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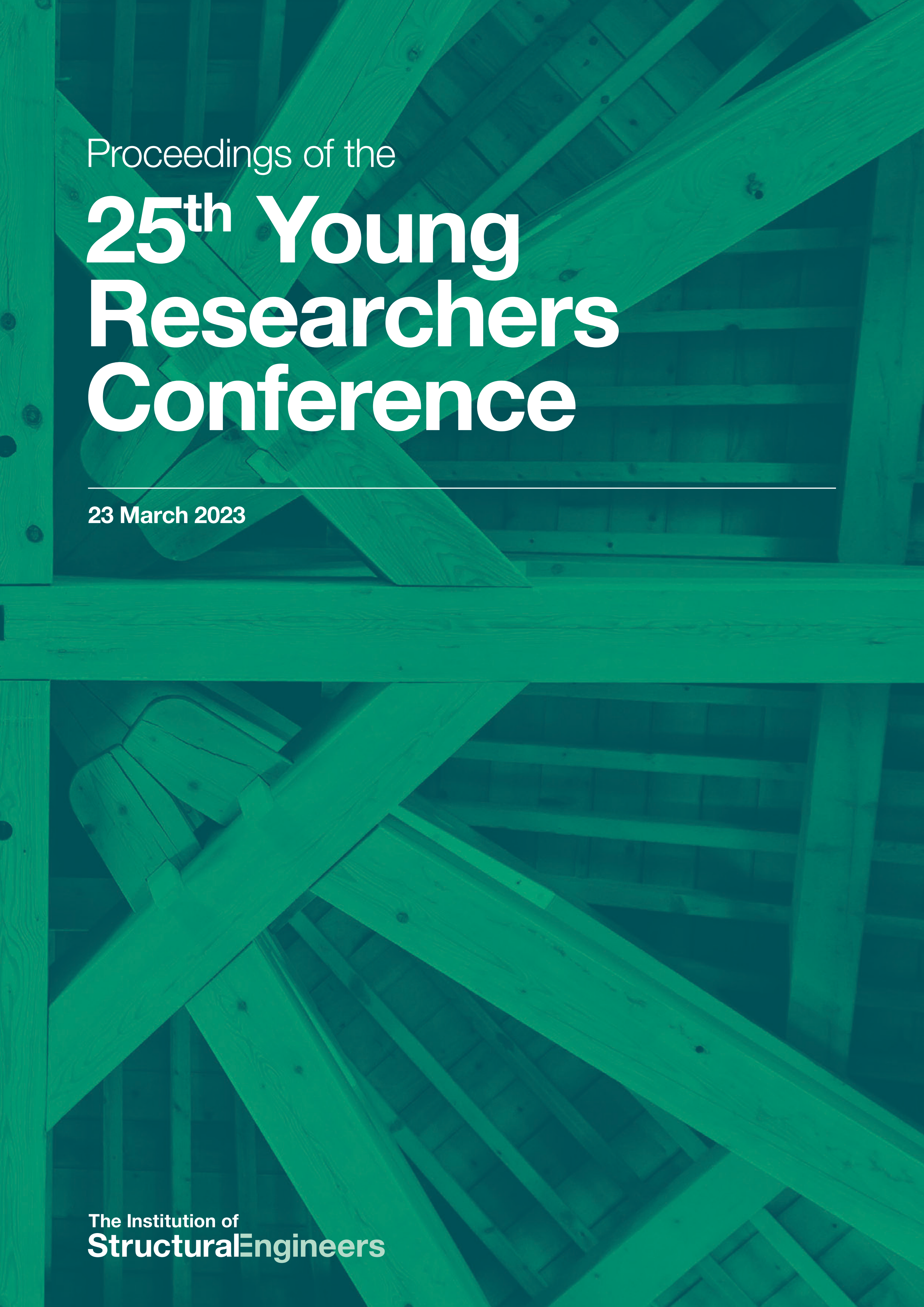

Proceedings of the

25th Young Researchers Conference

23 March 2023

The Institution of
StructuralEngineers

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This booklet contains synopses from researchers taking part in the 25th Young Researchers' Conference, organised by the Institution of Structural Engineers. The Institution bears no responsibility for the presentation or technical accuracy of the content in these synopses.

Conference sponsors and supporters

IABSE (British Group)

IABSE (International Association for Bridge and Structural Engineering) is a long established and well-respected international association dedicated to developing, sharing and disseminating structural engineering knowledge and expertise among its members. The British Group comprises those members currently working in the UK and organises a variety of events and meetings in the UK.

www.iabse.org.uk

Conference Programme – 23 March 2023

Time	Activity	Persons
13:00	Institution Welcome from Conference Chair	Leroy Gardner, Chair of the Research Panel, Imperial College London
13:05	**Keynote address: Achievable contemporary buildings** Drawing on sbp's experience with projects and research at the TU Berlin, Prof. Schlaich explores what we can already do and what still needs to be done to achieve our sustainability targets	Prof. Mike Schlaich, Partner, Schlaich Bergermann
Session 1		
13:35	Research presentation 1 – *Predicting the environmental response of critical infrastructure, using the first metal 3D printed structure as a case study*	Theo Glashier, Imperial College London
13:50	Research presentation 2 – *Post-installed reinforcement for 3D concrete printing technology*	Yangyunzhi Gao, National University of Singapore
14:05	Research presentation 3 – *Towards the adoption of metal 3D printing in structural engineering*	Ben Weber, Imperial College London
14:20	Research presentation 4 – *Structurally Superior Laminated Glass: A Proof of Concept*	Feyza Yildirim, University of Southampton
14:35	Break	
Session 2		
14:45	Research presentation 5 – *Optimising the environmental impact of deep foundations*	Kareem Abushama, University of Bath
15:00	Research presentation 6 – *Experimental study of DED-arc additively manufactured steel double-lap shear bolted connections*	Xi Guo, Imperial College London
15:15	Research presentation 7 – *Structural integrity of pultruded GFRP bridge decks with random fibre misalignments*	Matthew Poulton, University College London
15:30	Research into Practice Case Study Competition winner presentation – *Design of Efficient Steel Trusses to Resist Progressive Collapse*	Nada Elkady, Structural Engineer, Renaissance Associates Ltd.
15:45	Key research challenges	Mike Sefton, Associate Innovation Engineer, Expedition Engineering Ltd & Filip Kirazov, Senior Structural Engineer, Robert Bird Group
16:00	Certificates, prize giving	
16:15	Closing comments	

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

Poster presentations

Mechanical and structural behaviour of rubberised alkali-activated concrete (Synopsis. 1)
Mohamed Elzeadani – Imperial College London

Predicting the performance of concrete infrastructure from SHM data using automated clustering-based segmented regression (Synopsis. 3)
Harshita Garg – University of Leeds

Spatially defined tyre loads for FE analysis of GFRP deck (Synopsis. 5)
Zhaotian Yang – University College London

Development of Innovative Modular Building System with Enhanced Fire, Environmental, Structural and Thermal Performance (MOD-FEST) (Synopsis. 6)
Heshachanaa Rajanayagam – Northumbria University

Fire Performance of Prefabricated Cellular Lightweight Concrete Panels (Synopsis. 7)
Irindu Upasiri - University of Sri Jayewardenepura

Development and applications of lightweight high strength concrete made with lightweight aggregates (Synopsis. 9)
Sifan Mohamed Ibrahim – Northumbria University

Design of SupaCee sections with web openings – Bending and shear (Synopsis. 10)
Kajaharan Thirunavukkarasu – Northumbria University

Design of stainless steel structural systems by GMNIA with strain limits (Synopsis. 12)
Hou Un Chan – Imperial College London

Innovative beam profiles for modular construction (Synopsis. 13)
Elilarasi Kanthasamy – Northumbria University

Data-driven structural design models using physics-informed neural networks (Synopsis. 14)
Adrien Gallet – University of Sheffield

The development of assessment models for the FlexiArch bridge system experiencing bridge scour, under loading (Synopsis. 21)
Ben Millar – Queen's University Belfast

Thrust Layouts for Masonry Gravity Structures (Synopsis. 22)
Kavinda Isuru Nanayakkara – University of Sheffield

Keynote Speaker

Mike Schlaich

Professor of Structural Engineering, Technische Universität Berlin

Prof. Schlaich graduated with a Doctorate in Technical Sciences from ETH Zurich. He joined the structural engineering firm schlaich bergermann partner (sbp) in 1993. Today he is Member of Board at sbp, with six offices across the world, serving on prominent international projects and redefining the engineering fundamentals with cutting edge research. Mike's interests focus on the design of lightweight, sustainable and innovative structures that combine structural design with architectural aesthetics. He chairs the Department of Conceptual and Structural Design at the Technische Universität Berlin.

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:

Fernando Madrazo-Aguirre – *COWI*
Philip Pearson – *MoD*
Steve Matthews – *WSP*
Dr Jason Ingham – *University of Auckland*

Judging Panel:

The judging panels are formed from eligible members of the Research Panel.

Steve Matthews – *WSP*
Dr Bahman Ghiassi – *University of Birmingham*
Dr Stana Zivanovic – *University of Exeter*
Dr Donya Hajializadeh – *University of Surrey*
Prof. John Forth – *University of Leeds*
Samuel Latimer – *SWAL Engineering Ltd*
Prof. Zhenjun Yang – *Wuhan University*
Fernando Madrazo-Aguirre – *COWI*
Eva Gaal – *NHBC*
Dr Tony Jones – *MPA The Concrete Centre*

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Research into Practice Case Study Competition winner

Nada Elkady

Structural Engineer, Renaissance Associates Ltd

Design of Efficient Steel Trusses to Resist Progressive Collapse

Structural Engineer at Renaissance Associates Ltd. and PhD Candidate in Civil Engineering, School of Science, Engineering and Environment, University of Salford, United Kingdom. Main research interest is studying the progressive collapse of reinforced concrete structures.

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. Mithila is a member of the committee of IStructE Lancashire and Cheshire Regional Group.

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.

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.

Fernando Madrazo-Aguirre

PhD, DIC, CEng, MICE

Fernando is an Associate 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.

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 some 200 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 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

Dr. Yancheng CAI holds the Assistant Professor position in the Department of Construction and Quality Management at Hong Kong Metropolitan University, Hong Kong. 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 Member of the Institution of Civil Engineers, UK, member of Hong Kong Institution of Engineers (HKIE) and member of American Society of Civil Engineers. 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.

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.

Tony Jones

PhD, CEng, FICE, FIStructE

Tony is a Structural Engineer with over 30 years of experience in design, research and investigation of concrete structures. Tony is currently Technical Director at MPA The Concrete Centre. He provides guidance on all aspect of structural concrete design including performance in fire. Tony has been involved with the production of numerous industry guides and has been involved with the development of concrete structural codes for over 20 years. He is currently the UK Head of Delegation on the European design committee, which is responsible for Eurocode 2, Design of Concrete Structures, including the fire part.

Samuel Latimer

MSc, BSc (Hons), CEng, MIStructE

Samuel is a chartered structural engineer, PhD researcher and associate lecturer. He has over 10 years' experience within consulting engineering predominantly gained within the mid – high rise residential and refurbishment sector. Samuel now runs his own small structural engineering and concrete consultancy practice. His current research is focused on understanding the long-term properties of multi decade aged cement and concrete consisting of ordinary Portland cement, ground granulated blast furnace slag and pulverised fuel ash. He also lectures undergraduate civil and structural engineering students and degree apprentices.

Messaoud Saidani

BEng, PhD, SFHEA, PgCertLT, FIStructE, CEng

Messaoud is Senior Fellow of the Higher Education Academy, a Chartered Engineer and a Fellow of the Institution of Structural Engineers. After obtaining a 1st class honours degree in Civil Engineering, Messaoud embarked on a PhD in Structural Engineering at The University of Nottingham, which he successfully completed in 1991. He then stayed on as a post-doctoral research fellow working on a number of pan-European and UK projects. In 1995, he joined Coventry University to teach structural and material engineering. He is currently Associate Director of Research and Engagement at the Research Institute of Clean Growth and Future Mobility. Messaoud has over 25 years' experience in teaching, research and consultancy covering a large number of topics in structural engineering. In the past his research focused on the performance of connections in steel structures, properties of concrete manufactured with waste materials, and FRP connections. Current research is focusing on the circular economy in construction. Messaoud has authored over 200 papers and technical reports, and his research work is widely cited in journals and textbooks. He is a member of the editorial board of a number of international journals, and a reviewer of funding applications to a number of funding bodies, such as the EPSRC and the British Council.

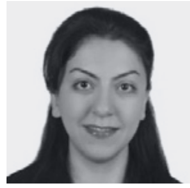
Dr Bahman Ghiassi

BSc, MSc, PhD, FHEA, MIStructE, CEng

Dr Ghiassi is an Associate Professor of Sustainable Infrastructure Materials and a Chartered Structural Engineer (MIStructE, CEng) in the School of Engineering at the University of Birmingham. He obtained his PhD in 2013, held two postdoctoral fellowships from 2014 to 2018 (including a Marie Curie Fellowship at the Technical University of Delft), was appointed as Assistant Professor of Structural Engineering at the University of Nottingham in 2018 and then joined the University of Birmingham in 2022 as an Associate Professor. His research centres around sustainable construction materials with the main focus on innovative alternative cements, cement-based composites, masonry and waste-based materials. In 2019, he was awarded the RILEM Gustavo Colonetti medal for his "outstanding scientific contribution to the field of construction materials and structures". Dr. Ghiassi is the author of more than 180 peer-reviewed scientific articles in reputable journals and international conferences. He has given several invited talks and keynote lectures and is an active member of international scientific committees including Chapter lead and Experimental Round Robin Testing Workgroup leader in the RILEM Technical Committee 290-IMC (Durability of inorganic matrix composites used for strengthening of masonry structures). He also sits in the editorial board of a number of journals including the ICE Journal of Construction Materials, Nature Scientific Reports, ASCE Journal of Composites for Constructions and International Masonry Society Journal.

Dr Donya Hajializadeh

BEng (Hons), MEng, PhD, CEng MICE, MIEI, EUR ING, MWES, FHEA



Donya is a Chartered Civil Engineer and Senior Lecturer in Bridge/Structural Engineering and Director of Employability at the School of Sustainability, Civil and Environmental Engineering, University of Surrey. Donya's principal areas of research interests include direct and indirect structural health monitoring, reliability, risk and resilience assessment of critical infrastructures, bridge traffic load modelling and simulation, data-driven solutions and digital twinning. She is a Fellow of the Surrey Institute for People-Centred Artificial Intelligence (AI) and an active member of several professional bodies, including the Institution of Structural Engineers (IStructE), the Institution of Civil Engineers (ICE), the Institution of Engineers of Ireland (IEI), the European Federation of National Engineers Associations (FEANI) and the Women's Engineering Society (WES). In 2022, she won the prestigious Department for Transport (DfT)'s Innovative Solution Award for her work in developing machine learning-based indirect damage identification systems for railway bridges.

Dr Stana Živanović

MEng, PhD

Stana is an Associate Professor at the University of Exeter. She was awarded her first degree in Structural Engineering from the University of Belgrade and her PhD from the University of Sheffield. Her research expertise is in the area of experimental and numerical modelling of both structures and humans, and understanding the way they interact with each other. She has contributed to researching different aspects of the vibration serviceability of civil engineering structures: modelling human actions (such as walking and jumping) and their dynamic interactions with footbridges, evaluating human response to vibration and assessing structural performance. She is also interested in dynamic performance of structures made of lightweight materials, as well as in channelling research findings into design guidelines.

Mechanical and structural behaviour of rubberised alkali-activated concrete

01 **Mohamed Elzeadani**
Imperial College London, UK

Project objectives and goals

Alkali-activated concrete are a class of materials that avoid conventional cement in the mix design, and instead, use industrial by-products (e.g., fly ash and blast furnace slag) alongside a chemical activator to form the binding gels. Rubberised concrete, meanwhile, involves replacing some of the natural mineral aggregates with rubber particles derived from worn-out vehicle tyres. This provides a recycling path for tyres and enhances certain characteristics of concrete, such as deformability and energy absorption.

While previous studies have looked intensively at alkali-activated concrete (Amran et al., 2020, Elzeadani et al., 2022), and rubberised concrete (Thomas and Gupta, 2016), research on rubberised alkali-activated concrete is still relatively new, and much remains to be done (Elzeadani et al., 2021). The objectives of this research project can be listed as follows:

- To develop a highly workable mix design with stable compressive strength development
- To assess the quasi-static mechanical properties and constitutive behaviour
- To evaluate the rate-dependent cyclic response and impact properties
- To assess the long-term creep response
- To study the steel confinement behaviour under concentric axial loading for both circular and square sections
- To assess the aramid fibre-reinforced polymer confinement effect under axial loading conditions with varying layer thicknesses

Description of methods and results

Concrete structures could be subjected to a wide range of loading rates during their service life. Fig 1 shows a range of loading rates that concrete structures are generally prone to. Concrete materials are strain-rate sensitive, i.e., their mechanical properties depend on the loading rate. Having highly deformable material, such as rubber particles, in the concrete matrix could increase this strain-rate sensitivity. A proper understanding of the mechanical properties under varying strain-rates is therefore necessary to be able to use rubberised alkali-activated concrete more efficiently.
The study method involves the experimental testing of rubberised alkali-activated concrete under different strain-rates. Specimens were prepared using ground granulated blast furnace slag as the main aluminosilicate precursor, while fly ash was added as a supplementary precursor. Anhydrous sodium metasilicate, in a solid state, was used as the chemical activator. River sand and crushed gravel were used as fine and coarse natural aggregates, respectively. Rubber particles from car and truck tyres were used and rubber contents of up to 60% replacement by volume of the total natural aggregates were considered.

Creep specimens were tested using creep loading rigs loaded at 10 and 20% of their compressive strength for 1-year. Quasi-static mechanical properties and rate-dependent cyclic constitutive behaviour were determined using servo-hydraulic testing machines after 28-days of concrete curing. The impact properties under relatively high strain-rates were determined using an instrumented drop-weight testing machine together with digital image correlation to get displacement readings. This included both compressive and splitting tensile impact tests.

The confined behaviour of rubberised alkali-activated concrete was also investigated using experimental and numerical methods. The experimental programme involved testing steel and aramid-fibre-reinforced polymer confined specimens under uniaxial compressive loading in a servo-hydraulic testing machine after 28-days of curing. Finite element modelling was then used to first validate the experimental results, and then expand beyond the experimental database to gain further insights into the confined member behaviour.

Potential for application of results

The study presents an optimised rubberised alkali-activated concrete mix design with high workability and high compressive strength that could be used for practical structural applications. The experimental results also shed light on the quasi-static mechanical properties, including the compressive strength, elastic modulus, splitting tensile strength and flexural strength. Analytical expressions and constitutive models are also introduced to help predict the quasi-static mechanical properties and full stress-strain response under varying rubber contents.

The rate-dependent cyclic material behaviour, simulating moderate and severe earthquake loading conditions, help derive constitutive models for the cyclic response and assess the unloading modulus and residual plastic strain after each loading-unloading cycle in the post-peak regime.

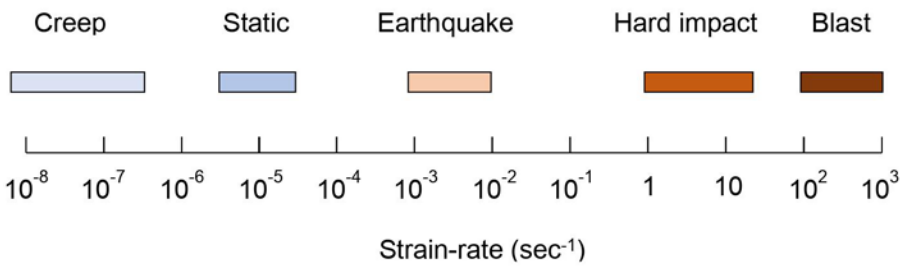


Fig 1 Strain-rates for different loading cases

This helps characterise the cyclic behaviour and cyclic degradation of rubberised alkali-activated concrete.

The impact results provide insights on the concrete response under high strain rates of up to 270 sec^{-1}. Analytical expressions for the dynamic increase factors at varying strain-rates are introduced as well to predict the compressive strength, elastic modulus, axial crushing strain and splitting tensile strength. These properties are important when modelling concrete structures under impact loading conditions.

The creep results highlight the creep strains and creep coefficients for this new type of concrete which are important for design purposes and long-term serviceability of concrete structures. Comparisons with provisions available in design codes are given and further recommendations are highlighted as well.

The results from the steel and aramid fibre-reinforced polymer confined specimens highlight the confinement behaviour and present possible structural application scenarios. The experimental results, complemented with numerical data, help present analytical expressions to predict axial load capacity of circular and square steel-confined members having different dimensions and different rubber contents. The results from the aramid fibre-reinforced polymer confined specimens help introduce constitutive models to predict member behaviour under different fibre thicknesses and different rubber contents.

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Further information

Mohamed Elzeadani (m.el-zeadani20@Imperial.ac.uk)
Ahmed Elghazouli (a.elghazouli@imperial.ac.uk)
Dan Bompa (d.bompa@surrey.ac.uk, d.bompa@imperial.ac.uk)

Structural integrity of pultruded GFRP bridge decks with random fibre misalignments

02

Matthew Poulton
University College London, UK

Project objectives and goals

The cost of maintaining the 1.1 million highway bridges in Europe is approximately €6 billion/year (Brady et al., 2004). In the UK alone, an estimated £1.16 billion is required to restore the load capacity of over 3,200 "substandard" bridges (RAC Foundation 2022). Rehabilitation of these bridges also risks excessive carbon emissions due to traffic diversions, which contribute up to 80% of the total carbon footprint of the bridge (Zhang et al., 2011). Glass fibre reinforced polymer (GFRP) bridge decks offer a lightweight, corrosion-resistant and sustainable option for new-build and replacement bridges. Prefabricated, modular GFRP deck panels weighing a little as 25% of the reinforced-concrete alternative can be delivered to site and quickly lifted onto the substructure using low-capacity cranes, which minimises traffic disruption, carbon emissions and project costs (Keller et al., 2014).

However, a persistent issue with in-service GFRP decks has been rapid local fatigue degradation of the wearing surface and underlying GFRP material due to tyre loading (Sebastian, 2021). Heavy lorry tyres impart a concentrated, non-uniform contact load onto the top surface of the deck, which in turn produces high multi-axial stress states within the nearby web-flange junctions (WFJs). These critical stress states are randomly exacerbated by erratic waviness, wrinkling, and folding (i.e., misalignment) of the fibre mats therein (Poulton and Sebastian, 2021, 2022). The origins, prevalence, and structural impact of these misalignments in pultruded decks are not fully understood, which has led to unexpected and premature local damage accumulating within in-service GFRP decks. To ensure that the next generation of pultruded decks are properly designed to withstand increasingly onerous tyre loads, more advanced experimental and numerical techniques must be developed that can account for the local effects of fibre mat misalignments.

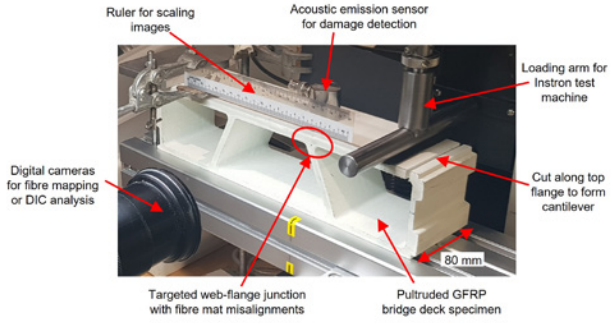

Fig. 1 GFRP deck cantilever testing set up

To that end, the objectives of the present study are to:

- Produce accurate digital maps to characterise the fibre mat misalignments within pultruded GFRP decks
- Use acoustic emission (AE) and digital image correlation (DIC) techniques to investigate the mechanics underlying progressive failure stemming from these variable fibre misalignments
- Develop non-linear numerical modelling that includes high-fidelity representations of the fibre misalignments and can predict the progressive failure of the WFJ

Description of methods and results

Tests were conducted on several specimens of a given pultruded deck system, which contained random fibre misalignments from manufacturing inconsistencies. Mapping of the fibre mat layers within each WFJ was achieved via an optical/digital method. Images of the polished cross-section of the WFJ were transferred to image processing software, wherein the coordinates of the interfaces between fibre layers were manually traced with an accuracy of less than 0.1 mm. These coordinates were transferred to CAD software, from which a high-fidelity geometric map of the fibre layers within each junction was generated.

To quantify the structural effect of these misalignments, a bespoke cantilever test method was developed that enabled statically determinate stress resultants to be applied to a WFJ, without artificially restraining (by clamping) fracture propagation into the adjoining webs and flanges. As shown in Fig. 1, the deck panels were cut into 80 mm wide specimens, and then a further cut was made across the top flange to form a cantilever rooted at one of the internal WFJs. A vertical quasi-static load was applied at lever arm distances of between 30-90 mm, which enabled the definition of moment-shear (*M-V*) failure envelopes for each WFJ. R15I-AST resonant-type AE sensors were placed on the deck's top surface. Further cantilever tests were performed with the addition of a 3D DIC system that served both to measure the full-field strains and to detect damage on the edge of the WFJ.

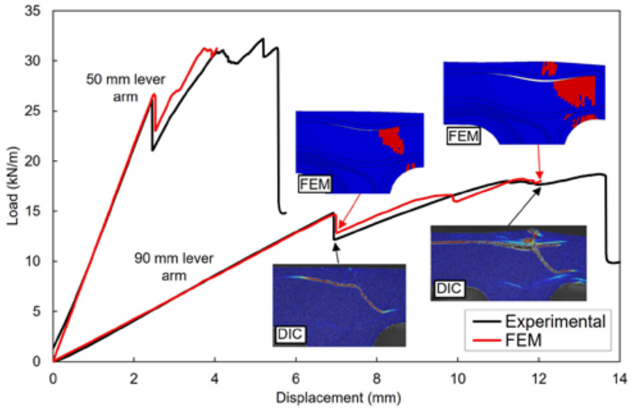

Fig. 2 Experimental and FE load-displacement plots and crack patterns for cantilever tests at 90 mm and 50 mm lever arm distances

Finally, the non-linear behaviour of the WFJs was modelled in FE (ANSYS) using the high-fidelity geometric model of fibre mat layers obtained via the optical/digital method described above. Cohesive zone modelling (CZM) and continuum damage mechanics (CDM) approaches were used to model inter- and intra-laminar damage, respectively.

Key results emerging from this research are as follows:

- The WFJs of the pultruded deck contained up to six categories of mat misalignment that were highly inconsistent between nominally identical junctions: for example, near-surface wrinkles were observed in all specimens with amplitudes of between 5-23% the flange thickness
- As shown in Fig. 2, the load response of the WFJs under cantilever loading was initially linear elastic, followed by a series of unique damage initiation events ('modes') that were each linked to a specific misalignment type. The damage mechanism for each mode produced variable load and tangent stiffness drops up to ultimate, which introduced pseudo-ductility. The sequence of damage modes and associated loads were sensitive to the applied M-V ratio and the misalignment profile
- The maximum 'knock-down' in moment capacity due to fibre misalignment was 44%
- As shown in Fig. 2, the non-linear load response and damage patterns predicted by the FE model were in good agreement with the experimental (load-displacement and DIC) data

Potential for application of results

The combined experimental (optical fibre mapping, cantilever testing, AE, DIC) and numerical (FE) approach developed in this study paves the way for improved design and analysis of pultruded profiles. Using these methods, the detrimental effects of fibre misalignments can be mitigated, or their beneficial effects (e.g., 'pseudo-ductility') can be strategically incorporated into the profile. Data from this study can also feed into design standards for FRP decks, for example the Technical Specification for the forthcoming Eurocode for FRP structures (FprCEN/TS 1901) and the UK's guidance document for FRP bridges CD 368, and into the European quality standard for pultruded profiles EN 13706-2:2002.

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Further information

Matthew Poulton: matthew.poulton.18@ucl.ac.uk
Professor Wendel Sebastian: w.sebastian@ucl.ac.uk (Supervisor)

Predicting the performance of concrete infrastructure from SHM data using automated clustering-based segmented regression

03

Harshita Garg
University of Leeds, UK

Project objectives and goals

Structural Health Monitoring (SHM) is an innovative approach for identifying physical and chemical changes in material properties that could allow early detection of susceptibility to deterioration, such as chloride-induced corrosion or cracking of concrete (ACI Committee 444, 2021). With the increase in monitoring of concrete structures, data collection from sensors is also accelerating while the value of the knowledge obtained is limited due to issues with data handling, smoothing and processing a large amount of noisy data (Nanukuttan et al., 2017). As a result, SHM for determining the material performance, such as electrical resistance of concrete, cannot be successful unless automated data processing is used. Thus, this research contributes in two ways:

- Theoretically, a systematic framework for analysing electrical resistance and temperature data was developed using automated clustering-based segmented regression, which can be used to obtain the steady-state condition of the resistance and thereby determine the diffusion coefficient to predict the performance of concrete
- Practically, this approach was adopted and implemented to the real-time data gathered from the embedded sensors to monitor the continuous changes in the repaired concrete of the Abercorn bridge in Northern Ireland and to assist in decision-making for the maintenance and/or repair needs

The diffusion coefficient is one of the primary transport mechanisms for the penetration of chloride ions into concrete, which cannot be regularly monitored, but can be calculated using steady-state resistance values. Normally the diffusion coefficient is determined either by performing non-destructive testing (NDT) of concrete in the lab or by using values based on mix proportions to predict the performance of concrete, and thereby its service life (Tang et al., 2012). This research aims to predict the service life performance of concrete structures using SHM data from electrical resistance sensors and extract insights from the data to make appropriate decisions for their maintenance management.

Description of Methods and Results

The framework developed for predicting the performance of concrete structures is shown in Fig 1. First, four years of SHM data were gathered from two sensor systems consisting of electrical resistance and temperature sensors installed in the repaired concrete at 20 mm depth from the deck surface of the Abercorn bridge. The collected raw data were converted into the desired format, and an Arrhenius relationship was used to reduce the influence of temperature on the resistance measurements (McCarter et al., 2012). The large fluctuations observed in the as-measured resistance were reduced in the standardised resistance.

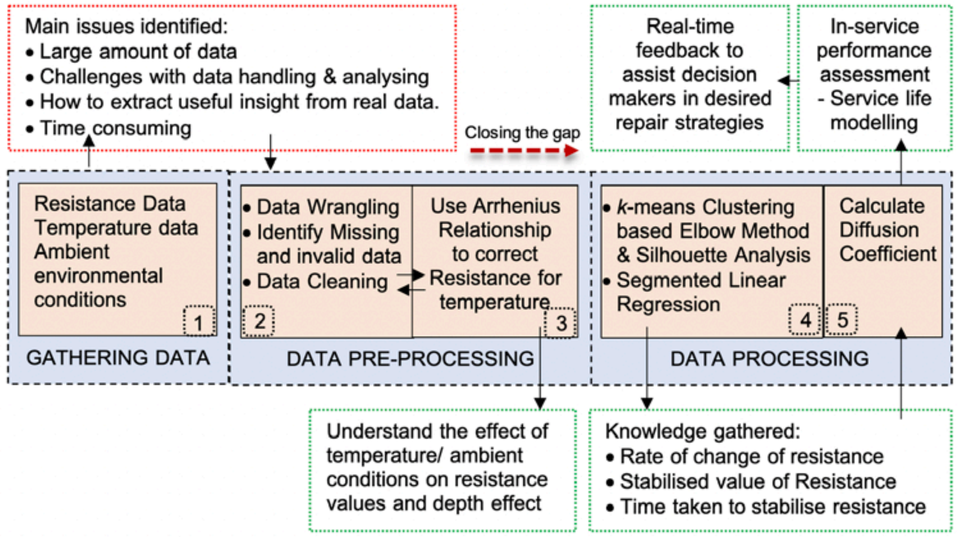

Fig 1 Framework for predicting the performance of concrete from SHM data

Sensor's location	Depth from deck surface (mm)	Rate of change of resistance (%)	Stabilised resistance (days)	Time taken to stabilise resistance (x 10^{-12} m^2/S)	Diffusion coefficient (x 10^{-12} m^2/S)	Average diffusion coefficient (x 10^{-12} m^2/S)
1 - near expansion joint	20	14.92	978.02	4.71	3.45	2.94
	50	11.93	958.89	5.32	3.06	
	70	17.93	970.00	7.05	2.31	
2 - away from the expansion joint	20	20.98	1194.29	5.27	3.08	2.55
	50	14.94	1257.00	6.09	2.67	
	70	18.57	1438.92	8.61	1.89	

Table 1 Determination of stabilised resistance/ diffusion coefficient values

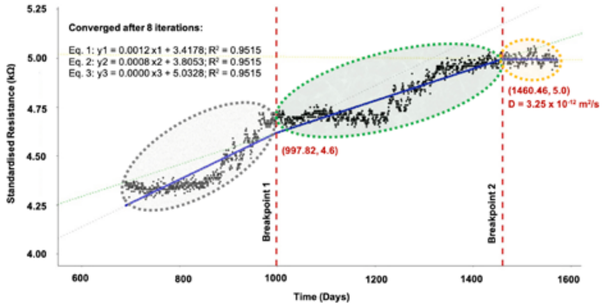

Fig 2 Automated k-means clustering-based segmented regression

Furthermore, the data were processed using artificial intelligence-based algorithms, such as k-means clustering-based segmented regression. The elbow method and silhouette analysis were used to identify the optimal number of clusters, whereas segmented linear regression divided the data into specific clusters and estimated the optimal segments for each cluster. The intersection point for the last two segments was the stabilised resistance value and the time taken to stabilise the resistance, while the linear segments in each cluster signify the rate of change in the resistance, as shown in Fig 2. Finally, the obtained stabilised resistance values were used to calculate the diffusion coefficient for predicting the performance of the repaired concrete.

Table 1 shows the results of the new methodology implemented to analyse the sensor data from the bridge. The predicted diffusion coefficients are in the range for good quality concretes (Tang et al., 2012), hence the repaired concrete is performing well. On comparing the results from the two sensors, sensor 1 gives a higher value, implying that contamination may seem to be arriving from the deck near the expansion joint. Data from the sensor further highlighted the impact of temperature and depth on resistance measurements near the deck surface. These results were cross-validated from the results in the literature to avoid over-prediction from the automated approach compared to carrying out NDT.

Potential for application of results

The developed application of data analysis framework provides a realistic prediction of the performance of concrete and, therefore, can be implemented for analysing both short-term and long-term resistance data from any concrete mix under any exposure condition. It can further assist maintenance engineers in making decisions and providing recommendations for maintenance and repair strategies, thereby improving the safety of concrete infrastructure. With the implementation of this automated data processing approach, the use of SHM could increase and better decisions reached from the SHM data.

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Further information

Harshita Garg (cn18hg@leeds.ac.uk)
Prof. P.A. Muhammed Basheer
(P.A.M.Basheer@leeds.ac.uk)

Structurally superior laminated glass: A proof of concept

04 **Feyza Nur Yildirim**
University of Southampton, UK

Introduction

Glass is one of the most used construction materials in building applications, as transparency and creative façade engineering are increasingly in demand. However, design and construction pose challenges due to brittle failure behaviour and the low tensile strength of glass (~ 40 MPa) (IStructE, 2015). Recent studies of reinforcing glass using adhesively bonded glass fibre reinforced polymer strips are proven to enhance strength, post-cracking resistance and ductility. Such as, Achintha and Balan (2017) showed that a higher load capacity and better displacement ductility were achieved between adhesively interlayer bonded GFRP units in glass compared to the respective equivalent annealed glass specimens that do not have GFRP enhancement. Achintha and Zirbo (2021) extended and showed that using GFRP reinforcement members where the bolted joints use externally bonded GFRP strips prevents instantaneous impact load causing brittle failure.

The present project developed an experimental proof of a novel glass-GFRP sandwich concept for the civil engineering industry, which ensures high load capacity, high flexural stiffness without significantly increasing weight, and safe failure behaviour compared to monolithic annealed and annealed laminated glass.

Glass-GFRP sandwich

In the present study, the glass-GFRP sandwich specimens were fabricated by combining two glass skins (top and bottom glass sheets) with a three-dimensional (3D) GFRP core using the VIP method. Fig. 1 shows a graphical illustration of the proposed idea of the glass-GFRP sandwich.

Materials

Annealed glass

3 mm thick annealed glass, cut into dimensions 400 x 100 mm, was used to make the glass-GFRP sandwich. In particular, the potential of a glass-GFRP sandwich is promising, where significant and post-fracture load resistance with the use of GFRP core, enhanced flexural stiffness of the sandwich compared to that of glass sheets alone, availability, low cost, low-embedded energy, easy constructability, etc. of annealed glass make them a better construction material compared to tempered or heat-strengthened glass. No edge treatments were used on the glass sheets.

3D GFRP

The present study was interested in 3D GFRP given its potential for ensuring the gradual failure behaviour of the sandwich, lightweight, and increased light transmittance impact than chopped strand mat-roving glass fabrics of the same thickness. The fabric consists of two S-shaped piles combined to form a pillar that is 8-shaped in the warp direction and 1-shaped in the weft direction. While warp yarns are placed in the direction of the fabric length, weft yarns are attached between the warp layers to form hollow piles (Parabeam, 2020).

Resin

Since the low viscosity helps more uniform composite vacuum infusion and flow faster through the dry fibre, a low viscosity (300-400 mPa-s) Polyester Polylite 32032-00 Acrylic Modified Clear Casting resin was used in the fabrication of glass-GFRP sandwich in order to ensure minimum negative visual impact, the connection between 3D GFRP core and top-bottom glass skins, uniform wetting and avoid the formation of no voids/hollows in the infused sandwich.

Fabrication

VIP is an efficient and effective fabrication method that uses vacuum pressure to drive low resin into a laminate a homogenous reinforcement section, creating high-strength and lightweight structures; very low viscosity resin is required for a better fibre-to-resin ratio and utilises a vacuum to infuse resin into the laminate by a perforated tube placed between a vacuum bag and resin container (Rajak et al., 2019). Yildirim et al. (2018) showed that low fibre volume fraction to adequate and uniform resin wetting where three-dimensional glass fibre composites fabricated by VIP improved bending strength properties and decreased void volume fraction.

Glass-GFRP sandwich was fabricated in one process impregnated VIP. Before starting the infusion, mould and sandwich materials were cleaned with acetone. PVC hose for the resin feed line, the resin inlet and the resin catch-pot with a vacuum pump were connected to the sealed vacuum bag. When the sandwich was totally wet, the resin infused stopped, and the fabricated specimen was left for 72 hours for curing. As expected, the fabricated sandwich specimen showed translucent characteristics. Despite the negative visual impact, the light transmittance properties are still good for application in the partition screen or bathroom windows.

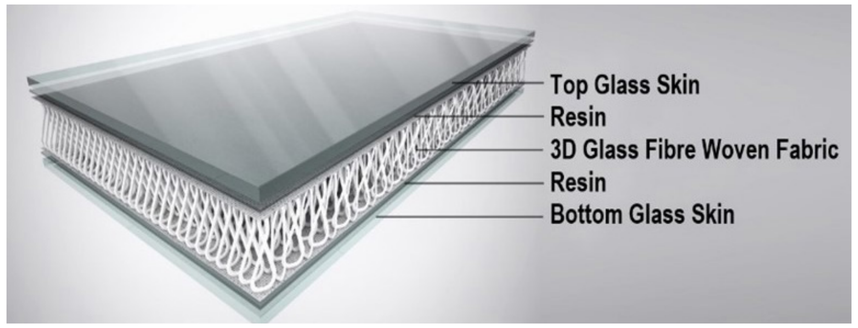

Fig 1 Schematic diagram showing the Glass-GFRP sandwich.

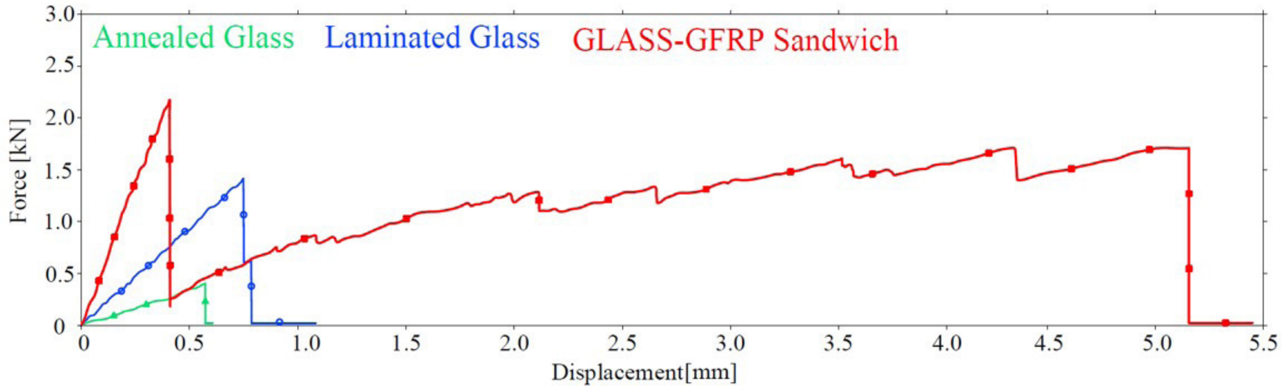

Fig 2 Load deflection relationship of Glass-GFRP sandwich test specimen compared to equivalent size commercial annealed glass and annealed laminated glass.

Results

The research investigated the peak load and post-crack behaviour of the glass-GFRP sandwich and compared this against annealed and annealed laminated glasses.

When annealed glass reached the peak load, around 0.5 kN, it failed straight away, as shown in Fig. 2. Annealed laminated glass showed a post-fracture resistance, around 1.5 kN, with a soft-non-structural PVB and did not fail ultimately. After the second kink, it failed completely. The glass-GFRP sandwich showed much higher load capacity and post-fracture load resistance. The first kink was around 2.4 kN, the sandwich specimen continued to carry the load, and the ultimate failure occurred due to the damage progression on the glass skins. The sandwich specimen kept its integrity, and the ultimate failure happened as a progressive loss of stiffness due to the damage progression on the glass skins.

Conclusion

A novel glass-GFRP sandwich was developed, and its feasibility has been validated. The peak load, post-cracked load resistance, and flexural stiffness of the glass-GFRP sandwich were significantly higher. VIP process can be used to fabricate a glass-GFRP sandwich by ensuring uniform wetting and avoiding the accumulation of the resin.

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Further Information

Feyza Nur Yildirim (F.N.Yildirim@soton.ac.uk)
Supervisor: Dr Mithila Achintha, School of Engineering, the University of Manchester
(Mithila.Achintha@manchester.ac.uk)

Spatially defined tyre loads for FE analysis of GFRP deck

05 **Zhaotian Yang**
University College London, UK

Project objectives and goals

Compared to the conventional bridge decks made from traditional materials, those made from FRP (fibre reinforced polymer) composites may exhibit more pronounced load responses to tyre loads, due to their anisotropic material properties and to the thin-walled multi-cellular configuration of pultruded profiles. Besides, the tyre-deck contact zone and contact pressure morph as a function of load, rendering the load response of FRP decks sensitive to the onerous spatial form of the tyre patch load. So it is worthwhile to study the FRP deck load response as affected by the tyre load's spatial definition.

This study aims to investigate the load response of GFRP (glass fibre reinforced polymer) decking under patch loads with different spatial forms including actual tyre loading, a square patch load and a circular patch load. To that end, the current study presents a comprehensive finite element (FE) study of the structural responses of a GFRP bridge deck to different spatial representations of tyre loads of different magnitudes (Yang and Sebastian, 2023). This research has the following objectives:

- Clarify the tyre load spatial definitions which morphs significantly as a function of load
- Clarify alternate patch load representations which are equivalent to tyre load patch
- Investigate the local stress field transformations induced by morphing of the tyre loads
- Investigate the influence of loading patch spatial form on the FE-predicted local responses within a GFRP bridge deck
- Determine the equivalent alternative patch load approximate to tyre patch load in terms of loading effect on GFRP deck, which can be used for simplifying the actual spatial tyre load definition

Description of method and results

This study investigates the effects, on the FE-predicted critical stresses local to tyre loads applied on multi-cavity pultruded GFRP decks, of simplifying the spatial definition of the tyre-deck contact patch load input to the FE model. Experimental verification of the FE model, up to 45 kN tyre load, enabled comparisons between three representations of the tyre loads. These were the actual tyre load (which morphed in contact patch shape and size, as well as in pressure distribution), along with circular and square patch loads of equivalent contact area and load to the original tyre patch.

Previous field test of truck tyre loading on the GFRP deck panel (shown in Fig.1) was conducted by Sebastian et al. (2017). And the contact pressure distribution (CPD) and local strains were recorded by monitoring devices. In this study, firstly, the measured tyre-deck contact loads are digitally converted into FE input patch loads, by extracting the CPD using fine grids overlaid on the colour-coded isobars across the contact zones. The resulting FE model, which applies these digitally-defined loads to the pultruded deck meshed using solid elements, is validated using experimental tyre load and local strain data (shown in Fig.2). Then, two simplified versions of the tyre patch loads, namely uniform pressure over equivalent square and circular patches, are alternately input to the FE model. Finally, numerical analysis can be conducted to predict the structural response of GFRP bridge deck under various patch loads.

According to the FEA results, it was found that use of both the square and circular patch loads led to FE-predicted peak through-thickness stresses very similar to those predicted for the original patches in the top flange and web-top flange junction zones. The exceptions were, between 25 kN and 45 kN, the relatively high through-thickness stresses which emerged from use of the circular patch load. And peak stresses (at maximum applied load) in the 10 to 16 MPa range emerged from the square and original load patch analyses. Note that the circular patch load led to prediction of severe internal stresses (approximately 40 MPa) which generously exceeded the square and original patch load values in the 25 kN to 45 kN ranges.

Fig 1. Field testing of deck panel using truck on outriggers

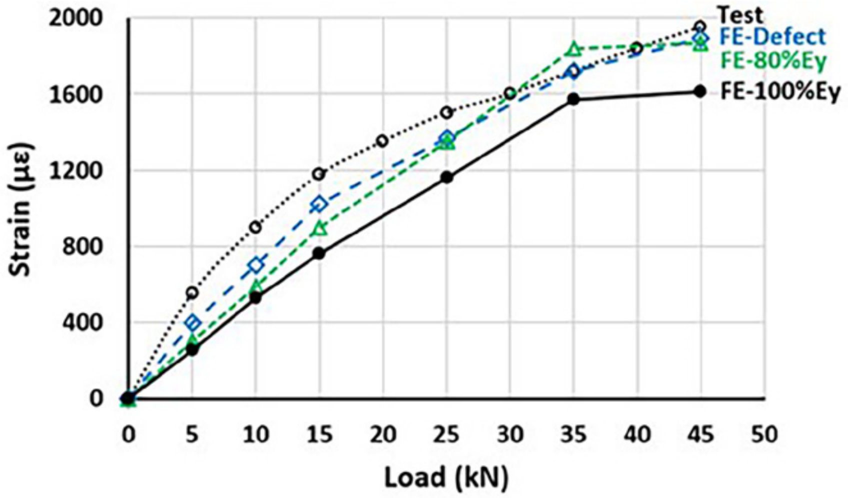

Fig 2. Validation of FE Analysis: Variation with load of transverse strain

In closing, conclusions are drawn on the spatial definitions which give the best compromise between numerical convenience and model reliability. Relative to the original tyre patch loads, the square patch loads enable similar predictive capability (on peak local stresses within the deck especially the web-flange junctions) across the entire range up to 45 kN which is relevant for fatigue, while the circular patch loads enable similar predictability only at lower loads, with significant deviation above 25 kN. The square patch is recommended, with a suggestion for further study.

Potential for application of results

The square static tyre load contact patch model, which increase in length with tyre load increase, is recommended for use across the 5 kN to 45 kN range. So in design of this type of GFRP bridge deck, researcher and designer could use square patch morphing with loads to conveniently represent tyre patch, when relating to structural analysis under tyre loads. Also in test, the square patch could be considered as the substitution of tyre patch for further fatigue study of GFRP bridge deck due to its stability and availability in experiment. For the present study, the square load patch appears to effectively approximate the actual load patch. For generalizing of the result, further studies should be conducted to establish whether similar observations apply to the other GFRP decks and / or other tyre types, loads and inflation pressures.

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Further information

Applicant: Zhaotian Yang (uceszy1@ucl.ac.uk)
Supervisor: Professor Wendel Sebastian (W.Sebastian@ucl.ac.uk)

Development of innovative modular building system with enhanced fire, environmental, structural and thermal performance (MOD-FEST)

06 **Heshachanaa Rajanayagam**
Northumbria University, UK

Project objectives and goals

The global construction market is forecast to grow by over 70% in 2025. Hence, to match this target, UK Government has developed a clear and defined set of goals for construction in the UK to achieve a reduction of greenhouse gas emissions and construction time by 50%, and the cost by 33% (Construction-2025, 2013). It is now established that modular buildings are a game-changer for the construction industry, reducing construction time while increasing quality, productivity and safety (Mark Lawson and Richards, 2010; Rajanayagam et al., 2021). Modular building system (MBS) implies an integrated structure in which the whole frame or building contains prefabricated room-sized volumetric modules or structural units fabricated off-site and then built on-site. MBS units are often fully equipped with the necessary infrastructure and transported to the site, then assembled on-site to form complete structures. This increases the productivity of construction by handling a large proportion of traditional onsite construction work at production yards or factories and by minimising the on-site work to installation. Despite a significant research gap in advanced techniques and structural performance, and lack of design guidance, the uptake of MBS techniques is emerging rapidly in most developed countries worldwide (Rajanayagam et al., 2022). There is an emerging interest in developing and adopting new MBS elements with enhanced overall performance, and studying the environmental impact of such adoptions in the lifecycle of MBSs. Identifying and utilizing the right alternate construction materials and procedures in MBSs will eliminate the risk of accumulating unnecessary embodied carbon & energy (EC and EE) in structural and other building elements and will give greater control over the amount of carbon emissions produced during operation (Robati, 2021). Therefore, it has become essential to propose a combined approach to study the overall (Fire, Environmental, Structural and Thermal (FEST) – Fig 1) performance enhancement of MBSs and to develop an innovative, sustainable MBS which can support overcoming the difficulties in the design and construction of MBSs. The present research intends to achieve this target with the following objectives,

Objective 1: Developing an understanding of the structural engineering design (with regards to FEST performance) of MBS components using experimental, theoretical and finite element/ numerical analysis.

Objective 2: Identifying the optimum, cost-effective and sustainable design configurations of MBS elements based on parametric studies and life cycle analysis (Fig 2).

Objective 3: Proposing an innovative, sustainable MBS design with enhanced FEST performance. And developing building design guidelines which will provide comprehensive structural and energy data for developed modular units.

Description of method and results

The research objectives were set to be achieved in five stages as follows,

Stage 01: Literature review on MBSs, steel connections and bracings, full-scale tests, 3D finite element analysis and MBS life cycle was conducted. Case studies were performed on currently used materials and elements in MBSs: Investigated and analysed existing FEST practices to establish their winnings and shortcomings.

Stage 02: Based on the literature review and case studies performed, developed and proposed conceptual designs for innovative cost-effective and sustainable design configurations of modular building elements.

Stage 03: Structural, fire and thermal performance of proposed design configurations were investigated by performing full-scale physical tests and numerical modelling; based on that, their strengths and weaknesses in relation to the overall performance of MBS were evaluated.

Stage 04: Validated models (from stage 03) will then be used for parametric studies to further optimize the design and to interpret the behaviour of MBS under different loading (structural, fire and thermal) conditions. MBS design with enhanced performance and reduced EC and EE will be proposed.

Stage 05: The accuracy of available design rules to predict the performance of the proposed MBS will be evaluated, and based on that a new set of design guidelines will be developed.

The outcomes of this research will be used in MBS construction practices and design methodologies, which can help increase public trust and reliability in MBS eventually increasing the adoption of MBS in the UK and other countries.

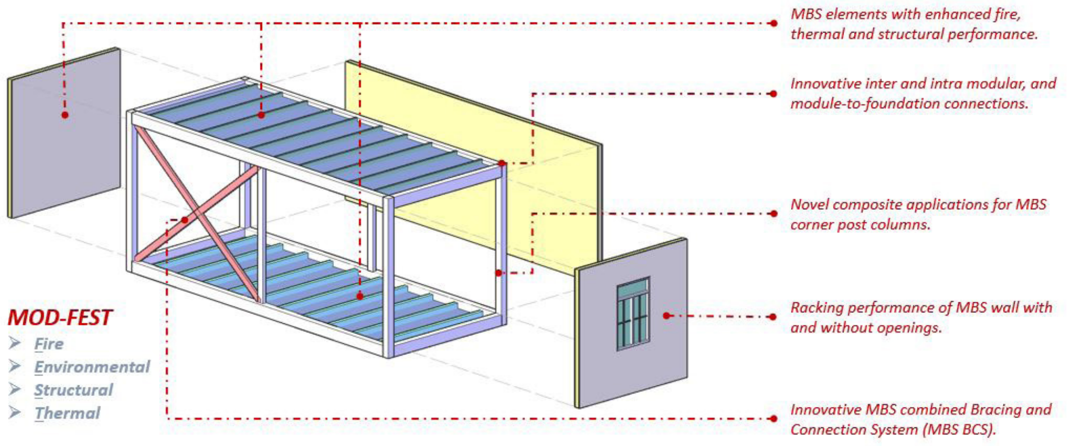

Fig 1 Graphical Illustration of the Project Overview

Potential for application of results

This research targets to perform a thorough study of many important parameters related to the structural, fire and thermal performances of MBS as single units and as a whole unit assembly, using theoretical, numerical modelling and experiments. This study will significantly contribute to advancing the knowledge for future netzero modular buildings. Hence, these research outputs will help promote the use of high-quality, sustainable and affordable MBSs by ensuring their structural performance and reduced lifecycle emissions (reduce wastage and disposal, promote recycling and encourage reusing).

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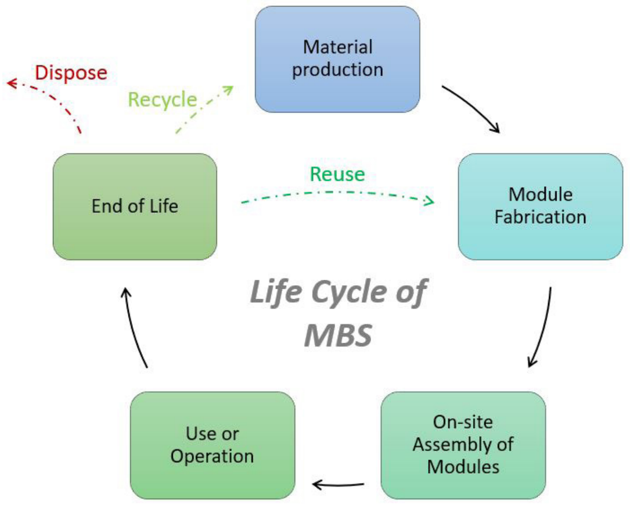

Fig 2 Life Cycle of Modular Building System (MBS)

Funding Body

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Further Information

Heshachanaa Rajanayagam (heshachanaa2.rajanayagam@northumbria.ac.uk)
A/Prof Keerthan Poologanathan (keerthan.poologanathan@northumbria.ac.uk)
A/Prof Brabha Nagaratnam (brabha.nagaratnam@northumbria.ac.uk)
A/Prof Phil Hackney (phil.hackney@northumbria.ac.uk)

Collaborators

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

Fire performance of prefabricated cellular lightweight concrete panels

07 I.R. Upasiri
University of Sri Jayewardenepura, Sri Lanka, and Northumbria University, UK

Project objectives and goals

Structural fire damage is a severe condition that a structure may be subjected to in its lifespan. Thousands of deaths, injuries, and millions of property damage are reported due to structural fires (Brushlinsky *et al.*, 2017). During a fire scenario, structure would undergo high-temperature exposure around 1200 0C. Fire spreading to adjacent compartments could be controlled or accelerated depending on the walling units; therefore, considering the structural elements, walling materials play a vital role. Cement block walls, brick walls, gypsum plasterboards with steel-lipped channel sections, and concrete walls are some popular walling unit types used in the construction industry. Among them, lightweight concrete wall panels are becoming popular due to their lightweight, easy erection, good sound insulation characteristics, and better thermal performance characteristics (Rytting, 2007; Singh, 2016). Lightweight concrete can be categorized as lightweight aggregate concrete (LAC) and cellular lightweight concrete (CLC). CLC can be further classified as foam concrete (FC) and autoclaved aerated concrete (AAC) (Kodur and Khaliq, 2010; Meyer, 2013). There are comprehensive studies conducted on the fire performance of normal weight concrete (NWC).However, there are limited studies conducted on the fire performance of CLC, which this study tries to fulfill through the following objectives.

- **Objective 1:** Investigate elevated temperature material properties of CLC
- **Objective 2:** Investigate the fire performance of prefabricated CLC panels
- **Objective 3:** Develop suitable fire design rules for CLC panels and their applications

Description of method and results

Methodologies followed to achieve each objective are illustrated in the diagram shown in Fig 1.

Material properties are important in evaluating the fire performance of structural elements exposed to fire. Since most of the material properties depend on temperature, to predict the fire performance accurately, it is mandatory to evaluate material properties at elevated temperatures (Kodur, 2014; Kodur and Khaliq, 2010; Mydin, 2010). Even though experimental methodologies are available, numerical techniques are lacking to evaluate material properties at elevated temperatures. Therefore, this study developed an artificial neural network (ANN)-based finate element (FE) model to extract the elevated temperature thermal diffusivity, thermal conductivity, and product of specific heat and density utilizing the temperature distribution obtained during the fire tests. The developed model was applied to the NWC, gypsum plasterboard, and FC wall panel fire tests, and good agreement was obtained with the experimentally measured properties.

Thermal FE models were developed to evaluate the insulation fire performance of wall panels using Abaqus (Michael Smith, 2009) FE modeling software and Matlab (MATLAB, 2010) program. The developed model was validated with the fire test and heat transfer test results of NWC and lightweight concrete. The fire performance of NWC wall panels was compared with the fire performance of lightweight aggregate concrete (with different lightweight aggregates) and CLC (FC and AAC) with the validated model. Further, the developed model was extended to evaluate the fire performance of wall panels exposed to realistic design fire. Thermo-mechanical FE models were developed to simulate the insulation, load-bearing, and integrity of fire performance of wall panels. Three novel modeling techniques were introduced. A sequentially coupled (SC) thermo mechanical FE model was developed incorporating Abaqus XFEM to simulate the wall element's e heat transfer, deformation, and crack propagation during fire exposure. Also, another SC thermomechanical FE model is proposed incorporating dynamic explicit analysis and failure stress or strain values to simulate heat transfer, deformation, and material damage during fire exposure. A fully coupled (FC) thermo-mechanical model was developed to simulate the heat transfer and stress distribution of wall elements during fire exposure using Abaqus software and Matlab coding. The FC model was further developed to accommodate stress plus temperature-dependent thermal conductivity. Developed thermo-mechanical FE models were compared with experimental fire test results to evaluate the validity of the models, and good agreement was observed.

Finally, the applicability of CLC in different walling units in industrial applications was studied. Heat transfer analysis was performed for CLC with composite sandwich panels (CSP), and CLC in light-gauge steel frame (LSF) wall panels was studied. Novel FE models were proposed and validated with the experimental studies available.

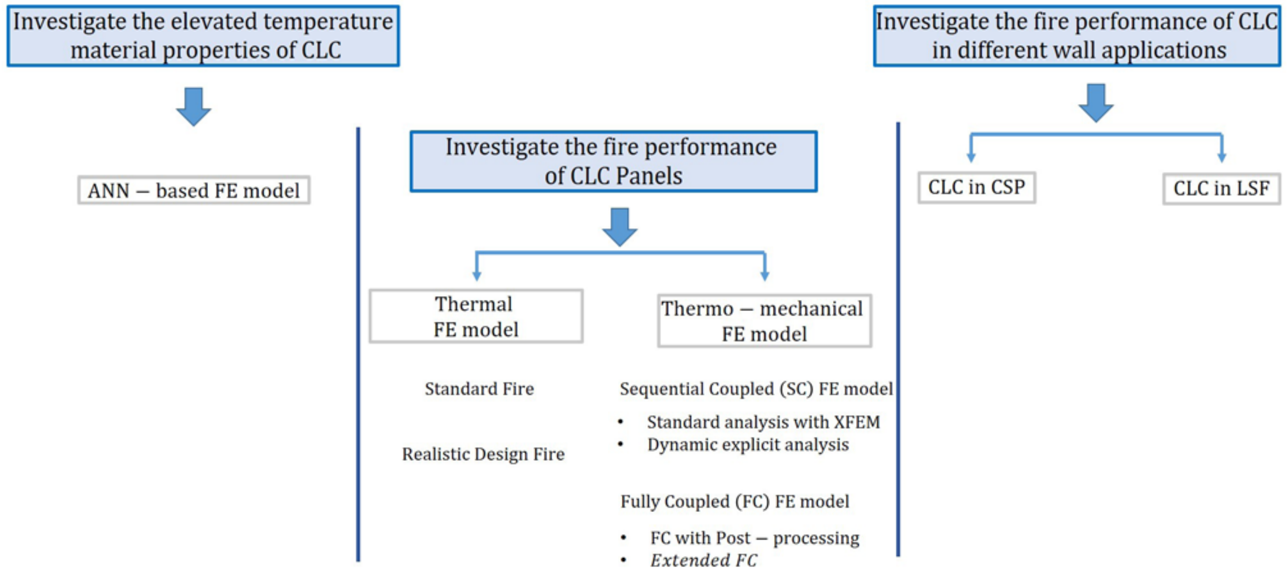

Fig 1 Overview of the research methodology

Potential for application of results

The outcomes of this research study are beneficial to the industry in evaluating elevated temperature thermal properties numerically, investigating the thermal performance of walling units exposed to realistic design fire, evaluating the thermo-mechanical behavior of walling units exposed to fire, and accommodating temperature plus stress-dependent properties in simulating fire behavior, and the applicability of CLC in common wall panel applications with improved fire performance

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Further information

I.R. Upasiri (irinduupasiri@sjp.ac.lk)
K.M.C Konthesingha (konthesingha@sjp.ac.lk)
Keerthan Poologanathan
(keerthan.poologanathan@northumbria.ac.uk)
S.M.A Nanayakkara (sman@civil.mrt.ac.lk)

Collaborators

University of Sri Jayewardenepura, Sri Lanka
Northumbria University, Newcastle, United Kingdom

Web crippling behaviour of cold-formed steel, stainless steel and aluminium channel sections with web openings

08

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

Project objectives and goals

With the rise of lightweight constructions, cold-formed (CF) steel, stainless steel and aluminium channel sections have been extensively used both as primary and secondary structural members. These sections are frequently fabricated with web openings to facilitate easy installation of service lines (Lian et al., 2016; Uzzaman et al., 2012). However, when subjected to transverse concentrated loading these web openings tend to induce member failure via web crippling (Yousefi et al., 2017).

Hence over the years, many research studies have been conducted to evaluate the web crippling behaviour of CF steel, stainless steel and aluminium sections with web openings. These research studies have resulted in developing web crippling design guidelines specified for each material type. However, most of these design guidelines overestimate the web crippling capacities of web perforated CF channel sections (Weerasinghe et al., 2022). Nevertheless, to date no unified design guideline has been developed to predict the web crippling strength of web perforated CF steel, stainless steel and aluminium sections. Identifying the existing research gap this research intends to develop unified design guidelines for predicting the web crippling response of web perforated CF steel, stainless steel and aluminium channel sections.

Description of method and results

Under this study, authors intend to develop unified design guidelines for predicting the web crippling response of web perforated CF channel sections subjected to all four loading conditions: end two flange (ETF) loading, end one flange (EOF) loading, interior two flange (ITF) loading and interior one flange (IOF) loading conditions. Web crippling response of web perforated CF steel, stainless steel and aluminium channel sections is assessed via a combined experimental and numerical approach. Nonlinear elasto plastic finite element software ABAQUS version 6.14 (2014) was used for numerical simulations.

Initiating the study numerical models were developed for web perforated CF SupaCee channel sections subjected to ETF loading condition. Circular web openings were considered in this study. Two bearing plates, web perforated SupaCee channel section and the connection between the bearing plates and channel section were modelled. Cross sections were modelled using center-line dimensions. Accounting for the thin-walled nature of channel sections, four node general purpose deformable shell element S4R was used to model the channel sections. Three-dimensional quadrilateral rigid element R3D4 was used to model the bearing plates. Mesh sizes were carefully selected to maintain high numerical accuracy and an efficient computational process (Fig 1). Incorporating the effect of material behaviour on web crippling response, material properties of CF steel, stainless steel and aluminium sections were modelled considering true stress-strain behaviour. Simulating the experimental behaviour contact between the bearing plates and the channel section was modelled considering the surface-to-surface contact technique. ABAQUS/Explicit solver and nonlinear quasi-static analysis were considered in simulating the slow movement of the bearing plates. Boundary conditions were appropriately assigned to simulate experimental conditions (Fig 1). These models were then validated using past experimental data. Following this, a comprehensive parametric study was conducted.

As per the results of the parametric study, the web crippling capacity of CF SupaCee stainless steel sections was higher than that of CF steel and aluminium sections (Fig 2). This was identified to be an outcome of the strain hardening observed in stainless steel sections. Despite the bi-linear strain hardening observed in CF aluminium sections, the web crippling capacities of CF SupaCee aluminium sections were lower than the other two materials (Fig 2). The low Young's modulus value observed in CF aluminium sections can be used to justify this behaviour. These results were used in assessing the adequacy of existing web crippling design guidelines for web-perforated CF channel sections. Based on the identified discrepancies, results of the parametric study were used in deriving new unified design guidelines for predicting the web crippling behaviour of web-perforated CF SupaCee channel sections subjected to ETF loading condition.

Subsequently, similar numerical investigations and full-scale structural tests will be conducted on web perforated SupaCee sections and Super Sigma sections for evaluating the web crippling response under all four loading conditions. These numerical and experimental investigations will be conducted considering different section depths, section thicknesses, corner radii values and opening sizes.

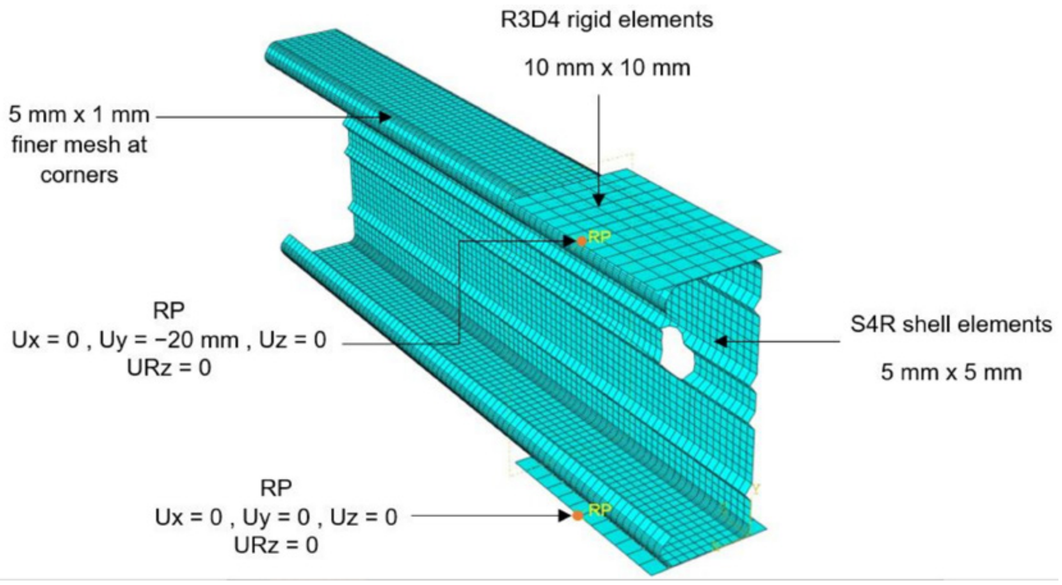

Fig 1 Element types, mesh sizes and boundary conditions used in the finite element model

Potential for application of results

Unified web crippling design guidelines developed under this study can be used in predicting the web crippling capacities of CF sections with web openings. Upon validation via full-scale structural testing, these unified web crippling design guidelines can be incorporated into the upcoming versions of the existing design guidelines, encouraging the use of CF steel, stainless steel and aluminium channel sections in the light-weight construction industry.

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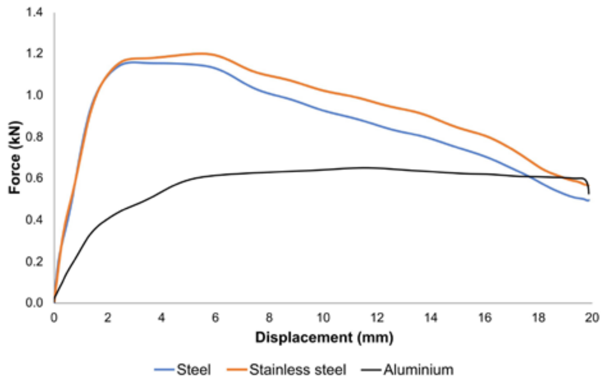

Fig 2 Load vs displacement behaviour of three identical SupaCee channel sections made out of CF steel, CF stainless steel and CF aluminium

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Further information

Hasini Weerasinghe (hasiniweerasinghe@sjp.ac.lk)
K.M.C Konthesingha (konthesingha@sjp.ac.lk)
Keerthan Poologanathan (keerthan.poologanathan@northumbria.ac.uk)
S.M.A Nanayakkara (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

Development and applications of lightweight high strength concrete made with lightweight aggregates

09 **Sifan Mohamed**
University of Northumbria, UK

Project objectives and goals

The overall aim of this study is to develop flowable lightweight high strength concrete (LWHSC) by using locally available materials, and to evaluate the structural performance of LWHSC filled cold-formed steel beams and thin slabs made with LWHSC. To achieve the aim, the following objectives are set.

1. Analyse the existing LWHSC mixes and develop a prediction model by using machine learning techniques.
2. Develop flowable LWHSC with locally available materials by using particle packing models and the machine learning prediction model. Target compressive strength is greater than 80 MPa and the target density is less than 2000 kg/m3.
3. Develop unconfined stress-strain relationships for LWHSC having compressive strengths greater than 80 MPa with densities less than 2000 kg/m3.
4. Infill the developed LWHSC in hollow flange cold-formed steel beams to enhance its structural performance and develop new design guidelines.
5. Evaluate the flexural performance of thin slabs made with LWHSC.

Description of methods and results.

As the initial step, a thorough appraisal of existing LWHSC mixes was performed based on an extensive literature survey. It was found that the mechanical properties of LWHSC can be greatly enhanced by strategically choosing the types and amount of binder, water to binder (w/b) ratio, fibres, and the lightweight aggregate (LWA) which is influenced by its particle size, crushing strength, water absorption, and porosity (Sifan et al., 2023).

Based on the database developed from the literature survey, reliable prediction models were developed based on effective machine learning algorithms namely support vector regressor, multilayer perceptron and extreme gradient boosting regressor. After finetuning the hyperparameters, the machine learning models predictions were very good even though the experimental data had high non-linearity due to material variability (see Table 1). In addition to that, ultra-high-performance concrete (UHPC) mixes were developed from locally available materials in the UK without fly ash and silica fume by using the particle packing model called the Modified Andreasen and Anderson (MAA) model. The strength of the UHPC mixes were in the range of 131 - 149 MPa with flow values of 634 – 756 mm.

Both the prediction models were utilised to develop flowable LWHSC mixes in the laboratory from the developed UHPC mixes by replacing the normal weight aggregate with fine sintered fly ash as LWA (see Fig 1). After many laboratory trials, LWHSC mixes were developed with the strengths up to 87 MPa with flow table spread of 250-300 mm.

The structural performance of LWHSC filled hollow flange cold formed steel (HFCFS) beams were evaluated by in depth finite element (FE) analysis using ABAQUS (ABAQUS, 2021). The compressive stress-strain relationship of LWHSC was carefully considered to define the material characteristics of LWHSC for the composite FE models. The results of the investigation were the flexural capacities, and the shear capacities were increased by up to 55% and 8%, respectively (Sifan et al., 2021, Sifan et al., 2022) (see Fig 2).

Performance indicators	Support vector regressor	Multilayer perceptron	Extreme gradient boosting
Coefficient of determination	0.74	0.81	0.87
Root mean square error (MPa)	6.40	5.49	4.57
Mean absolute error (MPa)	4.93	3.89	3.29
Mean absolute percentage error (MPa)	7.94	6.01	5.03

Table 1: performance of machine learning models to predict the compressive strength of LWHSC

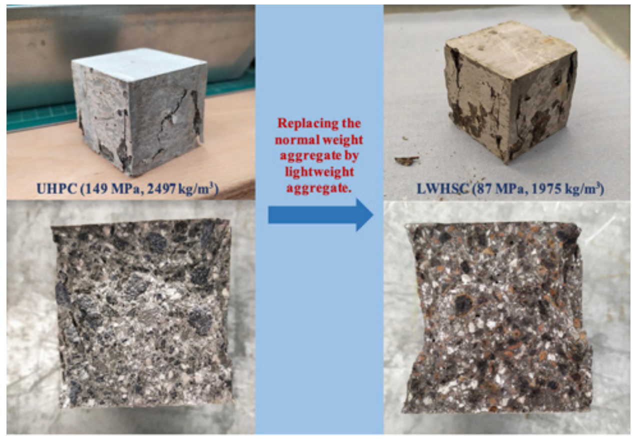

Fig 1: Development of LWHSC from developed UHPC mix

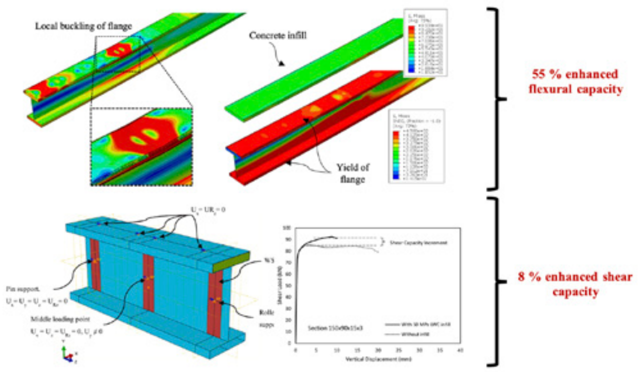

Fig 2: Enhanced flexural and shear capacities of LWHSC filled HFCFS

Potential for application of results.

Many structural engineers are concerned with lowering the density of the construction materials in order to minimise the self-weight of the structures without sacrificing their strength and durability. The developed LWHSC without silica fume and fly ash can be used for various structural applications. The developed machine learning model with optimum hyperparameter can be effectively used by the future researchers and construction practicians to develop sustainable LWHSC and to develop suitable design guidelines. The flowable LWHSC can be used for prefabricated thin slabs. Stress-strain relationship of LWHSC can be utilised by the researchers for future FE sturdies and design of structural elements. The LWHSC filled cold-formed steel beams have the potential to improve the overall structural performance in modular building construction.

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Funding body

Bespoke Concrete Ltd, UK.
European council.
Northumbria University, Newcastle upon Tyne, UK.

Further information
Sifan Mohamed
(sifan.i.sifan.mohamed@northumbria.ac.uk)
A/Prof. Brabha Nagaratnam
(brabha.nagaratnam@northumbria.ac.uk)
A/Prof. Keerthan Poologanathan
(keerthan.poologanathan@northumbria.ac.uk)

Collaboration

Department of Mechanical and Construction Engineering, University of Northumbria, UK
Department of Civil Engineering, South Eastern University of Sri Lanka, Sri Lanka

Design of SupaCee sections with web openings – Bending and shear

10 **Kajaharan Thirunavukkarasu**
Northumbria University, UK

Project objectives and goals

The construction industry seeks efficient solutions and creative ideas to address the deficiencies and accordingly the research carried out. Service integrations through floor beams are ideal to save the space in buildings especially in modular buildings where space saving is essential. However, the strength reduction in the floor beams due to the allocation of web openings for service integration is a vital issue. Hence, the goal of this research is to develop an efficient floor beam configuration by allocating service integration through the web openings of floor beams while minimising the strength loss of the section due to the material reduction from the web. Moreover, it enhances the aesthetic of a building which is one of the important aspects of the construction. To achieve the goal, the following objectives are placed:

- Idealization of suitable section profile
- Development of numerical models
- Comprehensive parametric studies
- Comparison of results with common sections
- Development of design approach

Description of method and results

Numerous section profiles have been emerged in the Cold-Formed Steel (CFS) industry to address various requirements (Keerthan and Mahendran, 2013). On that note, SupaCee section was introduced to the industry with enhanced structural capacity due to its features: longitudinal stiffener and return lips (Pham and Hancock, 2010). Fig.1 displays SupaCee section. This research recommends SupaCee section as a floor beam with web openings to include the service integration without compromising structural performance. To prove the validity of the recommendation, numerical models were developed replicating the actual section profile of SupaCee section and its properties to analyse the flexural and shear behaviour. The necessity of numerical model validation was considered and the developed models validated against the experimental studies carried out by Pham and Hancock (2010) for shear and Pham and Hancock (2013) for bending. The validation study is successful under all considered scenarios such as ultimate capacity comparison, failure mode comparison and load vs displacement curve comparison for both.

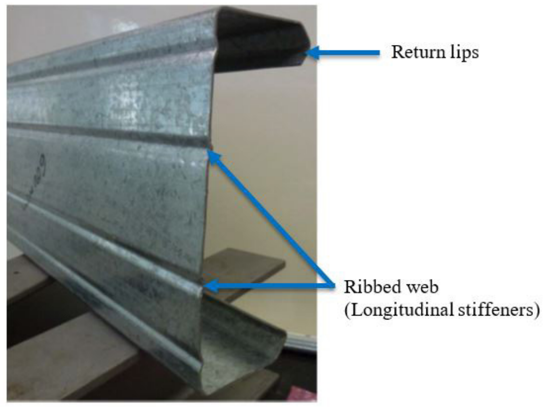

Fig 1 SupaCee section profile

Extensive numerical studies were conducted to analyse both shear and bending performance of SupaCee sections with circular web openings. Accordingly, different parameters including section depth, thickness, yield strength and web opening size were analysed with the results by defining different appropriate values to each parameter. Web opening sizes were defined as web opening diameter (d_{wh}) divided by effective depth of the section (d_1). The results were compared with each parameter and the Fig 2 illustrates the comparison of load vs deflection with different web opening ratios. Moreover, the ultimate shear and bending capacities of SupaCee section with web openings were compared with plain Lipped Channel Beam (LCB) and Table 1 presents the comparison.

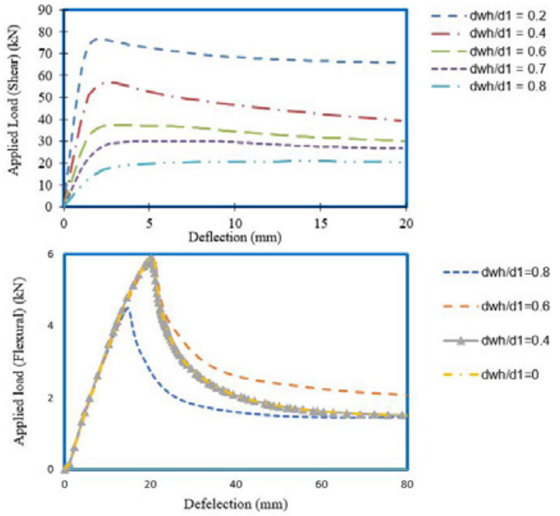

Fig 2 Comparison of load vs displacement curve with web opening ratios

Depth	Thickness	Yield strength	Bending capacity (kNm)				Shear capacity (kN)		
				SupaCee				SupaCee	
(mm)	(mm)	(MPa)	LCB	$d_{wh}/d_1 = 0$	$d_{wh}/d_1 = 0.4$	$d_{wh}/d_1 = 0.6$	LCB	$d_{wh}/d_1 = 0$	$d_{wh}/d_1 = 0.2$
150	1	300	2.47	4.12	2.95	2.83	17.09	20.38	17.40
150	2	300	6.30	9.05	7.00	6.78	42.09	44.27	40.57
150	1	450	3.65	5.89	4.48	4.26	23.36	29.42	24.29
150	2	450	10.11	13.05	11.41	10.84	61.44	64.84	59.11
150	1	600	4.18	7.23	5.73	5.30	28.22	36.84	30.32
150	2	600	13.42	17.07	15.15	14.46	79.45	84.81	76.23
200	1	300	3.38	6.04	4.14	4.05	19.76	25.55	22.88
200	2	300	9.55	12.98	10.80	10.56	55.83	57.29	54.77
200	1	450	4.45	9.11	5.88	5.77	25.48	31.46	29.90
200	2	450	15.05	21.89	17.05	16.80	79.91	83.05	75.72
200	1	600	5.01	9.54	6.93	5.89	30.17	37.31	35.53
200	2	600	18.59	29.02	21.25	20.60	98.38	102.25	92.80
250	1	300	5.08	9.55	7.01	6.90	21.36	27.19	23.72
250	2	300	16.94	19.05	18.57	18.09	61.74	67.29	58.05
250	1	450	6.76	11.11	9.55	8.98	26.80	32.82	30.57
250	2	450	24.85	28.85	27.92	26.77	85.86	90.91	80.40
250	1	600	8.35	13.44	11.39	10.44	31.43	38.88	36.88
250	2	600	30.27	38.2	35.22	32.46	106.62	112.34	100.61

Table 1: Bending and Shear capacity comparison of SupaCee (with and without web openings) with plain LCB

Results indicated that SupaCee sections perform better in shear and bending compared to LCB as plain SupaCee section showcase 3% - 30% shear capacity increment and 12.46% - 89.79% bending capacity increment compared to plain LCB. Moreover, SupaCee sections with web openings regularly performed better in both cases compared to plain LCB section. Hence, design guidelines were developed based on the obtained numerical results to predict the shear capacity and flexural capacity of SupaCee sections with web openings and the reduction factors were proposed for the equations proposed by Pham and Hancock (2010; 2013). Overall, the comprehensive numerical study insisted the significance of SupaCee section profile in terms of structural performance and provided the recommendations to the industry.

Potential for application of results

SupaCee sections with web openings can be the potential replacement to the conventional sections where service integrations are needed. Moreover, SupaCee sections can be utilized in modular constructions considering the enhanced structural performance. Overall, the recommendations are provided to replace the conventional CFS sections with SupaCee sections with an advantage of service integration option.

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Funding body

Northumbria University, Newcastle upon Tyne, United Kingdom
JC Consulting, Newcastle upon Tyne, United Kingdom

Further information

Kajaharan Thirunavukkarasu
(thirunavukkarasu.kajaharan@northumbria.ac.uk)
A/Prof. Keerthan Poologanathan
(keerthan.poologanathan@northumbria.ac.uk)
Craig Higgins (chiggins@jc-consulting.net)

Structural Behaviour of Cold-Formed Stainless-Steel Beams with Web Openings subjected to Shear, Bending and Combined Bending and Shear

11 **Muhammadh Ishqy**
University of Ruhuna, Sri Lanka

Research Introduction

Cold-formed Stainless Steel Lipped Channel Beams (SSLCB) are widely used in many structural applications such as floor systems (eg. Fig. 1) which include various shapes of web openings in the joists or bearers in order to facilitate building services within them. During the construction and service period, CFSS beams are often subjected to concentrated, localized loads or reactions. These concentrated forces acting on flexural members cause various localized structural failures. Opening in the web leads to the section being susceptible and it resulted in a reduction of shear and flexural capacities considerably (LaBoube *et al*., 1997).

Many parameters affect the shear capacity of cold-formed steel beams containing web openings. They are the shape, size and location of the web openings and the slenderness of the web element. Past researches (Keerthan and Mahendran, 2014; Pham *et al*., 2016; Wanniarachchi, Mahendran and Keerthan, 2017) have reported that the most influential parameter for the shear capacity of LCB with web openings is the ratio of the depth of web opening (dwh) to clear height of the web (d1).

Numerous research has been conducted to predict the structural behaviours of normal carbon steel cold formed LCB with web opening. But the findings of these studies on carbon steel LCB to predict the structural performance of stainless steel LCB directly is debatable since material behavior has distinctive differences. Therefore, this study is mainly focused on developing appropriate and precise design equations capable of predicting shear and moment capacities of the stainless steel LCB with web openings by using experimental test and numerical analyses.

Fig 1 CFS with web openings in flooring and joist

Objectives

- Ascertain the applicability of existing design rules to accurately predict the shear and flexural capacity of stainless-steel Lip Channel Beams (LCB) and modify the existing design rules or develop new design rules.
- Develop a comprehensive FE model simulating the shear and flexural behaviour of stainless steel LCB section.
- Develop a database of experimental tests results to investigate the shear and flexural capacities of the stainless steel cold formed LCBs with web openings.
- Identify key parameters affecting shear and bending capacities of stainless steel cold-formed LCB.
- Produce appropriate precise equations capable of predicting shear resistance and moment resistance for the stainless steel LCBs with different shape of web openings.

Methodology

Step 1: A comprehensive literature review will be conducted to understand the present status of the research area particularly regarding: existing available equations to predict the structural behaviours of stainless steel LCB and its limitations.
Step 2: A detailed literature review will be carried out to study the experimental setups and numerical modelling techniques to conduct the shear and flexural tests.
Step 3: Propose a comprehensive test plan to cover all the governing factors which affect shear, bending capacities of stainless steel cold-formed LCB with web opening and conduct the experimental tests.
Step 4: Numerical finite element model will be developed and precisely validated against experimentally tested specimens.
Step 5: Detailed parametric study will be undertaken using the validated model to develop an extensive shear, flexural capacity database.
Step 6: With the numerical analyses, equations will be proposed to predict shear resistance and moment resistance of stainless steel cold-formed LCB with web opening.

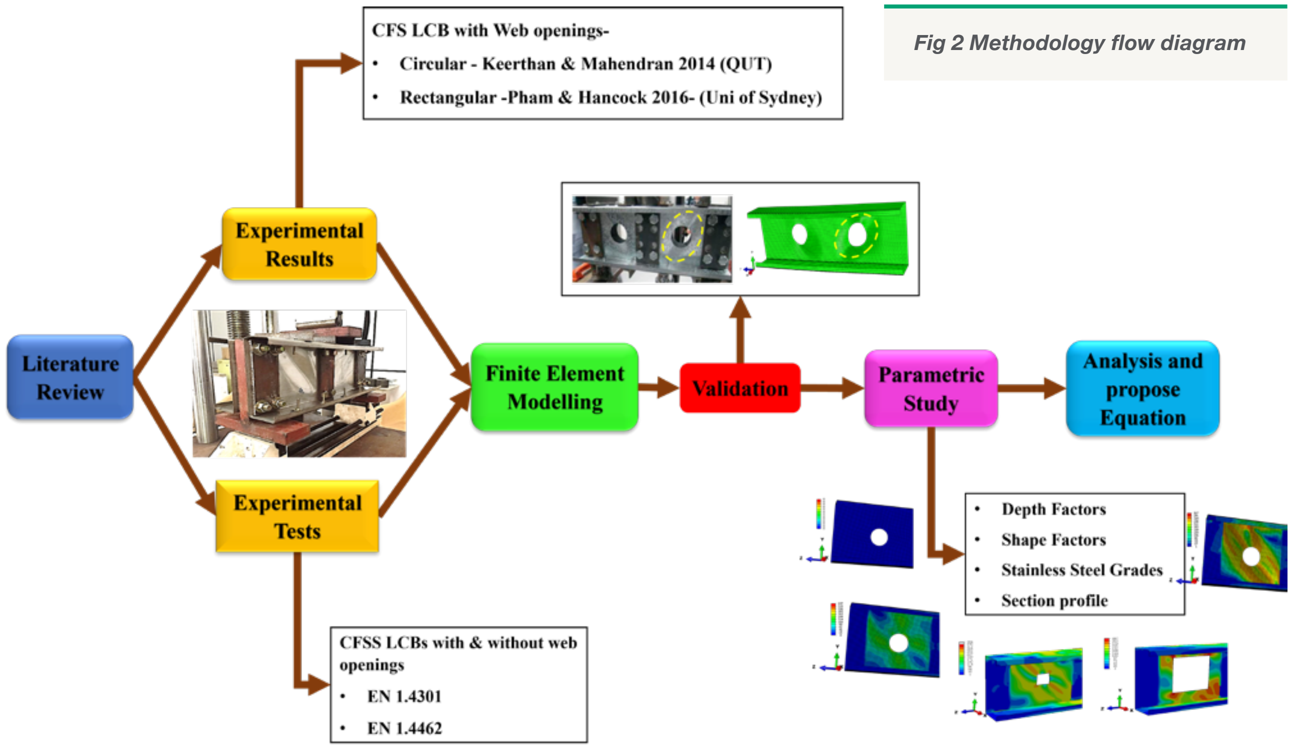

Fig 2 Methodology flow diagram

Step 7: Proposed equations will be validated against the experimental test results and finite element analysis results.
Step 8: Validated equations to predict the shear and flexural capacities of stainless steel cold-formed LCB with web opening will be compared to existing design rules
Step 9: Propose modification factors to the normal carbon steel cold formed LCBs with web openings to predict shear and flexural capacity of stainless steel cold formed LCBs with web opening.

The flow chart diagram (Fig.2) clearly illustrates the methodology to be carried out in this research.

Outcomes for this research

- Develop design equations to predict the shear and bending capacities of stainless steel LCB with web openings.
- Ease the work of designers within the civil engineering, and then other engineering disciplines to use the existing stainless-steel beams with web openings more economically and safely with more accurate design guidelines.
- Developed design equations from this research study will be proposed to be referred in the future when revisions of current cold-formed stainless steel design standards.
- Construction industries and steel manufacturing industries will get more benefit from this research outcome.
- Publish research articles and other scholarly publications disseminating the knowledge generated through the research, which will assist the advancement of knowledge both locally and internationally.

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Further information

Muhammadh Ishqy (ishqyfareed@gmail.com)

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Collaborators

Department of Civil and Environmental Engineering, Faculty of Engineering, University of Ruhuna; Faculty of Engineering & Environment, Northumbria University

Design of stainless steel structural systems by GMNIA with strain limits

12 **Hou Un Chan**
Imperial College London, UK

Project objectives and goals

Stainless steel is a high value material which has excellent corrosion resistance while retaining similar desirable mechanical properties to carbon steel. It is characterised by a rounded nonlinear stress-strain relationship with an early deviation from linear elastic behaviour and significant strain hardening. Due to the high cost of stainless steel, it is essential that the design standards recognise and accurately reflect these particular characteristics in order to facilitate efficient structural design. However, the current design standards for stainless steel structures were developed largely in line with those for carbon steel structures, which is based on an idealised bilinear (elastic, perfectly plastic) material response. With the widespread availability of powerful computers and improvements in analytical software, it is justifiable to exploit the advantages of more advanced analysis techniques to overcome the added complexities from material nonlinearity to traditional design methods. The aim of this project is to complement existing rules and develop new guidance on design of stainless steel structures based on advanced system analysis to promote a more widespread usage of stainless steel in construction applications.

Description of method and results

A novel design method based on system level geometrically and materially nonlinear analysis with imperfections (GMNIA) has recently been developed (Walport et al., 2022). In GMNIA, all the key behavioural features of structures, including the effects of instabilities and material nonlinearity, force and moment redistributions and member interactions, can be directly captured and therefore allows direct assessment of system strength from the global analysis. However, advanced analysis typically employs beam elements which are unable to capture instability at the cross-section level i.e. local buckling. Neglecting local buckling can result in overestimation of cross-section capacities and therefore unsafe structural design. In the presented method, this limitation is addressed by the application of strain limits determined from an experimentally derived continuous relationship between cross-section slenderness and cross-section deformation capacity (known as the Continuous Strength Method) to simulate the effects of local buckling. In this regard, failure is defined as the first occurrence of the attainment of peak load or strain limit in the global analysis and therefore the extent to which force and moment redistribution and strain hardening can be utilised are controlled in a systematic manner. In addition, the beneficial effects of moment gradients along member on cross-section stability can be accounted for by applying the strain limit to the compressive strains averaged over the cross-section elastic local buckling half-wavelength and allowance for the interaction between bending moment, shear and torsion can be made through the use of reduced strain limits.

Benchmark shell finite element (FE) models are developed using the general purpose FE software ABAQUS (2014) and validated against the experimental results on stainless steel continuous beams from the literature. The developed shell FE models are then used to generate benchmark results against which the accuracy of the presented method of design by GMNIA using beam FE with strain limits can be assessed, with both in-plane continuous beams and portal frames considered. The ultimate capacity predictions α_{ult} obtained from the presented design method and the traditional stainless steel design procedures according to EN 1993-1-4 (2021) are compared against the benchmark shell predictions α_{shell}, as shown in Fig 1 for 2-span continuous austenitic stainless steel I-section beams with a concentrated load applied at each midspan. The capacity predictions were normalised by α_{el}, which is the load factor at which first yield occurs. Additional capacity comparisons are provided in Fig 2 for single-storey single-span austenitic stainless steel frames with rigid supports. While no explicit guidance on the use of plastic analysis for stainless steel is given in EN 1993-1-4 (2021), it is assumed in the present work that plastic analysis is allowed for structures of class 1 cross-sections assuming a bilinear elastic, perfectly plastic material model with the yield stress taken as the 0.2% proof stress. It can be seen in both Figs 1 and 2 that the presented method gives close and generally safe-sided capacity predictions to the benchmark results. The overly conservative EN 1993-1-4 predictions also confirm the significance of appropriate allowances for the beneficial effects of plastic redistribution, strain hardening and local moment gradient in stainless steel design.

Potential for application of results

In the novel GMNIA-based design framework (Walport et al., 2022), the challenges presented by the highly nonlinear stress-strain response of stainless steel are overcome by employing advanced analysis technique and the application of strain limits. It has been shown that the presented method of design is able to provide more accurate and consistent capacity predictions than EN 1993-1-4 (2021). The method requires only the use of computationally efficient beam finite elements which are suitable for routine design in practice. It is envisaged that the introduction of an integrated system of rules and guidance on design based on advanced analysis in the forthcoming revision of design standards can allow for more efficient and safe stainless steel design, enhancing the awareness of engineers to the opportunity of using stainless steel as a solution to the expanding demand of resilient and sustainable structures.

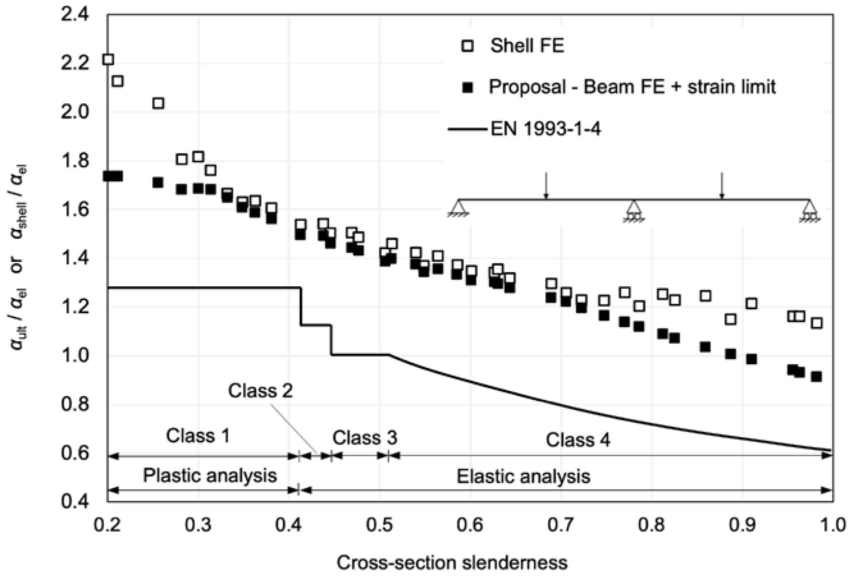

Fig 1 Normalised capacity predictions for 2-span austenitic stainless steel continuous beams of I-sections of varying cross-section slenderness with concentrated load applied at each midspan

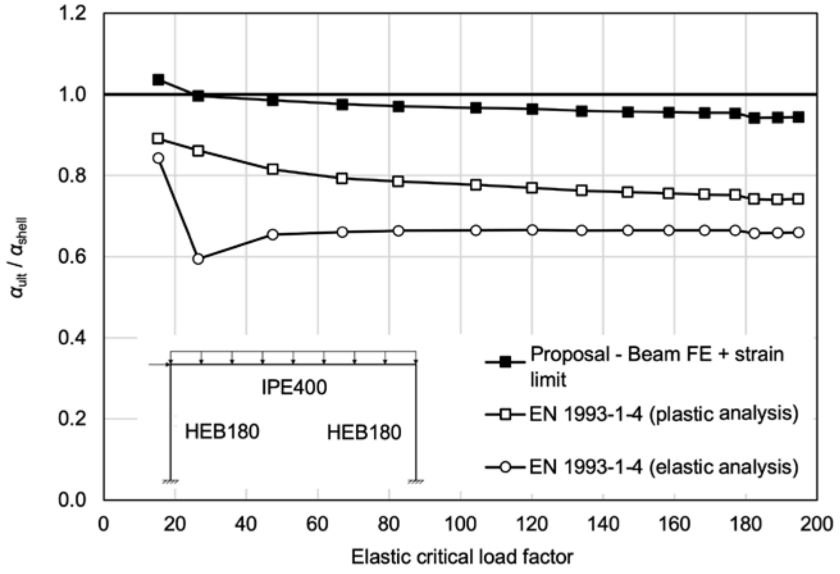

Fig 2 Normalised capacity predictions for single-storey single-span austenitic stainless steel frames

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Further information

Hou Un Chan (hou.chan19@imperial.ac.uk)
Or Dr. Fiona Walport (fiona.walport@imperial.ac.uk)
Or Prof. Leroy Gardner (leroy.gardner@imperial.ac.uk)

Innovative beam profiles for modular construction

13 **Elilarasi Kanthasamy**
Northumbria University, UK

Project objectives and goals

Modular construction industry is emerging quickly due to the immediate requirements of housing structures especially in the United Kingdom. Accordingly, structurally efficient and longer-span sections are needed in modular industry. Hence, built-up sections can be ideal to be considered due to their merits including improved stiffness, enhanced torsional rigidity and excellent structural performance. This research examines the flexural behaviour of considered innovative built-up sections. The main goal of this research is to develop an innovative built-up section to address the modular building industry's requirements. The following objectives were established to achieve the set goal.

- Development of innovative built-up section profiles
- Design of numerical model and validation
- Comprehensive parametric studies
- Comparison of results and setting selection criteria
- Finalize appropriate built-up section profile according to the selection criteria

Description of method and results

Comprehensive numerical study was carried out by including Cold-Formed (CF) sections such as benchmark Lipped Channel Beam (LCB), optimised LCB, folded-flange and super sigma and different materials such as CF carbon steel, CF aluminium and CF stainless steel. Table 1 presents the material properties. Past research (Wang and Young, 2016; 2021; Anbarasu, 2018) on built-up sections with different materials were taken into account in to developing numerical models and their validation process. Gatheeshgar et al. (2021) developed above optimised sections through Particle Swarm Optimisation (PSO) and they were taken to develop the built-up sections to analyse the flexural strength enhancement. Fig 1 displays the developed built-up sections and their respective optimised sections.

Numerical models were developed by replicating the experimental conditions of four point flexural test and Fig 2 illustrates the considered boundary conditions of the numerical models. Comprehensive parametric studied carried out and results of the Finite Element Analysis (FEA) were compared with respective single sections and other built-up sections. Results indicated that 99% - 238% flexural capacity increment for all considered built-up sections compared to their respective single section for all three materials. Table 2 presents the results and the flexural capacity increment percentage in the built-up sections. Significant flexural capacity increment was recorded for single and built-up sections of Super-Sigma and Folded-Flange compared to the other two sections: optimised LCB and benchmark. Folded-Flange built-up section showcased excellent flexural performance compared to super sigma built-up section and the maximum percentage of increment compared to the single section is 238% in aluminium folded flange section. Hence, the research recommends folded-flange built-up section is better section in terms of flexural performance and further research can be carried out to explore the overall structural performance of folded-flange built-up sections.

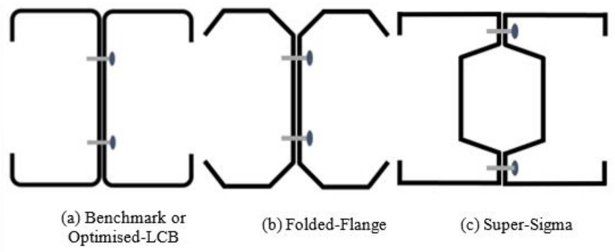
(a) Benchmark or Optimised-LCB
(b) Folded-Flange
(c) Super-Sigma

Fig 1 Proposed built-up section profiles and respective single sections

Material	Material strength (MPa)	Density (kg/m³)	Young's modulus (MPa)	Poisson's ratio
CF carbon steel	$f_y = 220$	7850	210000	0.3
	$f_y = 450$			
CF Aluminium	5052-H14 ($f_y = 180$, $f_u = 230$)	2700	70000	0.33
	3004-H48 ($f_y = 220$, $f_u = 260$)			
CF stainless-steel	1.4307 ($f_y = 220$, $f_u = 220$)	7850	210000	0.3
	1.4362 ($f_y = 450$, $f_u = 650$)			

Table 1 Material properties for parametric studies

Sections	Material strength	Capacity of single section	Capacity of built-up section	Fraction of increment	Percentage of increment
	(MPa)	kNm	kNm	Capacity of built-up sections/ Capacity of single sections	((Capacity of built-up - Capacity of single) / Capacity of single)*100
Benchmark	$f_y = 220$ MPa	5.40	16.05	2.97	197.22
	$f_y = 450$ MPa	10.41	24.60	2.36	136.31
	H14	2.10	6.30	3.00	200.00
	H48	2.55	7.35	2.88	188.24
	1.4307	6.00	16.05	2.68	167.50
	1.4362	12.45	25.50	2.05	104.82
Optimised-LCB	$f_y = 220$	7.35	16.55	2.25	125.17
	$f_y = 450$	13.28	29.10	2.19	119.13
	H14	3.00	7.80	2.60	160.00
	H48	3.60	8.55	2.38	137.50
	1.4307	7.65	16.65	2.18	117.65
	1.4362	14.85	32.40	2.18	118.18
Folded-flange	$f_y = 220$	7.80	18.45	2.37	136.54
	$f_y = 450$	16.60	39.45	2.38	137.65
	H14	3.90	12.90	3.31	230.77
	H48	4.65	15.75	3.39	238.71
	1.4307	8.70	21.00	2.41	141.38
	1.4362	18.75	43.35	2.31	131.20
Super Sigma	$f_y = 220$	6.30	13.50	2.14	114.29
	H14	2.70	8.70	3.22	222.22
	H48	3.45	11.25	3.26	226.09
	1.4307	7.35	16.80	2.29	128.57
	1.4362	15.45	34.50	2.23	123.30

Table 2 Results comparison of single section and built-up section

Potential for application of results

While modular construction projects are emerging, the necessity of promoting innovative section members to improve efficiency as well as sustainability aspects is increasing. Hence, folded-flange built-up sections could offer the requirements of modular industry as they showcase excellent flexural capacity and they also possess excellent attributes such as torsional rigidity and stiffness. In terms of sustainability, since folded-flange built-up sections offer high flexural capacity compared to two single folded-flange sections, material saving will be beneficial while reduced carbon footprint is another advantage which the world and construction industry is currently looking for achieving the sustainability targets.

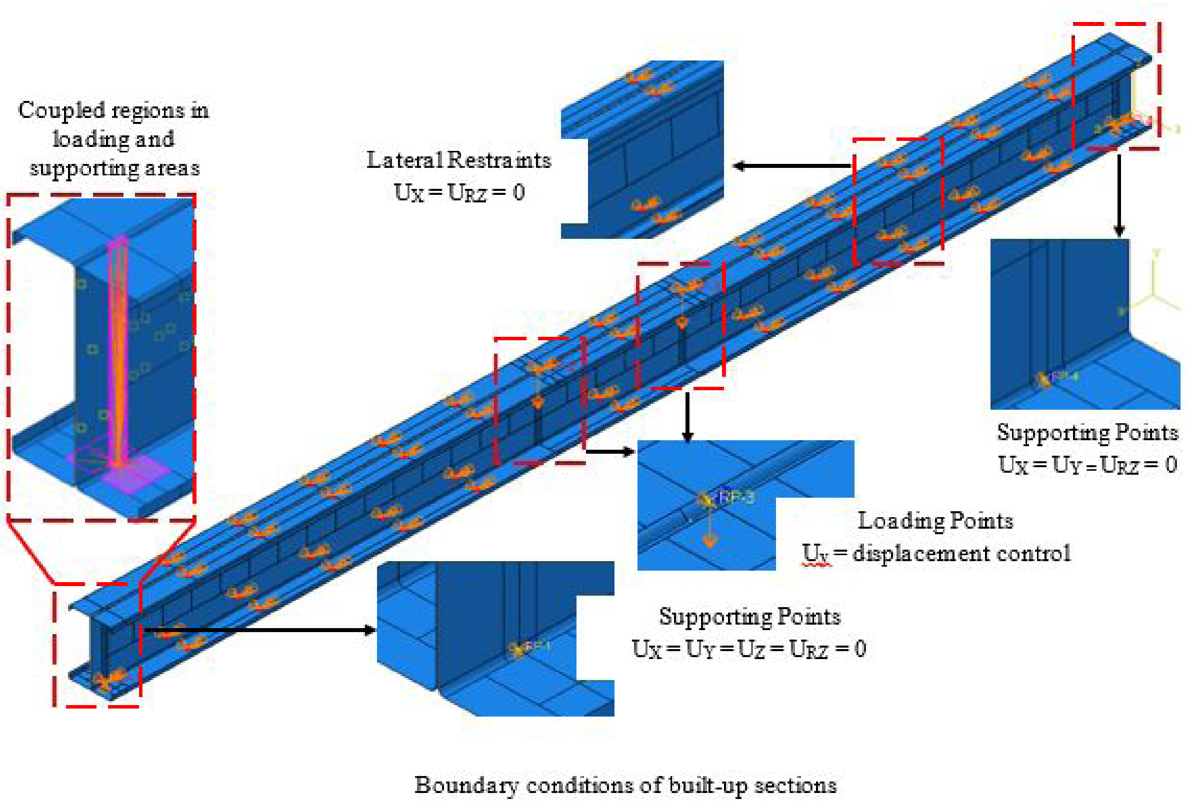

Fig 2 Assigned boundary conditions replicating the experimental scenario

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Funding body

Northumbria University, Newcastle upon Tyne, United Kingdom

The Home Engineers, Newcastle upon Tyne, United Kingdom

Further information

Elilarasi Kanthasamy
(elilarasi.kanthasamy@northumbria.ac.uk)
A/Prof. Keerthan Poologanathan
(keerthan.poologanathan@northumbria.ac.uk)

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Data-driven structural design models using physics-informed neural networks

14 **Adrien Gallet**
University of Sheffield, UK

Project Objectives and Goals

In clear opposition to structural analysis, the direct application of machine learning in structural design remains sparse (Thai, 2022). This knowledge gap is also present outside of academic literature, where the potential importance of data-driven approaches is acknowledged yet its application is unrecognised due to the apparent lack of high-quality datasets and the black-box nature of machine learned models (Debney, 2021).

This research addresses this knowledge gap by demonstrating how a data-driven design model for a continuous steel beam system can be developed, and aims to achieve the following objectives:

- Provide a novel philosophical perspective for structural design using an inverse problem approach.
- Explain how the structural influence zone allows the creation of generalisable machine learning models.
- Highlight the use of physics-informed constraints to address the "black-box" limitation of neural networks.

The goal is to emphasise the recent development of data-driven design models and the near- to medium-term implications for the future of structural design.

Description of Method and Results

The over-arching methodology is to approach structural design from an inverse problem perspective (Gallet et al. 2022) and applying it to the design of a continuous beam system shown in Fig 1. From this perspective, the design constraints (UDLs w and span values L) act as known priors from which the model parameters (here the cross-sectional properties) are to be estimated using known observations that consist out of structural requirements (such as ULS/SLS checks). Inverse problems can be solved either through iterative solvers or through learned data by mapping observations to model parameters heuristically based on a dataset of correct solutions. The latter approach gives rise to an explicit data-driven design model.

The key challenges faced when developing such a data-driven design model is to ensure it is generalisable (applicable to any continuous beam systems) and that it is accurate (small error variations).

The first challenge (generalisability) is handled through a novel concept termed as the influence zone, which is a statistical measure of how far surrounding information within a structural system can influence a given member. By knowing the size of the influence zone, one can ensure the necessary inputs are provided to the neural network. This allows the same predictive model to parse through a structural system, designing each member sequentially, based on the relative design information that sits within the influence zone of each beam.

The second challenge (ensuring accuracy) is tackled by forcing the network to make physically realistic predictions by relating the inputs (UDLs and span values) and output predictions (structural properties) based on beam theory equations (Bernoulli or Timoshenko). When this constraint, known as physics-informed learning, is applied during training of the neural network, it leads to accurate results as shown in Fig 2. This allows engineers to judge if the network is making physically realistic predictions, partially tackling the black-box limitation of neural networks.

By taking advantage of well-established methodologies in structural optimisation (Saka and Geem, 2013), one can map a series of design inputs to their corresponding model parameters that respect the structural requirements of the system. Whilst the creation of this synthetic dataset and the training of the model is computationally expensive, the computationally effort can be seen as a future investment to allow a single physics-informed neural network to solve all future design problems of the given structural type (here a continuous beam system) instantaneously.

Potential for Applications

The value of this type of a data-driven design model should be understood in context of its ability to provide real-time feedback on the design of structural systems, with the physics-informed constraint giving a practicing engineer a reason to trust its results as opposed to traditional black-box machine learning models. The design model provides actionable intelligence based on the breadth and depth of millions of design data-points, whose insight is immediately available to an engineer, without having to gain years of experience of working with that material or structural system first.

Unlike other heuristic tools such as span-to-depth ratios, which are technically "black-box" tools themselves, these data-driven design models are not restricted to conceptual design stages only. The predictions can be as detailed as the structural optimisation tools they rely on allow, meaning similar data-driven design models could be created from simple cross-section properties predictions as demonstrated here, down to the suggested bolt counts of steel end-plated connections.

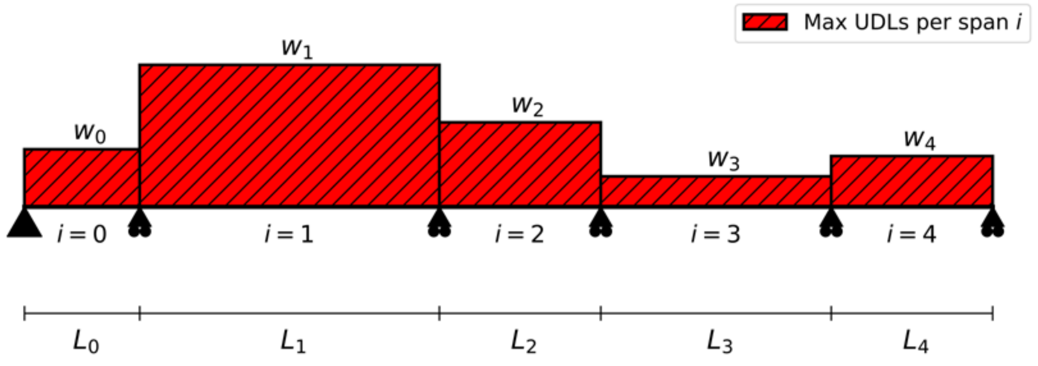

Fig 1 Continuous beam system variables

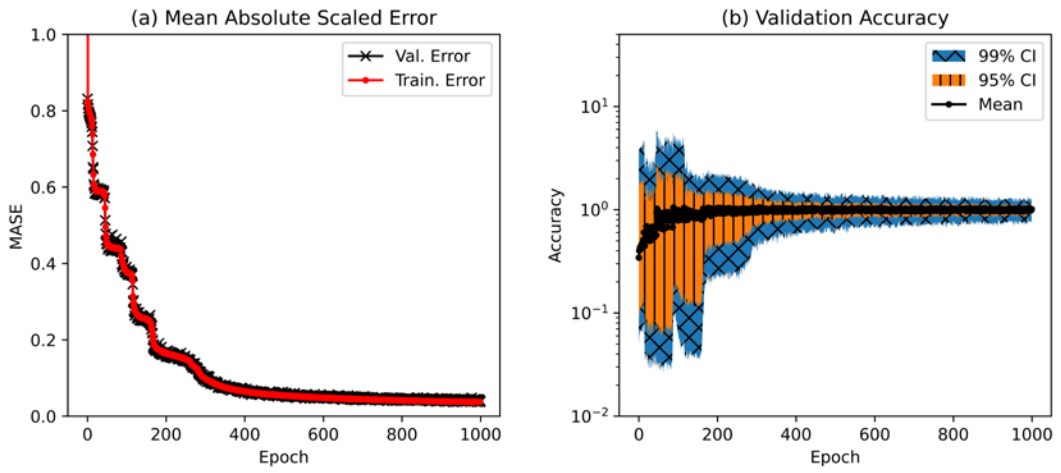

Fig 2 Training results of physics-informed neural network for continuous beam systems

These data-driven design models therefore simply facilitate meeting design requirements that are easily quantifiable (such as ultimate and serviceability limit states), and the intention is to allow structural engineers to focus on meeting other holistic requirements they are significantly better equipped to handle. These include ensuring constructable designs are created, effectively collaborating and coordinating with the client and architects to ensure the correct design information is available in the first place and thinking carefully about all potential sources of uncertainties that exist in construction (Mason and Manning, 2011). To tackle the modern structural engineering challenges we require modern tools, and data-driven design models could be one of them.

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Further Information

Adrien Gallet, PhD Research Student
(agallet1@sheffield.ac.uk)
Danny Smyl, Supervisor, (dsmyl@southalabama.edu)

Structural health monitoring of bridges under thermal load

15 **Sushmita Borah**
Nottingham Trent University, UK

Project Objectives and goals

Temperature load has predominant effect on long-term structural behaviour of bridges. Measuring bridge thermal response is as important as measuring its traffic induced response to ensure holistic structural health monitoring. Thermal response measurement is usually carried out with contact sensors such as accelerometers, potentiometers, strain gauges, LVDTs, FBG sensors etc. While these sensors are accurate, they require dense sensor network, labour intensive and cumbersome installation, and high overall cost. In contrast, vision-based monitoring (VBM) is a promising SHM technique with flexibility of low-cost options, non-contact sensing, simpler instrumentation and minimal physical access requirement. VBM utilizes advances in cameras and computer vision to measure deformation of targets on the bridge. The targets are high contrast artificial markers or bolts and nuts on the bridge. VBM accuracy is not investigated extensively for thermal response measurements [1-2], however, it has demonstrated good accuracy to measure traffic induced responses. This study examines the accuracy of VBM for thermal response measurement through laboratory experiments.

Description of method and results
The VBM based thermal response measurement methodology is shown in Fig 1. A laboratory testbed comprising of a simply supported aluminium truss equipped with GoPro cameras and contact sensors such as thermocouples and linear variable differential transformers (LVDT) is used in the experiments. Cyclic temperature loads are applied to the truss to simulate daily temperature variations. The test setup is shown in Fig 2. The contact sensors measure the temperature and displacement of the truss due to applied temperature cycles. Data from contact sensors are used evaluate accuracy of VBM. The VBM system employed in the experiments captured sequential images of targets with the cameras. Area based target tracking is used to obtain target coordinates from all images. The displacement of the targets is measured from VBM derived coordinates using equation 1 and 2. Here, d_x and d_y are the horizontal and vertical displacement of a target, where (x_i, y_i) is its coordinate in the current image frame and (x_1, y_1) is its coordinate in the first image frame.

$$d_x = x_i - x_1 \qquad (1)$$

$$d_y = y_i - y_1 \qquad (2)$$

Measured response trends by VBM and LVDT are comparable, indicating the accuracy of VBM to measure thermal responses. Thermal responses measured by VBM are higher than those of LVDT, signifying requirement for measurement resolution enhancement. The measurement resolution of VBM is 0.099 mm/°C and LVDT1 is 0.041 mm/°C respectively. This discrepancy can be attributed to non-identical target location for VBM and LVDT, resolution of the camera, efficiency of the feature tracking algorithm and robustness of LVDT output.

Potential application of results

This case study illustrates the feasibility and challenges of VBM for thermal response measurement. The results of this study will contribute to the knowledge of VBM accuracy for thermal response measurements. It provides a VBM application and data analysis framework for future applications to measure thermal response. Potential applications include field implementation in real-life bridges for long-term monitoring.

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Funding body

Nottingham Trent University.

Further Information

Sushmita Borah (sushmita.borah@ntu.ac.uk), PhD Candidate, Nottingham Trent University, UK
Supervisor: Prof. Amin Al-Habaibeh (amin.al-habaibeh@ntu.ac.uk), Professor, Nottingham Trent University, UK
Supervisor: Rolands Kromanis (r.kromanis@utwente.nl), Assistant Professor, University of Twente, The Netherlands

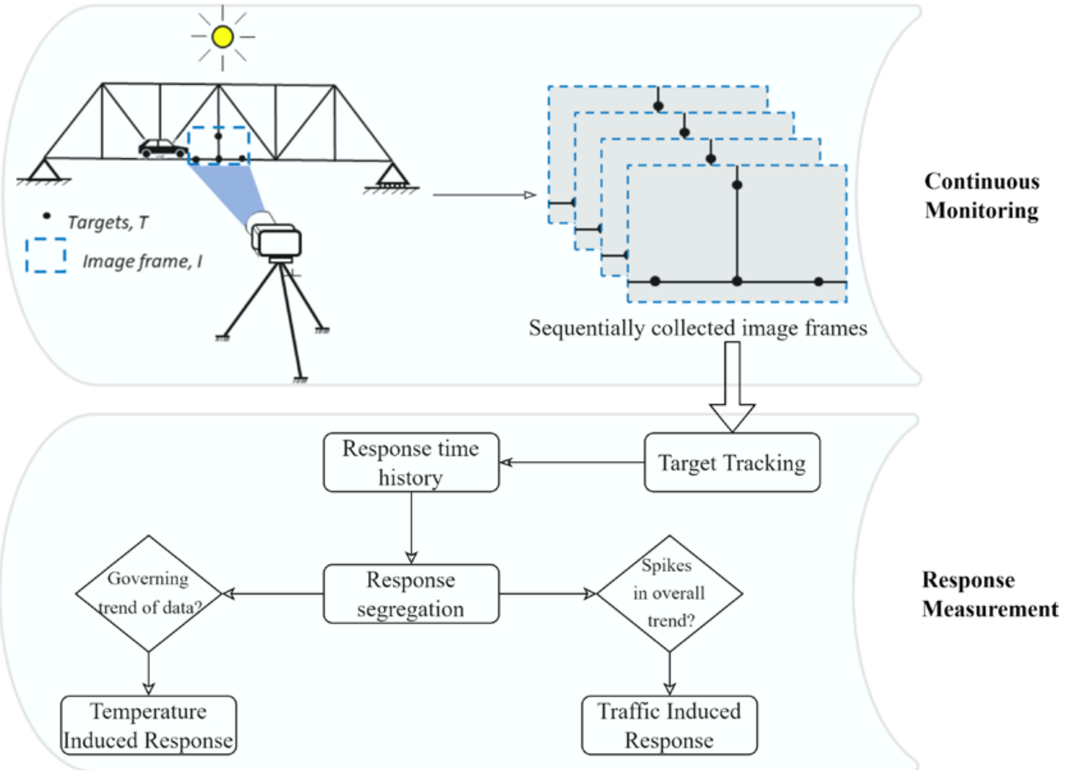

Fig 1 Vision-based thermal response measurement method

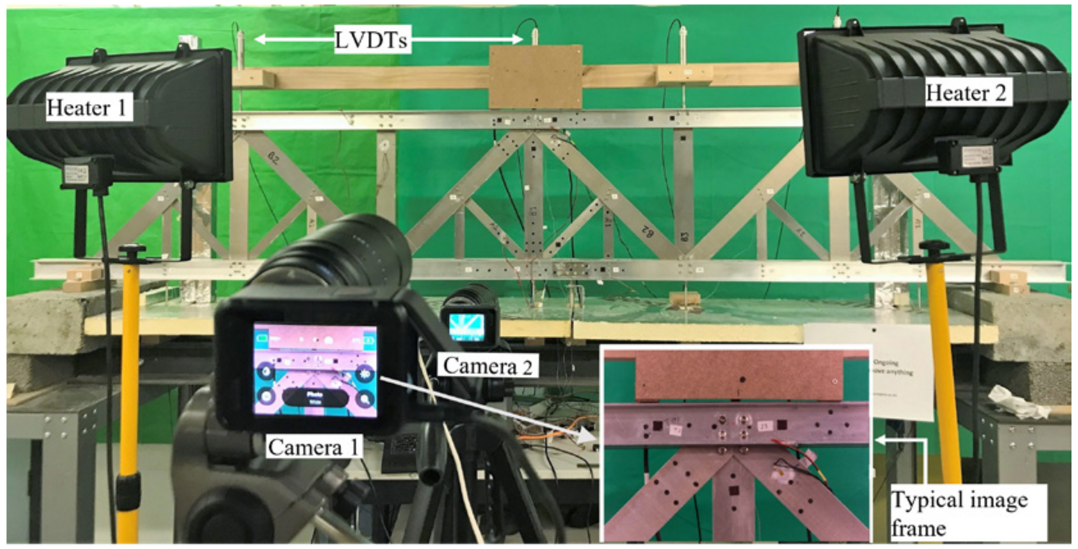

Fig 2 Test rig set up

Mechanical and microstructural analysis of wire arc additively manufactured steels

16 **Cheng Huang**
Imperial College London, UK

Project objectives and goals

Wire arc additive manufacturing (WAAM) is a metal 3D printing method that allows the cost-effective and efficient production of large-scale elements, and has thus gained great interest from architects and structural engineers (Gardner et al. 2020). Integration of this novel technology into the construction industry, however, requires the development of a clear understanding of the mechanical behaviour of WAAM materials. To this end, a comprehensive experimental study into the mechanical properties and microstructure of WAAM plates made of normal- and high-strength steels has been undertaken.

Description of method and results

A total of 137 as-built and machined tensile coupons were tested (Fig 1), extracted in various directions relative to the print layer orientation from WAAM plates of two nominal thicknesses, built using different deposition strategies. The influence of the geometric undulations inherent to the WAAM process and deposition strategy on the resulting mechanical properties was investigated. Microstructural characterisation was also performed by means of optical microscopy (OM) and electron backscatter diffraction (EBSD). The WAAM normal-strength steel plates exhibited a principally ferritic-pearlitic microstructure, while the WAAM high-strength steel plates displayed a mixed microstructure featuring ferrite, bainite and martensite (Fig 2). The EBSD analysis revealed a weak crystallographic texture, which explained the observed mechanical properties being almost isotropic. No significant differences in tensile properties were observed with the different deposition strategies, except for some variation in ductility. The geometric undulations of the as-built coupons resulted in some reduction in effective mechanical properties and a degree of anisotropy. Overall, the examined WAAM material exhibited consistent mechanical properties, a Young's modulus comparable to conventionally-produced steel plates, marginally lower strength, reflecting the slower cooling conditions than is customary, and good ductility.

Potential for application of results

Wire and arc additive manufacturing is a metal 3D printing technology that has the potential for significant impact on the construction industry. Fundamental experimental data on the mechanical and microstructural properties of WAAM materials are lacking. The results of the present study provide an insight into the material behaviour of WAAM steels, facilitating the broader application of WAAM in steel construction.

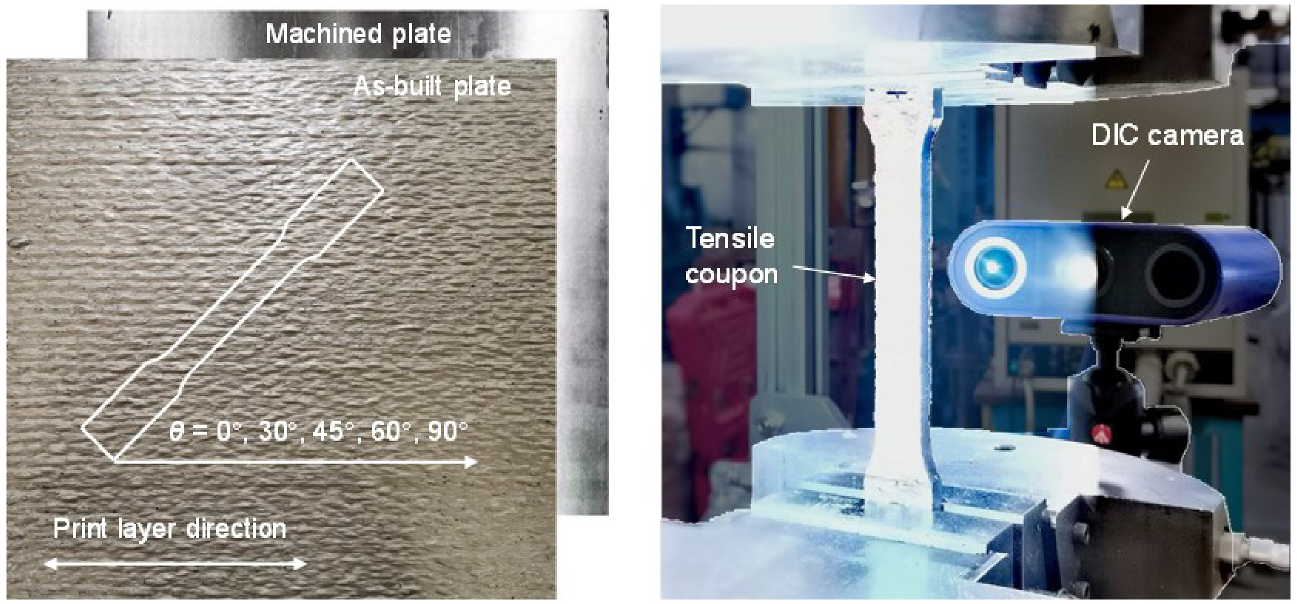

Fig 1 Material testing: as-built and machined sheet material (left) and test set up (right)

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Funding bodies

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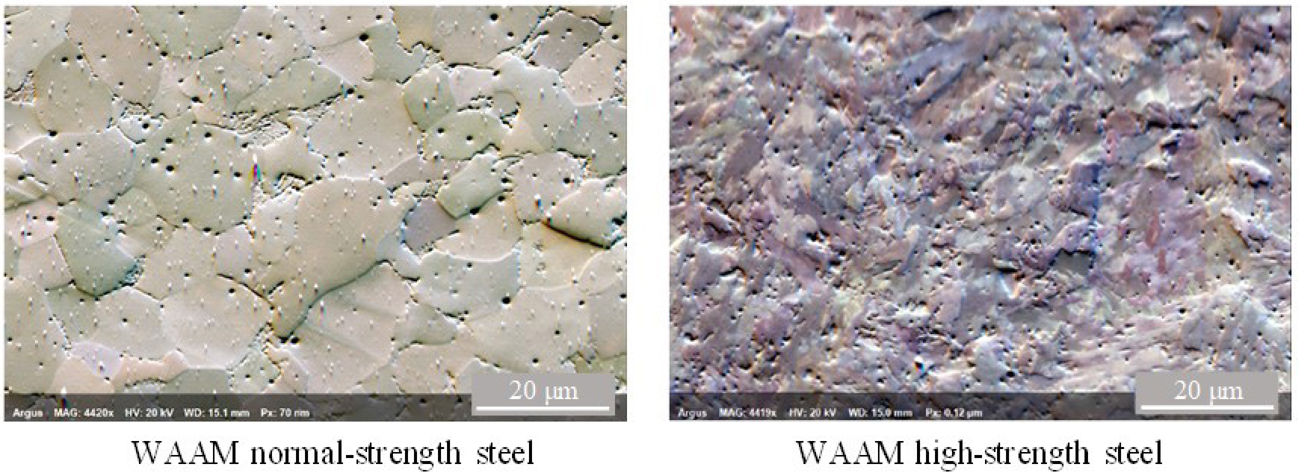
Further information

Cheng Huang (cheng.huang118@imperial.ac.uk)



WAAM normal-strength steel

WAAM high-strength steel

Fig 2 Typical microstructure of examined WAAM steels

Experimental study of DED-arc additively manufactured steel double-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) double lap shear bolted connections has been contacted at Imperial College London. The aims of the study are:

- To determine the ultimate capacities of test specimens
- To analyse the failure mechanisms of WAAM bolted connection subjected to double shear
- To assess the applicability of current design specifications
- To investigate the influence of geometrical and material anisotropy inherent to the WAAM process on the structural response
- To investigate the differences between the bolted lap connections subjected to single and double shear

Winter (1956) identified four distinct failure modes for bolted connections, namely shear-out failure, net section tension failure, bearing failure and bolt shearing failure with the latter type depending on the strength of the bolt rather than that of the connected plates. End-splitting discussed by Može and Beg (2014), and incidental block shear failure were also observed in the current test. The above-mentioned failure modes are addressed in the investigation herein.

Tests on WAAM bolted connections subjected to single shear have been conducted previously by Guo et al. (2022). The obtained experimental data along with the findings from the present study are used to compare the structural performance of single and double-shear connections.

Description of method and results

Sixty connection specimens of two different nominal thicknesses and two print layer orientations were then tested to failure. The geometry of the test specimens was determined by 3D laser scanning, while the deformation and strain fields were measured during testing using digital image correlation. The process of specimen preparation and the test setup are illustrated in Fig.1 and Fig.2 respectively.

The observed failure modes included shear-out, net section tension, bearing and end-splitting, while a new hybrid mode of shear-out and net section tension was identified for the first time. The test results were compared against the predictions of current design specifications, Overall, the structural behaviour of the tested specimens followed the anticipated trends, and the predicted resistances determined from the current design specifications were generally reasonable. There were, however, a number of exceptions to this, highlighting the need for new design provisions, together with appropriate safety factors, that are specific to this form of manufacture.

Potential for application of results

Although the structural behaviour of the examined specimens was generally found to follow the anticipated trends, the accuracy of the current design specifications can be improved further based on the results presented in this paper. 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 (x.guo19@imperial.ac.uk)
Supervisor: Leroy Gardner (leroy.gardner@imperial.ac.uk)

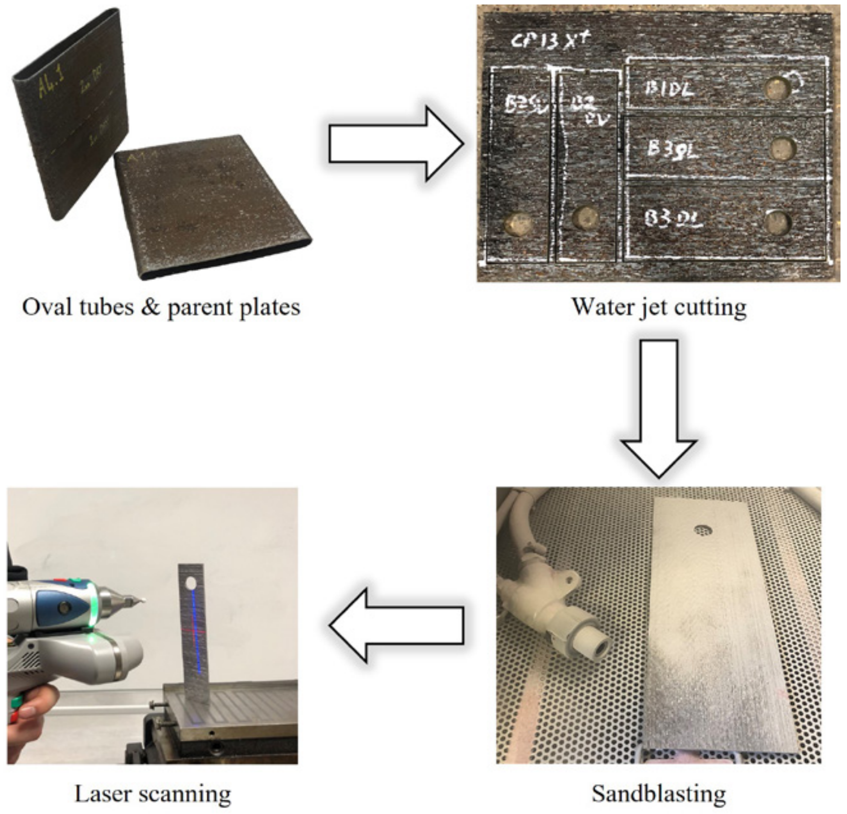

Fig1 Specimen preparation

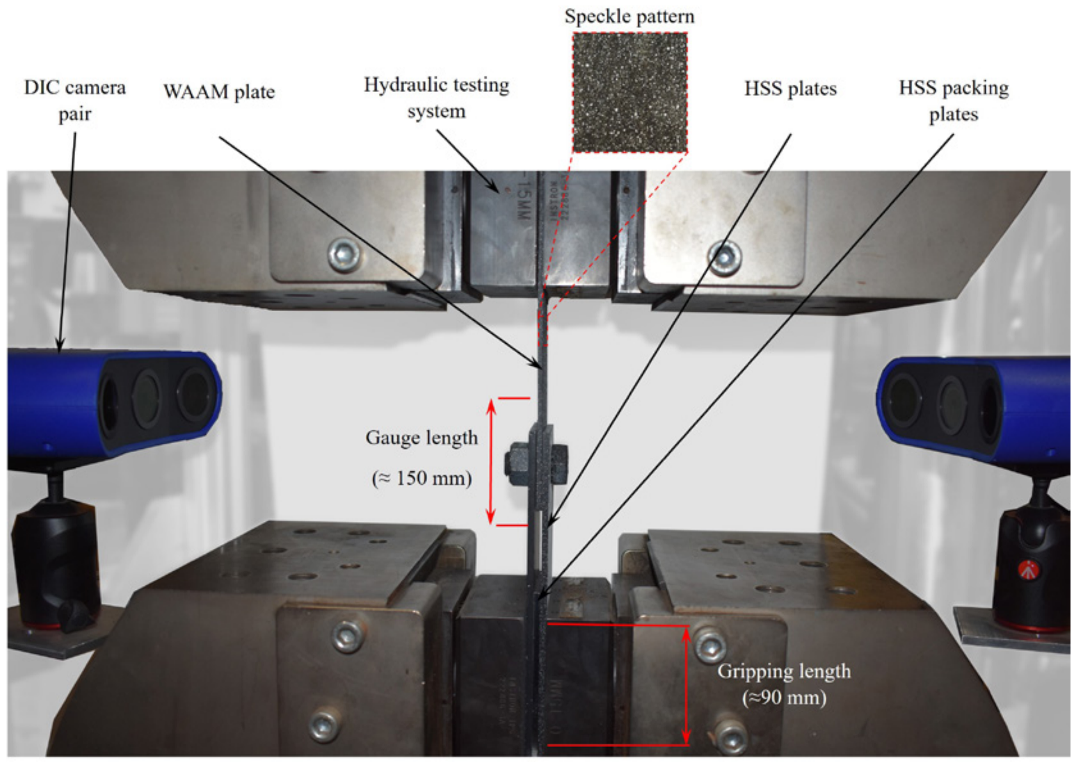

Fig 2 Test setup

Optimising the environmental impact of deep foundations

18 **Kareem Abushama**
University of Bath, UK

Introduction

A recent UN report has shown that the construction industry is one of the seven major sectors that contribute significantly to environmental pollution and was responsible for around 20% of energy-related CO2 emissions in 2020, and this is expected to increase during the upcoming years unless preventive actions are taken (UN Environment program, 2021). Many studies have addressed the carbon footprint of superstructures including life cycle assessments, trials to reduce the quantity of material used in construction and discovering new production techniques with lower environmental impact (Hawkins et al., 2020). However, the carbon footprint of substructures has only been investigated to a limited extent, this is believed to be due to a lack of certainty in the mechanical behaviour of soil and its interaction with structures as well as the construction complexity for deep foundations (Sandanayake et al., 2016).

Project objectives and goals

This project aims to establish a robust algorithm for optimising the environmental impact of piles bored or driven in different soil types. This will be achieved through optimising different design parameters (concrete grade, steel-to-concrete ratio and pile dimensions) across a multi-level optimisation algorithm tested for different pile-design cases. This aim will be achieved by fulfilling the following objectives:

- Testing the effect of concrete grade on the environmental impact of piles.
- Investigating the optimum pile's slenderness ratio for each design case.
- Testing the effect of steel/concrete ratio on the environmental impact of piles.
- Proposing a multi-level optimisation algorithm and testing for a case study.

Description of method and results

Testing the effect of concrete strength grade on the environmental impact of piles

The compressive strength of concrete is controlled by many factors i.e., cement content, cement-to-water ratio, etc., a combination of these different factors at different ratios would result in concrete mixes with different properties and strengths (Thilakarathna et al., 2020). Moreover, there is a strong correlation between concrete strengths and the resulted embodied carbon, which should be considered during the design stage.

A program is written to test the effect of F_{ck} on the environmental impact of piles in clayey soil at different design loads (1–7 MN) through calculating the minimal amount of material required to satisfy the three different pile design limits (geotechnical capacity, ultimate limit state and serviceability state) under a given load and at different concrete compressive strengths. The required material is then used to estimate the embodied carbon using carbon factors published by the IStructE manual (Orr et al., 2020). A part of the results is shown in Fig 1. and shows that the environmental impact of piles is strongly influenced by the chosen F_{ck} and that piles with low capacities favour low strength concrete which is not the case for piles of higher capacities.

Testing the effect of slenderness ratio (L/D) on the environmental impact of piles

Pile geometry and dimensions have a significant effect on its resistance, accordingly, a pile designed at the optimal slenderness ratio $(L/D)_o$ would incorporate the minimal amount of embodied carbon while achieving the required design resistance.

A program is written to calculate the minimal amount of material required to satisfy the different pile design limits under a given load and at different slenderness ratios. The required material is then used to estimate the embodied carbon using carbon factors. A part of the results is shown in Fig. 2 and shows that the optimal L/D will always lie between two critical slenderness ratios $(L/D)_c$ and $(L/D)_{cs}$, these two ratios depend on concrete and soil properties. A designer can significantly decrease the embodied carbon by adjusting the pile's dimension to fit with $(L/D)_o$.

Testing the effect of steel-to-concrete ratio on the environmental impact of piles

In practice, the amount of steel used for pile reinforcement is usually more than required to achieve the design limits, this significantly increases the amount of embodied carbon in the foundations.

A program is written to test the effect of steel reinforcement ratio (A_s/A_c) on the environmental impact of piles. Results show that A_s/A_c has a considerable effect on the amount of embodied carbon and that the optimal reinforcement ratio $(A_s/A_c)_o$ should be calculated for each pile and it depends on many factors including the steel production method, concrete properties and applied loads.

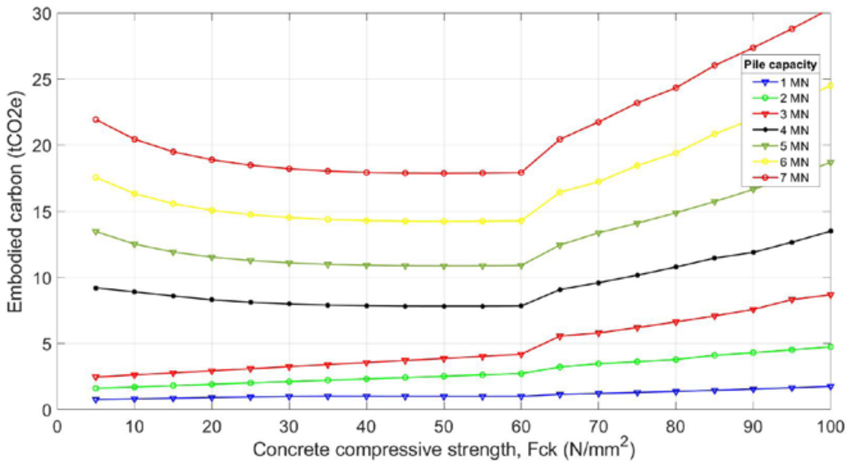

Fig 1 Total embodied carbon for piles of different load capacities at varying concrete compressive strength f_{ck}

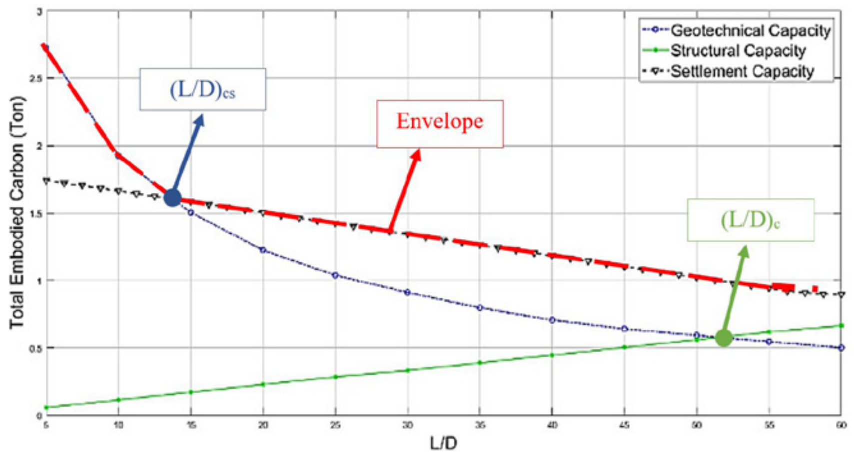

Fig 2 Total embodied carbon resulting from the amount of material required to satisfy each of the three design criteria at different slenderness ratios

Application of results

The proposed, multi-level optimisation algorithm is applied to a case study of deep foundations for a mono-rail train bridge in New Cairo – Egypt. The optimum F_{ck}, A_s/A_c and L/D are calculated given the design loads and tested soil properties. A significant cut of 54% of the embodied carbon is achieved showing promising results for a wider application, and proving that pile optimisation represents a significant opportunity for carbon savings in the built environment.

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Funding body

University of Bath, ESRC.

Further information

Kareem Abushama (kaa71@bath.ac.uk)
Will Hawkins (wh604@bath.ac.uk)

Towards the adoption of metal 3D printing in structural engineering

19 **Ben Weber**
Imperial College London, UK

Project objectives and goals

Additive manufacturing has been subject of widespread research interest and industrial applications in recent decades. However, the construction industry is only just starting to explore the benefits of this promising technology, mainly due to a lack of design codes which provide the necessary quality assurance procedures and standardise the manufacturing process (Wu et al., 2016). Wire Arc Additive Manufacturing (WAAM) is a metal 3D printing technique where an industrial robotic arm is used, in conjunction with a conventional welding unit, to deposit metal and create objects, with few limitations to their size or shape (Lange et al., 2020). Compared to other additive manufacturing methods, WAAM is of special interest to the construction industry due to its high deposition rate and the inherent surface tension of the molten metal, which allows for overhanging structures to be printed without the need for support material (Gardner, 2023). Topologically optimised structures, made possible by the digitally enabled manufacturing process, can exhibit the same structural strength but with considerably less material compared to those produced by conventional manufacturing techniques. This reduces the weight of the printed part and, due to the shorter manufacturing time, its associated costs (Cavazutti et al., 2011). The overall objective of this project is to establish a standard evaluation framework for WAAM structural elements. This can be achieved by developing a material model for different WAAM materials and validating it by analysing the underlying crystallographic structure. This model will subsequently be used in tests of structural WAAM specimens to develop a standard evaluation framework. To demonstrate its validity, a large topology optimised structure, which would be impossible to manufacture using conventional methods, will be designed, printed and verified, using the standard evaluation framework for WAAM structural elements.

Description of methods and results

Gaining insights into the material behaviour of WAAM was critical to determine the performance of printed structures. Through tensile coupon tests of various grades of carbon steel, captured via digital image correlation (DIC), material printed in different directions was examined. Several different printing strategies were investigated to determine the influence of different cooling rates and toolpaths on structural performance. Tensile coupons were 3D laser scanned before testing to correlate the geometry of specimens with their tensile behaviour. Finally, a crystallographic analysis of the material was performed using electron backscatter diffraction (EBSD) in a scanning electron microscope (SEM), with the aim of correlating the results of the tensile coupon tests with the underlying microstructure of the material. Overall, the tested materials showed very little anisotropy which was confirmed by a homogenous ferritic microstructure. Some reduction in ductility and strength was observed for coupons extracted perpendicular to the printing direction, owing to the influence of surface undulations on the tensile behaviour.

To verify the validity of the derived elastic and plastic material models, standard elements used in civil engineering, whose behaviour is well understood, such as I-beams, circular hollow sections (CHS) and square hollow sections (SHS), were tested in various loading scenarios to compare their performance against the predictions of design codes. Stub column, column buckling, full cross-section tensile, 3-point bending and continuous beam bending tests were carried out on the WAAM material. Comparing the behaviour of the printed elements against that of conventionally manufactured specimens, showed very similar, albeit slightly weaker tendencies. This was often governed by imperfections in the structures owing to the novel manufacturing process. Initial experiments on optimised columns and beams, impossible to produce by conventional methods, have already been carried out and, as predicted by finite element (FE) models using the developed WAAM material models, demonstrated a considerable increase in load carrying capacity and thus structural efficiency. Examples of this are shown in Fig 1.

In the next phase, fully capitalising on the design freedoms WAAM presents, we will investigate how different material layouts (topology optimisation) and printing orientations can be exploited to optimise the material utilisation across structures, to increase their strength and reduce weight as well as manufacturing time. Large-scale structures will be printed and undergo laboratory testing as part of this project. Comparing the simulation results against data acquired using real-life testing of these components, the performance of the developed material model can then be quantitatively analysed.

Potential for application of results

WAAM can only be widely adopted in the construction industry when guidelines exist to help engineers design code-compliant structures without the need for specialised tests of each individual component. Thus, the development of a standard evaluation framework is one of the most important steps to further promote the adoption of metal 3D printing in the construction industry.

In the short term, WAAM will most likely be used in the design of complex connections between conventional steel elements, such as those shown in Fig 2, as well as to strengthen new and existing structures. Longer term, WAAM could easily find applications in many high-profile construction projects. The design freedom provided by this technology will enable engineers to design lightweight, strong structural elements, impossible to realise by conventional methods, and architects will benefit from the freedom to incorporate intricate design elements into their creations.

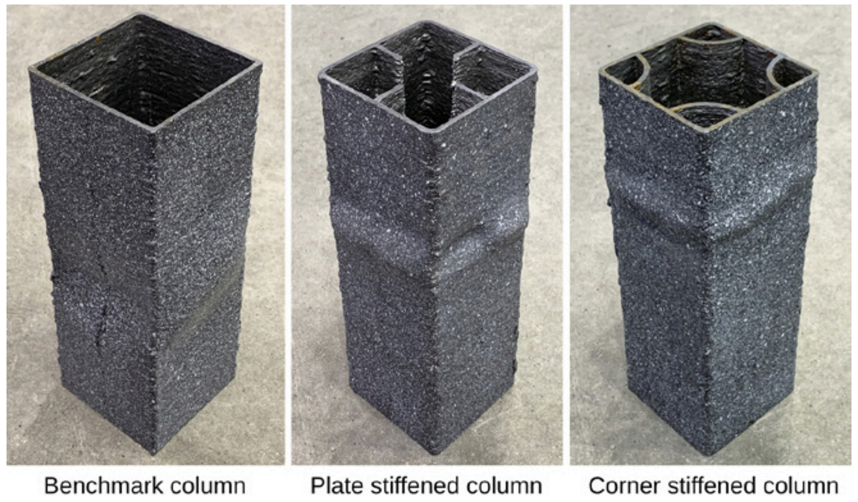

Fig 1 Optimised SHS stub columns

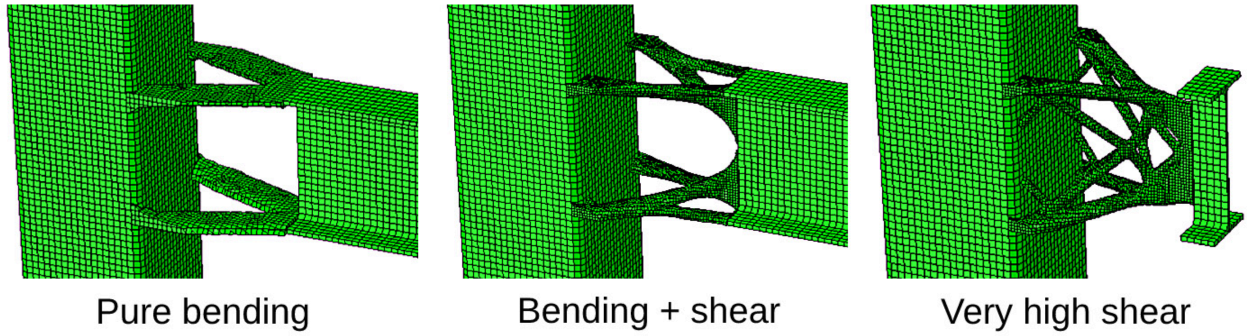

Fig 2 Design of topology optimised beam-to-column connections with different load cases (Gardner, 2023)

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Funding body

Fonds National de la recherche Luxembourg (FNR)

Further information

Ben Weber (ben.weber19@imperial.ac.uk)
Leroy Gardner (leroy.garnder@imperial.ac.uk)
https://www.imperial.ac.uk/steel-structures

Collaborations

Shimizu Corporation https://www.shimz.co.jp/en

Post-installed reinforcement for 3D concrete printing technology

20 **Yangyunzhi Gao**
National University of Singapore

Project objectives and goals

Productivity has long been a central issue in every industrial category. Compared to other sectors, the construction industry is frequently described as demanding a large amount of labour, lacking automation, and therefore low in productivity.

A considerable amount of literature and projects has developed around this topic of additive manufacturing (AM) in construction, which is also described as 3D concrete printing (3DCP). It will eliminate the demand for formwork, reduce the demands for labour on site, minimise material waste throughout the process, shorten the construction period, and thus lower the total cost and lifetime carbon emissions.

However, the 3DCP structure still faces challenges when seeking a mass application in the construction industry. The lack of a reinforcement method to meet current standards has long been a major concern with respect to its application.

Existing research recognises that concrete is brittle on its own and susceptible to tensile stress, which is why reinforcement plays a critical role for both conventional RC structures and 3D printed concrete. Until now, numerous reinforcement methods have been mentioned, which could be classified into ‘in-process’ and ‘post-installation’ reinforcement with their own pros and cons:

In-process reinforcement combines printing and reinforcing procedures into one, thus saving the total time cost in the fabrication process. The work by Marchment and Sanjayan (2021) suggests a coated rebar penetration method, while Hass and Bos (2022) showed the feasibility of using an automated screwing machine for reinforcement in 3D printed concrete samples. However, with respect to vertical steel reinforcement, current solutions are either destructive to printed concrete sections or excessively complicated to scale up in the fabrication process.

Post-installed reinforcement is relatively easier to adopt for 3D printers with few modifications. According to current research, steel bars can be installed vertically without difficulty. The study by Vantyghem et al. (2020) offers a solution of utilizing 3D printed holes as a place for post-tensioning reinforcement, and one another analysis by Asprone et al. (2018) reveals the feasibility of external steel frame connected with the 3D printed structures. Although they comply well with current codes or standards, none of the solutions satisfies the demand for automation reinforcement, as they focus on effectiveness rather than potential in automation. The involvement of labour work means no method was found to have potential for a fully automated reinforcing process.

This project aims to contribute to the application of 3DCP technology in the construction industry by providing a reinforcement method with the potential for fully automated production in the meantime.

Description of method and results

A 3D printed concrete reinforcement method was proposed, where steel bars were placed perpendicular to the printed layers and bonded to the hardened concrete by filling the grout in a predesigned ‘notch’ section. To install longitudinal steel bars near the bottom surface of the beams, a ‘notch’ section is designed to be printed during the 3D printing process. When hardened, the printed beam will be laid with the notch side toward the top before a straight bar is placed into the notch and the filling grout was pour/printed in to form its reinforcement. The detailed design and dimensions of the 3D printed beams are illustrated in Fig 1.

The feasibility of the novel reinforcement method was then proved by a smaller-scale 3D printing and flexural bending test, as is shown in Fig 2. All 3D printed beams reported higher resistance in flexural bending tests compared to 3D printed but without reinforcement. The tests revealed that, with proper design, this post-installed reinforcement could provide the desired resistance under the bending moment. The following scale-up tests will be conducted to further prove the performance of the reinforced 3D printed concrete beams in a more realistic context.

Potential for application of results

1) Compared to conventional precast concrete, these reinforced beams made with D printed technology eliminate the need for temporary support (wooden/steel moulds) and thus lower the labour demand and minimise waste in production, which will in the meantime increase the productivity of the construction industry.

2) Compared to the current 3D printed concrete, the proposed method has potential for fast and easy automated production, such as 3D printing by 3D printers and the reinforcement process by placing rebars and grouting on an assembly line. Fully automated production will make it possible for mass production in countries with higher labour costs or under extreme environmental conditions.

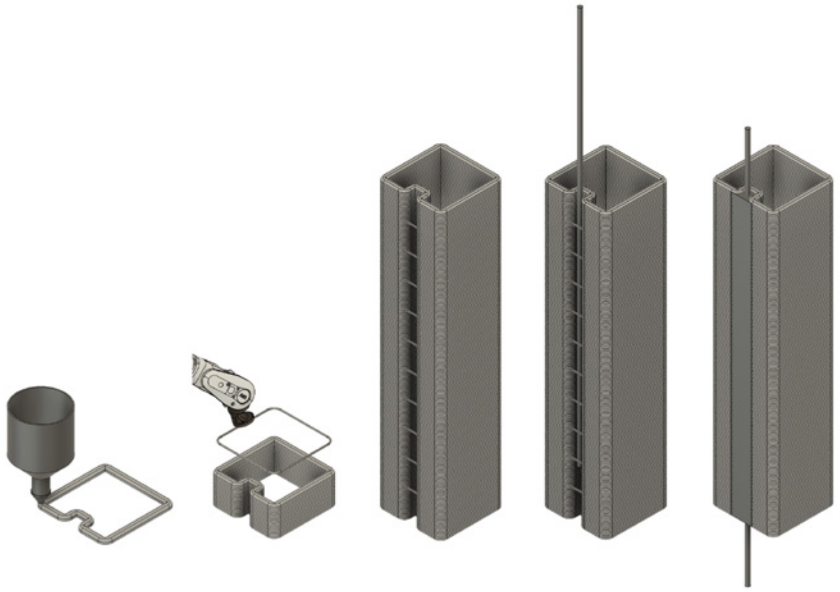

Fig 1 Reinforcement method for 3D printed beams in steps

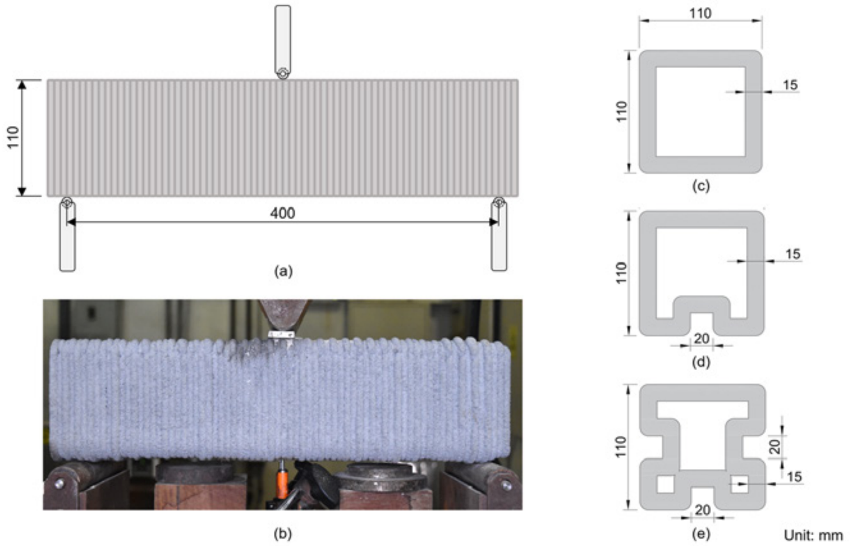

Fig 2 Test setup for flexural bending tests of the 3D printed beams

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Further information

Yangyunzhi Gao (gao.yang@u.nus.edu)
Hongjian Du (ceedhj@nus.edu.sg)

The development of assessment models for the FlexiArch bridge system experiencing bridge scour, under loading

21

Ben Millar
Queen's University, Belfast

Project objectives and goals

The FlexiArch bridge system developed at Queen's embodies the characteristics of the modular movement which will help make the future of civil engineering more sustainable. The climate is changing and with that comes the even greater risk of bridge collapse due to bed scour caused by increasingly common flood events. Until now the structural response of a bridge under loading has been analysed independently from the hydraulic process which cause the scour. The Queen's Hydraulics Research Laboratory is the first to consider the key forces driving bridge collapse (the hydraulic processes and structural form under load) and not treat them separately but consider them as two interconnecting elements. Experiments carried out in this fashion on a scale model of the novel FlexiArch bridge system will make use of computer-vision to record the dynamic response of the bridge under loading at various scour scenarios. This will contribute to the development of a finite element model and will form part of a package of tools which will allow key stakeholders to both analyse and prioritise bridge stock and continually monitor assets in real time which will help ensure the security of these vital pieces of infrastructure.

A 1:10 scale model of a typical FlexiArch bridge will be built in both the heavy structures laboratory and inside the flume tank in the hydraulics research laboratory (Fig 1). This model will be tested to produce data which will inform both the computer-vision model and the finite element model. The geometry of the bridge will be altered as the experiments progress to change the performance of the bridge. These alterations include changes to the number of arch rings, foundations, and skew.

This project will develop a system which can be used to measure deflections under load from a masonry arch bridge in real time. Ultimately this tool will be able to measure displacements at any point along the clear span of the arch and produce a 'heat map' style visual report for ease of understanding. Critically, this tool will allow any potential hinge formation between voussoirs along the arch to be detected and monitored. Since this is the failure mechanism of the arch bridge, it is important to be monitored accurately.

Finally, this tool will produce a report which will highlight key parameters of the asset's health measured against a bridge metric by the inspecting engineer for rapid stakeholder analysis. A finite element model of the FlexiArch bridge will be developed which can be used to predict the structural response of the bridge load under different load conditions with realistic and accurate scour conditions derived from flow patterns.

In order to develop the computer-vision system, a benchmark model will be constructed in the lab, under the Small Dartec Machine loading ram (Fig 2). This is the focus of the research at this stage.

Description of method and results

A calibrated camera will be set up with the bridge under consideration under the loading ram within its field of view. This video will then be analysed by the computer-vision-based deflection and hinge formation extraction tool developed in MATLAB. The tool will first stabilise the video and then using feature detection and matching, salient features will be identified and extracted from along the span of the arch. The movement of these features can be tracked over time as the video progresses and load is applied in a similar way to Lydon et al (2019). Any deviation from the original position of the salient features (when the bridge is unloaded) can be thus obtained. In this way, the deflection at any given point in time and space can be determined. The novel aspect to this research is the ability to monitor the formation of hinges in the arch ring. This will be achieved by utilising the same approach of feature detection used in the displacement measurement but with particular attention to the movement of blocks of features relative to adjacent blocks, indicating that voussoirs are moving apart and therefore hinges are forming. These approaches can be applied broadly over the entire span or concentrated on a specific area of interest. The scale model will be loaded under the Small Dartec Machine and displacements measured using the computer-vision method and by LVDT sensors. The camera and data logger for the LVDTs will be time synchronised so that the data produced by the LVDTs can be compared to the measurements taken by the computer-vision tool. In this way the computer-vision method can be validated.

The first in-depth experiment in this regard is underway as of January 2023 and results are expected to be gathered imminently.

Potential for application of results

While outlining some details of the full investigation planned, the use of computer-vision SHM to clearly identify the location of contraflexure is identified, and thus the location of potential failure hinge locations.

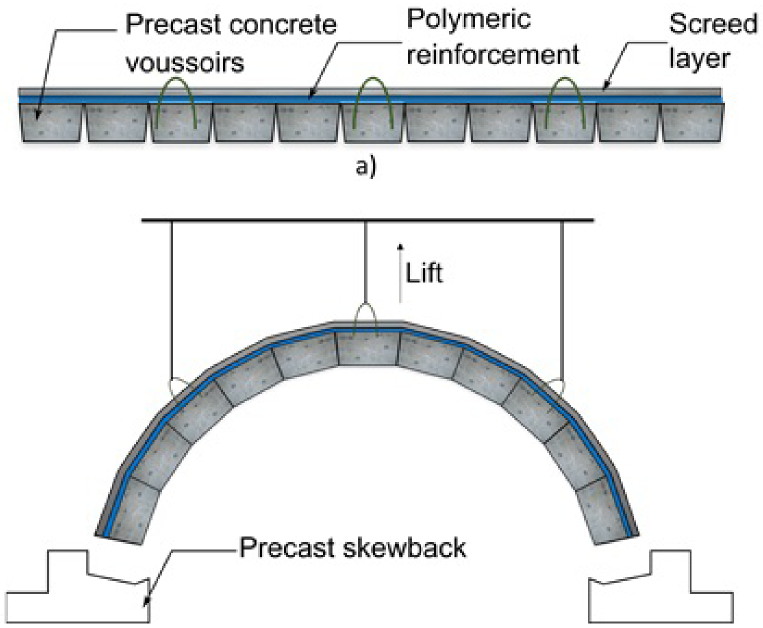

Fig 1 The FlexiArch arrangement

Although this project is primarily focused on the FlexiArch system, it could also be extended to conventional masonry arch bridges. Sloan et al (2019) identifies that these types of bridges make up 70% of our bridge stock, this is therefore of critical importance.

This project will help to improve and promote a culture of safety around bridges and increase the speed and efficiency while improving the accuracy of bridge monitoring and decreasing the cost through time saving. Rapid and accurate analysis of the current state of the condition of a bridge coupled with detailed predictions of its behaviour will help ensure the long-term security of these vital pieces of infrastructure.

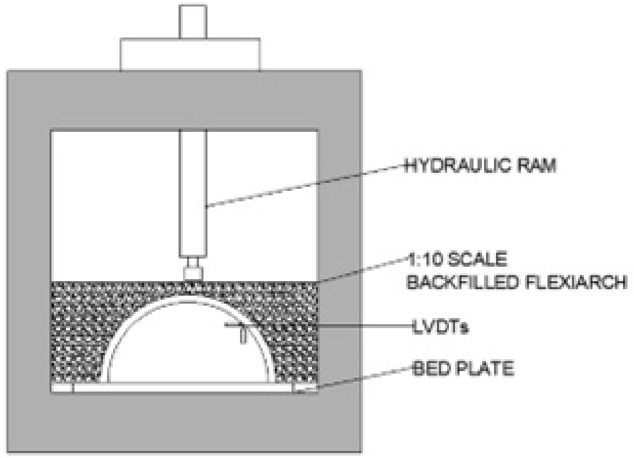

Fig 2 Scale model under the Small Dartec Machin

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Funding body

Department for the Economy (DfE)

Further information

Ben Millar (bmillar02@qub.ac.uk)
Professor G. Hamill (g.a.hamill@qub.ac.uk)
Professor S. Taylor (s.e.taylor@qub.ac.uk)

Thrust Layouts for Masonry Gravity Structures

22

Kavinda Isuru Udayanga Nanayakkara
University of Sheffield, UK

Introduction

Structural engineering professionals in the UK have declared a climate and biodiversity emergency, calling everyone in the building and construction industry into action towards a more responsible construction industry (IStructE, 2019). Amongst other things, the declaration calls for upgrading existing buildings for extended use, a shift to low embodied carbon materials, and minimisation of wasteful use of resources in structural engineering design.

Masonry gravity structures have been built all across the world, throughout history—from domestic dwellings to viaducts to imposing cathedrals (Kurer, 2008). While recognising that it is important to ensure longevity of these existing structures, masonry also provide an opportunity to build with low embodied carbon materials such as stone, which has garnered significant interest in recent times (Webb, 2020).

Design and analysis methods ranging from constructing thrust lines to building non-linear finite element (FE) models exist for the analysis of masonry gravity structures. However, some limitations in the thrust line method were recently identified (Heyman, 2009), while FE models demand computational power and user expertise (Roca et al, 2010).

The current project seeks to develop tools to assist engineers in reducing material consumption in the building and construction industry, with a focus on masonry gravity structures which work predominantly in compression.

Objectives

1. Study, understand and remedy the shortcomings observed in the traditional thrust line method.
2. Incorporating the remedies identified, develop a tool to assess load carrying capacity of masonry gravity structure.
3. Verify and apply the tool under various scenarios.

Methods and results

Thrust lines, following Hooke's observation of hanging chains and making use of graphic statics, have been extensively used for the design and analysis of masonry gravity structures (Nanayakkara, 2020). More recently, a shortcoming in the thrust line method was identified. The primary flaw stems from the unintended assumption that the structure is made up of vertical strips (Heyman, 2009)—disregarding the actual stone cutting; or stereotomy. Further, its treatment of tensile capacity of the material is ambiguous.

Thrust layouts are presented here recognising the actual block stereotomy and available, albeit limited, tensile capacity within blocks. The concept of thrust layouts improves upon the traditional thrust line method by ensuring the equilibrium of all individual blocks, whilst visualising the flow of forces through the structure.

Recognising the correspondence between graphic statics and ground-structure layout optimisation (LO), generation of thrust layouts is automated via a procedure termed thrust layout optimisation (TLO). The process involves a load carrying capacity evaluation step followed by post-processing steps to visualise the corresponding flow of forces. TLO further allows accounting for friction at block interfaces and does not require for the topology of the thrust layout to be given a priori. Convergence of this numerical method only depends on physically explainable parameters—nodal density and the maximum allowed tensile force in the thrust layout.

Thrust layouts identified via TLO provide a rich visual representation of force flows in masonry gravity structures, visualising forces flowing around internal holes, force flows resembling classical Michell structures associated with blocks rocking about vertices, and more familiar funicular thrust lines as well (Fig 1). Furthermore, plotting of transmissible self-weight vectors eliminate ambiguity as to how self-weight forces are mobilised.

In comparison to thrust lines, TLO gives more accurate estimates of collapse loads— for the flat arch on stone columns in Fig 1, thrust lines estimate a collapse load of 10.1 kN compared to 45.1 kN from TLO, which is verified by the rigid block method as the true collapse load. Furthermore, TLO provides insights to the behaviour of masonry structures—e.g. ineffective zones in masonry buttresses; load path in multi-ring arches; sliding failure at head in flying buttresses.

TLO can also be extended to determine the optimal (minimum volume) placement of strengthening measures in gravity masonry structures. Fig 2 shows the optimal locations for strengthening measures to increase the collapse load of the flat arch (in Fig 1) to 60 kN.

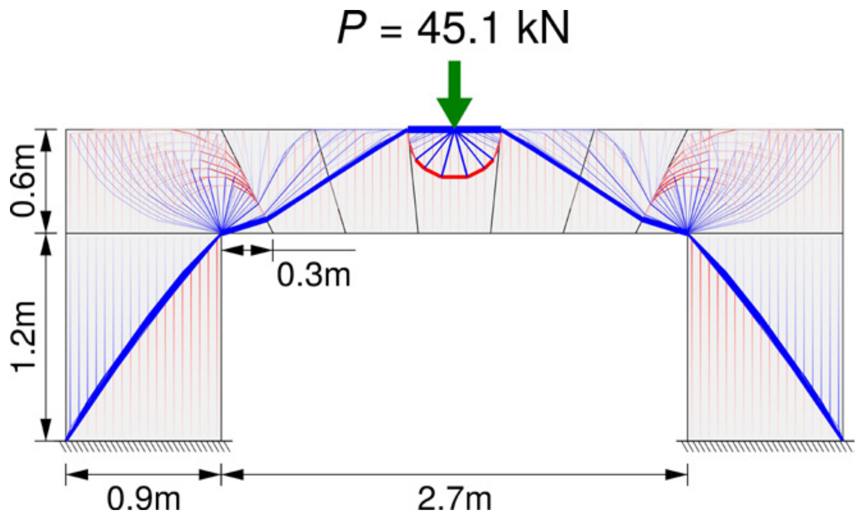

Fig 1 Thrust layout for a flat arch on stone columns at its collapse load. Lines in blue and red represent compressive and tensile forces respectively, and thickness correspond to the magnitude of the force (geometry as indicated; material unit weight 25 kN/m3; width 1 m considered).

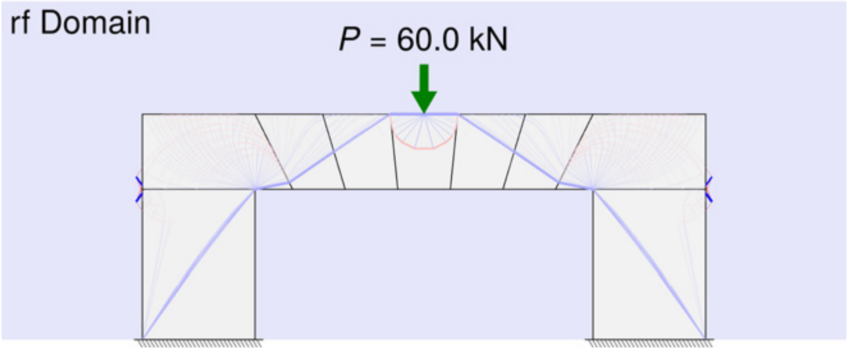

Fig 2 Optimal placement of strengthening measures for the flat arch where load capacity increased from 45.1 kN to 60.0 kN. Tensile and compressive strengthening elements in red and blue respectively. Thrust layout also indicated in a lighter shading.

Potential for application

The proposed thrust layouts and their implementation via TLO provides a tool for rapid assessment of load carrying capacity, and identification of strengthening measures where necessary, of masonry infrastructure and buildings. This would enable engineers to ensure the safety of structures, whilst not unnecessarily demolishing existing structures.

Furthermore, the tool allows for new building typologies to be identified: e.g. a stone arch in compression stabilised by a set of external steel tensile (and compression) elements. Previously, this type of structures were due to the imagination of the designer and only a handful of examples exist—e.g. the Future Pavilion at Expo '92 (Rice and Lenczner 1992).

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Predicting the environmental response of critical infrastructure, using the first metal 3D printed structure as a case study

23

Theo Glashier
Imperial College London, UK

Project objectives and goals

The built environment provides the critical infrastructure that underpins modern society; however, a significant proportion was built in the after-war period (1950s-1970s) and is now approaching the end of its service life (Van Breugel, 2017). As essential infrastructure ages, timely intervention can extend the useful service life, and significantly reduce whole life costs and societal disruption, with observed benefit-to-cost ratios of up to 6 (Hallegatte, S. et al., 2021). Furthermore, advancements in manufacturing technologies such as additive manufacturing (AM, i.e. 3D printing) are leading to a new generation of structures, characterised by anisotropic properties and high residual stresses (Buchanan and Gardner, 2019), that have less certainty in their long-term behaviour. Traditional visual inspection techniques are unsuited in informing timely maintenance interventions, while more advanced structural health monitoring (SHM) has struggled to transition from controlled experiments to real-world applications. The presence of environmental and operational variability (EOV), such as thermal effects, can significantly affect the structural response measured by a SHM network and mask the initial signs of damage in the built environment (Cross et al., 2013; Figueiredo and Brownjohn, 2022).

A new iterative regression based thermal response prediction (IRBTRP) methodology has been developed to predict the temperature-driven response of critical infrastructure. The aim of this project is to improve SHM damage detection through accurate thermal response predictions, using the MX3D Bridge (the world's first metal AM structure, see Fig 1) as a demonstration case study. The structure is a 12.5 m long, 2-4 m wide bridge, that was built using wire and arc AM (WAAM), and opened in Amsterdam in July 2021. A secondary aim is to gain new understanding on the long-term behaviour of metal AM structures.

Description of method and results

The MX3D Bridge is instrumented with a comprehensive sensor network, including 40 strain gauges, four load cells and 16 thermistors. A dataset collected during its two-month commissioning phase is employed to evaluate the novel IRBTRP methodology, which is split into reference and monitoring periods. The structure's baseline 'healthy' condition is determined in the reference period and is used to generate the thermal response models. During the subsequent monitoring period, the structure's condition is assumed to be unknown, therefore any deviation between the measured response and predicted baseline thermal behaviour is indicative of structural change.

The first step within the IRBTRP methodology is data preparation, which extracts the structure's thermal response from the recorded 'healthy' reference dataset. A developed traffic load removal algorithm removes pedestrian loading responses from the dataset based on load cell measurements. The next steps involve optimising parameters relating to signal pre-processing, regression algorithms (multiple-linear, robust and support vector regression, artificial neural networks) and post-processing, and generating appropriate thermal response models for each sensor.

The thermal response predictions are then determined for all sensors, and subtracted from the measured response to obtain the prediction error signals over the 'healthy' reference period. As the traffic loading has been removed from the response, these prediction error signals should tend to zero. Table 1 shows the root mean squared error (RMSE) expressed as a percentage of the reference period range for eight strain gauges over an unseen period, with an average error of 4.8%. The measured and predicted responses for two strain gauges (locations shown in Fig 1) during this unseen period are presented in Fig 2. This demonstrates the ability of the IRBTRP methodology to accurately simulate the MX3D Bridge's thermal response over the reference period. The temperature-corrected signals can then be used with anomaly detection techniques in the monitoring period, with the application of these to the MX3D Bridge and conventionally formed structures on-going. Due to the masking effect of EOV, damage detection is greatly enhanced when using temperature-corrected rather than response-only signals.

Strain gauge	RMSE (%)
B-SG04	4.1
B-SG05	7.2
B-SG12	3.1
B-SG13	3.4
B-SG26	3.5
B-SG27	2.1
B-SG38	11.9
B-SG39	3.2
Average (of presented strain gauges)	4.8

Table 1 Example RMSE for thermal response predictions of the MX3D Bridge strain gauges

Fig 1 The MX3D Bridge in Amsterdam

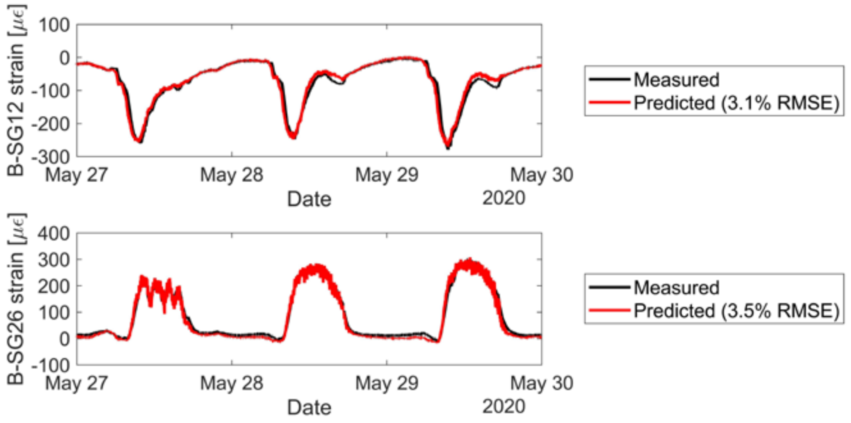

Fig 2 The measured and predicted thermal responses of two MX3D Bridge strain gauges

Potential for application of results

Traditional methods of infrastructure maintenance consist of visual inspections which often rely on the subjective assessment of visual defects (Helmerich et al., 2008), while applications of SHM have struggled in their application to operational infrastructure. The accurate thermal response predictions from the IRBTRP methodology can be combined with established anomaly detection techniques to enable faster damage identification than using response-only signals. This will facilitate more timely maintenance, reducing infrastructure downtime and whole life costs, whilst increasing societal safety and resilience. Accurate prediction of the thermal response for novel AM structures, such as the MX3D Bridge, enables greater understanding of their long-term behaviour and facilitates more widespread adoption within the built environment.

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Funding body

Skempton Scholarship, Department of Civil and Environmental Engineering, Imperial College London

Further information

Theo Glashier (t.glashier21@imperial.ac.uk)
Dr Craig Buchanan, Department of Civil and Environmental Engineering, Imperial College London; www.imperial.ac.uk/people/craig.buchanan; www.imperial.ac.uk/robotic-additive-manufacturing-lab

Collaborations

Dr Rolands Kromanis, Department of Civil Engineering, University of Twente; https://research.utwente.nl/en/persons/rolands-kromanis

Formulation of 3D beam element for two layered composite structures

24 **Yassir Wardi**
INSA de Rennes, France

Project objectives and goals

The project objective is the development of a new beam theory to study two layered composite structures in case of a general loadings, including warping effects. The theory will address beams working in large displacements and rotations. Using the co-rotational method, more sophisticated finite elements can be achieved, that can deal with a larger scope of structural phenomena. For instance, buckling analysis is one of key studies, where the co-rotational method proves to be useful, through the definition of a local reference that can track the element movement in space.

The research will progress through the following stages:
- Building a linear beam element, taking into account the deformability of the connection at the interface between the two layers
- Including geometrical non-linearities, by incorporating the co-rotational method with the developed linear beam model
- Formulating a materially non-linear beam element for timber-concrete composite structures
- Enhancing the timber-concrete element by the use of the co-rotational method to broaden the use spectrum of the beam element
- Investigating time effects using the developed beam element formulation

Description of method and results

The research development is, currently, limited to the first two objectives.

The formulation of the beam element can be summarized in two steps. The first step, involves the development of the local beam element, through the use of the virtual work theorem to determine the local stiffness matrix of the element. In fact, through the use of Hermitian shape functions, the stiffness matrix of the composite element can be expressed. Another alternative, was the use of the exact stiffness method, by solving the equilibrium equations of the element.

The development of the element local response, is based on the following assumptions:

- Euler-Bernoulli beam model is adopted for both layers
- The vertical separation between the two beams is not considered (no uplift)
- The local deformation and rotations are considered to be small
- The two layers are connected by a linear connector defined in the longitudinal direction of the beam
- The theory of Vlasov, will be implemented to define the warping effects

The second step, is mainly about the integration of the co-rotational method to the developed local linear response. The idea is to make use of the developed linear local theory to study geometrically non-linear problems.

Potential use of results

The developed theory can be integrated in all commercial structural software as a new composite beam element, that will enable engineers to design composite structures taking into account the effect of the connection rigidity at the interface.

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Funding body

Doctoral contract through INSA Rennes

Further information

Applicant: :Yassir Wardi (yassir.wardi@insa-rennes.fr)
Supervisor 1: Pr. Mohammed Hjiaj
(mohammed.hjiaj@insa-rennes.fr)
Supervisor 2: Pr. Pisey Keo (pisey.keo@insa-rennes.fr)

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Contact problems of two-layer beam taking into account slip and uplift

25 **Thaileng Oeng**
Institut National des Sciences Appliquées Rennes, France

Project objectives and goals

Nowadays, mixed steel-concrete structures are widely used in the field of civil engineering, especially in the public works sector with the most design of mixed large span bridges, or in the building sector with the fairly common use of floors with mixed slabs. However, steel-concrete structure seems to exist some inconveniences because of its interface. In the first main step of our research, we start to deal the contact problem with taking into account of slip and uplift phenomena at the interface, which effects to the deform-ability of composite structure while it is applied with many loading conditions. Both layers are assumed to be continuously connected at the element ends by two-directional springs: one direction is for considering longitudinal slip and the other one is for uplift. To avoid penetration between the layers, contact resolution methods such as penalty and augmented Lagrangian method.

Description of method and results

The steel-concrete composite beam in this present study is decomposed as the steel beam, a part of concrete slab, steel distributed connectors and reinforcement steel in optional case, see in Fig 1 which is represented as the continuous bond model.

In some load cases, both layers can be penetrated which are not allowed for the construction materials. Facing with the penetration problem, the penalty method, an extensive discussion of this method can be found in Kikuchi & Song (1981), and the augmented Lagrangian method are applied to ensure the non-penetrated issue between layers, Guezouli & Alhasawi (2014).

- Treatment of non-penetrated condition

Total Potential Energy with constraints in Augmented Lagrangian Method:

$$\tilde{\Pi}_{(u)} = \Pi_{(u)} + \lambda^T g_{(u)} + \frac{p}{2} g^T_{(u)} g_{(u)} \qquad (1)$$

where: λ: Lagrange multiplier
$\mathbf{g}_{(u)}$: gap vector
p: penalty parameter

Minimization of potential energy:

$$\frac{\partial \tilde{\Pi}_{(u)}}{\partial u} = 0 \qquad (2)$$

and obtain the residual function:

$$R_{(u)} = \Omega_{(u)} + \frac{\partial g_{(u)}}{\partial u}\lambda + p\frac{\partial g_{(u)}}{\partial u} g_{(u)} = 0 \qquad (3)$$

Compute the tangent operator:

$$\tilde{K} = K + \lambda^T \frac{\partial^2 g_{(u)}}{\partial u^2} + p\left(\frac{\partial^2 g_{(u)}}{\partial u^2} g_{(u)} + \frac{\partial g_{(u)}}{\partial u}\frac{\partial g^T_{(u)}}{\partial u}\right) \qquad (4)$$

The analogue computation is made for the penalty method with the distinct potential energy as:

$$\tilde{\Pi}_{(u)} = \Pi_{(u)} + \frac{p}{2} g^T_{(u)} g_{(u)} \qquad (5)$$

For this problem, the cantilever beam with 5 m length is composed of unconnected two identical layers, see Fig 2. It is noticeable as the best numerical example to investigate the performance of treatment non-penetrated problem.

The elastic modulus of both layers is 3500 kN/cm2. The height and the width of both layers are 5cm and 10cm, respectively. The load is applied incrementally, within 20 steps using displacement control method, at the tip of the lower layer so that the latter is deformed into a quarter circle. During deformation of the lower layer, the upper layer remains in contact and deforms with the lower layer. The analysis is performed with the present model using 10 elements. To treat the contact of the two layers, the resolution methods discussed earlier in this paper, i.e., penalty method (PM) and augmented Lagrangian method (ALM), are adopted and compared. The penalty parameter is taken equal to 108 kN/cm in both methods. Besides, the convergence tolerance of 0.0001 mm for nonpenetration condition is considered. Table 1 shows the number of iterations required for convergence for each load step. It can be seen that the number of iterations in ALM is larger than the one in PM at the beginning of load step. However, they are both equal after the third load step. It is worth mentioning here that increasing the penalty parameter in both PM and ALM does not improve the convergence rate. Instead, numerical problem occurs when the penalty parameter is larger than 108 kN/cm. The slip at the tip of the composite beam when the lower layer is bent into a quarter circle, obtained with PM and ALM, is 77.0690 mm and 77.0692 mm, respectively. It is worth mentioning that for vertically unseparated two-layer beam, the analytical solution of slip at the tip of the beam is 79.1665 mm, i.e., 2.65% of difference with the proposed model. This difference can be explained by the small uplift observed near the tip of the lower layer in the present model.

Load step	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
PM	12	5	5	5	5	5	5	5	5	5
ALM	14	14	5	5	5	5	5	5	5	5
Load step	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
PM	5	5	5	5	5	5	5	5	5	5
ALM	5	5	5	5	5	5	5	5	5	5

Table 1 Result: Number of iterations for each load step

Note: **PM** is penalty method, **ALM** is augmented Lagrangian method

To enforce the non-penetration between the layers, the methods generally used to solve the node-to-node contact problem, for instance the penalty method (PM) and augmented Lagrangian method (ALM), are used. Both resolution methods have been compared in the numerical applications presented in the paper. The comparison shows that more iterations are required in ALM. However, despite a low convergence rate of ALM compared to PM, the non-penetration condition is strictly respected in ALM. Hence, the unrealistic penetration between the layers can be prevented by using ALM algorithm.

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Funding body

French Government Scholarship (BGF)

Further information

Thaileng OENG (Thaileng.Oeng@insa-rennes.fr)

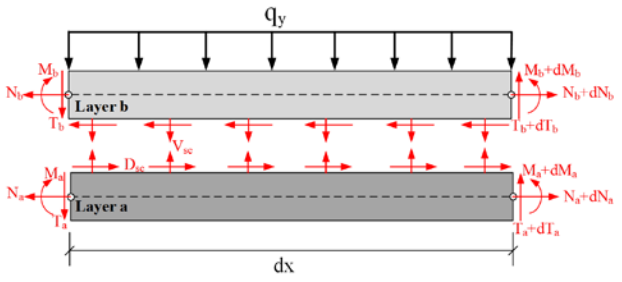

Fig 1 Representation of internal forces and shear connector forces in continuous bond

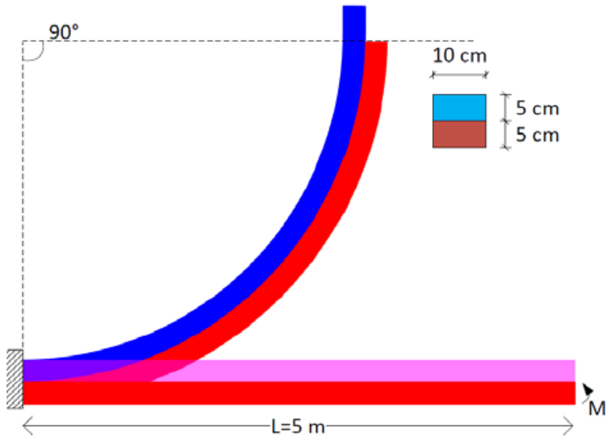

Fig 2 Numerical Example: Uniform bending of a cantilever beam

Collaborators

Laboratoire de Génie Civil et Génie Mécanique (LGCGM EA 3913), Department of Cvil Engineering and Urban, INSA Rennes.

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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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