEng, MIStructE

Eva is the Principal Engineer of the Innovation Team at NHBC. She received her MSc degree in Structural Engineering from the Budapest University of Technology and Economics in 2003, and she was awarded an MBA from Oxford Brookes University in 2010. She has been a Chartered Member of the IStructE since 2010. Before joining NHBC in 2016 she worked as a structural design engineer on various industrial, commercial and residential projects. Recognising the need of NHBC to embrace Modern Methods of Construction Eva was key member in setting up the NHBC Accepts service. Under this scheme her team is responsible for assessing Innovative Products and Prefabricated Building Units and assisting Manufacturers and Products Owners to develop and establish innovative products and construction methods acceptable to use in the UK construction market. Also her team is working in collaboration with NHBC Foundation to publish research papers for the industry.

Professor Zhenjun Yang
FIStructE, CEng, PhD, BEng

Zhenjun is a Professor in Structural Engineering and Computational Mechanics at Wuhan University, China and a Fellow of IStructE (since 2017). He has over 20 years of academic experience in a few UK (Coventry, Manchester and Liverpool) and China universities (Zhejiang). His main research interest is multiscale experiments and modelling of damage and fracture of concrete, fibre reinforced concrete (FRC) and polymers (FRP), in a view to optimise structural integrity, reliability and sustainability. He has secured over £2m research grants as PI from EPSRC UK and NSFC China etc and published over 100 SCI-indexed journal papers with 3300+ SCI citations and H index=34. He currently serves as an editorial member of 3 international journals, and has supervised over 15 PhD awardees and 5 PDRAs.

Dr Kamel Bilal
PhD, PSE

Dr. Bilal is a structural engineer in the Dams and Energy Sector at Stantec where he performs investigation, design, and analysis of dams, drydocks and heavy civil infrastructure projects. A Ph.D. holder in Structural Engineering and Mechanics, Dr. Bilal's research focuses on the simulation of behavior of complex concrete and composite structures under static and seismic loading and has been published in many journals and presented at nationally and internationally recognized conferences. His area of expertise also includes nonlinear numerical analysis for civil infrastructure projects including soil-structure interaction (SSI) and dynamic analysis. Dr. Bilal is a licensed professional engineer, young professional engineers committee member of ASCE/SEI and research and seismic and dynamic events panel member of iStructE.

Professor Brian Uy
BE (Hons 1), PhD, CPEng, CEng, PE, IntPE (Aus), NER (Civil & Structural), FIEAust, FICE, FIStructE, FASCE, FIABSE

Brian Uy is Professor of Structural Engineering and Head of the School of Civil Engineering at the University of Sydney. He is the Chairman of the Standards Australia Committees BD32 on Composite Structures for Buildings and BD-90-Part 6 on Steel and Composite Structures for Bridges. He is a current Vice President (Australasia and South East Asia) of The Institution of Structural Engineers and the Chairman of the Australia Regional Group of the International Association of Bridge and Structural Engineering.

Behaviour of the masonry arch bridge under foundation movement

01 **Ahmed Mohamed Naggasa**
University of Salford, UK

Aim and objectives

The aim of this thesis was to investigate the structural behaviour of masonry arch bridges subject to foundation movement.

This aim was achieved by pursuing the following objectives:
1. Establish a literature review of the current knowledge on masonry arch bridge analysis
2. Undertake physical testing of scale models of arches and masonry prisms, and then use the data to validate and calibrate a computational model developed using a FEA package
3. To carry out numerical simulation experiments validated against full scale arch tests
4. To contribute to better understanding predictions about the life span of arch bridges subject to foundation movements of identified magnitudes.

Abstract

There are around 40,000 masonry arch bridges around the UK, most of which are over 150 years old and require periodic assessment and rehabilitation to maintain acceptable capacity. There are several capacity assessment methods, however most rely upon the assumption of a four hinge collapse mechanism. In reality, most bridges will suffer foundation movement which will change the structural behaviour assumptions.

Method description

ABAQUS 3D models were created which were based on an arch ring G, tested to destruction at the University of Salford, as shown in Fig 1.

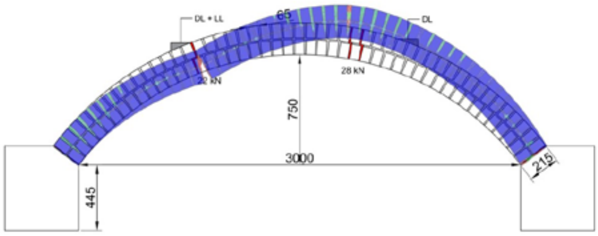

Fig 1 Arch G loading arrangement and geometric dimensions.

The ABAQUS 3D models used non-linear geometry and material analysis based on the techniques developed for the triplet models. This package was used to solve both dynamic step and static problems. The models used several novel methods such as XFEM which allowed the creation of masonry arch bridge models which present realistic cracking masonry elements that dissociated, for the first time. Also, cohesive behaviour was used to represent the shear sliding behaviour at the interfaces of the brick-and-mortar elements as one of the masonry arch bridge failure mechanisms. The results from this were validated by comparison with full-scale experimental test results. The validated model was then used to investigate the structural behaviour of the arch subject to sliding, settlement and rotational foundation movement.

The experimental test bridges comprised 3m span masonry arches of segmental shape and span: rise ratio of 4:1, built using high-quality class A engineering bricks without headers connecting the two arch rings. The bricks were nominally sized 214mm x 102mm x 65mm, with nominally 10mm mortar joints. The mortar constituent ratio was 1:2:9 (cement: lime: sand) (Melbourne, Wang, Tomor, et al., 2007). To reduce movement, the reinforced concrete abutments were tied with high tensile steel tie bars and bolted into the laboratory strong floor. The bricks and mortar material properties such as density and compressive strength were obtained from several experimental tests to be used as input values in the numerical study as shown in Table 1.

The experimental test bridges were loaded using hydraulic cylinders acting against a stiff reaction frame. Constant loading was applied to represent backfill – dead load (DL), at the quarter and three-quarter span points as shown in Fig 1. Monotonic loading to represent live load (LL) was applied at the arch quarter span, in 1.0kN increments up to the arch collapse load. The arch displacement was measured using linear variable displacement transducers (LDVTs) at the quarter and three-quarter span in vertical and horizontal directions.

The research investigated brick and mortar material properties to understand the interface interaction between the brick and mortar using a masonry triplet testing programme. The data was used in the numerical analyses using FEA models of brick triplets. The numerical analysis used the XFEM method to model a cracking joint without using a subroutine, which was later used in full arch ring models.

Bricks	Density		2200 kg/m³	
	Young's modulus of elasticity E_b		16000 N/mm²	
	Poisson's ratio		0.15	
Mortar	Density		1560 kg/m³	
	Young's modulus of elasticity E_m		1420 N/mm²	
	Poisson's ratio		0.2	
Steel Plate	Density		7800 kg/m³	
	Young's modulus of elasticity E_s		21000N/mm²	
	Poisson's ratio		0.2	
Mohr-Coulomb plasticity	Friction angle ϕ	Dilation angle ψ	Cohesion C	Tension cut off
	26.5	11	0.4	0.2

Table 1: Material properties for Arch G 3m span.

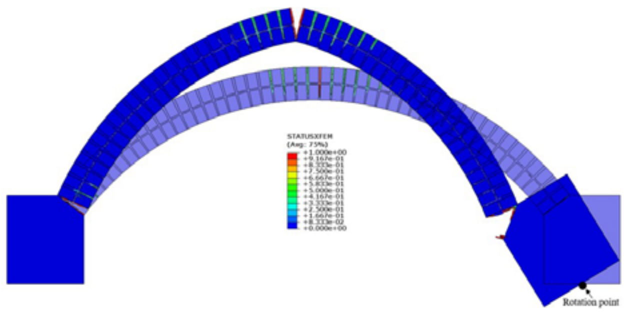

Fig 2 Deformed shape for 15mm (0.06 rad) rotational movement.

The geometry of the masonry arch bridge barrels was so complicated that it could not be modelled directly in ABAQUS, so geometry was created using AutoCAD, then imported into the FEA software. The ABAQUS program was selected to create FEA models, in which masonry may be modelled as either homogeneous or heterogeneous. To create a model as representative as possible heterogeneous material modelling was chosen, combined with an interface model for the joint between the mortar and bricks. In normal FE modelling the elements are connected at nodes, however, to more accurately model the masonry behaviour, an interface was used between the brick and mortar elements. Bricks were modelled as fully elastic eight noded elements. The mortar joints were modelled as non-linear material to present the nonlinearity behaviour at failure. The traction-separation law was used in the definition of cohesive interaction to predict damage initiation and damage propagation in the cohesive interaction. Also, the traction-separation law was used in the definition of mortar mechanical behaviour in connection with XFEM to predict the crack initiation and crack propagation in the full thickness mortar.

Result description

In conclusion, this research has created the first detailed micro model of the mortar joint behaviour which used XFEM to crack the mortar joint, without predetermined location as shown in Fig 2.
Structural behaviour of the arch ring was validated against full scale test results, at ultimate capacity the model was within 80% of the physical test result; crack locations and development were perfectly replicated.
Observations about structural behaviour of arches subject to foundation movement are:

- Four hinges are not needed to form a collapse mechanism
- Sliding movement produces greater hinge rotation than settlement movement
- Dispersed hinge formations only occur in analyses which involve both sliding and settlement movements

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Structural-acoustic optimization of concrete floors

02 **Jonathan Broyles**
The Pennsylvania State University, USA

Project objectives and goals

The building industry accounts for over 11% of global carbon emissions (de Wolf, 2017). To mitigate carbon emissions, structural optimization strategies have been shown to reduce the embodied carbon of structural systems in buildings (Hawkins et al., 2020). Specifically, prefabricated shape-optimized (Ismail and Mueller, 2021) and topology-optimized (Meibodi et al., 2018) concrete elements have been studied to have upwards of 70% material reductions. However little research has been done on the consequences of structural optimization on other building disciplines. For example, poor sound insulation between neighbouring building spaces is directly influenced by the mass of building structures. In response, this research project has the following objectives:

- Evaluate current acoustic metrics for incorporation within early building design multi-objective frameworks
- Calculate the embodied carbon for multiple floor types for comparison to optimized floor solutions
- Create a parametric model of concrete floor structures for design exploration
- Optimize concrete floor structures for environmental and acoustical objectives while ensuring structural integrity
- Validate numerical results through experimental testing

Description of methods and results

This project includes both numerical simulations and experimental testing, with unique methods for both parts. Computationally, a parametric model based on NURBS geometry is used for the shape optimization of one-way, two-way, and flat plate concrete floors. The floor systems have various geometric variables such as top slab depth or number of ribs, to parametrically manipulate the geometric design of the floors. After the geometry is defined, a structural simulation is conducted to ensure that the concrete floor design satisfies structural concrete design code (ACI-318). If the design satisfies the structural checks, an acoustic transmission model is used to find the sound insulation performance (Fig. 1). If a concrete floor does not satisfy the structural checks, it is removed from consideration within the optimization framework.

Shaped concrete slab specimens will be fabricated (Fig. 2), using bent sheet metal and wood formwork for experimental testing. To validate the acoustic transmission performance, a roving modal hammer test will be applied to the top slab surface to ascertain the modal response. Structurally, a four-point load test will assess the structural capacity of the concrete specimen. The experimental results will be compared to the numerical results previously found for future numerical work.

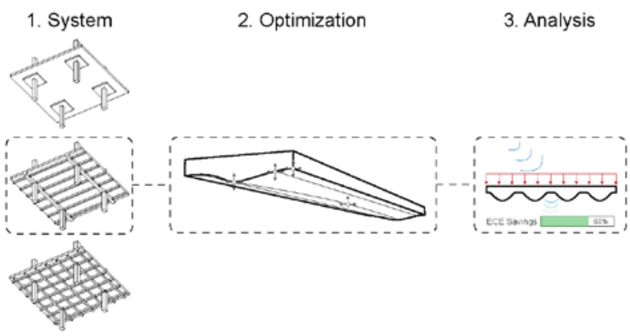

Fig 1 Structural-acoustic methodology applied to concrete floors.

The early findings of this work show that structural optimization of building elements often reduces the performance of secondary design considerations (Broyles et al., 2022). The inclusion of other competing building disciplines further emphasizes the importance of a designer to know the design needs on a level-by-level or even a room-by-room scale. Despite these complexities, structural optimization strategies are adequate for significantly reducing material quantity and corresponding embodied carbon emissions and can provide viable acoustic performance.

Potential for application of results

Potential applications of this research are as direct as encouraging the prefabrication of shape optimized concrete solutions to improving sound insulation requirements within building design code. However, this project specifically highlights why acoustics needs to be considered within structural optimization strategies. As found by early results, acoustics can be coupled with shape optimization with favourable results for both sustainability and sound insulation. This could lead to other structural-acoustic studies including the application of other vibration phenomena such as earthquakes or sound reflection within auditorium design.

Fig 2 Shaped concrete slab specimen.

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Funding body

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Further information

Jonathan Broyles (E: j.broyles@psu.edu)
https://www.bdg-psu.org/people-1

Collaborators

Dr. Nathan Brown, The Pennsylvania State University, Architectural Engineering

Dr. Micah Shepherd, The Pennsylvania State University, Applied Research Laboratory and the Graduate Program of acoustics

Fire analysis of cross-laminated timber (CLT) wall panels

03 Muhammad Yasir
Munster Technological University (MTU), Ireland

Introduction

Cross-laminated timber (CLT), in which the alternate layers are orthogonally oriented and adhesively bonded together is gaining popularity globally due to its enhanced structural capabilities. However, the application of timber in tall buildings is restrained due to fire safety concerns primarily due to its combustible nature.

Project objectives and goals

The current research will enhance the knowledge base for timber building specifically in CLT made with Irish timber. This research will contribute towards sustainable construction and work towards an increased understanding of CLT behaviour under fire conditions. Furthermore, this research will also provide the potential for employment growth, support an increased contribution of wood products to climate change mitigation, and maximise the use of local materials. This research project is based on the concept of modular CLT panels exposed to standard fire conditions to ensure compliance with the building regulations.

Description of methodology and results

In this research project, an experimental fire study of CLT wall panels manufactured from Irish Spruce was performed. Standard fire testing of the CLT panels was undertaken using the test kilns at Munster Technological University. The main fire-testing kiln was used for the fire testing which is a computer-controlled natural gas unit and can apply loading during fire testing using a 180kN ring frame around the kiln as shown in Fig 1. Two three-layered CLT wall panels of Irish Spruce boards were tested, that had a moisture content of 15% prior to testing. Both wall panels were 1200 mm long and 900 mm high with an overall thickness of 120 mm. The tested wall panels were designated as W-1 and W-2.

The wall panel was placed up against the front of the fire testing kiln, with its door open to one side. The CLT test panel was supported with steel members on the unexposed side of the panel as shown in Fig 1. The load cell on the top of the panel recorded the applied constant load of 85 kN throughout the test. This was applied using a spreader beam along the top of the panel, A strain gauge at the mid-span of the panel was placed to measure the horizontal displacement throughout the testing. The kiln was also equipped with a propane gas burner which was manually controlled to ensure the ISO-834 curve (ISO 834-1-1-1999) was followed for heating conditions in the kiln. Thermocouples were placed at the mid-depth of every layer and at the interface between each layer to measure the temperature variation with respect to time. The charring rate of CLT panels and their individual layers were measured by considering the temperature measured at various thermocouples from the exposed surface. During testing, the temperature in the kiln was recorded using a plate thermocouple. The kiln temperature recorded by the plate thermocouple and the temperatures measured at different K-thermocouples installed at various depths is shown in Fig 2.

After the test has completed, the burner was stopped, the panel was unloaded and then removed from the kiln. The testing panel was then cooled down using water. The uncharred depth of both W-1 and W-2 was measured which was 35 and 38 mm respectively. The charring times and overall charring rates of both W-1 and W-2 panels are shown in Table 1.

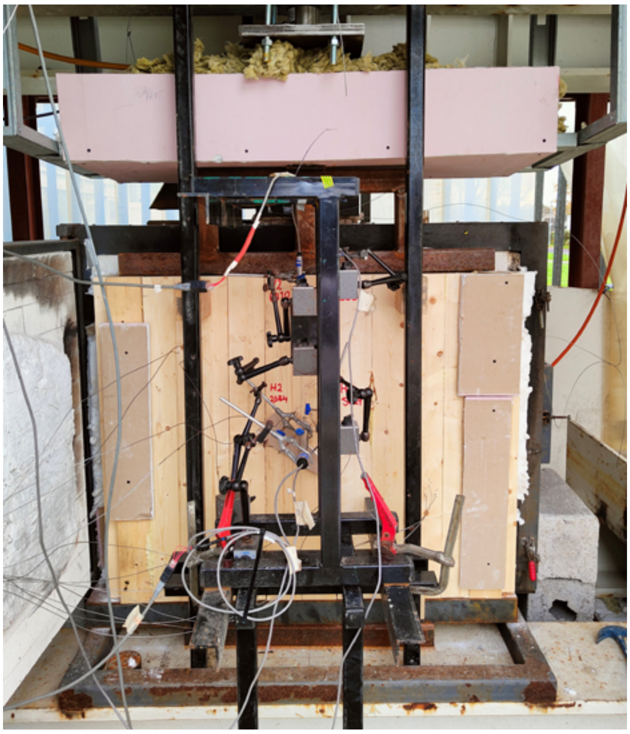

Fig 1 Testing panel in the kiln

Test name	Layer	Charring time (min)	Overall charring rate (mm/min)
W-1	1	81.5	0.58
	2	138.5	
W-2	1	83.5	0.55
	2	144.5	

Table 1 Charring time and charring rate of wall panels.

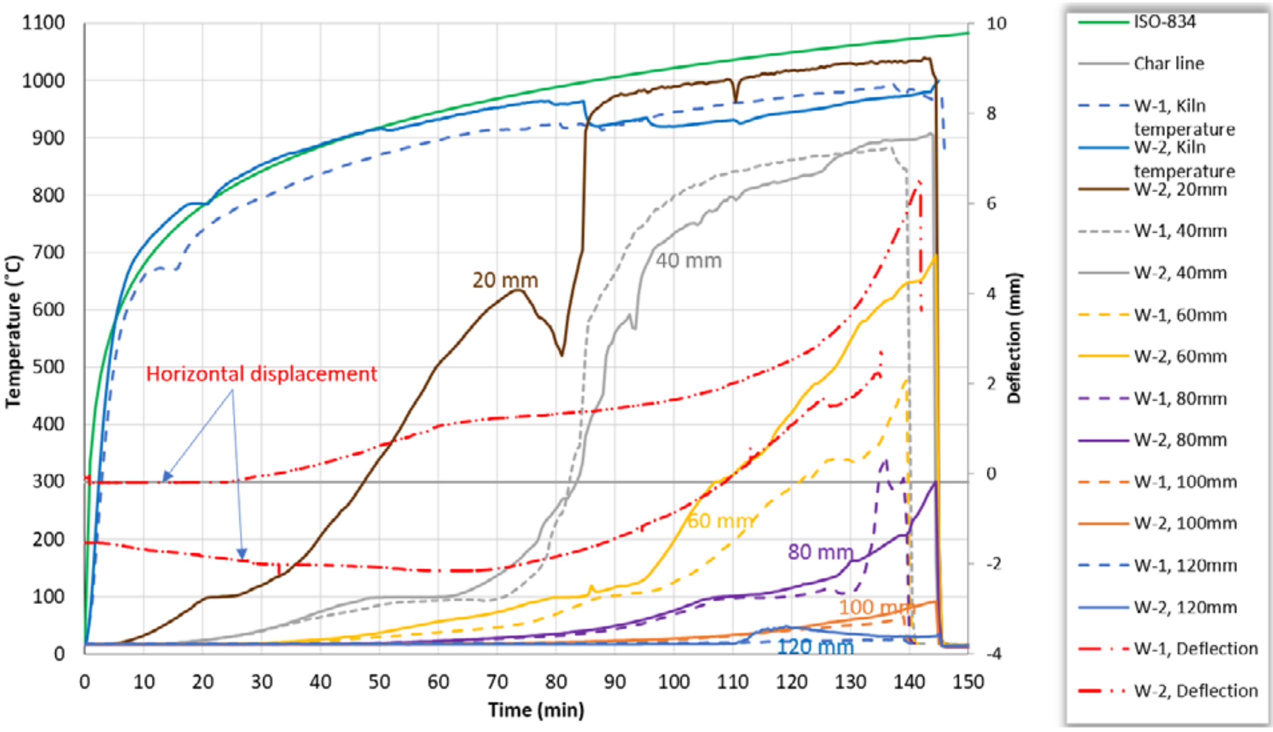

Fig 2 Test results (Temperature recorded by different thermocouples are marked with their distance from the exposed face of the kiln)

Summary

The average charring rate calculated for Irish Spruce CLT wall panels was 0.57 mm/min, which is less than that of a one-dimensional charring rate of 0.65 mm/min (EN 1995-1-2 2004). The total charred depth of 80-85 mm was measured after the tests were finished, which took an average of about 2 hours and 20 mins for both tests. Additional tests will be undertaken using different types of fire protection claddings applied on the exposed surface of the panels and their effect on the delaying of charring of each CLT test panel will be measured and investigated.

Potential for application of results

The research work will increase the database and knowledge base for buildings in timber, particularly in Cross Laminated Timber (CLT). Specifically, the work will increase the available database and information on the use of Irish grown timber and its behaviour under fire conditions.

Funding body

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Experimental analysis of blind bolted connections in concrete-filled tubular columns

04 **Manuela Cabrera**
University of Nottingham, UK

Research motivation

Blind bolts have been developed to overcome the difficulties when connecting open to hollow steel members as they can be installed on site from one side only. Ongoing research at the University of Nottingham has shown that the Extended Hollo-Bolt (EHB) blind fastener is able to achieve rigid or semi-rigid connection behaviour (Tizani et al., 2013). This fastener is a modification of the commercial Lindapter Hollo-Bolt (Lindapter International, 2021) which is characterised by an extended bolt shank and a nut at the end of the extension, which in combination with concrete-filled tubular columns, generates an anchoring effect. To fully characterise the behaviour of this connection, all the possible failure modes of the EHB connection need to be studied (Cabrera et al., 2021). Substantial research has been carried out on the behaviour of the connection when failure is either produced in the bolt component in tension (Pitrakkos, 2012) or the column face component in bending (Mahmood, 2015). However, due to the novelty of the blind fastener, the possible behaviour of the connection when the components can interact and produce a combined failure (i.e. combined bolt in tension and column face in bending) has not been studied yet. The inclusion of these bolts in design guidance to moment-resisting connections will widen the use of hollow sections as columns in multi-storey steel construction which represent many advantages from structural and architectural points of view.

Project objectives and goals

The aim of this research is to investigate the performance of the EHB blind fastener connection and failure mode when combined failure can occur under a tensile pull-out force.

To achieve the aim of this research the following objectives are set:

- Review the available literature of connections to Steel Hollow Sections (SHS) and blind bolted connections to build the necessary background and identify the gaps in knowledge
- Design and perform an experimental programme to investigate the behaviour of the EHB connection when combined failure mode can occur under monotonic tensile loading
- Identify the ranges of design parameters that produce a change in failure mode, from bolts in tension to column face in bending

Description of method and results

An experimental programme of 11 pairs of samples was developed to investigate the influence of varying the EHB design parameters on the connection behaviour and failure mode. The ranges of examined parameters are presented in Table 1. All the specimens were tested under monotonic tensile loading conditions at a displacement control rate of 0.015mm/s up to failure.

Fig 1 displays the experimental setup which involves a concrete-filled SHS, one pair of EHBs, a reusable rigid T-Stub, steel frames placed at the top of the SHS, and wooden supports at the bottom of the sample. Three independent measurement techniques were used to increase the reliability of the test results, i.e. linear potentiometers, video gauge camera, and a digital image correlation image system.

The ultimate strength and initial stiffness results are summarised in Table 2, as well as the failure mode. The ranges at which failure mode changes occur were identified from the test results as well as a new failure, column face in bending accompanied with sleeve fracture and bolt slippage, which had not been reported before.

The test results in Fig 2 show that, compared to equivalent samples from previous independent studies on the bolt in tension and column in bending components, the combined failure load-displacement curve exhibits the initial stiffness of the column component, while the ultimate strength corresponds to the ultimate capacity of the bolt. This means this sample developed the full strength of the bolt with 50% higher ductility.

Parameter	Tested values
Concrete strength (MPa)	C20, C40 & C80
Slenderness ratio	µ18.8, µ30,0, µ37.5 & µ47.6
Bolt grade	8.8 & 10.9
Bolt diameter (mm)	M16 & M20
Shank length (mm)	150, 170 & 190
Gauge distance (mm)	80, 140 & 180

Table 1 Ranges of tested parameters

*Table 2 Experimental results and failure modes. Specimen key: bolt diameter–shank length–bolt grade-gauge distance-concrete grade–slenderness ratio. *Benchmark sample. CB: column face in bending, BF: bolt fracture, CB+SF: column face in bending + sleeve fracture*

Sample	Strength (kN)	Initial stiffness (kN/mm)	Failure mode**
M16-170-8.8-140-C20-u30	300.0	111.1	CB
M16-170-8.8-140-C40-u30*	299.0	156.3	BF
M16-170-8.8-140-C80-u30	300.0	250.0	BF
M20-170-8.8-140-C40-u30	386.4	400.0	CB+SF
M16-170-8.8-80-C40-u30	290.0	127.8	CB+SF
M16-170-8.8-180-C40-u30	300.0	178.6	BF
M16-150-8.8-140-C40-u30	293.0	156.0	CB+SF
M16-190-8.8-140-C40-u30	292.6	155.7	BF
M16-170-8.8-140-C40-u18	300.0	156.2	BF
M16-170-8.8-140-C40-u37	300.0	156.3	CB+SF
M16-170-8.8-140-C40-u47	211.0	128.6	CB+SF

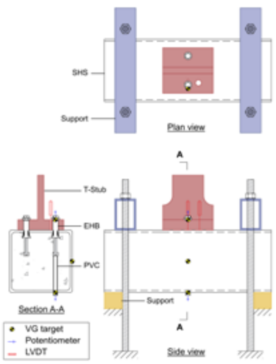
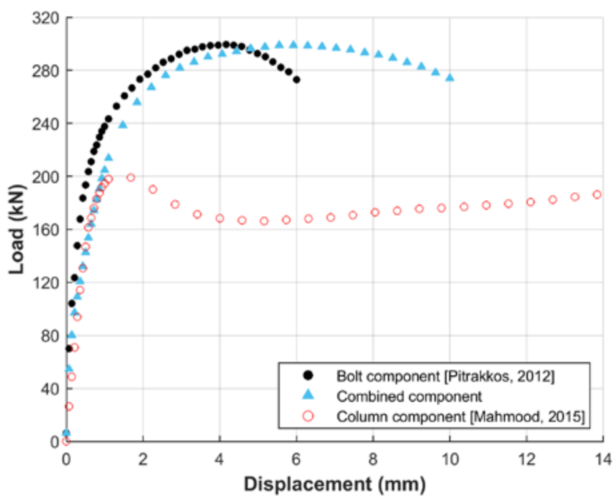


Fig 1 Test set up and instrumentation

Fig 2 Bolt, combined, and column components global vs load curves for samples with concrete grade 40MPs, bolt diameter M16, anchored length 80 mm, slenderness ratio 37.5, and gauge distance 140mm



Potential for application of results

The experimental programme has generated validation data to be used in finite element models. The results from these, in turn, will be used for generating metamodels (i.e. the model of a model) by means of Artificial Neural Networks (ANN). In this way, multiple design parameter combinations can be studied allowing a better understanding of the connection behaviour, and ultimately contributing to the production of design guidance.

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Further information

Manuela Cabrera (E: manuela.cabrera@nottingham.ac.uk)

Supervisors:
Walid Tizani (E: walid.tizani@nottingham.ac.uk),
Jelena Ninic (E: jelena.ninic@nottingham.ac.uk),
Fangying Wang (E: fangying.wang@nottingham.ac.uk)

Experimental investigation on axial compressive behaviour of novel FRP-ECC-HSC composite stub column

05 **Shuai Li**
The Hong Kong Polytechnic University, Hong Kong

Project objectives and goals

Fibre-reinforced polymer (FRP) is widely investigated and adopted in engineering applications in recent years (Lam and Teng, 2004). With the high strength-to-weight ratio and non-corrosive characteristic of FRP, FRP-concrete structures could exhibit more outstanding performance compared with traditional steel-reinforced concrete structures, especially in marine environments. A novel composite column, which consists of FRP, engineered cementitious composite (ECC) and high strength concrete (HSC), is proposed in this study as shown in Fig 1. The FRP-ECC-HSC composite column has an outer FRP tube, an inner HSC core and an ECC ring filling the space between the FRP tube and HSC core. Due to the high brittleness of HSC, localized cracks may occur on HSC in FRP-confined HSC columns, which leads to premature failure on FRP tube at the same locations (Ozbakkaloglu and Vincent, 2014). With the excellent tensile and cracking behaviour (Li et al., 2001), ECC ring is used to redistribute the localized strain from HSC core to FRP tube in the proposed novel composite column. The hoop strain distribution mechanism is shown in Fig 2.

The objectives and goals of this study are to (1) experimentally investigative the axial compressive behaviour of the proposed novel FRP-ECC-HSC composite stub column; (2) understand the interaction behaviour of the three components in the composite column.

Description of method and results

Eight specimens for FRP-ECC-HSC composite column were prepared and tested under monotonic axial compression. All of the specimens had the normal diameter of 200 mm (inner diameter for FRP tube) and the normal height of 400 mm. Two ECC ring thicknesses, 15 mm and 25 mm, as well as two grades of HSC were considered. As for the specimen ID, F, E and H are representing the FRP, ECC and HSC, respectively. 15 or 25 stands for the ECC ring thickness. Four FRP-confined HSC columns were also prepared for comparison with the proposed FRP-ECC-HSC composite columns. Two identical specimens were prepared, with “R” referring to the repeated specimens. Details of all the specimens are summarized in Table 1.

Twelve strain gauges were installed at the mid-height of the column in the hoop direction at every 30° ° to measure the hoop strain distribution. Four LVDTs were adopted to measure the full height axial shortening of the column.

All the specimens of FRP-confined HSC and FRP-ECC-HSC composite column experienced similar behaviour and failed by FRP rupture in the hoop direction. Major characteristics for all the tested specimens are summarized in Table 2 to quantify the axial compressive behaviour. F_1 and F_2 are the first peak load and the load at the initial point of the stress recovery branch, respectively; F_c and ε_{cc} are the ultimate load and ultimate axial strain at FRP rupture. $\varepsilon_{h,rup}$ is the average hoop strain at FRP rupture and k_ε is the FRP confining efficiency.

Conclusions

Within the current scope of this study, the following conclusions can be drawn:

Specimen ID	HSC core		ECC ring
	Grade	Diameter (mm)	Thickness (mm)
FE50H70-15 (-R)	C70	170	15
FE50H70-25 (-R)	C70	150	25
FE50H90-15 (-R)	C90	170	15
FE50H90-25 (-R)	C90	150	25
FH70 (-R)	C70	200	-
FH90 (-R)	C90	200	-

Table 1 Specimen details

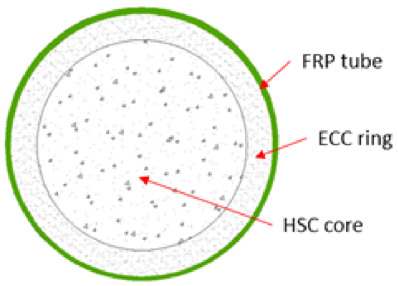

Fig 1 Section of FRP-ECC-HSC composite column

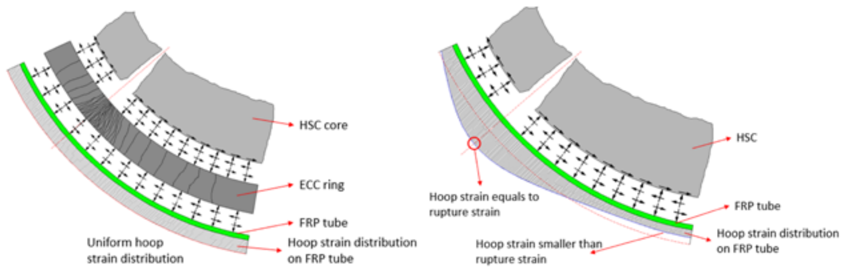

Fig 2 Hoop strain distribution mechanism for FRP-confined HSC column and FRP-ECC-HSC composite column

Specimen ID	F_1 (kN)	F_2 (kN)	F_c (kN)	F_2/F_1	F_c/F_1	ε_{cc}	$\varepsilon_{h,rup}$	k_ε
FH70	2777.1	2536.3	2791.9	0.91	1.01	0.0144	0.0116	74.4%
FH70-R	2786.3	2475.0	2862.3	0.89	1.03	0.0152	0.0121	77.6%
FE50H70-15	2626.6	2396.0	2966.0	0.91	1.13	0.0166	0.0127	81.4%
FE50H70-15-R	2506.2	2443.9	2773.3	0.97	1.11	0.0145	0.0117	75.0%
FE50H70-25	2193.7	2086.8	2706.5	0.95	1.23	0.0209	0.0143	91.7%
FE50H70-25-R	2177.7	2156.9	2582.5	0.99	1.19	0.0185	0.0139	89.1%
FH90	3195.2	2897.7	3165.5	0.91	0.99	0.0123	0.0117	75.0%
FH90-R	3266.9	2873.2	3172.3	0.88	0.97	0.0124	0.0112	71.8%
FE50H90-15	2979.9	2753.7	3021.3	0.92	1.01	0.0137	0.0125	80.1%
FE50H90-15-R	2954.9	2689.3	2972.0	0.91	1.01	0.0133	0.0121	77.6%
FE50H90-25	2578.5	2519.8	2809.2	0.98	1.09	0.0152	0.0133	85.3%
FE50H90-25-R	2630.4	2494.5	2709.5	0.95	1.03	0.0144	0.0128	82.1%

Table 2 Major characteristics for tested specimens

1. FRP-ECC-HSC composite columns can develop more uniform hoop strain distribution in comparison to the corresponding normal FRP-confined HSC columns. It demonstrates that the ECC can redistribute the hoop strain from locally cracked HSC core to the outer FRP tube
2. The uniform hoop strain distribution leads to a larger average FRP rupture strain. FRP confining efficiency was increased by 5-15% and 5-10% for C70 and C90 series, respectively. The failure of FRP-ECC-HSC composite columns was consequently delayed
3. Compared with FRP-confined HSC column, FRP-ECC-HSC composite column exhibits less load drop after the first peak in the axial load-strain curve. The transition period from the initial stage to the strain hardening stage becomes shorter with the introduction of ECC ring, as well as the increase of ECC thickness
4. The ultimate axial strain of FRP-ECC-HSC composite columns is obviously improved in comparison to FRP-confined HSC columns, showing a larger deformability and better ductility performance. The enhancement ratio increases with the increase of ECC proportion

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Further information

PhD student: Shuai Li (E: shuaaai.li@connect.polyu.hk)
Supervisor: Dr Tak-Ming Chan
(E: tak-ming.chan@polyu.edu.hk)

Structural performance of steel-concrete composite structures under combined actions and fire

06 **John Pascal Antwi**
Anglia Ruskin University, UK

The flexural strength and the composite action of steel-concrete composite beams depends on the connecting shear studs at the interface of the bottom steel beam and the top concrete slab. This project aims to investigate the structural performance of steel-concrete structures under combined actions and fire to evaluate the current design of shear studs in fire and make recommendations for its effective design. The following objectives under this broad aim have been identified:

- Analyse the key phenomena governing the behaviour of steel-concrete composite structures under combined actions and fire
- Develop and validate a simply supported steel-concrete composite beam under combined 40-minute ISO 834 fire heating and static load using ANSYS Workbench
- Carry out parametric analysis on the validated model considering load ratios, different fire scenarios, stud geometry and the beam span
- Evaluate the current design of shear studs and develop recommendations for the design of shear studs under combined service conditions and fire

The current design of shear studs according to EN 1994-1-2 under ambient conditions is based on both of the shear failure of the studs and the crushing failure of the top concrete. The shear failure of the studs depends either on its yield strength (rigid connectors) or its ultimate strength (flexible connectors). The crushing failure on the other hand, is dependent on the aspect ratio (ratio of height to diameter), the elastic modulus and the compressive strength of concrete. At fire conditions, thermal reduction factors are applied to the design formulas for shear studs under ambient conditions. According to Lim et al., (2020) using experimental push-out tests on shear studs found that the design shear resistance presented by the Eurocode 4 is a highly conservative estimation. However, Shahabi et al., (2016) concluded that the Eurocode 4 calculation of stud shear strength at elevated temperatures is to acceptable accuracy. Previous works on the investigation on shear studs in a steel-concrete composite beams under fire conditions are limited to experimental push out tests which is limited in scope and does not describe a real-world situation.

In this research, the physical steel-concrete test beam presented by Aziz et al. (2015) was redeveloped in the static structural and thermal stress component of ANSYS Workbench.

In the static structural component, five numerical models with different interface treatment to achieve composite action were subjected to a displacement control simulation to measure load-bearing capacity, load-slip capacity, stiffness and ductility. Four different frictional contacts models with coefficient of friction of 0.2, 0.15, 0.1 and 0.05 and another with the inclusion of the shear studs to achieve composite action.

The steel-concrete composite beam model with shear studs approximated better to the analytical solution using Eurocode 4 (EC4) calculations compared to the other four frictional connection models. However, the frictional models showed a higher load bearing capacity with increasing coefficient of friction compared to the stud connected steel-concrete composite beam model. Although, there was no significant change in the stiffness of the models, the stud connected model showed better ductility compared to the frictional contact models but recorded the highest slip at the interface of the top concrete slab and the bottom steel beam.

In the thermal stress component of ANSYS Workbench, a transient thermal simulation and a load control simulation were performed. The finite element model predictions for thermal distribution within the beam and the deflection-time curve showed a good agreement with the test beam results published by Aziz et al. (2015). The measured and the predicted deflection-time distribution showed a gradual increase in deflection of the composite beam in fire with time owing to temperature gradient and thermal bowing until 30 minutes. Excessive (runaway) deflections were recorded after 30 minutes due to the degradation and loss of stiffness of the concrete and steel materials. There was no convergence after 40 minutes in the simulation signalling failure of the numerical model. The difference in test beam measurements and finite element predictions can be attributed to heat transfer coefficients assumed and the thermal properties of steel and concrete assumed at elevated temperatures.

The applied maximum load in the load control simulation were varied as ratios of 0.2, 0.4, 0.6, 0.8 and 1.0 of the flexural capacity of the composite beam at ambient temperature. It was found after the simulation that the higher the load before a fire event, the earliest it fails under combined service actions and fire loading.

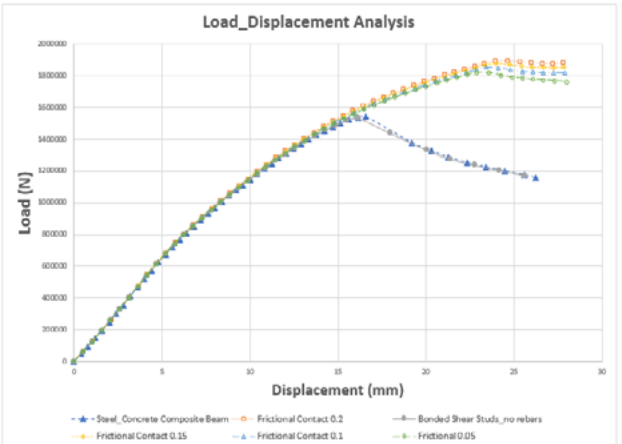

Fig 1 Load Displacement comparison of composite models under static load

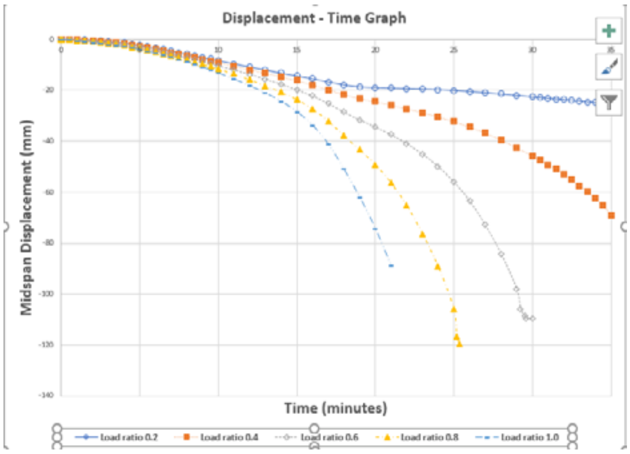

Fig 2 Model Validation

Parametric analysis considering combinations of different load ratios, fire scenarios, beam span, shear stud geometry and arrangement will be performed on the validated model to evaluate the macro performance of the steel-concrete composite beam and the micro performance of the shear studs under combined service actions and fire.

Finally, comparative analysis will be performed with universal steel beam (UKB sections) similar to that of the test beam and validated with results of (Aziz et al. (2015). The concrete strength and reinforcement ratio will also be varied and compared to the measured results of (Aziz et al. (2015).

This research addresses the gap in current design of shear studs in a steel-concrete composite beam under normal service conditions and fire. The flexural strength of steel-concrete composite beams depends on the shear performance of the shear studs that interlock the top concrete flange and the bottom steel beam. This research is useful for structural designers working on steel-concrete composite structures in buildings, bridges and towers. It is also beneficial to constructors and other professionals working in the construction space.

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Further Information

John Pascal Antwi (E: ja857@pgr.aru.ac.uk)
Supervisor: Dr Yingang Du (E: yingang.du@aru.ac.uk)

Mechanical performance of composite column connections with extended blind-bolt under shear loads

07 **Partha Pratim Debnath and Tak-Ming Chan**
The Hong Kong Polytechnic University, Hong Kong

Project objectives and goals

The popularity of fabricating beam-column connections with the use of high-strength blind-bolts have grown mainly due to its ease in installation, requiring less-skilled labour, demounatbility, and reduced wastages. The blind-bolts have been extensively used for connecting fabricated box or hollow section steel tubes with an open-section beam, and recently have also been widely accepted for inter-module connections due to reduced site works (Lacey et al., 2019). But the performance of bolted connections had insufficient moment resisting capacity and are usually regarded as pinned connections. Therefore, in this research the steel-concrete composite column having connections with modified blind-bolts are experimentally investigated to enhance the connection strength and stiffness. The blind-bolts have been modified with an extended shank and headed nut and has been experimentally and numerically investigated under tensile loading (Tizani and Pitrakkos, 2015, Debnath and Chan, 2021b, Debnath and Chan, 2021a). The performance of connection strength and stiffness was considerably improved due to the anchorage provided by the headed nut into the concrete core. As the performance of extended blind-bolt was well pronounced under tensile loading, its performance under shear loading also requires to be investigated. It is well perceived that under shear loading, the elongated bolt shank embedded into the concrete will have significant influence on the failure modes and connection performance due to the bolt shank bearing on concrete core and shearing at the tube-wall.

Thus, the important objectives of the project are to:

(a) Investigate the performance of composite column connections with extended blind-bolts under shear loading
(b) Provide component model to predict connection strength based upon experimental and numerical studies

The project goals are to:
(a) Provide direction towards developing moment-resisting frames with extended blind-bolted connections
(b) Develop design guidelines for extended blind-bolted connections, considering bolts in group

Description of methods and results

An experimental programme is undertaken at The Hong Kong Polytechnic University, to investigate the performance of extended blind-bolted connections with concrete-filled steel tubes (composite columns) under predominant shear loading. The experimental setup was made to resemble the practical boundary conditions as closely as possible, with fixed base support, and having sufficient length of column above and below the connection region. The blind-bolted connections were made through rigid plates in two opposite sides of the square composite column. The rigid plates were used instead of an open-section steel beam or thin plate to avoid the influence of plate thickness in the failure mode of the connection. To apply the shear loading, an inverted U-frame was fabricated and connected to the rigid plates and thus transfer the load to both the

Specimen	Peak load (kN)	Displacement at peak load (mm)	Failure mode
A-E65-C0-T6.3	238	14.3	Tube wall deformation around hole, bolt sleeve fracture, shank bending
A-E65-C40-T6.3	272	8.0	Bulging deformation around the hole, minor concrete cracks, bolt shear fracture
A-E92-C40-T6.3	286	9.1	Bulging deformation around the hole, bolt shear fracture
A-E107-C90-T6.3	266	9.5	Bulging deformation around the hole, bolt shear fracture
A-E92-C40-T8.0	293	11.0	Bulging deformation around the hole, minor concrete cracks, bolt shear fracture

Table 1

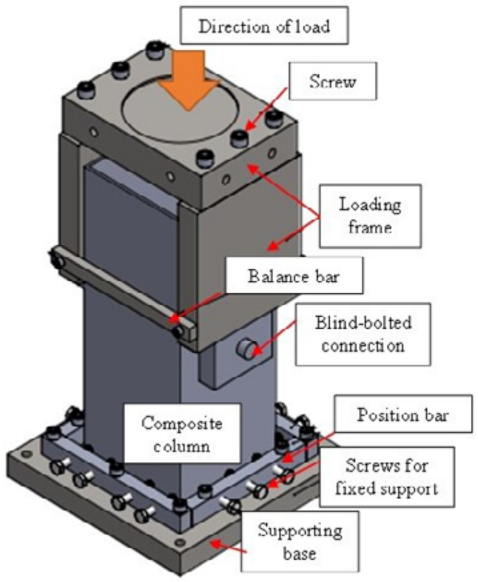

Fig 1 Schematic 3D view for the shear test set up

Fig 2 Tested specimen

connections in two sides. The schematic 3-dimensional view for the shear test setup is shown in Fig 1. The test was conducted using MTS Rock Mechanic system, and a loading rate of 0.3 mm/ min was maintained throughout.

For the investigation, several parameters including bolt embedment length, thickness of the steel tube and grade of concrete were considered to understand the influence on connection strength, stiffness, ductility and failure modes. To capture the deformations and failure patterns, displacement transducers, strain gauges and inclinometers were used during the experiment. The specimens are named in the format (1)-(2)-(3)-(4), where the first component refers to series name, second component refers to embedment length of the bolt in mm, third component refers to grade of concrete in MPa, and the fourth component refers to the tube wall thickness in mm. Table 1 presents the specimens and the corresponding peak loads and failure modes.

From the experimental tests, it is primarily observed that, for the steel column tested without any infill concrete, the connection failed at a lower load and higher tube wall deformation with significantly less stiffness, as compared to a concrete filled tube. The infill concrete not only enhanced the stiffness of the connection, but also an increase in 15% strength was observed. As the bolt embedment length was increased to 92 mm, there has been a further strength enhancement, indicating more load transfer to the concrete core, and thus increase in concrete contribution. When a higher-grade concrete and thicker steel tube are used, a significant change in peak load and stiffness can be observed, but the research also highlights that beyond a certain embedment length the connection capacity decreases. Therefore, it is required to obtain a combination of connection component strength with an optimum bolt embedment length to achieve desired strength and stiffness. A tested specimen is shown in Fig 2.

Potential for application of results

The findings of the ongoing experiments followed by extensive numerical analysis will be able to provide in-depth understanding of the behaviour of extended blind-bolted connection under predominant shear loading. The study will also be able to propose an analytical model to predict the connection capacity based on component strength, and thus make rational design for engineering application. The study can be taken forward to conduct experiments with combined tension and shear loading, and thereby developing a framework for moment-resisting bolted connection.

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Further information

Partha Pratim Debnath
(E:partha.debnath@connect.polyu.hk)
Tak-Ming Chan (E: tak-ming.chan@polyu.edu.hk)

Numerical study on structural behaviour of slim-floor composite beams

08 **Xinxin Xu**
University of Bradford, UK

Introduction

The CoSFB (Composite Slim-Floor beams) is a new type of composite structure in which the key feature is that an asymmetric steel-section with holes in the web is embedded in the infill concrete slab, and the infill concrete (with rebars or not) passing through the holes in the web. This concrete dowel is seen as an innovative shear connector.

Project objectives and goals

The finite element analysis is used to obtain the mechanism of shear transferring in composite slim floor beams, the aims are:

- Obtain the shear transfer mechanism between concrete slab and steel beam, shear resisting properties and flexural behaviour of composite slim floor beams
- Achieving the better understanding of the composite behaviour and failure mechanism to improve the properties of shear connections and integral composite system
- Develop the design procedures and methods for shear connections of the composite slim floor beams and composite slim floor beams

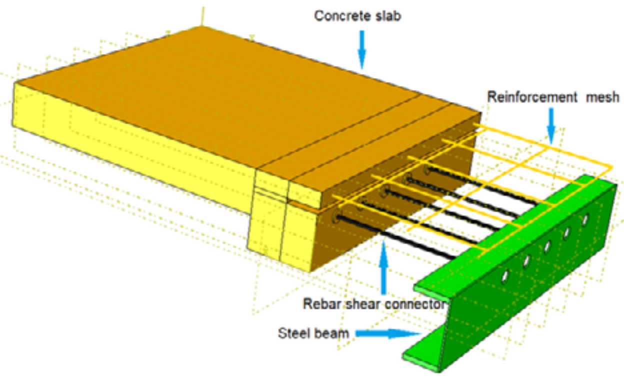

Fig 1 Component creation of a quartered tested POT specimen

In order to achieve this aim, there are objectives as follow:

1. A series of experiments data need to be collected from previous research project of University of Bradford, it is entitled 'Slim-Floor Beams – Preparation of application rules in view of improved safety, functionality and LCA'
2. Finite element modelling of composite slim floor beams can be simulated to access results by using SIMULA Abaqus/CAE, such as the shear resistance of shear connections, load-bearing and flexural behaviour of composite slim floor beams can be determined with the variety of the diameters of dowel and embedded rebar, material properties of concrete and steel section and so on
3. The simulation results of available should be evaluated and verified against the results of theoretical and experimental work from previous research
4. Developing the design methods and application rules in Eurocode 4 and outlook of numerical models analysis of composite slim floor beams

Description of method and results

The specimens of this project researched are mainly selected from the project entitled 'Slim-Floor Beams – Preparation of application rules in view of improved safety, functionality and LCA' (see Tables 1, 2 and 3). These models are used to analyse and validate against the results of push-out test and shear beam tests of slim-floor beams, flexural behaviour of slim-floor beams, and deflection and vibration of slim-floor systems, etc.

The modelling method has been conducted with similar modelling method for push out test by Fig.1, shear beam test and flexural beam test, which includes material properties determined (especially for the CDP, it has been analysed in detail as the concrete property has a great influence on the modelling results), loading and boundary conditions development and interaction and constraint analyse (contact factors have been analysed in detail between the concrete and steel, and better value has been recommend. Meanwhile, the effect of different interaction settings on modelling results have been analysed in detail).

Following the results comparation by Fig.2:

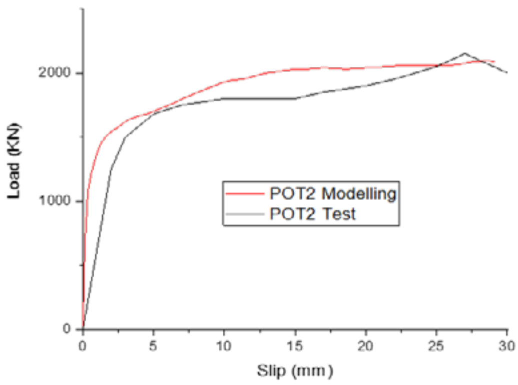

Fig 2 Comparison of Load – End slip from modelling and test

Series	Reinf. ∅	Hole ∅	Concrete	P_{Rk}	δ_{uk}	Failure
[-]	[mm]	[mm]		[KN]	[mm]	[ ]
POT 1	16	40	C25/30	220	21.2	Support
POT 2	12	40	C25/30	180	23.5	Shear connector
POT 3a	20	40	C25/30	309	17.9	Support
POT 3b	20	40	C50/60	358	24.7	Shear connector
POT 4	X	80	C25/30	75	10.2	Shear connector
POT 5	16	80	C25/30	242	20.5	Support
POT 6	16	40	C50/60	232	19.4	Shear connector
POT 7	16	40	C30/37	276	24.3	Shear connector
POT 8	20	40	C30/37	325	16.9	Support
POT 9	16	80	C30/37	245	39.7	Shear connector

Table 1 Overview Push-out test results

The feasibility of the model and modelling method has been validated for the shear resistance capacity and slip capacity of the shear connection and behaviour of shear beam test, and the model and modelling method are reliable and can be used to simulate these shear connector experiments on the concrete dowel shear connector system.

The outcomes form Abaqus do not fully catch the flexural performance of the composite slim floor beam through approach to the success. Therefore, more developments and improvements of modelling need to be implemented about flexure beam test on the composite slim floor beam in the future work. (Due to the limitation of the words and pictures, the simulation results of shear beam test in comparison of Load - End slip and Load – Mid span deflection, and flexural beam test in comparison of Moment - End slip and Moment – Mid span deflection have not been shown, but a better result compared with the experimental observations.)

SBT1a	-40% shear connection, with and without stirrups, eccentric loading
SBT1b	-40% shear connection, with and without stirrups, eccentric loading
SBT2	-40% shear connection, concentric loading, basic case
SBT3	-no shear connectors, eccentric loading
SBT4	-no topping, concentric loading
SBT5	-larger holes
SBT6	-shear studs
SBT7	-larger holes but without transverse bars passing through them

Table 2 Overview of the shear beam specimens

FBT1a	-basic test configuration (40% shear connection)
FBT1b	-basic test configuration with no bar, uniform distributed load
FBT2	-eccentric loading
FBT3	-100% shear connection
FBT4	-25% shear connection
FBT5	-no top cover
FBT6	-no shear connector
FBT7	-horizontal studs as shear connectors
FBT8	-large openings, without shear connector

Table 3 Overview of the flexural beam specimens

Parametric study

It has been represented that parameter of two mainly composite elements have a great influence on the composite slim floor beams:

- Influence of the concrete dowel size: the diameter of the concrete dowel has an influence on the load bearing capacity of shear connection, it provides the effective local compression resistance and tensile splitting resistance to shear connection. However, the slip stiffness of shear connection has a significant decrease with the increasing of the shear connector size. Therefore, the bigger size of shear connector should be avoided during the design of composite floor beams
- Influence of the concrete strength: the concrete properties have a great influence on the overall behavior of shear connection. The longitudinal shear resistance of shear connection can be significantly improved with increasing of concrete strength including compression strength and tensile splitting strength of concrete. Meanwhile, the slip capacity of shear connection can be developed with the increasing of concrete strength

Conclusion

The models of push out test and shear beam test have been developed and validated against the experimental test on the composite slim floor beam, and these models can be used for parametric study. Therefore, development of a series simplified calculation for slim-floor composite beams will be the main work for the next stage work.

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Smart net-zero energy structural control

09 **Lefteris Koutsoloukas**
University of Leeds, UK

Project objectives and goals

The project aims to develop a novel, energy-efficient, active tuned mass damper (ATMD) in order to minimize the dynamic responses of real civil structures. In achieving this aim, the following objectives were set:

- Develop a robust controller to account for parametric and actuator uncertainties which was proved to be efficient in other sectors
- Develop a machine learning based algorithm to achieve vibration dissipation while, achieving low power consumption
- Reduce the system's power consumption by designing a novel mode-of-operation of the mass damper where all passive, semi-active and active capabilities of the system are used and controlled by a reinforcement learning algorithm
- Design an energy harvesting system to make the ATMD self-sustained and to account for power-cuts during earthquakes which would cause the ATMD to lose its function

This project is a collaboration between the University of Leeds and the GERB (www.gerb.com). The company is responsible for the structural control of the real Rottweil tower in Germany. With their control scheme, the active system demonstrated poorer vibration dissipation performance than a conventional passive tuned mass damper (PTMD), which is an unexpected behaviour given the capabilities of the ATMD. Thus, the first two goals investigate ways to enhance the performance of the ATMD by utilizing ingenious algorithms and machine learning methods that have not been applied in structural control but have been proven to be efficient in other applications such as unmanned aircrafts, autonomous driving, and humanoid robots. In addition, the biggest hesitance towards implementing active control for structural applications is their high energy requirements. Thus, the third and fourth goals are set to take advantage from the available software and hardware, in order to firstly reduce its energy requirements and then turn it into a self-sustained system. This will lead to the application of the current findings to other structures.

Description of method and results

The Rottweil tower is a 245m tall structure located in Germany (Fig 1) and is a test-tower for high-speed elevators equipped with an ATMD (Fig 2). For the operation of the elevators, the top floor displacements of the tower cannot exceed a limit of 200mm. GERB provided the specifications of the installed ATMD, the wind load profiles and the finite element model of the tower which was used to derive a mathematical model of the tower. After discussing with GERB, it was realised that a possible reason for the deteriorated performance of the ATMD is that their control scheme did not account for parametric uncertainties that may arise from modelling errors, environmental effects (e.g. temperature) and damage, and actuator uncertainties. Thus, a robust algorithm capable for handling uncertainties, namely Robust Model Predictive Controller (RMPC), was implemented for the first time in civil structural control. Its performance was compared to the well-established robust controller, H_∞, and to a PTMD.

As seen in Table 1, the RMPC had an enhanced performance compared to the H_∞ and to the PTMD, and it managed to decrease the top floor displacements within the desired limit in contrast to the H_∞ and the PTMD. The work is published in Koutsoloukas et al. (2021a).

The realisation of gaining considerable performance through only a control strategy led to the rapid evolution of machine learning-based algorithms. Reinforcement learning (RL) is a machine learning biomimetic method which earns its effectiveness by interacting with a given environment. This means that the algorithm learns by trial-and-error until its capable of acting independently to achieve its

Floor	Uncontrolled	PTMD	H_∞	RMPC
Top	256mm	218mm	210mm	187mm

Table 1 Top floor displacements with parametric and actuator uncertainties

Floor	Uncontrolled	PTMD	LQR	DDPG
Top	248mm	226mm	195mm	192mm

Table 2 Top floor displacements

Fig 1 Rottweil tower

Fig 2 The installed ATMD

goals. RL algorithms have been proven to be efficient for the control of walking humanoid robots, meaning they could be promising when applied for structural control purposes. In Koutsoloukas et al. (2021b), a RL algorithm was investigated namely, Deep Deterministic Policy Gradient (DDPG) and compared to a PTMD and to the well-established controller, the Linear Quadratic Regulator (LQR). The DDPG was found to be efficient on dissipating the dynamic responses of the tower. As seen in Table 2, both the DDPG and the LQR managed to keep the top floor displacements within the desired limit in contrast to the PTMD. Moreover, the DDPG achieved its performance by requiring a lower power consumption compared to the LQR. This demonstrates the potential of applying RL algorithms for the control of the system using a novel mode-of-operation.

Potential for application of results

Koutsoloukas et al. (2021c) reviewed the structural control applications around the world. From the analysis that was conducted therein, it was documented that the industry is extremely sceptical on installing active control systems, and they tend to prefer the more conventional PTMDs. It is believed that one of the main reasons is that the PTMDs do not require external energy to operate. This work demonstrates the superiority of the active systems over the PTMDs when applied on real structures. Additionally, the next steps will lead towards turning the ATMD into a self-sustained system by harvesting its own energy. Finally, the findings of this work highlight the potential of implementing active control on every-day devices (e.g. medical equipment, sculptures) beyond one-off super tall buildings.

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Funding body

University of Leeds

Further information

Lefteris Koutsoloukas (E:cn15lk@leeds.ac.uk)

Collaborators

School of Civil Engineering, University of Leeds
Department of Electrical Engineering & Computer Engineering and Informatics
Cyprus University of Technology; GERB Vibration Control Systems

The role of vertical extensions in decarbonising the built environment

10 Charles Gillott
The University of Sheffield, UK

Background

By 2030, 41% of buildings' whole life emissions are expected to be from embodied carbon (UKGBC, 2021). Consistent with the transition to a circular economy, this has led to increasing recognition of the importance of reusing existing buildings, rather than demolishing and building new.

Vertically extending buildings offers opportunity to reduce embodied carbon whilst meeting an increasing population's growing demand for floorspace. Despite this, and recent introduction of vertical extension permitted development (PD) rights (HM Government, 2020), uptake remains limited. This necessitates a greater understanding of the technical and non-technical factors surrounding the adoption of building reuse strategies, as well as the potential for reuse and vertical extension beyond the single-building scale.

Project objectives and goals

The project may be split into 3 areas, with objectives as follows:

1. Explore current drivers and barriers of vertical extension (and wider building reuse), as well as potential enablers to boost future uptake.
2. Identify the amount by which the typical reserve structural capacity of existing buildings allows them to be vertically extended.
3. Investigate the potential for space generation that vertical extension offers at different spatial scales.

Description of methods and results

Objective 1:

A sequential, explanatory mixed methods study comprising an initial survey of 60 construction sector stakeholders has been completed, followed by 11 semi-structured interviews with those exhibiting particular experience in building reuse and vertical extension. This considered the views of researchers, planners, architects, engineers, quantity surveyors, contractors and clients. Both quantitative and qualitative data was collected, with the latter being processes in a latent, inductive thematic analysis.

This identifies that, although sustainability benefits are acknowledged, the *potential* to increase an asset value at a reduced cost is the primary driver for vertical extension. It is also suggested that if a business case for extension exists, this will drive its implementation regardless of the level of reserve structural capacity within the building.

Difficulty in ascertaining, and uncertainty in, the business case for building reuse projects are identified as barriers. This is contributed to by VAT rates, which presently favour new build over refurbishment or retrofit. Additional barriers include engineers' inexperience in appraising existing structures, poor availability of original design information, and the requirement to design within the constraints (e.g. structural grid, core size, floor-to-ceiling height) of an existing building.

Objective 2:

A parametric assessment framework has been implemented in Rhino 3D (Rhinocerous, 2021), utilising Grasshopper and GSA plugins (Oasys, 2021). Using inputted design criteria (imposed loads, structural grid, section sizes etc.), and with a focus on vertical load transfer systems, this appraises the structural resistance offered by a building using finite element analysis. Calculated design resistances are then compared with presently experienced design loads to identify reserve structural capacity.

A suite of case-study building designs obtained from structural engineering practices are to be analysed using the developed framework. These are selected to cover a range of building archetypes, providing results that detail the typical reserve structural capacity (kN/m^2) – and thus extendibility (no. of storeys) – of common building typologies.

Objective 3:

By assigning building attributes (age, use, building height, number of storeys etc.) (Geomni, 2020) to building footprint polygons (Ordnance Survey, 2021), existing buildings meeting the criteria dictated by vertical extension (PD) rights have been identified. Using the limits set out in PDs, the number of storeys which may permissibly be added to each building, and thus the floor area that can be generated, have then been calculated.

Repeating this process across the whole of England identifies the quantity of new useable floorspace that may be generated through vertical extension, where this is located, and over which existing building archetypes.
Potential for application of results

The results outlined above pertaining to objective 1 have already been used in the formation of policy and planning recommendations, for example: mandatory whole-life carbon assessments and regulation, and adjustment of VAT tariffs. Suggestions of amendment of undergraduate engineering education and compulsory CPD have also been made, including increased focus on structural appraisal techniques and circular economy in construction.

As well as in influencing objective 3, results meeting objective 2 will provide an initial insight into which building archetypes are likely to be particularly suited to vertical extension. This may be used within industry and policy formation to inform areas of focus for future reuse/extension projects, and to set initial extendibility benchmarks for use in concept design.

There is potential for the results obtained in meeting objective 3 to be applied in additional works considering the typical reserve capacity of each archetype (obtained from objective 2). Further analyses considering the impact of increasing density in the identified areas (e.g. on transport, service provision and wellbeing) may also be completed. Beyond research, these results may be used to inform future planning policy by identifying shortcomings of existing PD rights.

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Funding body

Engineering and Physical Sciences Research Council (EPSRC)

Further Information

Charles Gillott (E: cgillott1@sheffield.ac.uk)
Research profiles:
https://grantham.sheffield.ac.uk/scholars/charles-gillott/
https://urbanflows.ac.uk/vertical-extension-of-existing-buildings/

Collaborators

Danielle Densley Tingley, The University of Sheffield
Buick Davison, The University of Sheffield

Structural behaviour and design criteria of segmental high-speed railway bridges

11 **Javier Cañada Pérez-Sala**
Imperial College London, UK

Project objectives and goals

Precast Concrete Segmental Bridges (PCSBs) constitute an efficient and fast alternative for bridge construction that has been widely used in the past decades. The structural behaviour of this type of bridges is conditioned by the presence of joints between the segments where the steel reinforcement is interrupted.

Until recently, very few high-speed railway (HSR) bridges had been constructed using this technology (Combault, 2013). However, the interest in PCSBs for HSR is rapidly growing, as reflected by the choice of PCSBs for the two most significant structures in phase 1 of the High-Speed 2 project in the United Kingdom.

The existing research on PCSBs focuses on road applications, and despite several models being proposed for these bridges, none has addressed the effects of the loads generated by high-speed trains. Thus, this project aims at explaining the singularities and structural behaviour of PCSBs for HSR lines and propose a specific set of design criteria, including the optimisation of the prestressing.

Description of methods and results

Studying the behaviour of PCSBs for HSR lines requires developing an efficient numerical model for vehicle-structure interaction which also includes the critical features of PCSBs, namely, opening of the joints, concrete non-linearity and behaviour of the external prestressing.

In this project, a finite element model of a PCSB has been created using the software ABAQUS (Dassault Systèmes, 2018). Due to the absence of experimental data from PCSBs in HSR lines, the modelling strategies have been calibrated using the results from Takebayashi et al. (1994), who conducted a destructive test on a full-scale model of a precast concrete segmental span. The model has been further validated with the experimental results obtained by Fouré et al. (1991).

The proposed 3D model uses shell elements for the concrete box girder and beam elements for the prestressing tendons. The external tendons are allowed to slip at the deviators accounting for the effects of friction. The joints are modelled using node-to-node contact elements with null length and hard contact formulation. Friction at the joints follows a Coulombian model enforced through the penalty method. For the top slab, two contact elements are used in the thickness of the slab for each node of the mesh of the segment (Fig 1).

In general, the model has shown very good agreement with the experimental tests. The model matches well the experimental stiffness both before and after opening of the joints, accurately predicting the decompression and failure moments. The model also reproduces well the opening of the joints and the stress increments in the tendons.

The calibrated model has been used to analyse the influence of various parameters on the behaviour of the bridge such as the level of prestressing, the slip of external tendons at the deviators, the modelling approach for the joints, the debonding of internal tendons at the joints and the presence of epoxy at the joints.

After calibration, a model has been created for a benchmark case for a PCSB for HSR. The benchmark case is inspired in the viaduct of La Boëme (Cordova et al., 2013) in the SEA Tours-Bordeaux high-speed line in France.

The behaviour of this benchmark case has been studied under the static loads for railway bridges defined in the Eurocodes and the dynamic load of a real train (Pring, 2019). The levels of prestressing required to avoid joint opening under different service and ultimate limit states have been determined (Fig 2). The dynamic analysis of the bridge accounts for wheel-track interaction, irregularities of the track and rail-structure interaction. It has been observed that the opening of the joints changes considerably the dynamic behaviour of the bridge, but this joint opening is not expected to happen under the exploitation loads for the levels of prestressing required to comply with the service and ultimate limit states.

Potential for application of results

The results of this project would permit assessing the validity and establish the limits of applicability of simplified design approaches for PCSBs, such as ignoring the effects of the joints or the slip of tendons at the deviators.

Moreover, this project should allow defining a set of design criteria for PCSB for HSR that permit avoiding over-conservative design approaches. The development of these design criteria could help in extending the use of this type of bridges for high-speed lines and thus contribute to the wide implementation of prefabrication on

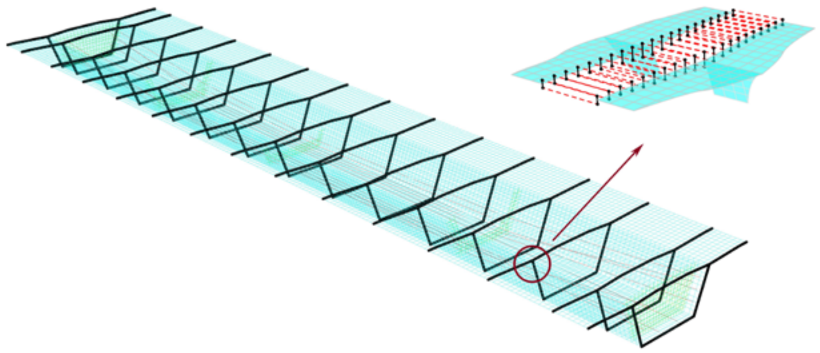

Fig 1 Finite Element mesh for the model of the test span and detail of the joints at the top slab

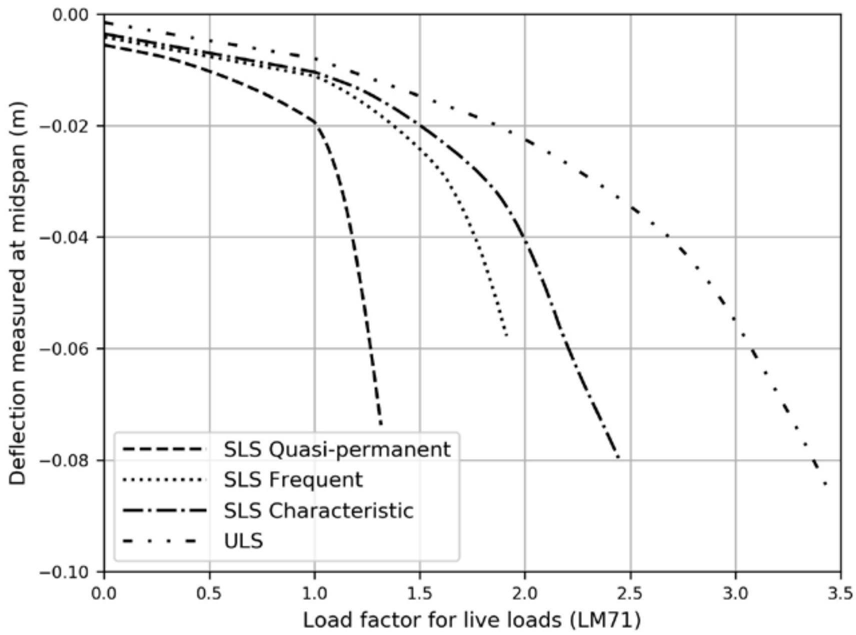

Fig 2 Live load – deflection curves for different levels of prestressing corresponding to the opening of the joints at different limit states

the construction of high-speed railway bridges regardless of the span length, with all its associated advantages in terms of economy, ease and speed of construction and environmental sustainability.

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Further information

Javier Cañada Pérez-Sala (E: jc12118@ic.ac.uk).
Ana M Ruiz-Teran (E: a.ruiz-teran@imperial.ac.uk (supervisor)).

Fire design of steel structures through second-order inelastic analysis with strain limits

12 **Hasan Murtaza**
University of Warwick, UK

Project objectives and goals

- To establish a fire design approach for structural steel members and systems.
- To provide engineers with an advanced structural steel fire design method which results in more accurate and efficient fire design of steel structures.
- To promote the use of finite element analysis in structural fire design in industry.

Description of method and results

The research project is aimed at developing a design approach referred to as second-order inelastic analysis with strain limits for the design of steel structures in fire. This method combines computationally efficient beam finite element (FE) analysis with capacity limiting strains to produce a self-contained design approach capable of predicting the behaviour of steel structures subject to both global local instability effects in fire. The strain limits are adopted to account for the effects of local buckling during analysis and are derived from the continuous strength method (CSM) base curve which relates cross-section deformation capacity with cross-section slenderness $\bar{\lambda}_p$ (Gardner, 2008). The loss of strength and stiffness, the spread of plasticity, global instability and thermal effects are fully taken into account by second-order inelastic analysis performed using beam finite elements. Previous research has successfully applied this method to the ambient temperature design of carbon steel and stainless steel structures (Fieber et al., 2020; Quan et al., 2020; Walport et al., 2021). The present research extends this method to the fire design of steel structures.

Modifications have been made to the second-order inelastic analysis with strain limits design approach previously established for room temperature structural steel design so that it can be employed for the design of steel structures at elevated temperatures. These include (i) changes to the base curve formulation to account for the rounded nature of the stress-strain material response in fire and (ii) the adoption of a steel material model and equivalent geometric imperfections appropriate for fire design. For the purpose of assessing the accuracy of the proposed method, results from benchmark shell FE models which are extensively validated against experimental fire tests found in the literature are used. Thus far, the proposed method has been assessed for the design of steel columns in fire. The assessment has comprised isothermal and anisothermal analysis techniques and included columns with axial and rotational end-restraints. The results indicate that the proposed method provides safe capacity predictions which are both more accurate and consistent compared to the ultimate strength estimations determined through the upcoming version of the European structural steel fire design standard prEN 1993-1-2 (2019). This can be seen in Fig 1 and Fig 2 which compare the capacity predictions from benchmark shell FE models $N_{ult,\theta,shell}$ to those achieved using the proposed method $N_{ult,\theta,prop}$ and prEN 1993-1-2 (2019) $N_{ult,\theta,EC3}$.

Potential for application of results

If the research continues to demonstrate that the proposed fire design by second-order inelastic analysis with strain limits approach provides accurate and safe-sided design predictions, there may be a possibility for its incorporation into design guidance in the future. This will furnish structural engineers in industry the opportunity to design structural steel members and systems in fire more accurately using the proposed fire design method.

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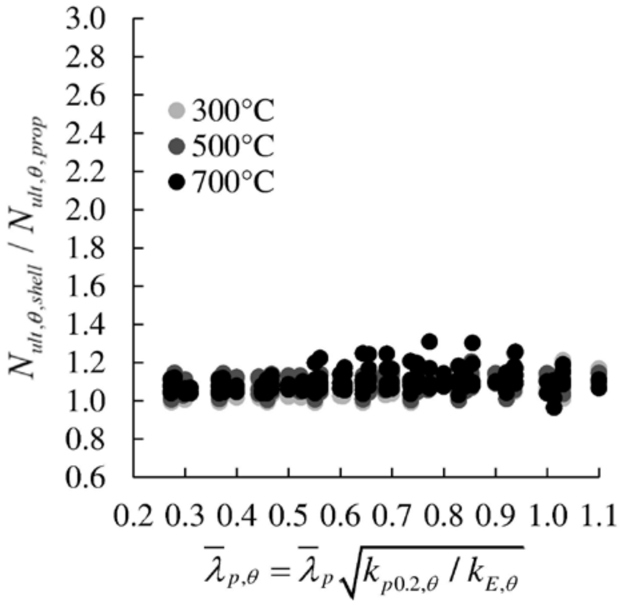

Fig 1 Comparison of the accuracy of the proposed method against benchmark shell FE model capacity predictions for steel columns analysed adopting the isothermal analysis method

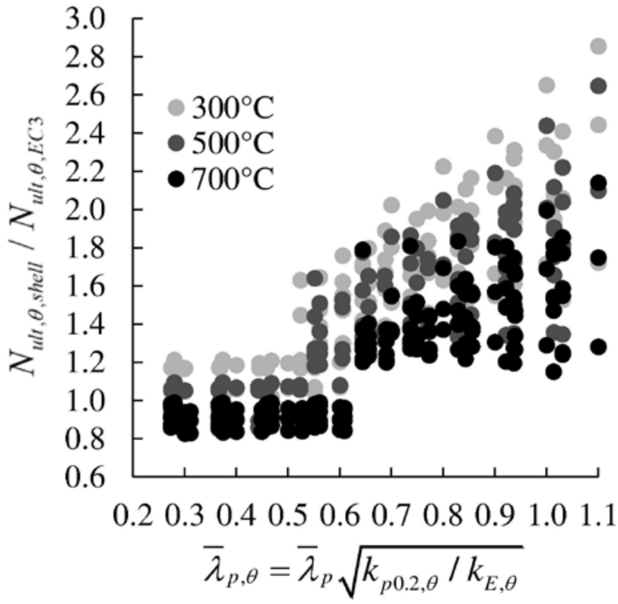

Fig 2 Comparison of the accuracy of prEN 1993-1-2 (2019) against benchmark shell FE model capacity predictions for steel columns analysed adopting the isothermal analysis method

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Funding body

University of Warwick

Further information

Hasan Murtaza (E: hasan.murtaza@warwick.ac.uk)
Merih Kucukler (E: merih.kucukler@warwick.ac.uk)

Bipedal inverted pendulum for modelling vertical pedestrian-structure interaction on footbridges

13 **Bintian Lin**
University of Exeter, UK

Project objectives and goals

The aim of this project is to enable accurate prediction of human-induced vertical vibrations on footbridges by developing a reliable model of a pedestrian. The model will, in turn, facilitate design of more comfortable and more sustainable structures. The main modelling challenge is to realistically account for how pedestrians interact with deck vibrations they are exposed to. A novel bipedal inverted pendulum (BIP) model has been developed to model the interaction. To achieve this, the following objectives have been set:

1. Develop and verify BIP model on rigid (non-vibrating) surface by comparing measured and predicted ground reaction forces (GRFs),
2. Build a theoretical framework for simulating BIP-represented pedestrian crossing a footbridge, and
3. Verify the framework on a footbridge by comparing the measured and simulated GRFs and the corresponding vibration responses.

Description of method and results

Modelling pedestrian's GRF based on data from rigid surfaces could overestimate the structural vibration response up to four times (Dang, 2014). More detailed recent studies of GRFs on wobbly bridges documented a drop in the amplitude of the main harmonic of the pedestrian-generated dynamic force, (Ahmadi et al., 2018), suggesting that the pedestrian adapts their locomotion style to the vibrating footbridge deck. This pedestrian-structure interaction is currently not addressed in the footbridge design guidelines, leading to over- or under-design of pedestrian structures. To improve this situation, it is crucial to develop a theoretical framework for describing human walking on vibrating structures. This project draws inspiration from the developments of the research field of biomechanics. For example, Geyer et al. (2006) proposed a BIP with a lumped body mass supported by deformable legs to model the characteristic M-shape of vertical GRF (Fig 1). Qin et al. (2013) upgraded this model by introducing damping to the leg and a control force acting on the mass. The hypothetical control force has not yet been verified by the real human walking data.

To achieve the first objective of this project, a novel BIP model has been developed to model human walking on the rigid ground (Fig. 1). As real legs deviate from the perfect spring (Riese and Seyfarth, 2012), the new model compensates for the energy dissipation due to leg damping by reducing the stiffness and increasing the rest length of the spring. The BIP has been calibrated and verified by comparing the simulated (grey line in Fig. 1) versus measured GRF (black line in Fig. 1).

For the second objective, the calibrated BIP has been applied to the footbridge. Motion equations of the coupling system have been derived, simulating the footbridge with either the modal coordinates or finite element model, to calculate the footbridge's vibration response (mid-span acceleration in Fig. 1) and BIP's walking GRFs.

To realize the third objective, the body motion and GRFs data have been collected from treadmill walking on vibrating platform (VSimulators). Vibration response of a full-scale footbridge (Exeter Bridge) remains to be measured in controlled walking tests and used for verification of the pedestrian model. Successful completion of the project will inform development of future vibration serviceability design guidelines for footbridge structures.

Potential for application of results

The outputs of this project can be used for:

- Modelling pedestrian traffic on footbridges.
- Accurate estimation of the pedestrian-induced vibration response of footbridges.
- Improved design of vibration control devices and improved comfort of pedestrian bridges.
- Update of vibration serviceability design guidelines for footbridges.

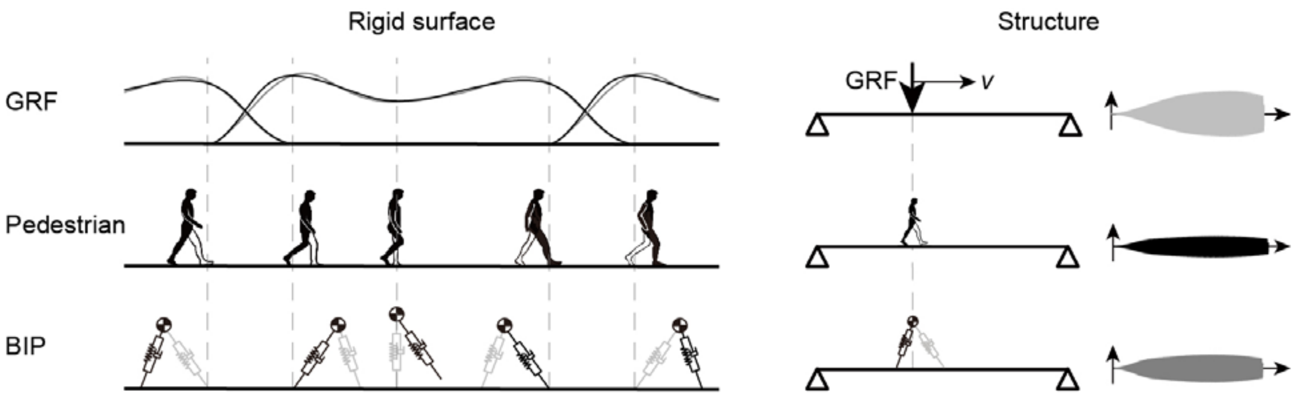

Fig 1 Modelling pedestrian walking on both rigid and vibrating surfaces

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Further information

Bintian Lin (E: b.lin@exeter.ac.uk)
Stana Zivanovic (E: s.zivanovic@exeter.ac.uk)

Collaborations

School of Civil Engineering, Harbin Institute of Technology.

Investigating the effects of freeze-thaw cycles on the bond behaviour of lime-based TRM composites

14 Ali Dalalbashi
University of Minho, Portugal

Introduction

Textile-reinforced mortars (TRMs) have recently received attention as a sustainable option for strengthening masonry and concrete structures. TRMs are composed of fibres (or grids) embedded in an inorganic matrix. The most critical parameters in the efficiency of TRMs for strengthening purposes are their mechanical performance and the bond behaviour at the fibre-to-mortar interface. However, the lack of information on their durability and long-term performance has limited their application.

Project objectives and goals

The project aims to investigate the role of freeze-thaw (FT) conditions on the micro-mechanical response of TRM composites. FT conditions are chosen as critical environmental conditions, mainly when TRMs are applied on the outside of the buildings. Two different TRM systems (glass-based and steel-based) commonly used to repair existing structures are used for the purpose of this study.

Experimental program

A set of TRM composite specimens was prepared and cured 90 days in the laboratory environments. Then, the specimens were exposed to zero and 360 FT cycles or stored in the lab condition as control specimens. FT cycles involved thawing (at 30°C and 90% RH for two hours) and freezing (at -10°C for two hours) the samples. After that, a series of multi-level post-exposure tests were conducted to investigate the material characterization and bond behaviour of TRM composites.

The material properties were determined by the differential thermal analysis (DTA), compressive strength, and flexural strength of the mortar. A single-sided pull-out test setup developed by (Dalalbashi et al., 2018) was used to investigate the fibre-to-mortar bond behaviour. To evaluate the bond length's role, different embedded lengths were considered for each type of fibre, as shown in Fig. 1, (50, 150, 200, and 250 mm for steel, and 50, 75, and 100 mm for glass-based TRM). Two U-shaped steel supports fixed the specimens during the pull-out tests (Fig. 2), and a jack applied tensile loads to the fibre under displacement-controlled conditions and at a rate of 1.0 mm/min.

Results and discussion

Material properties. DTA results illustrate that decarboxylation increases with time under the control and the FT conditions due to the large amount of $CaCO_3$ compared to the specimens at zero cycles. Therefore, the used lime-based mortar is still hardening at older ages under both conditions. Table 1 reports the changes in the strength of mortar under both conditions. The mortar compressive and flexural strength remains constant until the end of tests under both conditions. These observations show that the considered FT conditions do not have a detrimental effect on the mortar strength but lead to a slight enhancement of properties, possibly by promoting mortar hydration under high humidity conditions.

Strength [MPa]	0 cycle	Control	FT
Compressive	16.8	17.3	18.8
Flexural	4.5	4.7	5.0

Table 1 Changes in mortar mechanical properties

Pull-out response of steel-based TRM. Table 2 lists the changes in the pull-out response of steel and glass-based TRM composites under the control and the FT conditions with respect to the zero cycles. The peak load (PP), the debonding energy (Edeb), and the pull-out energy (Epo) are the main parameters obtained from pull-out tests. All pull-out parameters show, in general, a gradual decrement under both the control and the FT conditions. It can be inferred that the bond parameters are deteriorated equally under both conditions, showing the proposed FT condition was not harsh enough. It seems other parameters cause the bond degradation to occur in both conditions, such as the long-term shrinkage effect by forming micro cracks at the bond interface. Continuing hydration may lead to chemical shrinkage due to a reduction in the hydration volume of anhydrous compounds (Duran et al., 2014).

Pull-out response of glass-based TRM. Due to the same decrease in pull-out parameters of the glass-based TRM with 50 mm bond length under both conditions, the proposed FT condition does not affect the bond behaviour. One possible explanation is the negative impact of mortar hydration on the bond behaviour of these specimens, which continues until the end of the tests at both conditions. This negative effect can manifest in the form of chemical shrinkage or notching of the yarn surface due to the formation of precipitates (De Munck et al., 2018). On the other hand, the mortar hydration does not affect the pull-out

Fibre	Embedded length [mm]	Condition	Change in pull-out parameters with respect to zero cycles		
			P_P [%]	E_{deb} [%]	E_{po} [%]
Steel	50	FT	-29	-24	-32
		Control	-9	-94	29
	150	FT	9	-1	11
		Control	-32	-85	-1
	200	FT	-16	-75	11
		Control	-21	-22	-5
	250	FT	3	-37	-
		Control	-8	17	-
Glass	50	FT	-39	-85	-38
		Control	-39	-70	-33
	75	FT	18	300	-
		Control	13	-2	-
	100	FT	21	32	
		Control	16	2	

Table 2 Changes in the bond parameters

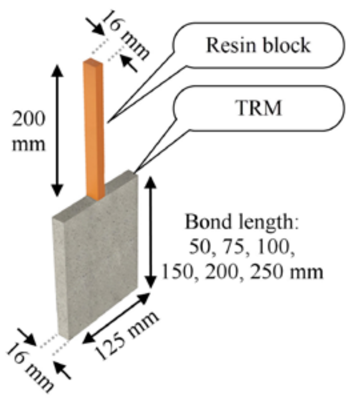

Fig 1 The geometry of pull-out specimens

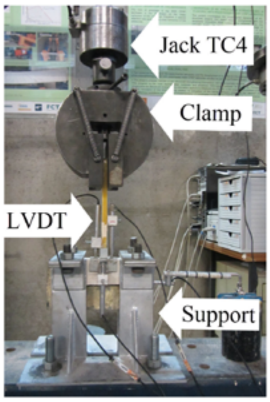

Fig 2 Pull-out test setup details

parameters of specimens with 75 and 100 mm bond length, which can be due to the longer embedded length of these specimens than specimens with 50 mm embedded length.

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Further information

Ali Dalalbashi (E: alidalalbashi@gmail.com)

Collaborations

Dr. Bahman Ghiassi
Assistant Professor, University of Nottingham, United Kingdom.

Dr. Daniel V. Oliveira
Associate Professor, University of Minho, Portugal.

New Zealand sustainable move towards cold-formed steel housing with thermally efficient structural solutions

15 **Yazeed Al Radhi**
The University of Auckland, New Zealand

Background

The construction industry motive towards the climate emergency response is shifting with unprecedented pace towards engineering practices embracing net-zero carbon solutions (Plan, 2015). In New Zealand, 20% of all energy is consumed in the building operational energy, while 65% - 70% of the operational energy come from electricity usage (MBIE, 2019).

New Zealand is committed to reduce emissions by 30% below 2005 levels by 2030. This is in response the Climate Change Response (Zero-Carbon) Amendment Act 2019 to a minimum of 20% (MfE, 2018). As a result, the demanding legislation in New Zealand to reduce energy consumption in buildings has challenged the research and construction sectors.Achieving this requires engineers to realise the impact of their designs on the industry emissions.

The population growth in New Zealand struggles with the lack of new housing. A shortfall estimate of 45,000 dwellings has been identified for Auckland only (Johnson et al., 2018). Fig 1 illustrates the national dwellings growth from 1995 to 2020. It indicates a large scope of residential development will be witnessed in the next two decades.

The New Zealand local dwelling is witnessing a market shift towards cold-formed steel (CFS) as it offers many advantages (Veljkovic and Johansson, 2006). Detached dwellings have been selected for this research, given it represents approximately 77% of NZ housing projects (McLaren et al., 2020). Moreover, the new builds are selected since they are the initial focus of Ministry of Business, Innovation and Employment (MBIE) frameworks since more stringent and complex regulations are foreseen (MBIE, 2020).

Furthermore, the framework suggests a public repository for data as most of the existing literature for NZ dwellings focused on timber-framed housing. It is estimated the NZ residential dwellings are 93.1% of timber and the remaining mostly steel framed in 2018 (Lockyer and Brunsdon, 2019).

Therefore, cold-formed steel housing is selected for this research to provide more understanding and data towards zero-net carbon construction. On the other hand, steel is a very thermal conductive material concerning its insulation and is susceptible to forming thermal bridges (Roque and Santos, 2017). Hence, it is considered another scope for this research.

Project objectives and goals

This research aims to analyse the impact of current construction methods on cold-formed steel on climate change and proposes structural framing solutions to reduce thermal bridging on CFS buildings.

The objectives of this research are:

- Assess climate change potential of a typical single-detached steel framed housing in New Zealand against timber house using life cycle assessment tool.
- Perform FEA thermal modelling to assess the building R-value for different steel wall arrangements inclusive of clear wall and framed walls.
- Conduct full-scale laboratory tests to validate the thermal & structural performance of the proposed walls systems
- Investigate staggered wall arrangement as an alternative towards thermally efficient walls.
- Validate and extend FEA models to a further parametric study.

No.	Gross Floor Area	Foundation	Frame	Cladding	Roof
House 1	196 m2	Concrete Waffle Slab	Timber	Timber Weatherboard	Metal
House 2	237 m2	Concrete Waffle Slab	Light Steel	Masonry	Metal

Table 1 Details of assessed new consented houses in New Zealand

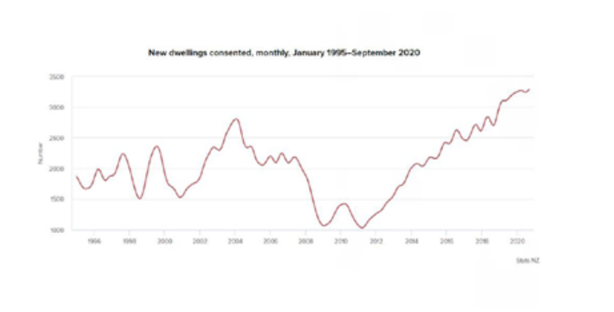

Fig 1 New dwellings consented monthly from Jan 1995 to Dec 2020 (NZ, 2020)

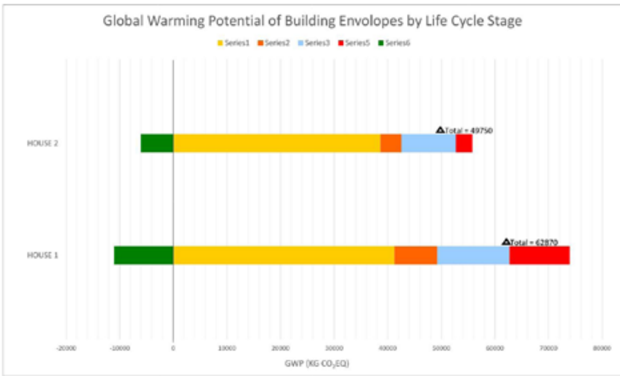

Fig 2 GWP of House 1 (Timber) and House 2 (Light Steel)

Description of method and results

Initially, the research assessed a new steel-framed house's life cycle analysis (LCA) with a concrete foundation as per detail in Table 1. The building construction is to be kicked off in 2022. A timber house of approximately a similar area is assessed for comparison.

Findings of the global warming potential (GWP) of the building envelopes by life cycle stage is detailed in Fig 2.

The research extends the scope to investigate the thermal efficiency of exterior walls as part of proposed structural framing solutions. The research dictates most of the scope on the thermal efficiency of steel walls, which shall improve the house's operational energy. Thermal FEA models are developed to assess the current steel arrangements. Full experimental testing is planned to validate the numerical outputs. Proposed new walls solutions of staggering the studs one of the thermal solutions.

Potential for application of results

The research is conducted in collaboration with NAHS, BRANZ and the University of Auckland to implement the findings for new industrial design guidelines. The research will encourage steel manufacturers towards passive energy construction techniques in sresponse to the zero-net carbon motive in New Zealand.

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Funding body

Callaghan Innovation, New Zealand.

Further Information

Yazeed Al-Radhi (E: yalr550@aucklanduni.ac.nz)

Collaborators

Department of Civil Engineering, University of Auckland, New Zealand.

National Association of Steel Housing (NASH), New Zealand.

Building Research Association New Zealand (BRANZ).
FrameCAD Limited.

Feasibility study of novel inter-modular connections for a reinforced concrete modular building

16 **Hafiz Zain Saeed**
MONASH University, Malaysia

Abstract

The increased productivity demands have revolutionized the precast industry from 2D to 3D; providing prefinished prefabricated volumetric modules that are connected onsite using efficient connections. Most of the existing connections require lot of site activities and delay the completion time which is among the major setbacks to this technology. However, in case of reinforced concrete modular buildings which ensure less or even maintenance free structures, in-situ wet connections are implemented which accommodate the various construction and fabrication eccentricities unlike the bolted connection for steel modular buildings.

The present research proposes a novel connection technique for joining the vertically stacked reinforced concrete load bearing modular walls using cold-formed steel sleeve and high strength grout. This connection will not only ensure safety and integrity of the structure but is more convenient to implement on site with least workers; enjoying the full benefits of this modular technology. The feasibility of proposed connection under uniaxial tensile load is investigated by numerical simulation in popular finite element software Abaqus. Simplified design equations predicting the strength of proposed connections will be developed along with set of design guidelines for the modular construction industry.

Introduction

With increase in outspread of pandemics, there is a need to find new alternative construction techniques that would increase the construction productivity, safety and efficiency (Liew et al., 2019) (Zhao et al., 2019). The development of a modular composite building will solve many problems including shortage of housing facilities, construction delays, material wastage and storage issues at congested sites etc., faced by the modern construction industry.

Inter-module connections (connection at module level) play an important role in overall performance of the modular building (Chua et al., 2020). These are executed onsite with a possibility of optimization and responsible for transferring various forces between the adjacent and stacked modules. Various researchers around the globe investigated the mechanical performance of different inter-modular connections (Sørensen et al., 2017, Lacey et al., 2019, Espoir et al., 2020, Dai et al., 2020). However, most of the existing research focuses on steel modular buildings with complex connections details and less research is available for connecting reinforced concrete load bearing modular walls.

Problem statement

Despite the prime importance of connections there are still areas in this field which needs further thorough understanding. Also, lack of designer's experience with advance structural system, poor understanding of the overall modular building behaviour and lack of support from the government are commonly claimed to place this advance construction technology at a disadvantage when compared to traditional in-situ construction. Generally, the reinforced concrete load bearing modular walls have thickness in range of 90mm to 120mm and therefore the existing proprietary and non-proprietary grouted sleeve connections are not suitable for such narrow width modular walls. Thus, research is needed to further improve the connection techniques and widespread its application by proposing a robust and efficient inter-module connection.

Research objectives and scope

The objective of this research is to introduce and access the feasibility of a novel high strength grouted cold-formed steel sleeve connection in multi-storey reinforced concrete modular building, aiming for fast and easy installation. To investigate the load transfer and interlocking mechanism, the mechanical performance of proposed connection

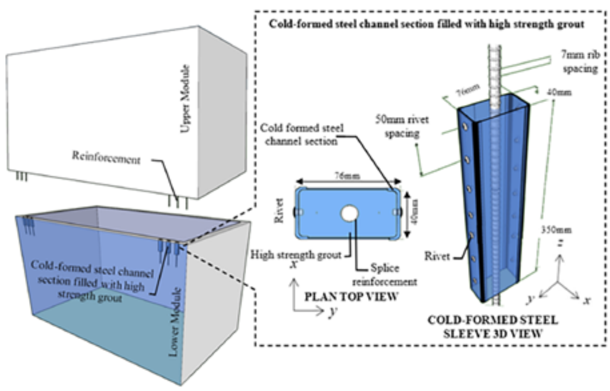

Fig 1 Structural components in proposed grouted sleeve connection in reinforced concrete walls of modular building

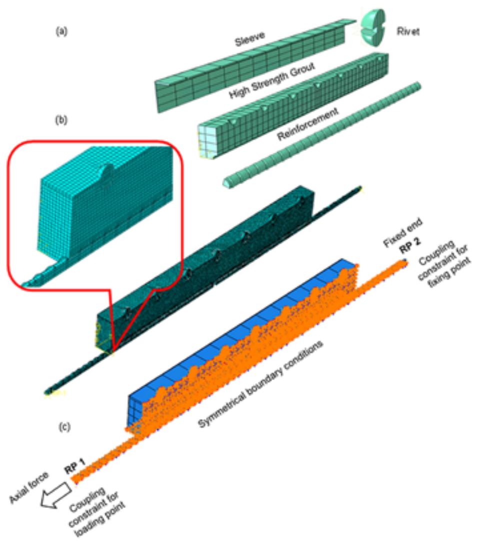

Fig 2 Numerical modeling with (a) Partitioning of geometry (b) Meshing assembly and (c) Displacement constraints and boundary conditions application in Abaqus

under axial tension load will be investigated using a commercially available FE package i.e., Abaqus/Explicit. The ultimate load for each of the design specimen and corresponding stress and failure modes will be examined. The analysed result of the validated numerical model will help in developing simplified expression for calculating minimum required sleeve length (function of grout strength and diameter of spliced reinforcement) for developing equivalent strength of the spliced reinforcement.

Proposal of novel grouted sleeve connection

In present research, cold formed steel channel sections are utilized as sleeve for the proposed novel connection. Refer to Fig 1 for the sketch drawings of the proposed connection. The 350mm sleeve length of cold formed steel channel section will be joined using rivets; resulting in interlocking system to avoid the grout sleeve slippage failure mode. Two reinforcement bars of diameter 10mm are inserted in the high strength grout that will transfer the required forces from upper module to lower.

Numerical modelling for feasibility study of proposed grouted sleeve connection

Numerical modelling has been conducted in Abaqus/Explicit for the feasibility analysis of proposed connection. Based on the symmetry in geometry, only one-quarter of the specimen is modelled as shown in Fig 2. The geometry consisting of sleeve, reinforcement, grout and rivets as parts are partitioned, meshed and applied with appropriate boundary conditions to efficiently utilize the computations resources. The system response converged with a loading rate of 2mm/sec and mesh size of 2mm. For simulating the cracking behaviour of grout, Concrete Damage Plasticity (CDP) model is used in Abaqus. This initially developed FE model will be calibrated after the experimental works and used for extensive parametric studies on the proposed connection at later stage of this research.

Preliminary Results

Force-displacement (F-d) curves have been plotted for different sleeve lengths i.e., 250mm and 350mm with grout strengths of 70MPa and 90MPa. For 250mm sleeve length having 70MPa grout strength the first peak declining phase is taking place at a force equivalent to yielding force in the reinforcement and therefore this sleeve length and grout strength is not appropriate for the experimental works. Also, at the yielding state of reinforcement almost 85% of grout was damaged and the ultimate strength of the reinforcement is not reached even at the end of the simulation. Therefore, a 350mm sleeve length with a grout strength of 70MPa or higher value is selected for the proposed grouted sleeve connection as it is utilizing the steel reinforcement more efficiently i.e., ultimate strength of reinforcement at outer ends is achieved at 29.1mm displacement. Also, the U3 displacement along the direction of force is plotted for the aforementioned sleeve lengths to investigate the grout-sleeve behaviour. The maximum value of grout-sleeve slip for 250mm sleeve was found to be13.90mm and the same for 350mm sleeve was observed as 3.25mm. Therefore, with a 100mm increase in sleeve length there was 76% decrease in the grout – sleeve slip behaviour.

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Further information

Hafiz Zain Saeed (E:hafiz.saeed@monash.edu)

Supervisor - Dr. Chua Yie Sue
(E: chua.yiesue@monash.edu)

Co-supervisor - Dr. Daniel Kong
(E: Daniel.Kong@monash.edu)

Testing and analysis of wire arc additively manufactured steel single lap shear bolted connections

17 **Xi Guo**
Imperial College London, UK

Project objectives and goals

An experimental investigation into the structural performance of wire arc additively manufactured (WAAM) single lap shear bolted connections printed using steel weld wire with a nominal yield strength of 460 MPa has been contacted in Imperial College London. The aims of the study are:

- To test the ultimate capacities of the test specimens
- To analyse the failure mechanisms of WAAM bolted connection subjected to single shear
- To assess the applicability of current design specifications
- To investigate the influence inherent to the WAAM process on the structural response of examined connections

Early investigation by Winter (1956) identified four key failure modes for bolted connections, namely shear-out, net-section, bearing and bolt shear with the latter type depending on the strength of the bolt rather than that of the connected plates. Other failure modes such as localised tearing failure identified by Rogers and Hancock (2000), splitting failure discussed by Može and Beg (2014) and other researchers and tilt-bearing failure introduced by Teh and Uz (2017) were also be observed in lap shear bolted connection tests. The above-mentioned failure modes are addressed in this investigation.

Anisotropy was observed in previous research into the structural behaviour of WAAM element by Kyvelou et al. (2020) and other researchers, which is also investigated in the current study by varying the printing strategies. The obtained experimental data were used to assess the applicability of current design specifications developed for conventional bolted connections to WAAM bolted connections.

Description of method and results

A total of sixty tests on specimens of different nominal thicknesses, printing strategies and geometric features, including end distances and plate widths, were carried out. The geometry of the test specimens was measured using 3D laser scanning and the use of digital image correlation (DIC) allowed detailed monitoring and visualisation of the surface strain fields that developed during testing, providing valuable insight into the developed failure mechanisms. The process of specimen preparation and the test setup are illustrated in Fig.1 and Fig.2 respectively.

The exhibited failure modes were generally in line with those described in the literature for conventional steel connections, while some interaction of different failure mechanisms was also observed. Comparisons were made between the test results and the capacity predictions obtained using current design standards. The comparisons showed that the behaviour of the WAAM connection specimens generally follow anticipated trends. Further research is however required to assess reliability and to derive suitable safety factors for use in the design of WAAM connections.

Potential for application of results

Although the structural behaviour of the examined specimens was generally found to follow the anticipated trends, recalibration of the current design equations for application to WAAM connections will be needed to achieve the required level of reliability. A finite element study will be carried out in future research in order to support the subsequent establishment of design rules.

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Further information

Applicant: Xi Guo (E: x.guo19@imperial.ac.uk)
Supervisor: Leroy Gardner (E: leroy.gardner@imperial.ac.uk)

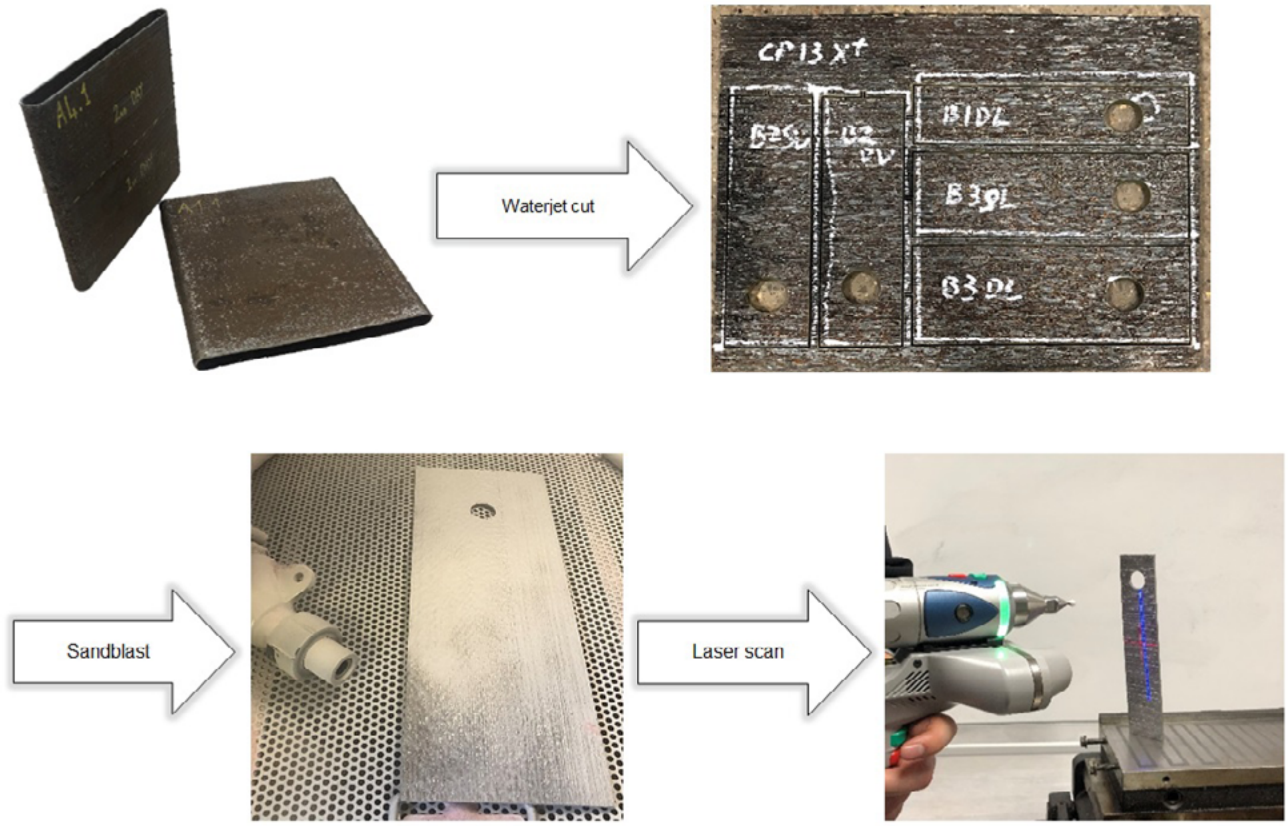

Fig 1 specimen preparation

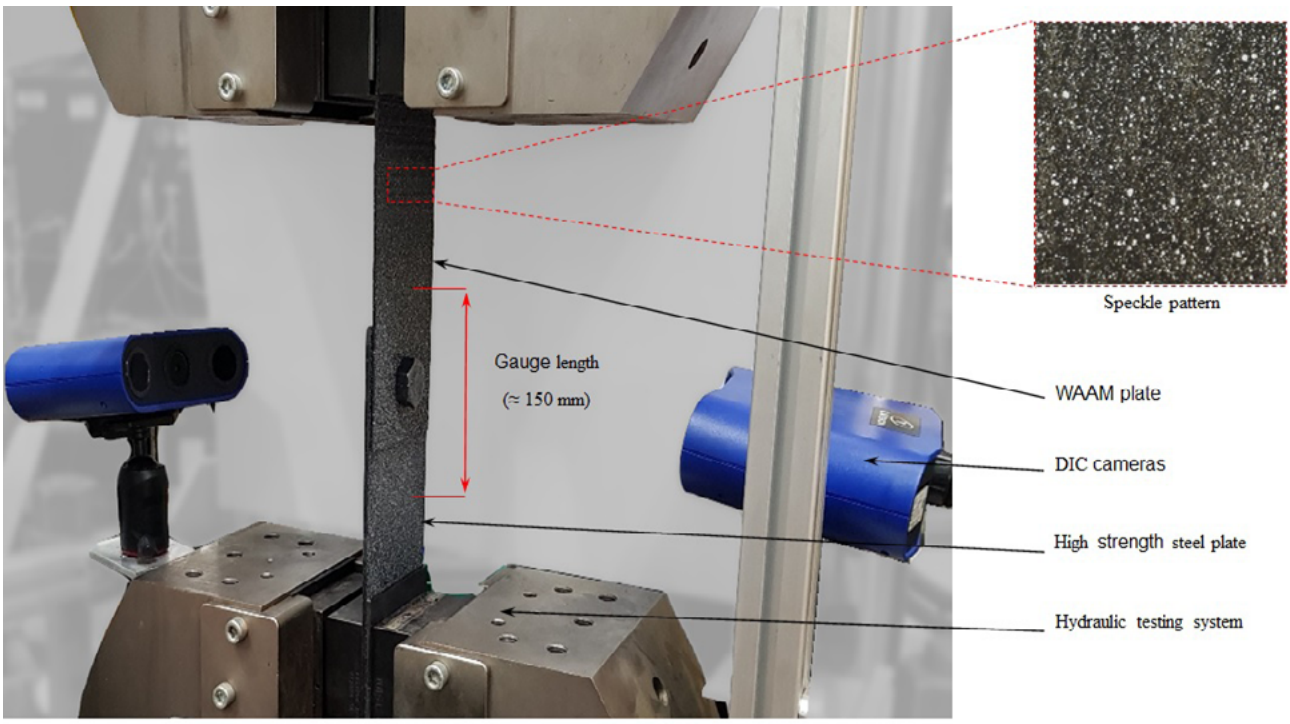

Fig 2 Test setup

Appraisal of traditional structural systems and development of system-specific assessment guidelines: A case study of unreinforced masonry buildings in southern India

18 **Krishnachandran S**
IIT Madras, India

Project objectives and goals

Successful adaptation of existing structures to varying environmental demands require investigations into traditional structural systems which stood the test of time and changing environmental conditions. In this regard, region-specific materials and construction techniques are of prime importance. Many a times, individual components in sustainable and energy efficient structural systems cease to continue and get replaced with newer ones only due to the marginal improvements attained in certain aspects of the system, including load carrying capacity, savings in construction time and cost etc. However, these replacements would not fully serve the purpose in terms of structural performance of the entire structural system since the system capacity would be limited by a weaker element in the load path. Hence, it would be more appropriate to strengthen and restore the component for its structural deficiencies rather than to entirely replace the same. While doing so, it is also necessary to make sure that the strengthening schemes are based on systematic assessment protocols which are specific and appropriate for the system under consideration. This is to ensure that the modifications introduced do not increase the vulnerability of other structural components in the load path, thereby not resulting in unintended failure mechanisms. This research work looks at improving the structural response of unreinforced clay brick masonry buildings in the southern part of India by characterizing different components in the load path, developing strengthening methodologies for the same and addressing the effects of proposed strengthening on other structural components. It also results in the development of an assessment protocol specific for such structural systems so that the failure propagation is based on weak link identification.

For unreinforced masonry buildings, the seismic energy path consists of a primary system, composed of the in-plane walls and a secondary system composed of the diaphragm and out-of-plane walls. The seismic input acceleration initiates response of the primary system at the ground story. Further, the response of the primary system is transferred to the secondary system at the upper story which filter and amplify the input signal and feeds it back to the primary system at the upper story (Priestley, 1985). The seismic capacity of the structure is derived from the primary system as the secondary system filters the input signal based on the dynamic characteristics of the same. Therefore, the stability and structural adequacy of the secondary system is equally important in the structural assessment of unreinforced masonry buildings.

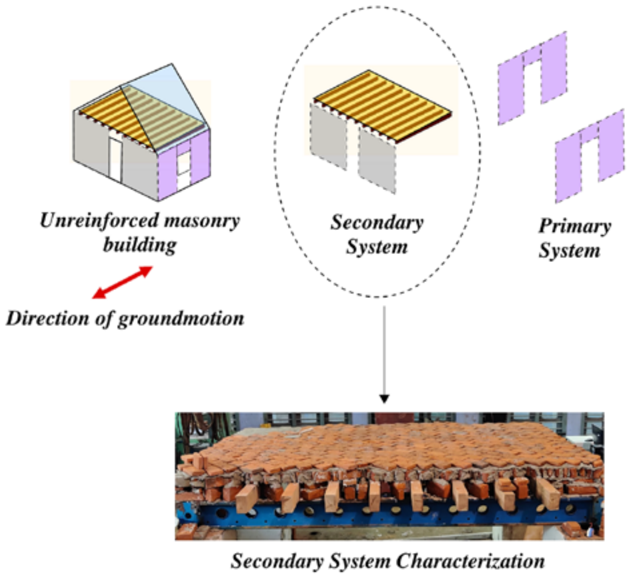

Fig 1 Secondary system characterisation

Masonry buildings across the world are characterized with primary system belonging to different typologies of masonry (stone masonry walls, clay brick masonry walls, CMU walls, multi-leaf masonry walls etc.) and secondary system belonging to different diaphragm typologies (timber floors, concrete slabs, composite slabs etc.). In this context, it is important to characterize the responses of both primary system and secondary system in masonry buildings across the world to identify the weak links and ensure that the strengthening interventions are specific and valid.

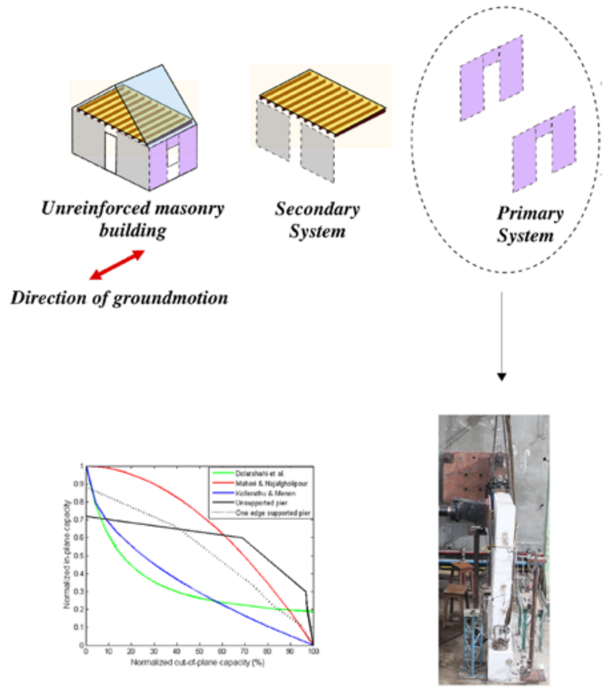

Fig 2 Primary system characterisation

Description of method and results

In this work, the characterization of primary and secondary systems and strength hierarchy of different elements in the load path of typical unreinforced masonry buildings in southern India (Figure 1) were fixed followed by identifying the weak links in the system. The first weak link was identified as the diaphragm/floor slab in the system which is a traditional diaphragm typology composed of timber joists and two overlays (first, brick masonry with lime mortar overlay and second, brick bat lime concrete overlay) having shear transfer with the joists only through interface friction. This was identified as a potential weakness of the component during seismic actions and a reason for the decline in its prevalence. However, considering this apart, the thermal transmittance and energy efficiency of this diaphragm typology are considered as important advantages associated with it. Existing strengthening guidelines recommend the addition of concrete overlay or integrate the joists with the surrounding walls with anchors to stiffen the diaphragm. However, these do not develop an integral force transfer between the joists and the overlay. Therefore, strengthening solutions were developed for improving the lateral response of this typology by integrating the timber joists and the overlay, which improved the strength and stiffness of the system. Further, the effect of this strengthening on the combined response of the secondary system including the supporting out-of-plane walls were investigated through numerical studies. Results indicated that the existing empirical formulations for the stability of out-of-plane walls as per the Indian assessment guidelines (BIS 1905) prove to be inadequate and the seismic demand on these needs to be modified accounting for the stiffness of the secondary system including the diaphragm and out-of-plane walls.

Further, the potential implications of strengthening and stiffening the diaphragms on the primary system response was investigated using experimental and numerical studies (Figure 2). It was observed that the orthotropic nature of the diaphragm, along with stiffening and integral connectivity between the diaphragm and in-plane walls could result in additional seismic demands in the orthogonal direction. Thus, studies were carried out on the effects of orthotropic diaphragms in generating bidirectional seismic demands and the possibilities if these on reducing the capacity of the in-plane walls (Figure 2).

Potential for application of results

An assessment scheme for building typology considered in this study based on weak link identification was developed to ensure that the strengthening of such systems was based on a systematic assessment framework. The assessment scheme follows the order of vulnerability in the seismic load path for the typology of masonry buildings considered in this study. Summarizing, through this research work, seismic improvement of a traditional, sustainable and energy efficient diaphragm typology was carried out without affecting the structural adequacy of the associated structural members. The effects generated on the primary system due to the strengthening and stiffening of the secondary system was addressed through experimental and numerical studies by developing a systematic assessment framework which takes these effects into account.

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Further Information

Krishnachandran S (E: krishnchandran@gmail.com)
Arun Menon (E: arunmenon@iitm.ac.in)

Rework and Its Impact on Engineering Productivity in Building Design: A Design Research Analysis

19 **Yvonne Y.B. Wong**
Singapore University of Technology and Design, Singapore

Introduction

The objective for studying the Building Design (BD) process is to understand a phenomenon in Singapore's BD process that creates substantial iteration and rework due to change requests at the critical and final stages of the detailed design process. We are specifically looking at the design work to specify structural elements in buildings from the concept stage to the final Issued For Construction (IFC) stage, as performed by structural engineers.

Due to the nature of the checks and the cost of rework under strict time pressure, the final approved designs are, by experience, overdesigned with respect to structural safety. This means that the structural elements require more material than needed, which is not only costly but also results in a large environmental footprint. Our assumption is that applying and analysing suitable design process models will provide the insights that are necessary to improve the BD process (Wong et al., 2021b).

Research Problem Statement

The research questions explored are:

- Research Question 1: How do building regulations and submissions cause rework and iteration in the building design process?
- Research Question 2: What affects engineering productivity in the building design process? And how?
- Research Question 3: How much do rework and iteration affect engineering productivity in the building design process?

Sub questions

a. What are the various regulations and their costs and impact on the design workflow and process of the industry? I.e., What are the costs to stakeholders to comply with regulatory requirements in the design process? E.g., time and effort for submission procedures, uneconomical design etc.
b. How can engineering productivity in building design across different project type, scale, and degrees of regulatory intervention be measured?
c. To be able to answer the research questions and hypotheses, I have employed the C-QuARK method to identify and summarise the constructs, variables and data required in Table 1 below.

Project Objectives and Goals

The PhD thesis aims to create a productivity metric that can measure engineering productivity across project types, sizes, and degree of interventions. With this information, further analysis can be done like Cost-Benefit Analysis or streamlining of the design process.

Constructs	Variables	Type of Data	Method & Target
Design Process Modelling	Building plan submission processes	Qualitative	Design process modelling of submission processes involving all stakeholders
Stakeholder Design Experience	Design workflow bottlenecks	Qualitative	Interview with stakeholders to identify common bottlenecks
Costs to stakeholders to comply with regulations	Design effort/ resources required	Quantitative	Data collection to quantify costs to comply with building regulation
Engineer Productivity Measure	Weighing all costs and benefits of building design regulations	Quantitative	Economic/Cost benefit analysis to measure and quantify loss in productivity across projects.

Table 1 C-QuARK Method to Summarise Research Constructs and Variables

Description of method and results

the chosen method that will tie Action Research with varying research methods for subtopics is a Design Research Methodology (DRM)(Blessing and Chakrabarti, 2009). This approach was chosen as design process methodologies are not widely deployed in the study of design processes (and consequently engineering productivity) in the AEC industry despite being applied to other fields of engineering (Wong et al., 2021a).

Potential application of results

The thesis focuses on engineering productivity that includes design activities required in the AEC industry to achieve required structural plan drawings for construction. It is found from extensive literature that most productivity studies in the AEC industry are focused on studying construction-related productivity and by studying engineering productivity, it will then cover the entire process (from concept to construction stages). By focusing on engineering productivity in the design stages, productivity studies in the AEC industry will be enhanced.

The value of this research is a measure/ rubric to assess engineering design productivity of the design process and workflow across various building project types, scale and external interventions. With this productivity measure, it is possible to quantify the effects (intended, perceived and actual) of statutory intervention in this process and consider the potential benefits of applying digital building regulations to streamline workflows.

In summary, it is believed that this work contributes to knowledge in several key ways. Firstly, it sheds light on a unique building design process in Singapore's AEC industry. It presents some of the issues in engineering productivity especially in the context of rework and iterations, Through the study, the problem in engineering productivity in the AEC industry can be first identified and then measured. This would build the Corpus of engineering productivity-related data in Singapore.

The second key contribution is the formulation of an engineering productivity measure/ metric that can measure across building projects of different types, scales, and degrees of intervention. This can be applied to improving building design processes irrespective of the complexity or cost by introducing this objective metric into building project management.

For example, by measuring the difference in engineering productivity of design processes with different degrees of intervention, we can compare the value or costs of this intervention. In the same vein, this difference can help in decision making, all of which could eventually streamline design processes.

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Further information

Yvonne Y.B. Wong (E: Yvonne_wong@mymail.sutd.edu.sg)

Supervisor: Sam Conrad Joyce
(E: sam_joyce@sutd.edu.sg)

Co- Supervisor: Lucienne Blessing
(E: lucienne_blessing@sutd.edu.sg)

Web Crippling Strength and Behaviour of Cold-Formed Thin-Walled Channels with Web Openings

20 **Hasini Weerasinghe**
University of Sri Jayewardenepura, Sri Lanka and Northumbria University, UK

Project objectives and goals

Cold-Formed (CF) thin-walled steel channel sections are widely used in residential and industrial buildings both as primary and secondary structural members (Ma et al., 2015; Ye *et al*., 2016). These channel sections are often fabricated with web openings to facilitate for easy installation of electrical and plumbing services (Lian *et al*., 2016; Uzzaman *et al*., 2012). Apart from CF steel, CF stainless steel and CF aluminium sections with perforated webs are among the most commonly used CF channels in the construction industry. When subjected to concentrated loading these channel sections, with their high slenderness ratio and web perforations are prone to web crippling, which is a critical localized member failure mechanism (Yousefi *et al*., 2017).

Therefore, the current structural usage of CF sections with web perforations has generated a need to conduct a comprehensive study on its web crippling behaviour. But, to date no such comprehensive study has been carried out to derive a unified equation for predicting web crippling strength of CF steel, stainless steel and aluminium sections. This has resulted in reducing the structural value of CF channels with web openings. Present research intends to bridge this knowledge gap via achieving following objectives.

Objective 1: Investigate web crippling behaviour of web perforated CF steel, stainless steel and aluminium sections through experimental studies and finite element analysis.

Objective 2: Define unified design guidelines for predicting the web crippling behaviour of web perforated CF steel, stainless steel and aluminium beams based on the web crippling data gathered through experimental studies and finite element analysis.

Description of method and results

In order to achieve the objectives of the research, methodology is divided under six stages as shown in Fig 1.

Initiating the research, a detailed literature survey was conducted on the web crippling behaviour of CF thin-walled sections with web perforations, web crippling test methods and finite element model development. Under this the impact of materials, opening configurations and sectional properties of CF channels upon its web crippling behaviour was studied. Based on the reviewed literature it was identified that the web crippling behaviour of web perforated CF stainless steel and CF aluminium sections has poorly being studied in comparison to CF steel sections. As a result, only a limited number of design guidelines have been developed for predicting web crippling capacities of web perforated CF stainless steel and aluminium channel sections. Furthermore, inconsistencies of existing design guidelines in predicting the web crippling capacities of CF steel, stainless steel and aluminium sections with web openings were acknowledged. Moreover, it was identified that none of these specifications have established unified design guidelines for predicting web crippling behaviour of perforated CF sections.

Based on the identified web crippling behaviour, finite element models were developed for simulating web crippling behaviour of lipped CF channel sections with web openings, subjected to end two flange (ETF) loading condition. Simulations were conducted using the ABAQUS (2017) finite element software, considering the non-linear quasi-static analysis. These models were then validated using past experimental data. Subsequently, similar finite element models will be developed and validated considering the end one flange (EOF) loading, interior one flange (IOF) loading and interior two flange (ITF) loading conditions.

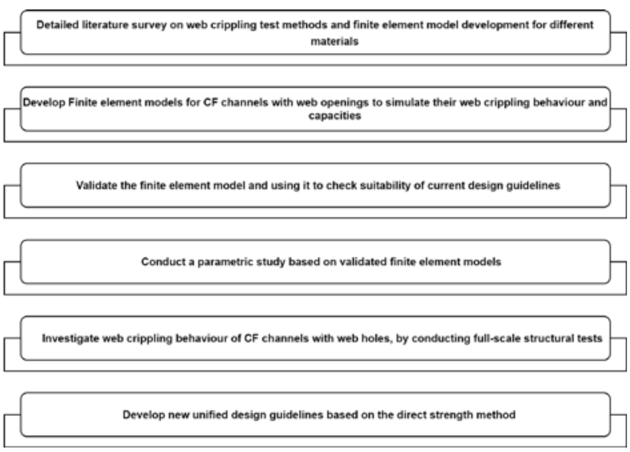

Fig 1 Overview of the research methodology

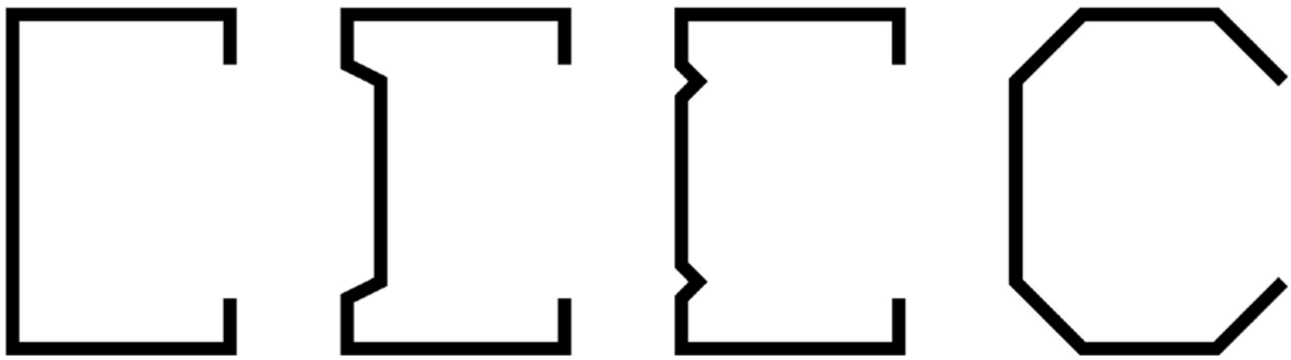

Fig 2 CF channel sections to be considered in this research

Following this, parametric studies will be conducted based on the validated models, considering four types of channel cross sections (Fig 2), perforated with circular, elliptical, square, rectangular and hexagonal opening configurations.

Then to identify the structural behaviour full-scale structural tests will be conducted on CF steel, stainless steel and aluminium channel sections, considering above four sectional geometries and five opening configurations. These tests will be conducted considering different section depths, different opening sizes, opening locations and all four loading conditions.

Based on the results of these simulations and experimental data, accuracy of the existing web crippling design guidelines for CF channel sections will be assessed. Finally, unified design equations will be defined for predicting web crippling behaviour of CF steel, stainless steel and aluminium sections with web perforations. These unified design equations will be derived based on the direct strength method.

Potential for application of results

Unified design guidelines proposed to be developed under this study can be used in predicting the web crippling capacities of CF sections with web openings. Following the thorough investigation conducted under this study, these design guidelines can be incorporated in the upcoming versions of the existing design guidelines, benefitting the whole light weight construction industry.

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Further information

Hasini Weerasinghe (E. hasiniweerasinghe@sjp.ac.lk)

K.M.C Konthesingha (E. konthesingha@sjp.ac.lk)

Keerthan Poologanathan
(E. keerthan.poologanathan@northumbria.ac.uk)

S.M.A Nanayakkara (E. sman@civil.mrt.ac.lk)

Collaborators

Department of Civil Engineering, University of Sri Jayewardenepura, Sri Lanka

Department of Mechanical and Construction Engineering, Northumbria University, Newcastle upon Tyne, UK

Enhancing the robustness of PBBS precast concrete systems

21 Kamil Riedel
Imperial College London, UK

Introduction

Product based precast concrete building solutions represent the future of prefabricated framing systems due to standardisation of components and significant reductions in on-site working due to use of innovative connections and elimination of in-situ concrete toppings. D-Frame is a structural system designed by Laing O'Rourke that utilises this approach. It consists of inverted U-planks, that sit on inverted T-beams, which span over columns reducing the floor deflections, with typical bays spanning 9 x 9 m. Connection between the T-beams is achieved through half lap joints offset to one side of columns near the point of contraflexure as shown in Fig 1. This research studies the impact of the half-lapped joint design on the robustness of the D-frame system to sudden column removal.

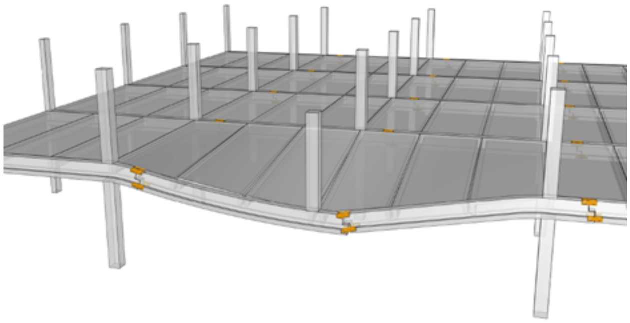

Fig 1 D-Frame deformed shape after column removal

Description of method and results

The influence of sudden column removal on building response is assessed using energy balance concepts (Izzuddin, 2008). In this approach, a static pushdown analysis is carried out to determine the displacement of the damaged bay needed to meet the dynamic energy demand. The final step is to transform the static response into a pseudo-static curve which is used to assess the dynamic response. A damaged bay of the D-Frame was modelled in Adaptic (Izzuddin, 2019) using a component-based method in which the half-lapped joint was simulated using a system of rigid links and contact springs. Restraint from the adjoining undamaged floor and columns was simulated with horizontal and rotational springs. Concrete and reinforcement were modelled separately with beam-column elements, connected with springs to simulate the bond-slip properties. Bond-slip was modelled in accordance with Model Code 2010 (fib, 2013). The bond strength was reduced around the joint and adjacent to the supporting columns to simulate spalling of cover at large reinforcement strains. In the presented analyses, reinforcement rupture was assumed to occur in axial tension at a strain of 15%. This neglects localised bar bending which can cause premature failure.

The design of the half-lapped joint went through several iterations and is still under development. Initially, continuity of ties at the half-joint was achieved through plates attached to the top and bottom of the beam with countersunk bolts. The extendibility was limited by the premature rupture of the plates prior to the development of significant catenary action. This was due to the short distance between fixings connecting the plates to the beam. An alternative half-lap connection was developed in which continuity of reinforcement across the joint is achieved by means of coupler brackets. Coupler brackets in adjoining beams are connected on site with hinged fixings that just provide axial restraint. To maximise bar extension prior to fracture, the reinforcement was debonded to either side of the coupler brackets. The predicted response of the D-Frame system to sudden column removal is shown in Fig 2. The initial peak in the force is characterised by the compressive arching action that is followed by slight softening. The onset of catenary forces at the displacement of about 800mm further strengthens the response of the beam. The peak load capacity of the D frame system was limited by rupture of the bottom reinforcement at the central half-joint.

For comparison, Fig 2 also shows the response to sudden column removal of an equivalent in-situ reinforced concrete beam with the same geometry and loading as the D-frame beam. The bottom bars at the removed column fractured at a displacement of around 800mm resulting in a significant drop in resistance, which is not recovered in the pseudo static response even in the catenary stage. Final failure of the in-situ beam occurred due to the top reinforcement rupture at the column interface. Fig 2 shows that the response of the D-frame system compares very favourably with that of a normally detailed in-situ beam not specifically designed for accidental column removal.

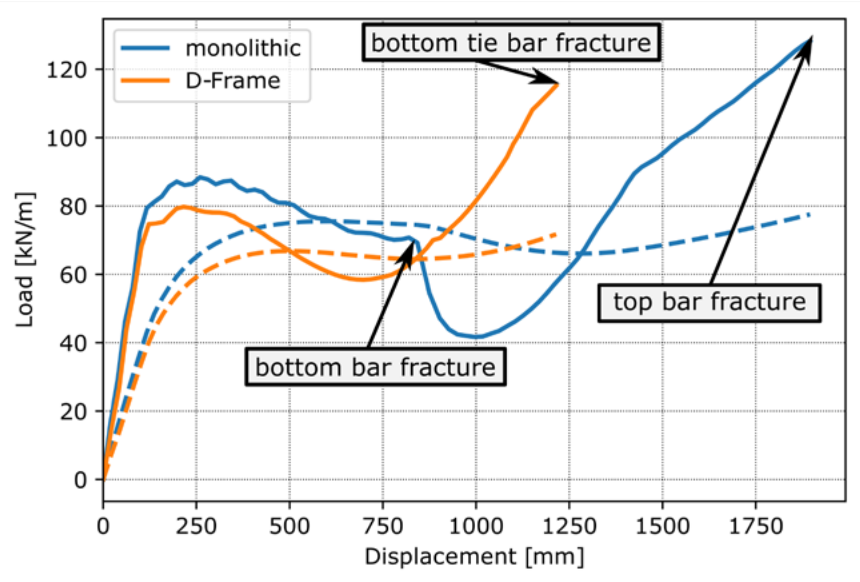

Fig 2 Sudden column removal analysis (continuous line – static curve, dashed line – pseudo-static curve)

Potential for application of results

The major challenge in designing precast concrete frames for sudden column removal is that of ensuring that ties between members have adequate strength and deformability. In the D-frame, continuity of ties is achieved through steel couplers which are connected together on site. Deformability of the reinforcement is increased by debonding the reinforcement to either side of the couplers. Fig 2 shows that the predicted response of the D-Frame connection is potentially comparable to that of a normally detailed monolithic beam.

Funding body

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Collaboration

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Development of Innovative Modular Connection and Bracing System

22 **Heshachanaa Rajanayagam**
Northumbria University, UK

Project Objectives and Goals

There are intense demands on housing production in various parts of the industrialised world. Modular Building Systems (MBS) are well recognised to have the ability to play a vital role in addressing the housing crisis at present. Modular construction is the process of off-site manufacturing of modules or prefabricated blocks, which are then transferred to the site and readily assembled. This contemporary building technique is a cost-effective and rapid construction solution, which can significantly impact the current housing market crisis. Despite a significant research gap in advanced techniques and structural performance, the uptake of MBS techniques is emerging much rapidly than on-site building practices. The adaption of volumetric prefabrication in building construction is rising in most developed countries worldwide (Deng et al., 2017; Navaratnam et al., 2019; Wang et al., 2019). The modular Bracing and Connection System (BCS) is the key and also, on the other hand, the main challenge in the construction of MBSs (Mark Lawson and Richards, 2010; Jammi and Sanjeevi, 2021). Different types of modular BCS techniques are adopted in the current construction industry rather than a particular one, which is mainly due to the fact that the currently used types of techniques are having unique challenges in meeting all the standard design and construction specifications of MBSs (Lacey et al., 2018). Therefore, it has become essential to propose and develop an innovative, cost-effective combined BCS for MBSs (as illustrated in Fig 1) to overcome the difficulties in the design and construction of MBSs. The present research intends to achieve this target with the following objectives,

Objective 1: Studying the winnings and shortcomings of existing MBS connections and bracing systems and, based on that introducing an innovative modular construction scheme that involves a set of combined BCS in conjunction with the module installation techniques.

Objective 2: Analysing the performance of the proposed combined BCS system in overall MBS through specific design standards, experiments, and numerical analysis; Based on that, developing and disseminating a comprehensive specific design standard for the proposed BCS.

Description of Method and Results

The research objectives are set to be achieved in five stages as follows;

Stage 01: A thorough literature review on MBSs, steel BCSs, interlocking connections and techniques, full-scale load tests, 3D finite element analysis was conducted. Case studies were performed on BCS types used in MBSs: Investigated and analysed existing BCSs used in MBSs, including temporary and permanent connections, to establish its winnings and shortcomings.

Stage 02: Based on literature review and case studies performed, developed and proposed conceptual designs for innovative BCS designs (Fig 2). The proposed conceptual BCS models were optimized based on industrial design and fabrication experts' inputs.

Stage 03: Structural behaviours and properties of proposed BCS (such as shear, moment, axial tension, combined actions and bi-directional loading) will be measured by performing full-scale physical tests; based on that, their strengths and weaknesses in relation to the overall performance of MBS will be evaluated.

Stage 04: 3-dimensional finite element models (based on the experimental test results from stage 3) will be developed and validated to interpret the internal stress distribution (and simulate their behaviour and capacities) within the BCS components of MBS. Parametric studies will be then performed to further optimize the design and to interpret the behaviour of BCS under different loading conditions.

Stage 05: The accuracy of available design rules for the proposed modular BCSs to predict the performance of the MBS will be evaluated, and based on the limitations and behaviour of the proposed unique BCS, a new set of design rules and testing standards will be developed.

The outcomes of this research will be used in MBS construction practices and design methodologies, which can increase the prevalence of prefabricated MBS in the UK and other countries. This will not only facilitate the design process but also will help in increasing public trust and reliability over MBS.

Potential for Application of Results

This research targets to perform a thorough study of many important parameters related to the structural and mechanical behaviour and performances of MBS as single units and as a whole unit assembly, using numerical modelling combined with experiments on proposed BCS.

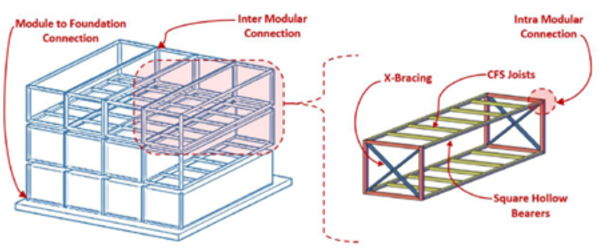

Fig 1 Graphical illustration MBS connections and bracing

This study will significantly advance the knowledge and understanding of the combined performance and operation of innovative BCS for MBS proposed. Hence, these research outputs will support in advancing and promoting the use of high quality and affordable MBSs by ensuring their structural performance and accelerated construction through reliable bracing and connection systems.

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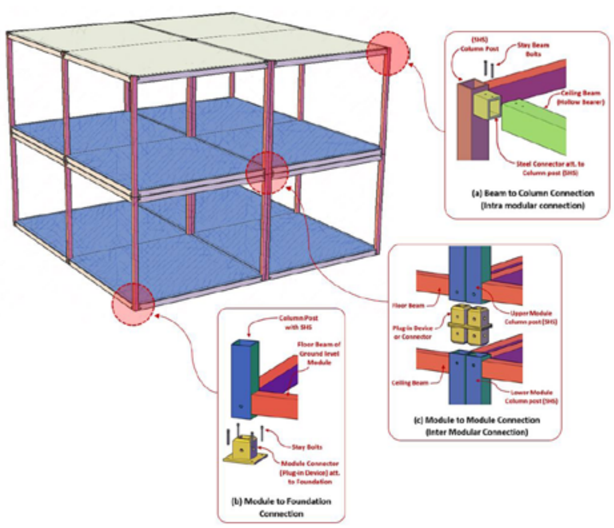

Fig 2 Proposed conceptual design of modular connections

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Further Information

Heshachanaa Rajanayagam
(E. heshachanaa2.rajanayagam@northumbria.ac.uk)

A/Prof. Keerthan Poologanathan
(E. keerthan.poologanathan@northumbria.ac.uk)

Dr Brabha Nagaratnam
(E. brabha.nagaratnam@northumbria.ac.uk)

Prof. Phil Hackney
(E. phil.hackney@northumbria.ac.uk)

Collaborators

Faculty of Engineering and Environment, Northumbria University, Newcastle Upon Tyne, UK.

ESS Modular, Crag Ave, Clondalkin Industrial Estate, Dublin 22, Ireland.

Strategies for low carbon data-driven structural design

23 Sandie Kate Fenton
Cergy Paris University – Vrij Universiteit Brussel

Project objectives and goals

The building industry is estimated responsible for nearly 40% of total global energy-related CO2 emissions. To reduce this impact and achieve an environmentally-informed design, both a comprehensive understanding of influential factors and a mastering of assessment tools are essential. (UN Environment Programme, 2020)

Today, every building material in a given context can be associated to a CO2e factor, resulting from the analysis of it Global Warming Potential (GWP) throughout its entire life cycle (Graedel, 2010). Eqn 1 shows how to compute the GWP of a building structure (Gibbons et al., 2020).

Description of data, method, and results

A. Data

The building structure dataset used, assembled, and shared by Price & Myers (Gholam, 2020), lists qualitative and quantitative features (Table 1), alongside GWP footprints, computed with a classical element-wise material computation.

B. Method

The method involves pre-processing data, defining a learning model, fine-tuning it by varying modelling parameters, and assessing its capacity to fit the data.

$$\sum_{\substack{structural\\elements}} [\text{Quantity (kg)} \times \text{ CO2e material factor} \left(\frac{\text{kgCO2e}}{\text{kg}}\right)] = \text{GWP building (kgCO2e)} \qquad (1)$$

$$y_i = h(x_i) = \theta_0 + \theta_1 * x_{i,1} + \theta_2 * x_{i,2} + \cdots + \theta_m * x_{i,m} = \theta^T x_i = \theta_0 + \sum_{j=1}^{m} \theta_j x_{i,j} \qquad (2)$$

θ: parameter vector; θ_0 : bias; m : number of variables, x_i : i^{th} sample; y_i: i^{th} predicted target value

$$\theta = (X^T X)^{-1} X^T Y \qquad (3)$$

$$pred = X\theta \qquad (4)$$

The digitalization of the building industry has facilitated the introduction of GWP assessment tools in the structural engineering practice (Tamke, 2018). However, it is rarely assessed at early design stages, when changes with highest impact are made, but fixed geometrical and material information - hard variables - are unavailable (Jusselme, 2020). Identifying alternative ways of assessing GWP, based on descriptive data already available in competition briefs - soft variables - could address this challenge. In this research, we aim to learn from the assembled data of built building structures, to first identify variables influencing GWP values, then build a model capable of estimating the GWP of building structures from them.

Qualitative features are converted using one-hot coding to a vector of binary features, to which the quantitative features are added. There is a non-linear relation between target (y) and input variables (xl, xt), the training is based on known labels (CO2e/m2 values), and the predicted data is continuous. Observations suggest resorting to regression-based learning models (Broucke et al., 2019).

To start, a polynomial regression model is built, for which the hypothesis function h(θ) of the model can be expressed as a linear function of all variables (Eqn 2). Since the number of samples is limited, but superior to the number of features, the function is calibrated using the normal equation (Eqn 3). The predictions can then be calculated from these θ values (Eqn 4). Cross-validation is used to ensure the robustness of the model: the dataset is split into 5 subsets, the model is trained on 4 and tested on the remaining one.

	Feature	Example
Quantitative Input xt	'GIFA (m2)'	9843
	'Storeys'	8
	'Typ Span (m)'	7.5
	'Typ Qk (kN/m2)'	4
Qualitative Input xl	'Sector'	'Educational'
	'Type'	'New Build (Brownfield)'
	'Basement'	'None'
	'Foundations'	'Piles (Pile Caps)'
	'Ground Floor'	'Suspended RC'
	'Superstructure'	'In situ RC'
	'Cladding'	'Masonry + SFS'
	'BREEAM Rating'	Very Good'
Output	'Cal tCO2e_per_m2	0.23

Table 1 Quantitative and qualitative variables

C. Results

We have identified the need for rapid GWP estimates at early design stage, and suggested predicting them from "soft" values available in design briefs. A simple polynomial regression learning from pre-processed qualitative and quantitative values was tested. The model failed to predict target values, reaching a maximum of 26% accuracy on tested sets.

Next, 4 models - support vector regression, kernel regression, lasso regression and fully connected neural networks - will be built, trained, and evaluated on the dataset. They should address overfitting and underfitting issues, deal with outliers and help discard features with lesser influence in order to achieve higher predictive accuracy. The models performance with various solvers and optimizers will be compared. Constrained optimization will be further developed on selected models in order to constrain results within selected domains and typologies of interest.

Potential for application of results

This research investigates alternative strategies to predict the GWP of a building structure, relying on "soft" features, rather than "hard" features such as detailed materials and quantities. This could allow to identify contextual features that influence the GWP of building structures, and use them to predict their footprints. This understanding could help guide design decisions at early stages, and be implemented into an interactive tool for low carbon data-driven structural design.

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Further information

Sandie Kate Fenton (E. sfenton@bollinger-grohmann.fr)
Klaas De Rycke (E. kderycke@bollinger-grohmann.fr),
Lars De Laet (E. Lars.De.Laet@vub.be),
Samuel Rufat (E. samuel.rufat@u-cergy.fr),
Gabriele Pierluisi (E. gabrielepierluisi@gmail.com),

Collaborators

EUR Humanities, Creation, Heritage (PSGS HCH), "Investissement d'Avenir ANR-17-EURE-0021".

Laboratoire de recherche de l'école nationale supérieure d'architecture de Versailles - ENSA-Versailles, https://leav.versailles.archi.fr/

Laboratoire Mobilités Réseaux Territoires Environnement - Université de Cergy Pontoise, https://www.cyu.fr/mobilites-reseaux-territoires-environnement

Faculty of Architectural engineering, Vrij Universiteit Brussel, https://www.vub.be/en/study/architectural-engineering

Department of Electronics and Informatics – ETRO, Vrij Universiteit Brussel http://www.etrovub.be

Nikolaos Deligiannis (E: Nikolaos.Deligiannis@vub.be),

Adrian Munteanu (E: Adrian.Munteanu@vub.be)

Potential of low-grade kaolinitic clay as a cement substitution in concrete

24 **Kwabena Boakye**
Coventry University, UK

Project objectives and goals

This project seeks to:

- Identify and characterise suitable low-grade kaolinitic clays materials from source in the UK for mainstream use in cement and concrete applications.
- Assess calcining conditions (temperature, time) and their effects on reactivity of clays.
- Establish the reactivity of calcined clays, effects on fresh concrete behaviour and long-term properties (durability, strength, microstructure) while benchmarking them against reference materials ordinary Portland cement.

Description of methods and results

Naturally occurring clay, which is originally used for brick production, was obtained from H.G Matthews Ltd., a brick manufacturing company in Bellingdon, England. The clay sample, after getting rid of debris and unwanted substances, was dried in an oven at 50°C for 24 hours and crushed into smaller sizes using a hammer mill. It was then calcined for 2 hours in a furnace at a temperature of 600°C with a heating rate of 10°C/min. This calcination temperature was selected based on the previous studies of other researchers (Du and Pang, 2018; Dixit). Using a laboratory type ball mill, the calcined clay was milled into a fine powder. The BET fineness and specific gravity of the calcined clay were found to be 21.3m^2/g and 2.61 respectively. Chemical composition of the OPC, raw and calcined, as determined by XRF is presented in Table 1. TG/DSC analysis of the clay used in this work is also shown in Fig 1.

CEM-I (52.5N) cement was partially replaced with the calcined clay in weight percentages of 10 wt.%, 20 wt.% and 30 wt.%. 50 × 50 × 50mm mortar cubes were prepared according to methods specified by BS EN 196-1:2016, using a cement to sand ratio of 1:3 and water/binder ratio of 0.5. The mortar cubes were cured under water and their respective compressive strengths determined after 3, 7 and 28 days. Compressive strength results are shown in Fig 2. Setting times and water demand, as determined using methods described in BS EN 196-3:2016, is also shown in Table 2.

From the XRF analysis (Table 1), chemical compositions of all the samples were within acceptable limits. The calcined clay contains 40.54% SiO_2 which exceeds the ASTM C 618 minimum of 25% required for pozzolans. The value of SiO_2+Al_2O_3+Fe_2O_3 for the calcined clay is 94.71%. This is higher than the 70% minimum requirement in ASTM C 618 for pozzolans.

Fig 1 is a TG/DSC analysis of the raw clay. There is an appreciable mass loss of about 1.71% between 50 – 100°C which is usually the evaporation of absorbed water in a process called clay dehydration. Dehydration at this temperature could also culminate into the dissipation of water locked up within the internal layers of montmorillonite.

As temperature is increased, there is a mass loss of 2.31% and a wider exothermic peak shows up between 458°C and 531°C which typically corresponds to the dehydroxylation (the removal of structural water molecules) of Kaolinite and the formation of Metakaolinite. There also appears to be two small peaks overlapping between 580°C and 699°C with a total mass loss of 0.24%. This could be the dehydroxylation of Illite and montmorillonite.

The setting time and water demand is presented in Table 2. CEM-I recorded the least water demand of 26.5%. This however increased by 8.9% when it was replaced with 10% calcined clay. The water demand continuously increased as percentage replacement increased from 10 - 30%.

Oxides	SiO_2	$A1_2O_3$	Fe_2O_3	MgO	CaO	Na_2O	K_2O	SO_3
Clay	59.95	0.82	6.51	1.3	0.14	1.6	1.29	0.07
Calcined clay	40.54	28.75	25.42	1.40	0.25	0.20	1.07	0.19
CEM-1	21.0	4.4	2.7	1.6	66.7	0.6	1.99	2.27

Table 1 Chemical composition of raw materials

Material	Initial set, min	Final set, min	Water demand, %
CEM-1	158	245	26.5
10% CC	180	275	29.1
20% CC	185	290	31.2
30% CC	195	315	35

Table 2 Setting time and water demand of cement and calcined clay

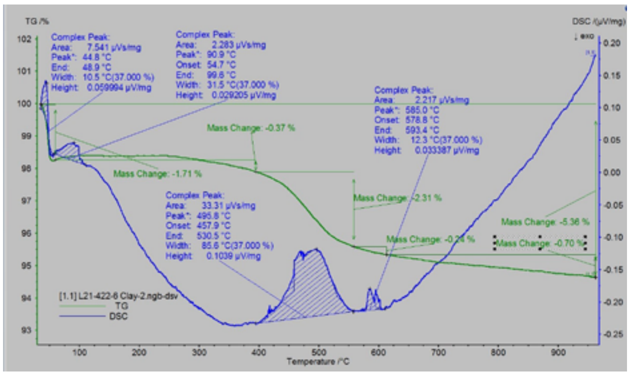

Fig 1 TG/DSC analysis of clay

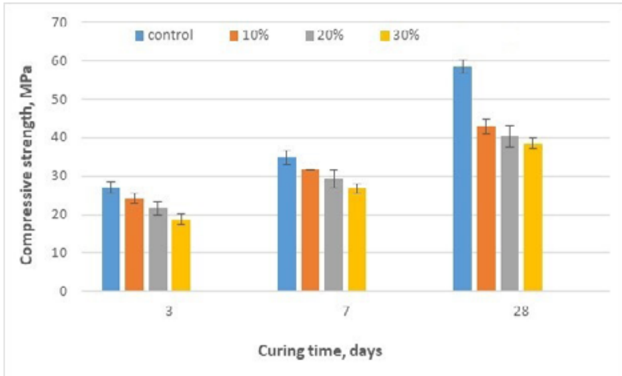

Fig 2 Compressive strength results cement with varying content of calcined clay

The compressive strength results are shown in Fig 2. Compressive strength is seen to decrease as calcined clay content increased from 10% – 30%. However, all the compressive strength results recorded at 3, 7 and 28 days were greater the minimum limits prescribed by EN 197-1.

Potential for application of results

The studied calcined clay material possesses the requisite oxides in their right quantities and qualifies to be a pozzolan. This, however, should be interpreted with caution. Other test should be carried out to determine its pozzolanic reactivity at varying percentage replacement. The Na_2O eq for the blended cement is higher than the maximum permissible limit of 0.6% per ASTM C150 and could potentially lead to alkali silica reactivity with reactive aggregates.

The incorporation of calcined clay to the cement increased its water demand and consequently, the setting time. Excess water is known to adversely affect concrete properties, lowering mechanical strength, and increasing the risk of failure due to shrinkage. Excess water can render a mortar too fluid to be workable and weaken adhesion at the mortar-masonry interface thus lowering bond strength (Costigan and Paiva, 2010).

Replacing cement with calcined clay up to 30% recorded a 28 days compressive strength of 38.6MPa. This strength, even though falls below the control, is still within acceptable limits for masonry works and medium strength structures. Replacing with 20% could be comparable to Class 42.5N cement.

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Funding body

Coventry University & BRE Trust

Further information

Kwabena Boakye (E. boakyek4@uni.coventry.ac.uk)
Morteza Khorami (E. aa8186@coventry.ac.uk)

Development of modular wall panel with improved fire, energy, and structural performance

25 **Dilini Perera**
Northumbria University, UK

Light-gauge Steel Frame (LSF) systems can be susceptible for catastrophic failure in fire accidents and less energy efficient due to the high thermal conductance of Cold Formed (CF) steel elements and resulting thermal bridging effect. Numerical studies on the structural fire and energy performance of chosen parametric walls have been conducted in this study.

Project objectives and goals

With the objective of developing a modular light-gauge steel frame (LSF) wall panel with improved fire, energy and structural performance for volumetric modular units, several goals have been established.

- Thorough literature review on existing modular LSF wall panel designs along with their benefits and drawbacks
- Investigate on the related parameters that influence the fire, energy, and structural performance of a LSF wall panel
- Conduct analytical studies on fire, energy, and structural performance of modular LSF wall panels, involving the identified variables
- Propose design guidelines for modular LSF walls to obtain a required fire, energy, and structural performance

Description of method and results

The thickness of wall boards, wall board material, the choice of full cavity insulation versus non-insulated option, the type of insulation material and the geometry of cold-formed (CF) studs can be listed as the prime parameters that few researchers have been concerned when it comes to the conventional LSF wall systems. Considering these variables together with modular LSF wall panel designs practiced in the UK and other European countries, the research parameters have been chosen for the current study. Hence, conventional and modular LSF wall arrangements, single and double layers of gypsum plasterboards, incorporation of cavity insulation at different ratios (i.e. insulation ratio – IR) and innovative concepts, namely the back blocking panels (BB) and discontinuous insulation (DI) options are the research variables in this study.

After the careful selection of variables, deriving the fire resistance levels, energy performance levels and the analysis of structural adequacy at different load ratio (LR) values are the concern. In this event, finite element (FE) approaches have been adopted since reliable full scale experimental studies were available to conduct initial validation of the FE models. The full scale structural fire experiments conducted by (Gunalan et al., 2013) have been re-created as FE models in Abaqus CAE, commercially available explicit software and the heat transfer analyses (HTA) results were produced for each case where quite appreciable agreements were obtained between those numerical and previous full scale experimental results. Similarly, for energy performance studies, the results presented by (Roque and Santos, 2017) were validated with Abaqus CAE FEMs.

The FEM techniques used in the studies, ambient and elevated temperature thermal properties of the wall materials, validations of structural fire and energy tests have described in detail in (Perera et al., 2021a, Perera et al., 2021b). Moreover, the FEM methods adopted in the studies are summarized in Fig. 1.

Next, all the parametric wall panels chosen to cover the research scope were modeled by extending the validated structural-fire and energy performance test specimens. Subsequently, 2D and 3D heat transfer analyses were conducted deriving the time-temperature variations through wall thicknesses for 240 minutes and U-Values for all the parametric wall panels. Temperature contours produced for a single wall specimen in this study is presented in Fig.2. Time-temperature plots through wall thickness, as those subjected to standard fire were analyzed against the Eurocode 3 standard and critical hot flange (HF) temperature versus LR at the structural fire failure to deduce the corresponding insulation and structural fire resistance levels (FRL).

Finally, the structural-fire and energy performance of all the considered wall specimens were analyzed to produce the design guidelines for modular LSF walls with required fire, energy and structural performance. The key research findings can be listed as,

- Rather than going for 'no cavity insulation' or 'full cavity insulation' wall specimens, integrating cavity insulations at about 0.4 ratio provide enhanced structural fire resistance to the LSF wall panels at 0.2 to 0.4 LR values.
- Innovative wall panel designs, on single and double plasterboard sheathed wall panels have resulted in enhanced structural FRLs up to 30% and 70% respectively.

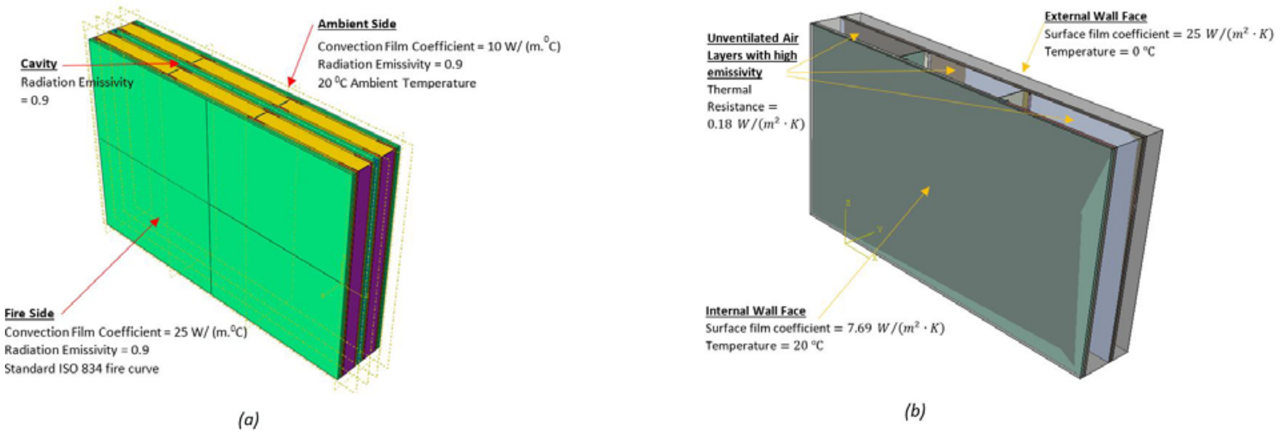

Fig 1 FEA modelling details of (a): Fire Performance Analyses and (b): Energy Performance Analyses

- Back-blocking panels and discontinuous insulation do not influence the U-Value
- 0.2 to 0.4 insulation ratios are proposed for better energy and fire performance

Potential for application of results

As described in the previous section, the research study is proposing guidelines to obtain modular LSF wall panel with improved fire, energy and structural performance at reduced weight and reduced cost. Moreover, mathematical models have been established for U-Value variations and structural-fire ratings with respect to the selected research parameters. Therefore, this research project has a very high potential in improving the industry practices on modular LSF construction.

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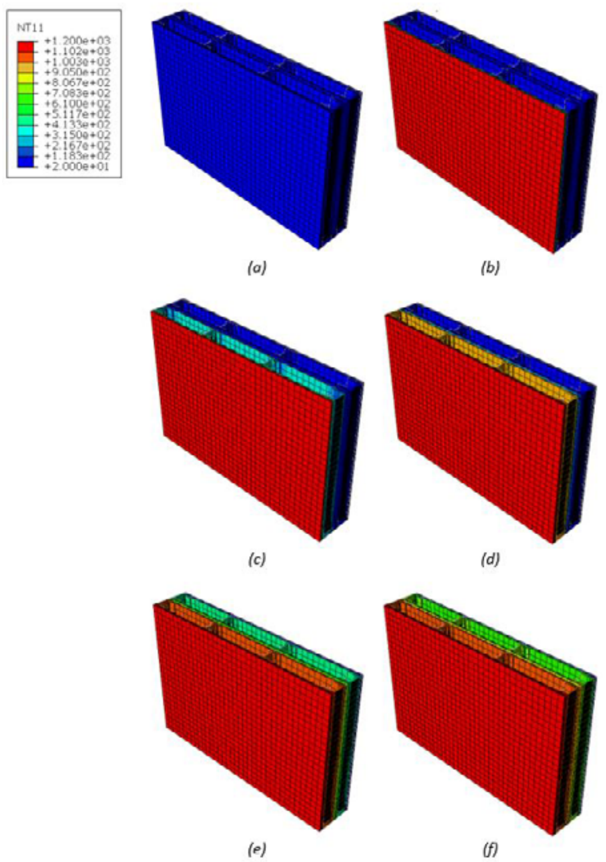

Fig 2 Temperature Contours derived from HTA of Modular Double Plasterboard Wall Specimen with Back Blocking panels and No Cavity Insulation at (a): 0 minutes; (b): 30 minutes; (c): 60 minutes; (d) 120 minutes; (e): 180 minutes and (f): 240 minutes

Further information

Corresponding Author: Dilini Perera
(E. dilini.perera@northumbria.ac.uk)

Project Supervisor: A/Prof. Keerthan Poologanathan
(E. keerthan.poologanathan@northumbria.ac.uk)

Seismic-resilient steel structures based on Self-Centring devices. Optimised solutions and general design procedures

26

Ludovica Pieroni
University College London, UK

Background, motivations, and objectives

Earthquakes represent one of the deadliest and costliest natural hazards worldwide as demonstrated by several historic and recent seismic events (EEFIT Mission Reports). In the past few decades, a significant effort has been made to improve the seismic performance of structures and infrastructures by developing innovative technologies and increasing the earthquake-risk awareness of the international public and governments (Bertero and Bozorgnia, 2004). However, there is still a strong need for advanced resilience strategies to support Disaster Risk Reduction objectives.

It is noteworthy that current seismic design procedures, suggested by codes and applied worldwide, are based on the energy dissipation related to structural damage ensuring the life safety of the occupants but leading to large direct (e.g., casualties, repair cost) and indirect (e.g., downtime) losses after an extreme event. This design philosophy strongly impacts the overall resilience of affected communities, especially when the damaged structures include strategic facilities such as hospitals, fire stations, etc., that must remain operational in the aftermath of a damaging earthquake.

To address these issues, several studies are currently ongoing for the definition of innovative solutions (e.g., the use of energy dissipation devices) able to increase the seismic resilience of structures by minimising structural damage and allowing a fast recovery after catastrophic natural disasters (Freddi et al., 2021). Moreover, the capability of the structures in minimising residual drifts represents an important aspect to be considered. In fact, large residual drifts are often observed after high-intensity earthquakes, and these may jeopardize the buildings' repairability.

In this context, the use of Self-Centring (SC) devices represents an efficient strategy to produce minimal-damage seismic-resilient structures able to limit the residual drifts with significant advantages in terms of improved seismic performances (Chancellor et al., 2014). These devices dissipate the seismic input energy through dedicated fuses (e.g., friction dampers) and control the self-centring capability of the structure through specialised systems (e.g., post-tensioned bars). Despite advanced research studies have been developed to propose and experimentally test new typologies of SC devices (Ricles et al., 2001) less consideration has been paid to the definition of general procedures for their design and applicability; and aspects related to their effectiveness, reliability, and robustness still represent unresolved issues. For these reasons, their use in real buildings is still limited and further research is needed.

The present research focuses on filling these gaps by defining optimised solutions and general design methodologies for seismic-resilient steel structures based on SC devices. The research focuses on Moment Resisting Frames (MRFs), nevertheless, the aim is to extend the study to other structural typologies (e.g., steel Concentrically and Eccentrically Braced Frames).

Description of method and results

The obtained results provide general procedures, application tools, and optimised solutions to apply SC devices in steel MRFs. The results show the adequacy of this innovative technology on a wide range of building structures ensuring improved seismic performances in terms of structural damage and residual deformations. It has been demonstrated that the extensive use of SC devices produces a fully damage-free and self-centering response but represents a limit to the practical application due to the increase of structural complexity and cost. Therefore, optimised strategies are delineated to define the effective placement of a limited number of SC devices maximising their beneficial effect on the seismic performance. A general approach is proposed to easily define the optimal placement of SC devices hence promoting their use in practice.

The methodology used consists of the following steps: 1) critical literature review, 2) definition of an optimised design procedure for SC devices, 3) implementation of advanced finite element models; 4) parametric analysis on the most relevant design parameters which influence the seismic performance of steel MRFs with SC devices 5) definition of a general approach (i.e., genetic algorithm) to define the optimal placement of SC devices; 6) design of case-study structures; 7) Performance-based assessment: static push-pull analyses, incremental dynamic analyses, fragility curves.

Potential for application of results

The outcomes of the present research are of interest to many seismic-prone countries worldwide and have a direct impact on the seismic-resilience of buildings increasing their safety and their economic sustainability after an earthquake. The findings offer an efficient strategy for the seismic-risk mitigation of existing steel structures and the development of new structural systems, playing a key role in reducing casualties and socio-economic losses during seismic events. The definition of optimised solutions and general design methodologies for seismic-resilient steel structures based on SC devices represents a chance to reflect the academic research developed on this technology in policymaking and building codes. Additionally, the exploitation of the achieved results, in terms of design and recommendations can be disseminated to practicing engineers, architects, and contractors to promote the use in practice of SC devices as an innovative solution for seismic-resilient steel structures.

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Further information

Applicant: Ludovica Pieroni (E. ludovica.pieroni@ucl.ac.uk)
Supervisor: Dr. Fabio Freddi (E. f.freddi@ucl.ac.uk)

Department of Civil, Environmental & Geomatic Engineering, University College of London, London, United Kingdom

Development of Ultra High Performance Green Concrete with lightweight aggregates

27 **Sifan Mohamed**
Northumbria University, UK

Ultra-high performance (UHPC) concrete is a well-known new generation concrete that has very high strength and durability characteristics. Plenty of research has been conducted on UHPC under the area of such as improving the strength and durability, reducing the CO_2 emission from UHPC, lowering the cost of production, optimizing the particle packing, and utilizing it in various real time structural applications. However, there are almost no studies to develop UHPC under the lightweight concrete category. This research mainly forces on developing UHPC with suitable locally available materials in the UK including lightweight aggregates to reduce the density of the concrete compared to the normal weight UHPC. The objectives of the project are set:

- Develop normal weight UHPC with locally available materials in the UK by using particle packing models.
- Analyse the existing lightweight high strength concrete mixes and develop a prediction model by using machine learning techniques.
- Reduce the density of the UHPC by partially or fully replacing the normal weight aggregate with suitable high strength lightweight aggregates without significantly compromising its strength.
- Infill the developed lightweight high strength concrete in hollow flange cold-formed steel beams to enhance its structural performances and develop new design guidelines.

Development of normal weight UHPC.

As an initial step, a control mix of normal weight UHPC was developed by using locally available materials in the UK. The Modified Anderson and Anderson (MAA) particle packing model was successfully employed to obtain the maximum particle packing to minimize the pores inside the UHPC. MAA particle packing model was utilized by previous researchers to obtain the maximum particle packing, by only considering the particle size distribution of the ingredients[1-3]. Due to the fact that usually a high amount of cement is needed to achieve UHPC, the production of UHPC generates a relatively high amount of CO_2 emission than conventional concrete. Reducing the amount of cement may directly contribute to the reduction of the overall strength of the concrete [4, 5]. Therefore, limestone powder was used as a supplementary cementitious material (SCM) as it acts as a filler, increases the flowability, and supports the pozzolanic reaction. Silica fume (SF) and fly ash (FA) were very frequently used SCMs in the UHPC because of their high pozzolanic reaction. However, these SCMs were purposely omitted in this study because of the health hazards caused by very fine particles in SF, and the sustainability issues of FA in the UK. FA is a by-product of the coal combustion process in coal power plants. It is forecasted that most of the future electricity production might move towards renewable energy sources and the coal power plants in the UK may become inactive. Even without the presents of SF and FA, the UHPC achieved the average compressive strength of 125.6 MPa with 750 mm flow.

Fig 1 Flow and failure mode of UHPC

Machine learning prediction and development of lightweight high strength concrete

Existing lightweight high strength concrete mixes in the literature were collected and the reputed machine learning algorithms are being used do develop a prediction model to optimize the mix.

Development of Finite Element (FE) numerical models

FE models have been developed to simulate the behaviour of hollow flanged cold-formed steel beams filled with lightweight high strength concrete. The results revealed that concrete infill can increase flexural performance up to 55%.

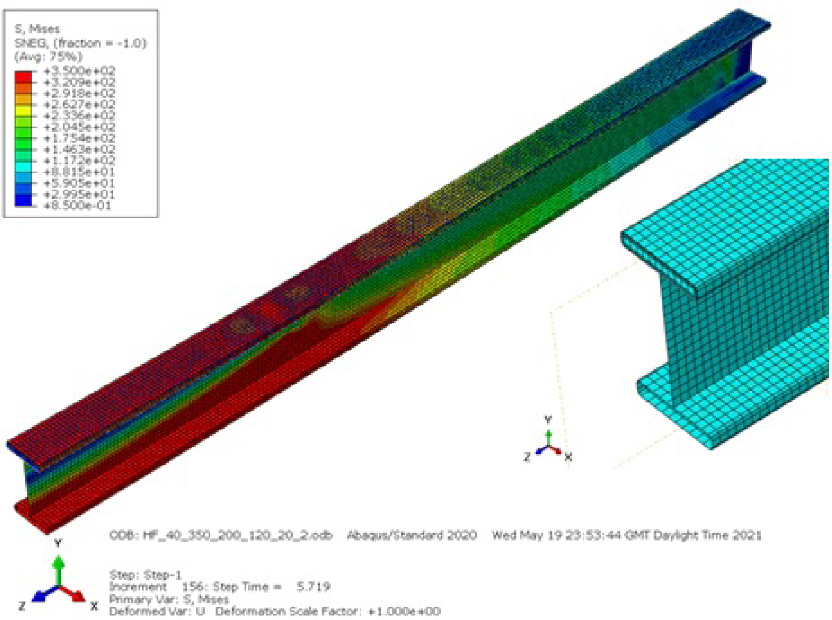

Fig 2 FE numerical simulation of lightweight high strength concrete filled hollow flanged cold-formed steel beams

Potential application of the lightweight UHPC

Many structural engineers' concern is to reduce the self-wight of the structures by reducing the density of the construction materials without compromising their strength and durability performance. Construction materials such as lightweight UHPC would decrease the self-weight of the structures, thereby the potential of using it in a very high-rise building is high. Also, it will cut down the additional cost involved in handling and transporting the materials as well as prefabricated structural elements. Lightweight UHPC can be used to produce eye-catching street furniture with different textures and colours with very thin profiles because UHPC has high strength and longer durability compared to normal concrete. This potable street furniture can be used in domestic gardens and even in industrial areas. The cold-formed steel beams filled with lightweight UHPC can increase the structural performance with the potential applications in modular building construction.

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Bespoke Concrete Ltd, UK
Northumbria University, Newcastle upon Tyne, UK

Further information

Sifan Mohamed – PhD student at Northumbria University (E. sifan.i.sifan.mohamed@northumbria.ac.uk)

Dr. Brabha Nagaratnam – Principal supervisor

A/Prof Keerthan Poologanathan – Co supervisor

A/Prof Marco Corradi – Co supervisor

Enhancement of modular building system in terms of sustainable performances

28 **Elilarasi Kanthasamy**
Northumbria University, UK

Project objectives and goals

The UK government initiated sustainable development progress in 2003 by forming a task group to ensure environmental protection, effective usage of materials and stability of economic growth and employment (Piroozfar, 2010). Moreover, Construction 2025, the strategy plan of the UK, aims at a 33% reduction in initial and lifetime costs, 50% faster construction, 50% lower emissions and 50% improvement in exports by 2025. However, in the post-Brexit period, the construction industry is facing huge issues such as labour shortage, high material costs and funding shortages (Poologanathan, 2021). Therefore, recovery plan (Buildoffsite Offsite Sector Response to COVID-19 Impact, 2020) is in progress to achieve the targets in terms of housing demand and sustainability, and modular construction is highlighted as the main theme in the recovery plan considering the new norms regard to the pandemic, such as social distancing and less crowding. Therefore, advances in modular construction method will benefit the construction industry of the UK near soon. Steel is the highest-rated and standout material for Modular Construction (MC) considering its advantages and Cold-Formed Steel (CFS) is highly preferred in MC as a portal steel frame system and load-bearing elements over hot-rolled steel (Gatheeshgar et al., 2020). Therefore, advances in technology towards sustainability generated innovative ideas in the CFS industry will achieve more sustainable benefits.

The overall aim of this research is to develop innovative MC Beams (MCBs) with enhanced structural and sustainable performances using optimisation techniques, experimental and Finite Element (FE) analyses. This research will lead

<table>
<tr><th>Model Description</th><th>Flexural capacity of single section (kN)</th><th>Screw Spacing (mm)</th><th>Material Strength (MPa)</th><th>Flexural Capacity (kN)</th><th>Capacity enhancement comparing to single section (%)</th></tr>
<tr><td rowspan="8">Open built-up section</td><td rowspan="4">11.31</td><td>50</td><td rowspan="4">450</td><td>23.81</td><td>110.52</td></tr>
<tr><td>100</td><td>23.76</td><td>110.08</td></tr>
<tr><td>200</td><td>23.72</td><td>109.73</td></tr>
<tr><td>600</td><td>23.56</td><td>108.31</td></tr>
<tr><td rowspan="4">12.48</td><td>50</td><td rowspan="4">600</td><td>27.57</td><td>120.91</td></tr>
<tr><td>100</td><td>27.48</td><td>120.19</td></tr>
<tr><td>200</td><td>27.44</td><td>119.87</td></tr>
<tr><td>600</td><td>27.42</td><td>119.71</td></tr>
<tr><td rowspan="4">Close built-up section with single screw</td><td rowspan="2">8.38</td><td>100</td><td rowspan="2">450</td><td>20.00</td><td>138.66</td></tr>
<tr><td>600</td><td>16.49</td><td>96.78</td></tr>
<tr><td rowspan="2">9.43</td><td>100</td><td rowspan="2">600</td><td>23.67</td><td>151.01</td></tr>
<tr><td>600</td><td>19.59</td><td>107.74</td></tr>
<tr><td rowspan="4">Close built-up section with double screws</td><td rowspan="2">8.38</td><td>100</td><td rowspan="2">450</td><td>21.04</td><td>151.07</td></tr>
<tr><td>600</td><td>17.35</td><td>107.04</td></tr>
<tr><td rowspan="2">9.43</td><td>100</td><td rowspan="2">600</td><td>24.18</td><td>156.42</td></tr>
<tr><td>600</td><td>20.47</td><td>117.07</td></tr>
</table>

Table 1 Flexural capacity enhancement for open and closed built-up sections comparing to their single section

Loading conditions	Proposed Equations		
ETF	Design Approach-1	$R_b = 2.27t^2 f_y \sin\theta \left(1-0.21\sqrt{\frac{r_i}{t}}\right)\left(1+0.21\sqrt{\frac{N}{t}}\right)\left(1-0.03\sqrt{\frac{d_1}{t}}\right)$	(1)
	Design Approach-2	$R_b = 0.65t^2 f_y \sin\theta \left(1-0.21\sqrt{\frac{r_i}{t}}\right)\left(1+0.21\sqrt{\frac{N}{t}}\right)\left(1-0.03\sqrt{\frac{d_1}{t}}\right)\left(1+4.68\sqrt{\frac{250}{f_y}}\right)$	(2)
	DSM	$\frac{R_b}{R_{b,y}} = 1$ for $\lambda \leq 0.40$	(3)
		$\frac{R_b}{R_{b,y}} = 0.67\left(1-0.17\left(\frac{1}{\lambda}\right)^{1.15}\right)\left(\frac{1}{\lambda}\right)^{1.15}$ for $\lambda > 0.40$	(4)
ITF	Design Approach-1	$R_b = 3.57t^2 f_y \sin\theta \left(1-0.21\sqrt{\frac{r_i}{t}}\right)\left(1+0.07\sqrt{\frac{N}{t}}\right)\left(1+0.21\sqrt{\frac{d_1}{t}}\right)$	(5)
	Design Approach-2	$R_b = 1.52t^2 f_y \sin\theta \left(1-0.21\sqrt{\frac{r_i}{t}}\right)\left(1+0.06\sqrt{\frac{N}{t}}\right)\left(1+0.20\sqrt{\frac{d_1}{t}}\right)\left(1+2.56\sqrt{\frac{250}{f_y}}\right)$	(6)
	DSM	$\frac{R_b}{R_{b,y}} = 1$ for $\lambda \leq 0.88$	(7)
		$\frac{R_b}{R_{b,y}} = \left(1-0.12\left(\frac{1}{\lambda}\right)^{0.56}\right)\left(\frac{1}{\lambda}\right)^{0.56}$ for $\lambda > 0.88$	(8)

Table 2 Proposed design Equations for high-strength CFS lipped channel sections under web crippling

to novel built-up configurations made of yield strengths ranging from low strengths to high-strengths for MCBs and new design guidelines to in line with European and International standards. To achieve the desired outcome, the following objectives are set.

- Optimisation studies of MCBs for enhanced structural and sustainable performances
- Development and validation of FE models with experimental results
- Parametric FE analysis of MCBs
- Developing new design approaches in line with European and International standards

Description of method and results

Even though modular construction is one of the emerging modern methods of construction, improved structural performance and material efficiency are the key targets of modular construction which are yet to be achieved to attain the sustainability targets. Following studies have been undertaken to attain the sustainability performances of a modular building by improving its structural performance and material efficiency.

Structural performances of built-up sections: This research intended to study the sustainable performance of built-up sections in terms of modular construction needs such as improved flexural performance, sustainability performances and effective material usage. In this study, lipped channel sections and an innovative unlipped channel sections with intermediate stiffeners were chosen for open and close built-up models respectively with different screw arrangements. Fig 1 depicts the considered sections for this study and a corner-supported modular building system with conventional beam profiles and proposed innovative built-up sections. Flexural capacity enhancement for built-up models comparing to single models and effect of screw spacing analysed and provided in Table 1.

A noticeable structural improvement was observed in closed built-up sections than open sections compared to their single sections when both the sections covering an almost similar coil length.

Structural enhancement of high-strength CFS profiles: CFS fabricated using high-strength steel have recently been utilised in construction due to their numerous advantages. Web crippling behaviour of CFS unlipped channel section with high-strength material (up to 1000 MPa) was investigated in this study under two-flange load cases using 486 numerical studies. Finite Element model setup of both load cases are illustrated in Fig 2. Existing design equations were not suitable to predict the ultimate web crippling capacity for high-strength CFS channel sections. Thus, modified design equations were proposed following the same technique of current design standards and a new Direct Strength Method (DSM) approach was developed (Eqns 1-8) and provided in Table 2.

Where, R_b- web crippling strength, f_y- material yield strength, t- section thickness, θ- angle between the plane of the web and the bearing surface, r_i- inside corner radius, N- bearing length, d_1- Flat portion of web, $R_{b,y}$- Yield load, λ- Slenderness of the section.

Above proposed equations were showed greater accuracy with mean of 1.00 and COV of less than 0.07 for all equations.

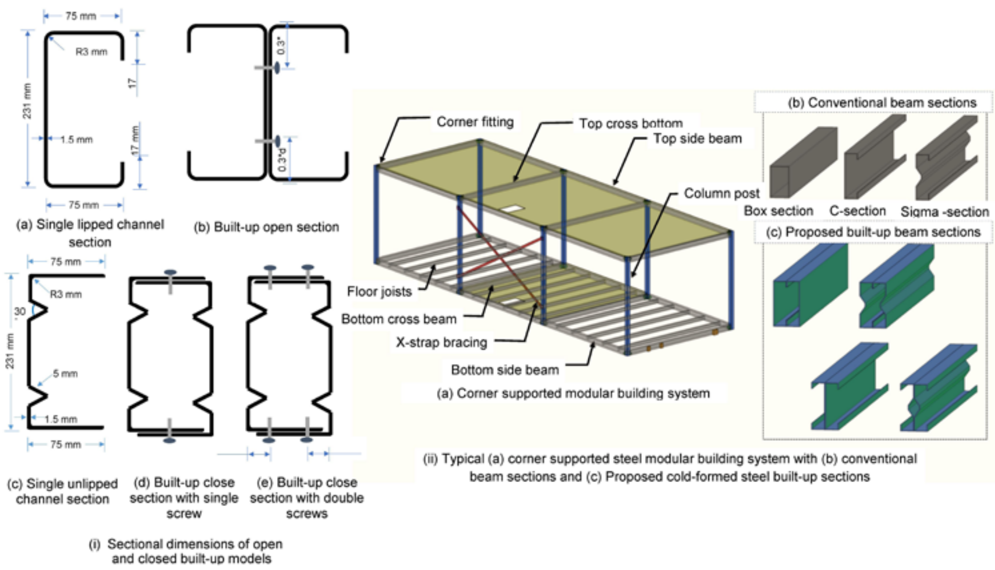

Fig 1 Parametric sections and a corner-supported modular building system with conventional beam profiles and proposed innovative built-up section

Potential for application of results

Since built-up sections enhance the flexural capacity, they will reduce the required material and minimize the weightage of the construction building. Secondly, the built-up sections are torsionally stable and have a load-bearing capacity; thus, minimal lateral restraints are required to restrain the joist. Thirdly, as the second moment areas of these built-up sections are much greater than traditional sections, they can be used for long spans. Therefore, the required number of intermediate columns will be reduced. Reducing the number of columns would increase the space in the constructions and enhance the indoor atmosphere condition. Therefore, using these built-up sections into the modular construction will positively impact in terms of sustainability performances and structural performances, as well as encourage the usage of lightweight materials. Moreover, high-strength CFS offer Superior strength-to-weight ratio, possibility to designing structural components with small dimensions and light weights and a promising material for relatively heavy structures (long-span and high-rise). Therefore, combining both of the built-up sections and high-strength material will positively affect the sustainability of modular constructions. Moreover, research studies on closed built-up sections with hollow flanges are also in progress, introducing various ideas of filling hollow spaces using various materials (lightweight concrete and timber) and on the other hand, the hollow area could be effectively utilized to accommodate the service conduits in modular building.

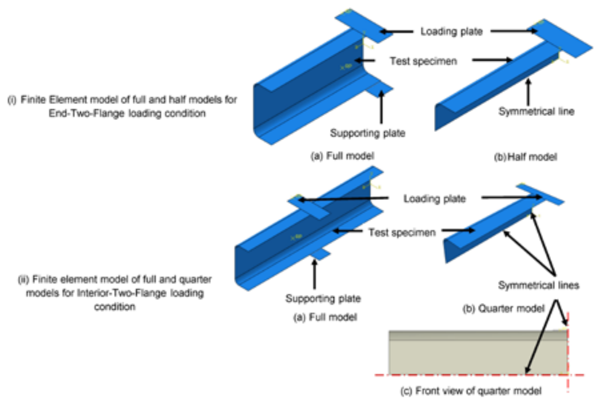

Fig 2 Finite Element model setup of both load cases (ETF and ITF)

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Funding body

Northumbria University, Newcastle upon Tyne, UK
The Home Engineers, Newcastle upon Tyne, UK
European Research Council

Further information

Elilarasi Kanthasamy
(E. elilarasi.kanthasamy@northumbria.ac.uk);
A/Prof Keerthan Poologanathan - Principal Supervisor;
A/Prof Marco Corradi and Dr Brabha Nagaratnam - Co-supervisors

Additively manufactured stainless steel corrugated shells: shape optimisation and experimental validation

29 Ruizhi Zhang
Imperial College London, UK

Project objectives and goals

Axially compressed circular cylindrical shells with large diameter-to-thickness ratios are known to be highly sensitive to initial geometric imperfections, which can drastically reduce their load-carrying capacity. Severe knock-down factors on their theoretical buckling loads are typically employed in the design of slender shells to account for their imperfection sensitivity, which greatly impairs their structural efficiency. This issue can be addressed by optimising the cross-section profiles of the shells, which now becomes practical with the innovative metal additive manufacturing technique.

The aims of this work are to develop a type of free-formfree form corrugated shell which is insensitive to local imperfections and to explore the structural performance and application of such corrugated shells produced by metal additive manufacturing.

Description of method and results

The Particle Swarm Optimisation (PSO) algorithm, the cross-section profile generation and numerical analyses were integrated into the shape optimisation of the corrugated shells. The smooth corrugated cross-section profile was determined by a non-uniform rational basis spline (NURBS) curve through a series of control points, which were assumed to be equally spaced circumferentially and only allowed to move within the maximum allowable displacement in the radial direction. The cross-sections were constrained to be either mirror-symmetric about two axes or rotationally symmetric. The radial positions of the control points in the first quadrant were therefore employed as the design variables.

The objectives of the optimisation procedure were to maximise the resistance to local buckling and to minimise the sensitivity to local geometric imperfections. The buckling loads of perfect and imperfect shells with positive and negative imperfection amplitudes were considered in the optimisation process. The initial imperfection pattern was chosen as the lowest elastic buckling mode shape obtained from a linear bifurcation analysis (LBA), and the imperfection amplitude ω equal to $\frac{1}{25}\sqrt{Rt}$ (Class B fabrication quality according to EN1993-1-6 (CEN, 2017)) was employed to factor the imperfection pattern. The PSO algorithm was employed to search for the optimum (or near optimum) in a large design space within a reasonable computation time. The optimisation algorithm was implemented using Matlab scripts, which automatically control the generation and dynamic movement of control points, the NURBS curves and surfaces in Rhino and the LBA, geometrically and materially nonlinear analysis without and with imperfections (GMNA, GMNIA) in Abaqus. The flowchart of the optimisation procedure can be seen in Fig 1.

The key results for four optimal candidate shells and their reference circular shell with an outer diameter D=200 mm, a thickness t=0.7 mm, a length L=200 mm and imperfection amplitudes ω, including the perimeter of the centreline l_c, the elastic local buckling stress σ_{cr}, the buckling load of the perfect shell P_0, the minimum buckling load of the imperfect shells min(P_+, P_-), the ultimate stress f_{ult} given by Eqn 1, the knock-down factor γ given by Eqn 2, the ratio between the ultimate stress f_{ult} and the 0.2% proof stress $\sigma_{0.2}$ and the ratio between the ultimate stress f_{ult} and the ultimate stress of the reference circular cylindrical shell $f_{ult,cyl}$, are summarised in Table 1. Overall, the rotationally symmetric wavy cylindrical shell with N=16 was shown to be the most optimal with the highest ultimate stress and the lowest imperfection sensitivity among the four candidate designs.

$$f_{\mathrm{ult}} = \frac{\min\,(P_0,P_+,P_-)}{\mathrm{A}} \quad (1)$$

$$\gamma = \frac{\min\,(P_+,P_-)}{P_0} \quad (2)$$

Five free-form corrugated cylindrical shells with different equivalent diameter-to-thickness ratios were optimised using the method described above, produced using the metal additive manufacturing technique, powder bed fusion (PBF), and tested under axial compression to investigate their structural responses and to verify the benefits derived from the optimised corrugated geometries. 3D laser-scanning and Digital Image Correlation (DIC) techniques were employed to capture the initial geometries prior to testing and deformation fields of the test specimens during testing, respectively. All corrugated shells exhibited axisymmetric deformation modes and failed by prominent local buckling in the troughs of the corrugations. The key test outputs, including the peak load N_u, the end shortening at the peak load δ_u, the ratio between the peak load N_u and plastic load $\sigma_{0.2}A$, equal to the ratio $f_{ult}/\sigma_{0.2}$, are reported in Table 2. Also presented are the optimisation results and measured geometries of all shells. All shells failed at around the expected plastic load $A\sigma_{0.2}$ except the specimen W200×0.7 due to the measured

Symmetry	N	lc (mm)	σ_{cr} (MPa)	P_0 (kN)	$min(P_+, P_-)$ (MPa)	f_{ult} (MPa)	γ	$\frac{f_{ult}}{\sigma_{0.2}}$	$\frac{f_{ult}}{f_{ult,cyl}}$
Circular	-	626.1	672.2	158.4	81.2	185.2	0.513	0.440	-
Mirror	16	750.3	931.6	231.6	223.2	425.0	0.964	1.010	2.295
Mirror	21	889.9	1466.3	273.2	267.5	429.5	0.979	1.020	2.318
Rotational	16	799.3	1180.4	246.0	244.1	436.4	0.993	1.036	2.355
Rotational	21	831.2	1328.2	255.9	253.0	434.9	0.989	1.033	2.348

Table 1 Optimisation results of wavy cylindrical shells and their reference circular cylindrical shell

Specimen (Dxt)	Optimisation results				Measured properties and test results						
	$min(P_+, P_-)$ (kN)	γ	$\frac{f_{ult}}{\sigma_{0.2}}$	$\frac{f_{ult}}{f_{ult,cyl}}$	t (mm)	L (mm)	ω_{mea} (mm)	A (mm²)	N_u (kN)	δ_u (mm)	$\frac{f_{ult}}{\sigma_{0.2}}$
W150×1.0	297.2	0.997	1.081	1.398	1.03	159.9	0.55	669.6	298.8	1.04	1.026
W180×1.0	346.8	0.991	1.065	1.552	1.08	188.2	0.28	803.3	344.2	1.14	0.985
W150×0.7	196.8	0.988	1.057	1.789	0.76	159.7	0.21	505.9	221.0	0.97	1.005
W180×0.7	235.1	0.996	1.050	2.044	0.75	189.5	0.26	527.0	220.5	0.98	0.962
W200×0.7	244.1	0.993	1.036	2.355	0.73	209.7	0.64	583.1	215.3	0.87	0.849

Table 2 Optimisation results, measured geometric properties and key test results of five shells

specimen length and imperfection amplitude larger than the assumed values. To a certain extent, the experimental results confirmed the effectiveness of the adopted PSO algorithm.

Potential for application of results

The optimised corrugated cross-section profiles were demonstrated to have much lower imperfection sensitivity and higher axial resistances compared with their reference circular sections through experiments, indicating a promising potential for structural applications. Also, the manufacture of structural components with complex geometries, such as the free form corrugated shells investigated herein, can be achieved by metal additive manufacturing.

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Further information

Ruizhi Zhang (E. r.zhang18@imperial.ac.uk)
or Prof Leroy Gardner (E. leroy.gardner@imperial.ac.uk)

Collaborators

Research group of Laser Processing, Mechanical Engineering, School of Energy Systems, Lappeenranta University of Technology www.lut.fi/web/en/school-of-energy-systems/research/laser-processing

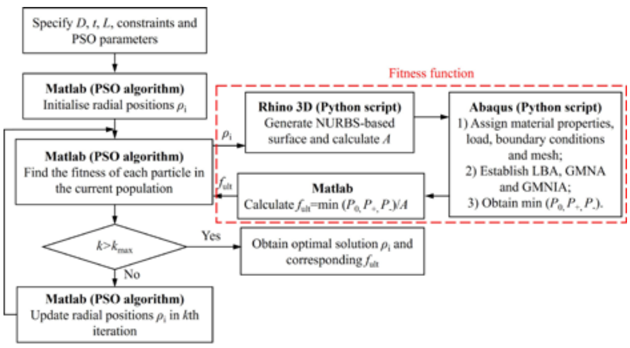

Fig 1 Flowchart of optimisation procedure

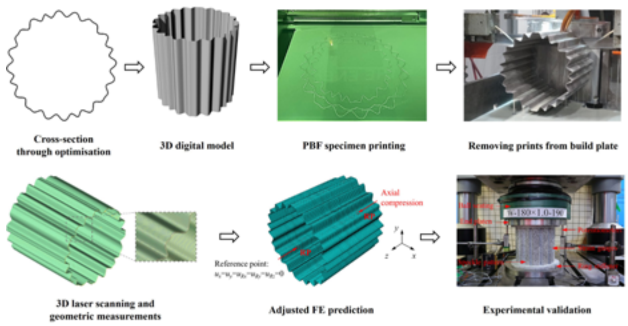

Fig 2 Procedure from optimisation to experiments

Human jumping on slender flexible structures

30 **Nimmy Mariam Abraham**
University of Exeter, UK

Project objectives and goals

Vibration serviceability limit state governs the design of modern, slender, lightweight structures. The people using these structures not only walk or stand, but also perform activities like jumping, especially during music and sports events on grandstands or vandal loading on footbridges. McDonald and Živanović (2017) provide valuable insight into the intra- and inter-subject variability in performing jumping. They found that the structural response to human actions is more sensitive to cycle by cycle variations in the activity frequency than variations in peak force and contact ratio. Nevertheless, understanding of human actions on vibrating structures is limited, but is crucial for developing models for vibration serviceability assessment. Xiong and Chen (2021) published a dataset that includes force time histories of jumping guided by metronome or music, performed by single persons and groups of people in different group sizes. However, their results are limited to jumping on rigid (i.e. stationary, non-vibrating) surface. Yao et al (2006) were the first to measure jumping forces on a moving platform and demonstrated the effect of the flexibility of the structure on the dynamic response and force generated by humans when they feel the structural motion while jumping. This study shows that human jumping on vibrating surfaces differs from that of non-vibrating surfaces. The aim of the present study is to investigate the intra-subject variability in ground reaction force (GRF) and activity frequency to understand how humans adapt their jumping under vibrations. This is achieved by fulfilling the following objectives:

1. Perform tests involving jumping on vibrating and stationary surfaces
2. Estimate the variability in jumping frequency and GRF peaks by calculating their coefficient of variation (CoV)

Description of method and results

Tests involving jumping on vibrating and non-vibrating surfaces were conducted in the VSimulators (motion platform) facility at the University of Exeter. Four healthy test subjects (TSs) participated in the study. They were asked to jump on the vibrating surface at specific combinations of metronome- controlled activity (jumping) frequency, platform's vibration magnitude and platform's vibration frequency. They were also made to jump at different time instances of a vibration cycle (e.g. in-phase with the platform or out-of-phase). The parameter values are listed in Table 1. Kinetic data (GRF) and kinematic data during human activity were measured using force plates embedded into the floor of the platform and reflective markers attached to human body and tracked by a system of cameras.

The TSs were instructed to position themselves in the VSimulators as shown in Fig. 1 and jump so to match the metronome beat. Each test configuration (out of 18 feasible combinations) lasted 30 s. TSs were subjected to these conditions in random order with sufficient resting intervals. During the interval, the TSs were asked to rate the vibration on a scale from 0 to 10, in relation to their comfort during jumping.

The raw GRF data were low pass filtered using a fourth order zero phase Butterworth filter with cut off frequency of 10 Hz. These were then processed to remove the inertia of the force plate. Peaks and time periods were then extracted on a cycle-by-cycle basis from the GRF data. The GRF peaks were normalised with the TS's weight and the activity time periods (T_p) were normalised with the target time period (target T_p). The CoV of normalised peaks and time periods were calculated for each data record and averaged under the following categories: platform vibration magnitude, platform frequency, activity frequency, frequency match between platform and activity and initial phase angle between platform and activity. The average CoV of normalised time period and average subjective vibration rating are shown in Fig. 2 for feasible combinations of platform (f_p) and activity frequency (f_a). CoV of normalised time period represents the variation in jumping frequency. Cases with stationary condition (hollow markers) are also included for comparison. The figure shows that activity frequency varies more on vibrating surface than on stationary surface. For jumping on vibrating platform, low frequency vibration causes more variability and more discomfort than high frequency vibration. Higher variability is observed for the cases where platform and activity differed than the cases with frequency match. Similar observations were made for variation in GRF peaks. The average subjective rating of vibration are also in agreement with these findings. This indicates that variability is associated with discomfort. The study shows that humans adapt their jumping on vibrating surfaces by changing their frequency and force.

Test variable [Unit]	Values
Activity frequency, f_a [Hz]	2.0, 2.8
Platform's vibration magnitude [m/s²]	0.0^S, 2.0
Platform's vibration frequency, f_p [Hz]	0.0^S, 2.0, 2.8
Platform-activity phase angle [°] when $f_a = f_p$ (initial phase angle when the frequencies do not match)*	0, 90, 180, 270

*Table 1 Test variables (S - stationary platform; *Only applicable to tests on moving platform)*

Fig 1 TS jumping on VSimulators platform

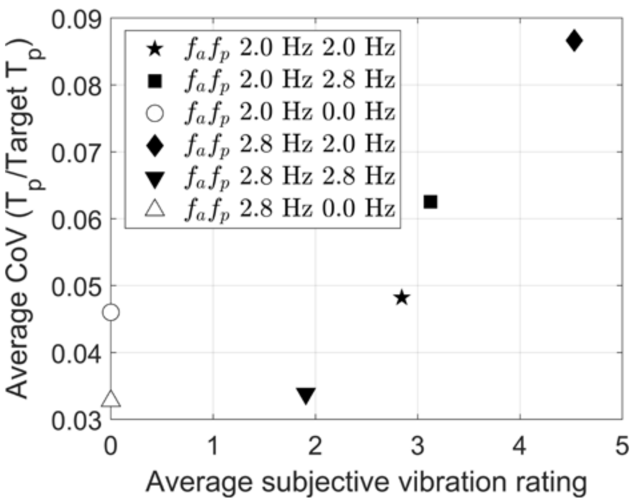

Fig 2 Human response to vibration for frequency match conditions between platform and activity while jumping

Potential for application of results

The results could be utilised in future for studying human structure interaction and development of reliable models for jumping on lively structures. This will lead to reduction in the conservativeness of the contemporary design codes and facilitate design of more environmentally friendly structures.

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Funding body

College of Engineering, Mathematics, and Physical Sciences (CEMPS), University of Exeter

Further information

Nimmy Mariam Abraham (E. na484@exeter.ac.uk)
Stana Živanović (E. s.zivanovic@exeter.ac.uk)

Thermal Behaviour of Precast Concrete Beam-to-Column Connections Subjected to Severe Fire Conditions

31 **Noor Azim Mohd. Radzi, Roszilah Hamid, Azrul A. Mutalib, A. B. M. Amrul Kaish**
Universiti Kebangsaan Malaysia

Project objectives and goals

The study investigates the thermal behaviour of precast concrete beam-to-column connections subjected to severe fire conditions. The objectives of this study are:

- To perform a full-scale fire test and investigate the thermal behaviour of a different type of precast concrete beam-to-column connections exposed to the cellulosic fire curve for 2 hours.
- To evaluate the influence of indirect action resulting from the thermal expansion and deformation to the moment-rotation-temperature characteristics of precast concrete beam-to-column connections.
- To perform the coupled thermal-structural finite element analysis (FEA) to validate the experimental result and predict the different fire scenarios involving precast building.

Previous work by Heiza et al. (2016), Raouffard and Nishiyama (2017), and Teja et al. (2019) on the fire exposure of the beam-to-column connection led to further investigation of the subject area, especially on the precast building connection.

Description of method and results

The test set-up is shown in Fig 1. The laboratory furnace with the dimension of 1500 mm (W) x 1500 mm (L) x 1500 mm (H) is used for the heating based on ISO 834 and ASTM E119. A total of eight samples consisting of different types of precast concrete beam-to-column (monolithic, corbel, nib, and inverted E nib) is prepared, as shown in Fig.2. Each type of connection is divided into control and heated sample. The column dimension is 300 mm x 300 mm x 2275 mm, and the beam dimension is 200 mm x 450 mm x 1250 mm.

The load is applied to the control sample in ambient conditions to get the first crack and ultimate loads. Then, the heated sample is preloaded with the first crack load value and remains constant during the 2-hour cellulose fire exposure. The sample is cooled down at ambient temperature before applying the gradual load until it fails.

The coupled thermal-structural finite element analysis (FEA) using ANSYS Workbench is performed to validate the experimental result and execute the parametric study.

This study is underway, and results will be obtained in the near future.

Potential for application of results

This study provides the critical thermal behaviour of precast concrete beam-to-column connections subjected to severe fire conditions, including the internal temperature distribution, moment–rotation curve, load-displacement curve, load – reinforcement strain curve, connection characteristic, connection classification, thermal behaviour, failure mode, and crack pattern.

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Further information

Noor Azim Mohd. Radzi (E. p100973@ukm.edu.my)
Roszilah Hamid (E. roszilah@ukm.edu.my)

Collaborators

None

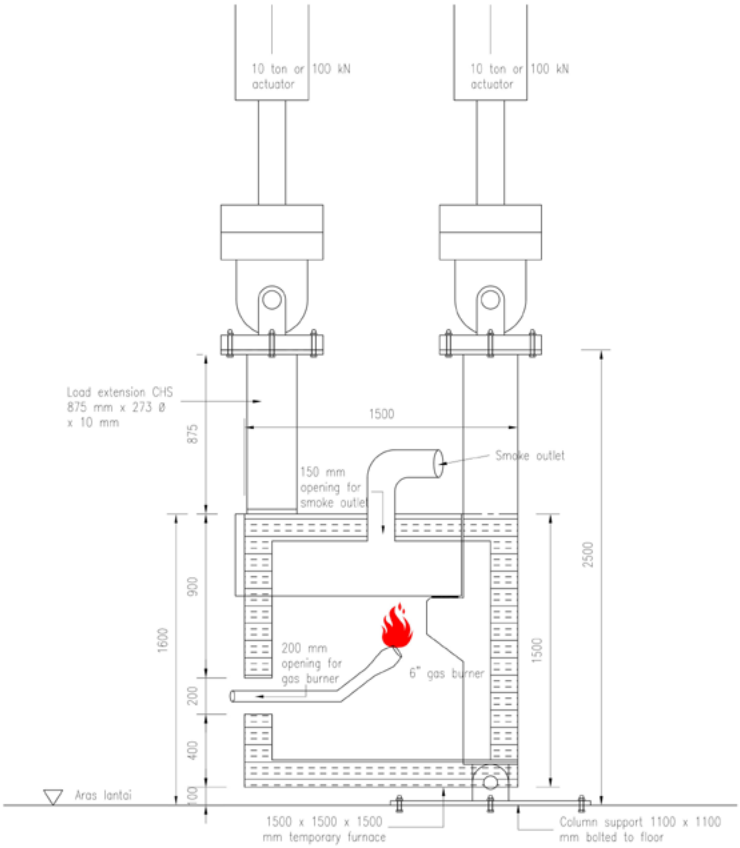

Fig 1 Test set up

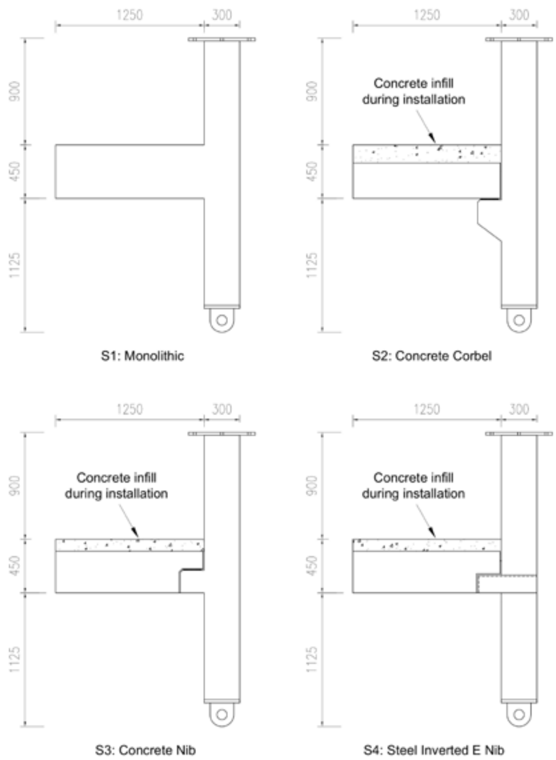

Fig 2 Experimental samples

Structural response and design recommendations for aluminium alloy structural elements

32 Evangelia Georgantzia
Liverpool John Moores University, UK

Project objectives and goals

The application of aluminium alloys as structural material has increased over the last years owing to their favourable properties, i.e., high strength-to-weight ratio, ease of fabrication, high degree of workability, considerable ductility, excellent thermal conductivity, high corrosion resistance and attractive appearance at their natural finish. The aforementioned advantageous features have contributed to increased usage of aluminium alloys in structural applications, where their application can allow for a reduction of the total structural weight. However, a thorough literature review (Georgantzia et al., 2021) denoted that the international design guidelines do not provide accurate strength predictions, which are opposed to an economical and efficient design philosophy. This is related to the fact that their formulae are based on limited amount of experimental and numerical results. Moreover, the design codes sometimes adopt similar principles to their steel structure counterparts, without sufficient consideration of the differences between the two materials. Additional research work on aluminium alloy structural elements can lead to modifications of the existing design codes and potentially will remove the existing limitations during their design. On the basis of the reviewed papers (Georgantzia et al., 2021), research topics which left unexplored or have limited number of reported studies have been identified. Particularly, some of these topics include the cross-sectional, flexural and flexural buckling response of structural elements employing tubular, channel and composite aluminium-concrete cross-sections. These concerns were thoroughly addressed in the current academic thesis. However, the present study focuses on the investigation of a) the flexural response of channel sections under minor axis bending and b) the rotational capacity and moment redistribution of aluminium alloy indeterminate structures employing stocky tubular cross-sections. The 6082-T6 heat-treated aluminium alloy is a relatively new alloy, although it has been rapidly employed in numerous of structural applications owing to its high strength. Hence, the investigated specimens were made from 6082-T6 heat-treated aluminium alloy providing a clear understanding about its structural behaviour. The applicability and accuracy of the European design codes (British Standards Institution, 2007) and a series of design methods have been assessed. Appropriate design recommendations have been, also, presented. Complementing the existing knowledge, the principal goal of the present study is to potentially boost the employment of aluminium alloys as an alternative construction material, capable of efficiently responding to the challenges encountered in real-life structures.

Description of method and results

Testing and finite element modelling studies have been executed to provide a better understanding about the flexural behaviour of channel and tubular cross-sections. The adopted testing methodology included the following four steps: i) Tensile tests on 6082-T6 aluminium alloy coupons to determine the material mechanical properties of both materials. ii) Measurements of the geometric properties of the specimens. ii) Measurements of the initial local and global geometric imperfections of the specimens using a linear height gauge machine. iii) Execution of tests. The adopted finite element modelling methodology included the following five steps: i) Development of the finite element models together with a detailed description of the modelling assumptions. ii) Validation of the finite element models against the test results. iii) Execution of parametric studies in order to examine the effect of key parameters on the structural performance. iv) Analysis of the results and assessment of relevant design codes and methods.

The obtained test and numerical results for the channel sections were utilised to assess the European design codes (British Standards Institution, 2007). The applicability of the Continuous Strength Method (CSM) (Zhao and Gardner, 2018) for stainless steel channel sections and the Direct Strength Method (DSM) (American Iron and Steel Institute, 2012) were also evaluated. An alternative design method based on the plastic effective width concept (Bambach et al., 2007) was proposed for slender channel sections under minor axis bending. This method accounts for the inelastic reserve capacity which is in accordance with the experimental and numerical observations. Regarding the tubular cross-sections, the obtained test and numerical results were utilised to assess the accuracy and applicability of (i) the traditional plastic design method, (ii) the European design codes (British Standards Institution, 2007), (iii) the plastic hinge method included in Annex H of (British Standards Institution, 2007), and (iv) the CSM (Su et al., 2016). Relative comparisons demonstrated the potential of applying plastic design in aluminium alloy indeterminate structures. Notably, the plastic hinge method and the CSM which accounts for strain hardening at the cross-sectional level and for moment redistribution at the system level were found to provide the most accurate design strength predictions, resulting in more economical cross-sections and utilising the full potential of aluminium alloys' plastic deformability.

Potential for application of results

Extensive experimental and numerical studies on the structural performance of 6082-T6 aluminium alloy structural elements have been carried out. The obtained results were analysed and utilised to assess relevant design specifications and methods, extending the pool of performance data on the structural response of aluminium alloy components, thus contributing to the development of more refined design rules in line with the observed structural response. This hopefully will increase structural engineers' confidence towards a more frequent employment of aluminium alloys in structural applications.

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Further information

Evangelia Georgantzia (E. E.Georgantzia@2019.ljmu.ac.uk)
Dr Michaela Gkantou (E. M.Gkantou@ljmu.ac.uk)

Pressurized sand damper as a sustainable solution for the response modification of structures

33 **Kostas Kalfas**
Southern Methodist University, USA

Project objectives and goals

This research is motivated by the failure of the end seals of the fluid dampers that were installed on the Bay Bridge, in San Francisco. Matier and Ross (2013) reported that these failures resulted in detrimental oil leakage. Such failures are not in-line with the current sustainable engineering technologies, where the design and construction of structural systems should meet acceptable performance levels in present and future years without compromising the ability of future generations to use, maintain, and benefit from these structures.

The fluid dampers dissipate energy from the passage of oil through orifices or valves. They suffer from viscous heating (a substantial increase of their temperature) when they are subjected to prolonged excitations; resulting in fatigue and catastrophic failures, which can be disruptive and costly.

This work proposes an innovative, low-cost, fail-safe, sustainable energy-dissipation device in which the material surrounding the moving piston and being enclosed within the damper housing is pressurized sand. The proposed sustainable pressurized sand damper (PSD) does not suffer from the challenge of viscous heating (the dissipative performance of granular materials shows limited dependence on temperature (Saeki 2005)) and failure of its end seals, and it can be implemented in harsh environments with either high or low temperatures. Its symmetric force output is velocity-independent, and it can be continuously monitored and adjusted at will with standard commercially available strain gauges installed along the post-tensioned rods that exert the pressure on the sand. The experimental results provide a good understanding of the PSD, which exhibits a stable hysteretic cyclic behaviour with increasing pinching at larger strokes (Kalfas and Makris 2022). One of the most attractive advantages of the PSD is that it consists purely of traditional materials (sand and steel) in association with post-tensioning; with which practitioners are most familiar.

Description of method and results

The proposal of this sustainable device is based on the concept of a steel sphere with radius R that moves with a constant velocity v. In the absence of gravitational forces within a sufficiently large, enclosed sand medium, the sphere is pressurized with a pressure p along its direction of motion. The shearing forces on the moving sphere from the sand flowing around its surface dominate over the inertia forces of the sand grains. It can be said that the developed shear stresses on the steel sphere, due to the sand grains, are nearly velocity-independent; given that these are hysteretic stresses. The drag force, applied to the moving sphere is the projection along the direction of motion of the shearing strength that is mobilised along the sand-steel interface and the passive normal stresses that develop on the front of the moving sphere.

$$F_S = f(p,R) = \Pi_S p R^2 \quad (1)$$

, where Π_S is the dimensionless coefficient that accounts for the spherical geometry, the Poisson effect that controls the level on normal stresses along directions other than the direction of motion, and the projections discussed previously. Eqn 1 shows that F_S is proportional to p and is quadratic to R.

Regarding the dimensions of the prototype PSD (Fig 1), a sphere with radius R=1.125in (2.8575cm), that is mounted to the shaft/piston rod with diameter d_{pr}=1.25in (3.175cm) is moving within the finite domain of the cylindrical damper housing with diameter D=4.875in (12.3825cm) and length L=24in (60.96cm). Therefore, the drag force on the sphere also depends on the stroke of the damper, u, and on the clearance between the sphere and cylindrical housing. By following the same reasoning as previously, the drag force on the sphere moving along the axis of the cylindrical damper housing is:

$$F_d = f(p,R,u,D) = \Pi_S p R^2 \varphi\left(\frac{u}{R},\frac{D}{R}\right) = Q\varphi\left(\frac{u}{R},\frac{D}{R}\right) \quad (2)$$

, where $p=4F/(\pi D^2)$ is the pressure along the direction of motion of the shaft; Π_S is the new dimensionless coefficient that also considers the friction stresses that develop along the moving shaft; $\varphi(u/R,D/R)$ is the dimensionless function that depends on the normalised stroke, u/R, and clearance, D/R; and $Q=\Pi_{SD}\, pR^2$ is the strength of the PSD.

The manufacture and testing of the prototype PSD took place in the Structures Laboratory of SMU (Fig 1). The 245-kN hydraulic actuator imposes a cyclic displacement history $u(t)=u_0 \sin(2\pi f_0 t)$ on the attached sand damper at multiple amplitudes, frequencies and pressure levels. After the damper housing is filled with the dry sand, the end cap is hand-tight, while the damper is vertical. Subsequently,

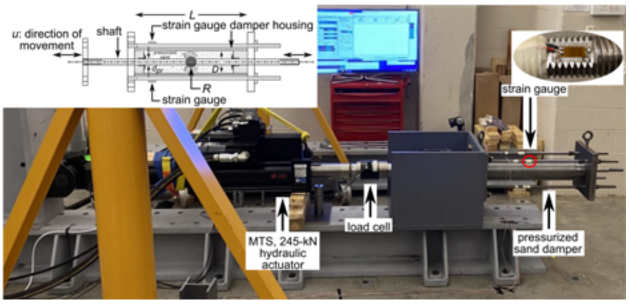

Fig 1 Experimental setup; SMU Structures Laboratory. Schematic of a PSD. Detail of a commercially available weldable strain gauge

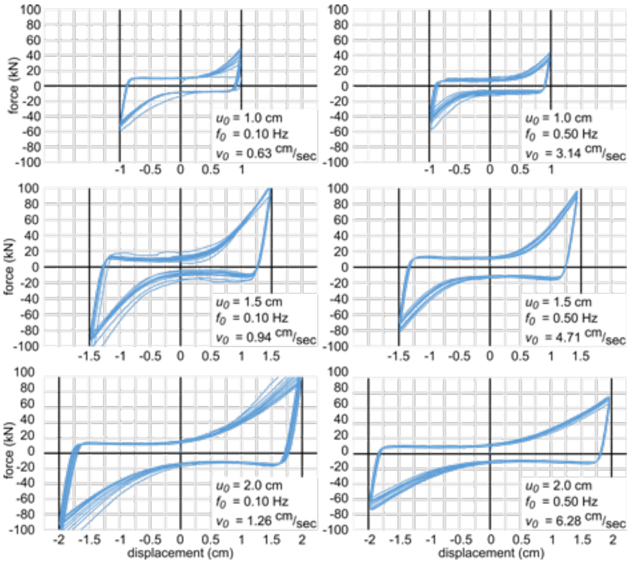

Fig 2 Recorded force-displacement loops at various amplitudes, and frequencies; exerted pressures, p=1MPa

the damper is mounted on the steel angle of the experimental setup in its horizontal position (Fig 1). Then, the damper is post-tensioned at the desired pressure. Fig 2 plots the recorded force–displacement loops from the prototype PSD. The force output when the sphere is passing through the origin (that is when the sphere reaches its peak velocity during its harmonic motion) is nearly velocity-independent. By observing Fig 2, one concludes that the shape of the hysteretic loops together with the pinching behaviour that manifests at larger displacements is essentially not affected by the local behaviour prior to yielding.

Potential for application of results

The results from this research will give a valuable insight into the potential application of a new sustainable solution for the protection of structures against natural hazards. The work aims at contributing to the current trends of sustainable engineering technologies. The extensive experimental campaign will allow for the generation of the macroscopic model of the PSD which will be applied to high-rise buildings and bridges to investigate their response under seismic actions.

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Funding body

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Further information

Kostas Kalfas (E. kkalfas@smu.edu)
Project Supervisor: Prof Nicos Makris
(E. nmakris@smu.edu)

The Institution of
StructuralEngineers

The Institution of Structural Engineers
International HQ
47-58 Bastwick Street
London EC1V 3PS
United Kingdom

T +44 (0)20 7235 4535
E mail@istructe.org
www.istructe.org

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