Proceedings of the

26th Young Researchers Conference

2 May 2024

The Institution of StructuralEngineers

Contents

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 – 2 May 2024

Time	Agenda	Persons
13:00	**Welcome**	Chair: Dr Pete Winslow, Chair of the Research Panel.
13:05	Keynote Speaker: R&D within Infrastructure	Tina Vejrum, Senior Technical Director, COWI
13:35	Presentation 1 + Q&A	Kemmar Webber – Innovative optimization method for internally voided concrete building elements. (Bauhaus University Weimar)
13:50	Presentation 2 + Q&A	Shane Hossell – Timber vault floors for low-embodied carbon buildings (University of Bath)
14:05	Presentation 3 + Q&A	Milindu Jayasekara – Disproportionate collapse resistance of timber beam-column connections (University of Cambridge)
14:20	**Break**	
14:30	Presentation 4 + Q&A	Nada Elkady – Unveiling the potential of scaling in progressive collapse studies (Salford University)
14:45	Presentation 5 + Q&A	Mohameed El Ashri – 3D Modelling of Masonry Arch Bridges (Imperial College London)
15:00	Presentation 6 + Q&A	Bowen Liu – Three-dimensional response of a full-scale masonry arch bridge under static and cyclic loads (University of Leeds)
15:15	**Poll to audience**	Chair: Dr Pete Winslow
15:20	Guest speaker: Working with Low Carbon Brick Alternatives for repairs to Imperial Sized Bricks in Historic Buildings	Katie Hood, Senior Project Engineer, Narro Associates
15:30	Pecha-Kucha	Andy Cross, Network Rail Efe Aydog, ARUP
15:45	Certificate, prize giving	Head Judge: Steve Matthews
16:00	Closing comments	Chair: Dr Pete Winslow
16:15	**Conference ends**	

To note: the programme is subject to change.

Poster presentations

Near-surface mounted FRP flexural retrofitting of concrete members using nanomaterial-modified epoxy adhesives *(Synopsis 2)*
Mohammad Al-Zu'bi – Brunel University, UK

Optimising the C-S-H formation in Calcium hydroxide and Glass powder hardened paste: Theoretical and Experimental approaches *(Synopsis 4)*
Gaurav Chand – University of Manchester, UK

Mechanical properties and composite structural behaviour of rubberised alkali-activated concrete *(Synopsis 5)*
Mohamed Elzeadani – Imperial College London, UK

ArchIMEDES: The Development of computer vision based structural health monitoring methods for predicting scour at bridges *(Synopsis 6)*
Ben Millar – The Queen's University Belfast, UK

Exploring optimal geometries for reinforced concrete piles *(Synopsis 10)*
Kareem Abushama – University of Bath, UK

Shielding History: Protection of Historical Buildings against Explosions *(Synopsis 14)*
Ashraf Nayel – Imperial College London, UK

The hypothesis of massless structure in computing the waterborne debris impact forces on structures is not accurate when the structure-to-debris mass ratio is higher than a critical value *(Synopsis 15)*
Alessandro de Iasio – University of Nottingham, UK

Designing auxetic structures through topology optimization *(Synopsis 18)*
Shubham Saurabh – Indian Institute of Technology Roorkee, India

Physics-informed neural networks for structural health monitoring applications *(Synopsis 20)*
Anmar Al-Adly – University of Exeter, UK

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Keynote Speaker

Tina Vejrum

Senior Technical Director, COWI

Tina is Senior Technical Director in COWI and has been working on international infrastructure projects for 30 years. After completing her PhD, she started her career as a structural engineer on the Great Belt Fixed Link in Denmark. A highlight in Tina's career as a bridge engineer is the record span Stonecutters Bridge in Hong Kong – a project she worked on for 10 years from the design competition through detailed design and concluding with three years on site during construction. Today she is responsible for technical development in COWI's international team of structural designers working on some of the largest and most complex infrastructure projects in the world. In parallel, Tina is Affiliated Professor at the Technical University of Denmark, a Board member of the COWI Foundation and active in a number of professional associations, notably the International Association for Bridge and Structural Engineering (IABSE), where she is currently serving as the President.

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.

Dr Pete Winslow
Research Panel Chair

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Conference Team

Presentation Selection Panel:

Dr Rabee Shamass – *Brunel University*
Gary Robinson – *Ridge & Partners LLP*
Livia Garcia – *Rail Safety and Standards Board*
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*
Jaylina Rana – *Buro Happold*
Dr Donya Hajializadeh – *University of Surrey*
Prof. John Forth – *University of Leeds*
Fernando Madrazo-Aguirre – *COWI*
Dr Stana Zivanovic – *University of Warwick*
Dr Muhammad Basheer – *Heriot-Watt University*

IStructE Support:

Jane Black – *Head of Technical Secretariat Services*
Rebecca Cohen – *Secretariat Executive*
Zhixi Gu – *Training and Events Coordinator*
Brigette Long – *Marketing and Communications Executive*

Research into Practice Case Study Competition 2023 winner

Katie Hood

Senior Project Engineer, NARRO Associates

Katie Hood is a Senior Project Engineer at NARRO Associates, Structural Engineers in Edinburgh. She specialises in bespoke engineering solutions for conservation of historic structures, refurbishment, new build, and art installations. Katie started her career as a physics major working first in optics and then in materials science in the nuclear industry in the UK and France. She made her way into structural engineering though working on sustainable building projects in Europe where she learned to build with natural materials and then studying a conversion course to a masters in structural design at UCL. Since 2018 she has been working at Narro, building experience across a broad range of projects. In 2022 she won a Scholarship with the Society for the Protection of Ancient Buildings to spend a year specialising in historic building conservation. The intersection of Katie's experiences in materials engineering, historic building conservations and sustainability have led to several interesting collaborations with academia with the aim of understanding the behaviour of the existing built environment and building and repairing better for the future.

Research Panel members

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.

Dr 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 Pete has worked for smaller companies, which included delivery of high ropes courses, and of the UK's first purpose built climbing centre 'The Arc'. Pete joined Hydrock two years ago, leading a team predominantly in the Science and Tech sector. Pete is a reviewer for ICE proceedings journals, has been industry partner for research dissertations, as well as panel member on IStructE 'research' and 'futures' groups.

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.

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, FIStructE

Jason obtained his doctorate from the University of California San Diego in 1995 and is a Professor of Structural Engineering and Deputy Dean in the Faculty of 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.

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 Fellow 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.

Professor P.A. Muhammed Basheer, FREng

PhD, DSc, FIAE, FICE, FIStructE, FACI, FICT, FIAAM, CEng

Basheer, as he is known, is Chair in Civil Engineering and Executive Dean of the School of Energy, Geoscience, Infrastructure and Society at Heriot-Watt University, Edinburgh. Formerly he was chair in Structural Engineering and Head of School of Civil Engineering at University of Leeds, UK. 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 35 PhDs to successful completion and published nearly 440 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. HM King Charles III bestowed him with the Commander of the Order of the British Empire (CBE) in July 2023 for his services to civil engineering.

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), FTSE, FRSN, FIEAust, FICE, FIStructE, FASCE, FSEI, FIABSE

Brian Uy is Scientia Professor of Structural Engineering at the University of New South Wales and Honorary Professor of Structural 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 Vice President 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.

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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 Rwayda Al-Hamd
B.Sc., M.Sc., PhD, FHEA

Rwayda is a lecturer in civil engineering at Abertay University. Rwayda's research focuses on the resilience of structures. Her research goals are accelerating the building of climate-proof structures and developing sustainable construction materials that meet the current market need for net-zero construction. Her fundamental interest is how structures react to extreme loading conditions like fire and floods: her resilient and sustainable infrastructure research expertise bridges modelling, experimental work, machine learning, and data-driven analysis.

Professor Tai Thai
PhD, FIEAust, CPEng, MIStructE

Tai is an ARC Future Fellow (also former ARC DECRA Fellow) and Professor of Structural Engineering at the University of Melbourne. He is a member of Standards Australia Committees BD23 on structural steel and BD32 on composite structures (responsible for drafting Chapter 5-Design of Composite Joints of composite standard AS/NZS 2327). With a combined expertise in structural engineering and computational mechanics, his research mainly focuses on developing structural systems and computational tools for advanced design of buildings, bridges and other infrastructure with an emphasis of safety, sustainability and resilience.

Michaela Gkantou
MEng MSc PhD CEng MICE MIStructE FHEA

Michaela obtained her PhD from the University of Birmingham in 2017 and is now a Reader in Structural Engineering at Liverpool John Moores University. She is committed to teaching both at undergraduate and postgraduate level. Her research interests are primarily focused on the investigation of the performance and design of structural members through testing and finite element modelling. She has been involved in various UK and European research projects on materials and structures and has co-authored over 40 journal publications, examining the response of high strength steel, stainless steel, aluminium alloy and composite structures. She is a Chartered Member of the Institution of Civil Engineers (ICE) and of the Institution of Structural Engineers (IStructE), a member of the ICE Merseyside Branch Committee, a member of the Technical Chamber of Greece and a member of Women's Engineering Society. She is also a member of the British Standard Committee: CB/203 - Design & execution of steel structures and of B/525/9 - Structural use of aluminium.

Jaylina Rana
BEng(Hons) MRes EngD CEng FICE

Jaylina is an Associate Structural Engineer in the London Structures Team at Buro Happold Engineering Ltd. She has over 15 years of experience, with exposure in designing a variety of building and infrastructure projects, both the UK and abroad. Jaylina has previously led construction projects at Laing O'Rourke, Arup, and The Concrete Centre. She has a specialised engineering doctorate from the University College London on the 'Structural Behaviour of Twinwalls', which was used validate the design principles and optimise the manufacture, assembly, and implementation of twinwalls in the construction industry. Her main expertise is the development and innovation of precast concrete and DfMA (Design for Manufacture and Assembly) structural products. Jaylina is a chartered engineer and is a Fellow member of the Institution of Civil Engineers and a graduate member of the Institution of Structural Engineers. She is also a committee member of the fibUK, Design Practice, Risk and Structural Safety and the Research Panel committees at the Institution of Structural Engineers.

Dr Youyi WEI

BEng, PhD,CEng, MIStructE, MHKIE, BEAM Pro

Dr Youyi WEI is a Structural Engineer of the Development and Construction InnoTech Team at Housing Department, HKSAR. He received his PhD degree from the City University of Hong Kong in 2014 and has more than 10 years of working experience in the engineering industry and research institutions. He dedicated to the R&D and application of cutting-edge technologies and has extensive experience in construction innovation, structural design and project management. He has been responsible for various projects, including the application of drones and AI technology in construction projects, materials and design for product-based Modular Integrated Construction (MiC), smart corrosion monitoring systems for MiC structure, smart construction sites, projects Integrated management and analysis platforms, etc. He now plays a key role in driving innovation and technology development in public housing projects. He is a Chartered Engineer and Member of the Institution of Structural Engineers and Hong Kong Institution of Engineers, and a BEAM Professional of Hong Kong Green Building Council.

Dr Rabee Shamass

BSc MSc PhD FHEA

Dr Shamass is Senior Lecturer in Structural Engineering, College of Engineering, Design and Physical Sciences at Brunel University London. Before joining Brunel, he was a Lecturer and then Senior Lecturer in Structural Engineering at London South Bank University (LSBU). His research experience is in buckling shell structures, stainless steel structures, fibre-reinforced polymers, fatigue performance, reinforced concrete, numerical modelling, sustainable construction materials, composite structures, utilization of construction and industrial waste materials, seismic performance of structures, and the application of machine learning (ML) in structural/civil engineering. His research goal is to propose efficient design guidance and recommendations that can help the engineering community and support our mission to ensure sustainable, cost effective and safe use of construction materials. Currently, he is interested in low-carbon concretes and cementitious materials (e.g. Alkali-activated concretes; calcinated clay cements), carbon sequestration in concrete, and machine learning in interdisciplinary research way.

Livia Garcia

BE(Hons), BA, MA, CEng, MIStructE, MICE, MHKIE, CMEngNZ

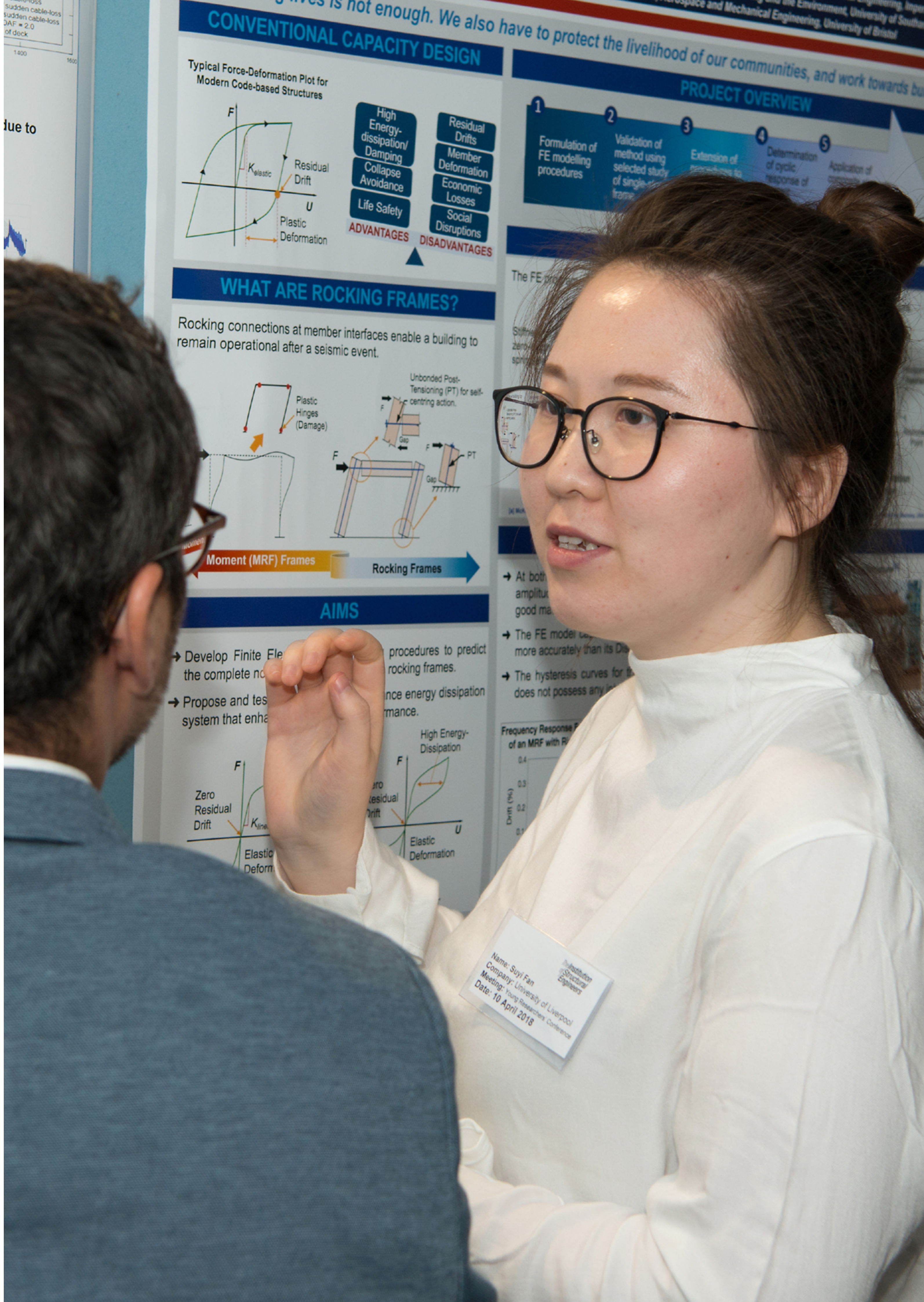
Livia is a Principal Civil Engineer currently with Rail Safety and Standards Board (RSSB), UK. She graduated in Engineering from the University of Auckland and has worked in New Zealand, Hong Kong and United Kingdom. Her previous experience includes designing highways viaducts, working as a resident engineer for infrastructure projects, as well as carrying out project engineer assurance roles in the railways. Companies that she has worked for include Beca Carter Hollings and Ferner (New Zealand), Maunsell Consultants (Asia) Ltd (Hong Kong), Network Rail (UK) and so on. Her current role with RSSB is to draft standards and guidance notes for the Great Britain railway industry, mainly on bridge structures related topics such as evaluating excessive dynamic effects in underline bridges . Livia is also involved in research projects managed by the International Union of Railways (UIC), for example derailment mitigation measures and bridge fatigue. In addition, she is currently actively participating in the revision process of the National Annexes for some of the second generation Eurocodes which are relevant to GB railways.

Dr Gary Robinson

MA(Cantab), MEng, EngD, CEng, MICE, MIStructE

A doubly chartered engineer, with both the Institute of Civil and the Institute of Structural Engineers. Gary has worked as part of design teams on buildings both in the UK and internationally, gaining significant experience in both structural design and industry-applied research. Gary gained an engineering doctorate due to his work in assessing the structural performance of precast building typologies, publishing numerous papers in leading engineering journals and conferences. Gary has over 18 years of experience in the design and assessment of structures in steel, timber, concrete, and masonry for commercial, industrial, educational, leisure, and residential buildings with a background in the design and delivery of high-rise concrete frames.

Since joining the EWAS team in January 2023, Gary has been involved in several UK and international disputes. These have included UK litigation proceedings involving numerous reinforced concrete frames, a large international arbitration focusing on the refurbishment of a landmark 1970's RC framed building in Qatar and a series of adjudications on a high profile, multi-million pound, steel-framed, mixed-use, UK development.



Three-dimensional response of a full-scale masonry arch bridge under static and cyclic loads

01 **Bowen Liu**
University of Leeds

Project objectives and goals

Masonry arch bridges form a significant part of the infrastructure stock in the UK. With the gradual degradation of material properties due to environmental effects, natural disasters, and climate change, as well as the increasing demands in the modern traffic system, understanding the damage accumulation and failure mechanisms of masonry arch bridges under loading is of critical importance.

Previous studies have extensively investigated the failure mechanism of masonry arch bridges under plane-strain conditions (Melbourne and Gilbert, 1995; Sarhosis et al., 2016; 2019). However, the behaviour of full-scale masonry arch bridges exhibits strict three-dimensional (3D) characteristics, particularly when subjected to eccentric patch loading. Despite this, failure modes of the masonry arch bridge considering 3D effects and interactions between different elements have not been fully studied. Additionally, the lack of the experimental data presents significant challenges for researchers and engineers in validating their numerical models. Therefore, the overall aim of the project is to gain an improved understanding of the 3D behaviour of masonry arch bridges under various loading scenarios (i.e., static, quasi-static, and fatigue loads), primarily utilizing laboratory experiments. The specific objectives include:

- Characterise the material properties and mechanical parameters of masonry arch bridge, as well as the interaction between masonry and backfill materials.
- Investigate the 3D response, damage accumulation, crack propagation, and failure mechanisms of full-scale masonry arch bridges under different loading scenarios.
- Develop and validate a high-fidelity numerical model to represent the mechanical response of low-bond strength masonry arch bridges.

Description of method and results

Type A engineering bricks, type O mortar (cement:lime:sand=1:2:9), and MOT type I graded limestone were adopted to construct a full-scale masonry arch bridge in the George Earle Laboratory at the University of Leeds. Materials properties, tensile and shear strength at unit-mortar interfaces were determined through small-scale laboratory tests (Liu et al., 2023a). Also, frictional parameters between masonry and backfill materials were characterised through large-scale shear box tests (Liu et al., 2023b).

A full-scale masonry arch bridge was constructed and tested under laboratory conditions. Fig 1 shows the test rig set up. Specifically, reinforced concrete end walls were constructed to accommodate the bridge, and a steel reaction frame was fabricated to provide the reaction force for the load application. The bridge consisted of abutments, spandrel walls, backfill, and an arch barrel. The arch barrel

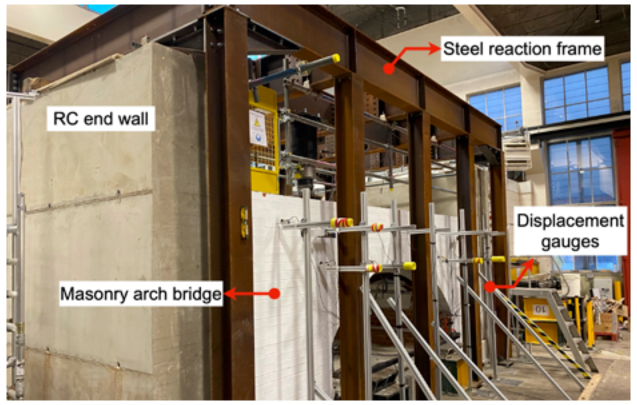


Fig 1 Test rig setup

No. of test	Loading type	Loading location	Loading level
T1 to T9	Static & cyclic	Nine locations	Low-level (150 kN)
T10 to T18	Static & cyclic	Nine locations	Mid-level (250 kN)
T19	Static	Quarter span	High-level (560 kN)
T20	Static	Quarter span	Failure-level
T21	Static	Three-quarters	Failure-level

Table 1: Loading protocol

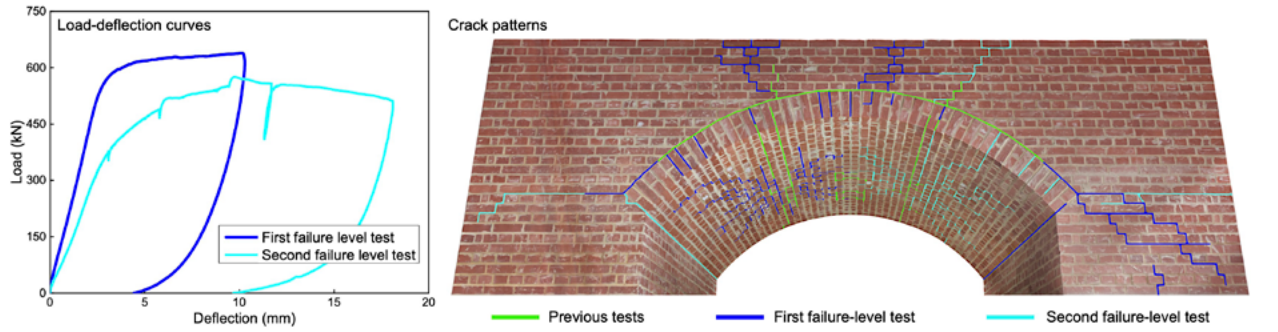


Fig 2 Load-deflection curves and crack patterns obtained from T20 & T21

was constructed as a single-ring arch with a header bond pattern. It had a span of 3,000 mm and a span-to-rise ratio of 4:1. An English bond pattern was adopted for spandrel walls to enhance their resistance against the lateral soil pressure.

Nine loading locations were selected, including those over quarter-span, arch crown, and three-quarters, along the longitudinal central line and two off-centre lines near spandrel walls. Four loading magnitudes were sequentially applied to induce the increasing levels of damage. Table 1 summarises the loading protocol. Regarding the instrumentation, a DIC system, four accelerometers, and over 50 displacement gauges were used to comprehensively capture the 3D response of the bridge. Moreover, ground penetrating radar (GPR) profiles were acquired to image and compare the internal structure of the virgin and failed bridge.

Both 3D effects and global damage of the masonry arch bridge were induced. The arch behaved as a four-hinge mechanism. Fig 2 shows the load-deflection curves and crack patterns obtained from T20 and T21, respectively. The load-carrying capacity of the bridge was identified to be equal to 639 kN. When loading at the three-quarters span on the failed bridge, only a 10% reduction in the bridge's residual strength was observed. However, the stiffness of the bridge decreased by around 35%. Extensive cracks were initiated and propagated on the spandrel walls. Moreover, the maximum out-of-plane deflection of spandrel walls was detected to be equal to 5.27 mm during T21.

Potential for application of results

The observed localized damage and crack patterns indicated 3D effects and substantial interactions between components of the bridge. These findings offer valuable insights into the damage accumulation and failure mechanisms of real masonry arch bridges. Moreover, the comprehensive dataset obtained from material characterisation and well-instrumented bridge can be adopted to develop and validate simple/high fidelity numerical models representing low bond strength masonry arch bridges. With the validated model, the behaviour of bridges can be predicted more accurately. This holds great significance in the evaluation of serviceability and permissible limit states of masonry arch bridges, the formulation of repair strategies, and the early detection of collapse risks.

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Near-Surface Mounted-Fibre Reinforced Polymers flexural retrofitting of concrete members using nanomaterial-modified epoxy adhesives

02 **Mohammad Al-Zu'bi**
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Project objectives and goals

The research study mainly aims at interjecting the nanotechnology to create a novel Near-Surface Mounted-Fibre Reinforced Polymers (NSM-FRP) technique for flexural retrofitting of concrete members, through adopting the nanomaterial-modified epoxy adhesives (NMEAs) for enhanced structural performance and mechanical behaviour. The primary aims of this study will be realised by accomplishing the following objectives:

- Developing a novel NSM-FRP retrofitting through, mainly, using NMEAs, taking other parameters (i.e. material properties and retrofitting design) into consideration.
- Integrating the characterisation of the NMEAs with the results of structural testing to provide a comprehensive and efficient assessment.
- Establishing a correlation between retrofitting parameters and structural performance for the optimum retrofitting applications.
- Disseminating the study findings, providing engineers and research community with a solid basis for future research.

In the context of Externally-Bonded Reinforcement (EBR)-FRP retrofitting applications, Rousakis et al. (2014) explored multi-walled carbon nanotubes (MWCNTs) to repair and strengthen epoxy resin systems for FRP-confined concrete cylinders. Their findings affirmed MWCNTs-reinforced epoxy resins' potential for advanced crack repair in high-performance concrete. A parallel study by Irshidat et al. (2015) focused on enhancing RC columns with CNTs-modified epoxy, revealing a 12% increase in axial load-carrying capacity and a 19% boost in toughness for specimens using CNTs-modified epoxy compared to those bonded with neat epoxy (NE). Notably, both CNT's and NE specimens exhibited a ductile failure mode.

Irshidat et al. (2016) continued their research, investigating the flexural capacities of RC beams strengthened by carbon FRP (CFRP) sheets using both neat epoxy (NE) and epoxy modified with CNTs. The results indicated a 5% increase in the ultimate loads of beams and significant improvements in stiffness (35%) and toughness (28%) when using CNTs-modified epoxy. The study also highlighted the modified adhesive's ability to delay the propagation and debonding of CFRP sheets, attributed to enhanced concrete-epoxy adhesion.

In another investigation by Irshidat and Al-Saleh (2016), the influence of CNTs-modified epoxy on bond-slip behaviour between concrete surfaces and carbon and glass FRP sheets in concrete prisms was explored. The outcomes demonstrated a notable enhancement in bond strength (35% and 52% for carbon fibre, 26% and 83% for glass fibre) and slip at failure for specimens using CNTs-modified epoxy. Interestingly, NE-bonded specimens failed due to debonding at the interface between the fibre sheet and concrete surface, while specimens bonded with CNTs-modified epoxy experienced cohesive failures.

Reflecting on these studies, it is evident that the application of NMEAs in structural retrofitting has received limited attention. Previous research has predominantly focused on EBR-FRP strengthening/retrofitting applications, emphasizing CNTs as adhesive nano-fillers. This underscores the need for a comprehensive exploration of NMEAs in NSM-FRP applications to unlock their full potential in high-performance retrofitting and bonding systems, providing valuable insights into bonding agents and FRP reinforcements.

Description of method and results

The NMEAs were synthesised by incorporating 0.1 wt.% of carbon nanofibres (CNF), silica nano powder, cellulose nanocrystals, nano clay or graphite nano powder into epoxy adhesive. The synthesis of the NMEAs is shown in Fig 1.

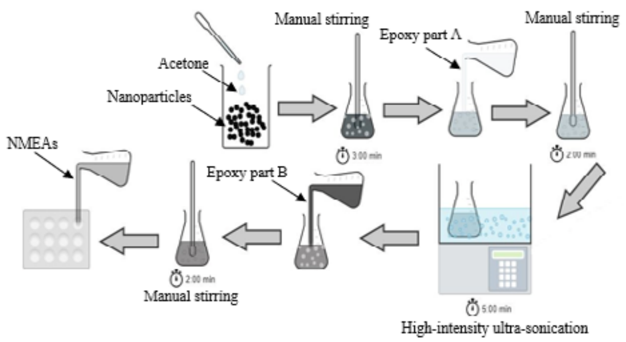

Fig 1 Synthesis of the NMEAs

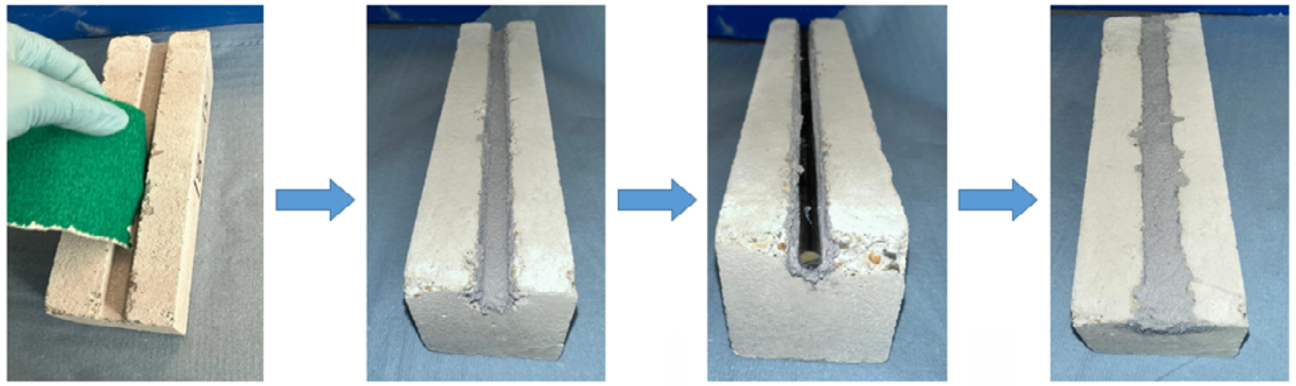

Fig 2 Retrofitting procedure

The NSM-FRP retrofitting process was then implemented on the concrete specimens starting with the roughening of the groove sides using sandpaper. The grooves were subsequently cleaned using an air compressor to eliminate any generated dust. Following this, the grooves were partially filled with either NE or NMEAs. Afterwards, the FRP bars were positioned within the grooves and gently pressed, enabling the paste to flow around the strip and to fully fill the space between the bars and the groove sides. Finally, the grooves were filled with additional adhesive, and the surface was levelled. The retrofitting procedure is also shown in Fig 2. The retrofitted specimens were then air-cured at room temperature for 7 days to guarantee a proper curing of the adhesive and to ensure sufficient bond between concrete, adhesive and FRP reinforcement.

The retrofitted concrete specimens were then tested under three-point bending test. The ultimate loads, flexural strength and displacements at maximum loads (described as maximum displacements) were then recorded using a data acquisition system, and the modes of failure were also monitored.

Results showed that using silica, clay and graphite NMEAs rather than NE increased the load capacity by about 17%, 5% and 15% respectively, but about 37% and 9% capacity decreases were observed with using CNF- and cellulose-modified epoxies. For the ductility response, it was observed that about 49% and 36% ductility increase was obtained with using CNF and cellulose NMEAs, respectively over NE, but about 12% reduction was noticed in the graphite specimens. Silica and clay NMEAs could enhance the ductility by about 19% and 24%, respectively.

The failure modes of tested specimens showed that unlike what occurred in the NE-bonded specimens, utilising carbon-based NMEAs was able to prevent the interfacial debonding, which could not be completely avoided in the specimens retrofitted using silicon-based NMEAs.

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Equivalent sway imperfections and sway-member imperfection combinations for GMNIA-based steel design

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Project objectives and goals

In general, two types of geometric imperfection need to be considered in the design of structural systems: global frame out-of-plumbness and member out-of-straightness. Residual stresses can also cause premature yielding and loss of stiffness, and should therefore be accounted for in structural design. For modelling convenience, the combined effects of geometric imperfections and residual stresses are often accounted for by the application of increased geometric imperfections, commonly referred to as equivalent geometric imperfections. For design by geometrically nonlinear analysis with imperfections (GNIA), the recommended amplitudes of equivalent bow and sway imperfections are provided in EN 1993-1-1. For design by geometrically and materially nonlinear analysis with imperfections (GMNIA), amplitudes for equivalent bow imperfections are included in EN 1993-1-14; however, no provisions exist for global sway imperfections in GMNIA-based design. Furthermore, there is a lack of guidelines for the appropriate combination of frame and member imperfections. With the more widespread availability of digital tools as well as the introduction of the new EN 1993- 1-14, it is expected that GMNIA-based structural design will become more common. Therefore, there is a growing need for the development of a comprehensive set of rules regarding the application of imperfections; this is addressed in the presented research, with equivalent geometric sway imperfections for use in design by GMNIA, as well as imperfection combination rules, derived, as detailed in full in Chan et al. (2023).

Description of method and results

The basic value of the equivalent geometric sway imperfection for use in GMNIA $\phi_{0,\mathrm{GMNIA}}$ can be expressed by:

$$\phi_{0,\mathrm{GMNIA}} = \phi_{0,\mathrm{geom}} + \phi_{0,\mathrm{rs}} \tag{1}$$

where $\phi_{0,\mathrm{geom}}$ is the pure geometric sway imperfection and $\phi_{0,\mathrm{rs}}$ is the additional sway imperfection to account for the effects of residual stresses. A procedure similar to that adopted by Lindner and Gietzelt (1984) was employed to determine the required amplitude of $\phi_{0,\mathrm{rs}}$. To investigate a range of scenarios, a series of I-section profiles, column slenderness values, column normal forces and column base support conditions were considered. Both column orientations (i.e. major and minor axis buckling) as well as three grades of hot-rolled carbon steel and three grades of stainless steel were studied. The finite element (FE) models employed in the present study were developed using the general purpose FE software Abaqus. The equivalent sway imperfections were calibrated based on the residual stress patterns in ECCS (1984) for hot-rolled steel I-sections and in Yuan et al. (2014) for stainless steel I-sections.

A clear dependency of $\phi_{0,\mathrm{rs}}$ values on the axis of buckling was observed. Additionally, for hot-rolled steel, the $\phi_{0,\mathrm{rs}}$ values were found to be dependent on the cross-section depth-to-width ratio. To capture this, it is proposed that $\phi_{0,\mathrm{GMNIA}}$ be a function of the imperfection factor α. Two proposals are made herein, as given by Eqns 2 and 3. Proposal 1 ($\phi_{0,\mathrm{GMNIA,1}}$) retains the form of Eqn 1 and only associates the additional sway component $\phi_{0,\mathrm{rs}}$ with α, while Proposal 2 ($\phi_{0,\mathrm{GMNIA,2}}$) mirrors the provisions for equivalent bow imperfections for use in GMNIA by directly relating the total equivalent sway imperfection to α.

$$\phi_{0,\mathrm{GMNIA,1}} = \phi_{0,\mathrm{geom}} + \alpha/100 \tag{2}$$

$$\phi_{0,\mathrm{GMNIA,2}} = \alpha/50 \tag{3}$$

An imperfection combination strategy for selecting the appropriate imperfections at the system and member levels for use in design by GMNIA is also developed. Five frame behavioural groups are defined based on the sway ($\alpha_{\mathrm{cr,sw}}$) and non-sway ($\alpha_{\mathrm{cr,ns}}$) critical load factors. The design recommendations are summarised in a flow chart in Fig 1. In the cases when both member and frame imperfections need to be considered, the application of equivalent geometric imperfections at both member and system levels can lead to duplication of the effects of residual stresses. To avoid this, the critical load factor ratio $\alpha_{\mathrm{cr,ns}}/\alpha_{\mathrm{cr,sw}}$ is used to determine the dominant form of buckling, and the effects of residual stresses are allowed for by using equivalent geometric imperfections at the corresponding critical structural level (i.e. system or member) with only geometric imperfections being defined at the other.

An overview of the performances of the imperfection combinations according to the proposed framework r_{t} relative to benchmark predictions r_{e} for a total of 876 hot-rolled and stainless-steel frames is provided in Fig 2. Additionally, the results according to the current EC3 provisions are provided for comparison. It can be seen that the current EC3 sway imperfections cannot always accurately capture the effects of residual stresses and can lead to unsafe predictions, with benchmark to predicted

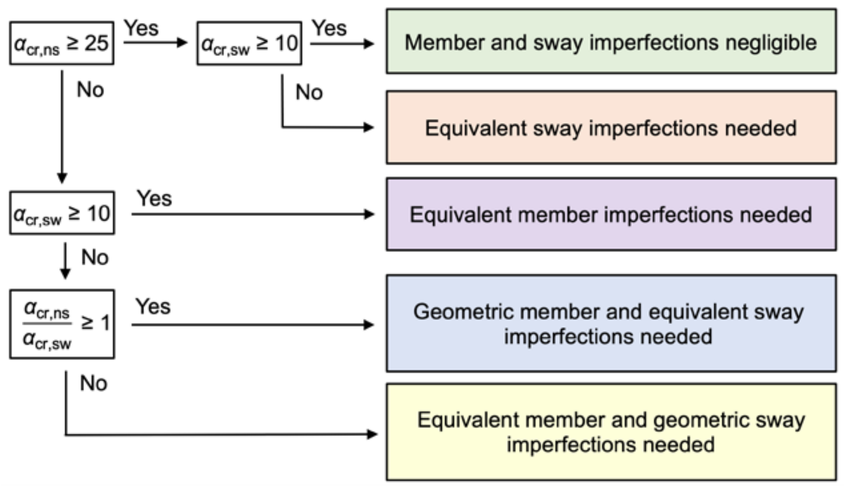

Fig 1 Flow chart providing an overview of the design recommendations for the application of member and frame imperfections in GMNIA-based design.

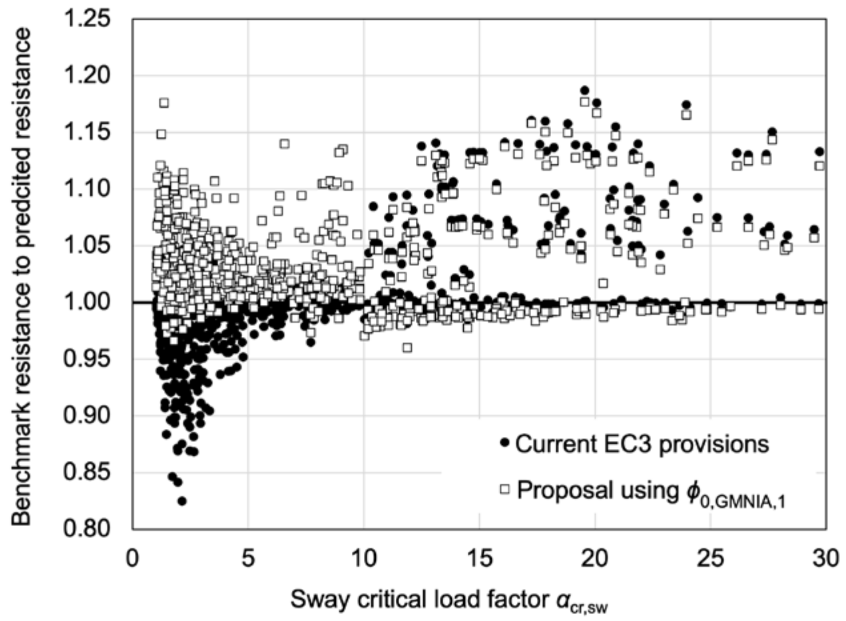

Fig 2 Comparison of benchmark r_{e} to predicted r_{t} resistances ratios obtained from imperfection combinations determined according to proposed framework and current EC3 provisions.

resistances ratios $r_{\mathrm{e}}/r_{\mathrm{t}}$ as low as 0.82 obtained. In contrast, the newly derived equivalent sway imperfections are able to provide safe-sided results.

Potential for application of results

The proposed framework can be incorporated into design by GMNIA and provides clear and rational guidelines on the treatment of geometric imperfections and residual stresses. The use of the newly derived equivalent sway imperfections in frames which are sensitive to sway buckling is important for structurally sound design of both hot-rolled and stainless-steel structures. The form of the proposals is closely in line with the current EC3 provisions and, therefore, can be easily incorporated into the upcoming code revisions without introducing significant alterations.

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Optimising the C-S-H formation in calcium hydroxide and glass powder hardened paste: Theoretical and experimental approaches

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Project objectives and goals

The use of waste glass powder as a supplementary cementitious material (SCMs) over the conventional SCMs such as fly ash, silica fume, ground granulated blast furnace slag (GGBS) exhibit more futuristic approach because the conventional SCMs generation is decreasing due to shifting of energy production towards renewal sources. Researchers have extensively used waste glass powder as a partial replacement to cement and investigated the pozzolanic property of silica present in glass powder with hydrated cement by-product namely calcium hydroxide (Portlandite) to form strength imparting compounds calcium-silicate-hydrate (C-S-H) (Jani and Hogland, 2014). Besides, such detailed studies on glass powder use in concrete, no research has explicitly reported on the chemical reaction between calcium hydroxide and glass powder because of which the replacement percentage of cement with glass powder is limited up to 20%. Therefore, there is a lack of understanding on the properties of C-S-H formed during reaction between calcium hydroxide and glass powder.

The present study investigates the formation of C-S-H during calcium hydroxide and glass powder reaction theoretically using mole concept theory and then applies the same theory to mix design the calcium hydroxide and glass powder ratio in the mix. Further, the study focuses on the Ca/Si ratio optimisation in C-S-H theoretically and experimentally to improve the strength contributing characteristics of C-S-H which could be used to improve the replacement percentage of cement with glass powder over the current wisdom of 20%. This research has the following objectives:

- Theoretical analysis of calcium hydroxide and glass powder chemical reaction using mole concept theory
- Theoretical optimisation of the Ca/Si ratio in C-S-H formed during calcium hydroxide and glass powder reaction
- Experimental investigation of calcium hydroxide and glass powder hardened paste based on its compressive strength
- Experimentally analysing the Ca/Si ratio in C-S-H formed during calcium hydroxide and glass powder reaction using X-Ray diffraction (XRD) analysis

Description of method and results

The SiO_2 present in glass powder reacts with $Ca(OH)_2$ to form C-S-H in the mix. The chemical reaction during this mechanism is shown in Eqn. 1 and the mole concept theory was used to calculate the total grams of the reactant and product of the reaction using their atomic molar mass of the element Ca = 40, O = 16, Si = 28, H = 1.

$$
\begin{array}{cccc}
3[Ca(OH)_2] & + \; 2SiO_2 & + \; H_2O & (CaO)_3\,(SiO_2)_2(H_2O)_4 \\
CH & S & & C-S-H \\
3\times(40+(16+1)\times2) & 2\times(28+16\times2) & & (40+16)\times3+(28+16\times2)\times2+(1\times2+16)\times4 \\
x & 0.54x & & 1.62x
\end{array}
\quad (1)
$$

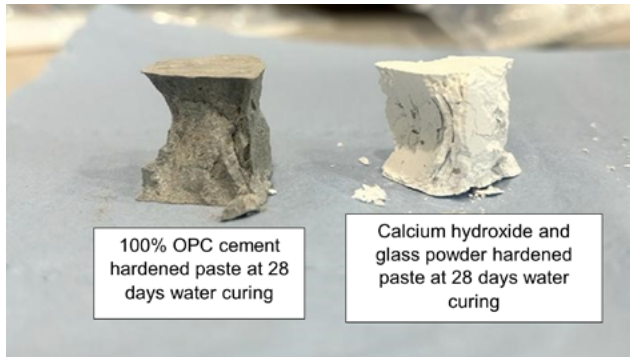

Fig 1 Failure pattern of 100% CEM-I cement hardened paste and calcium hydroxide and glass powder hardened (CH-GP) paste at 28 days after crushing in compression test.

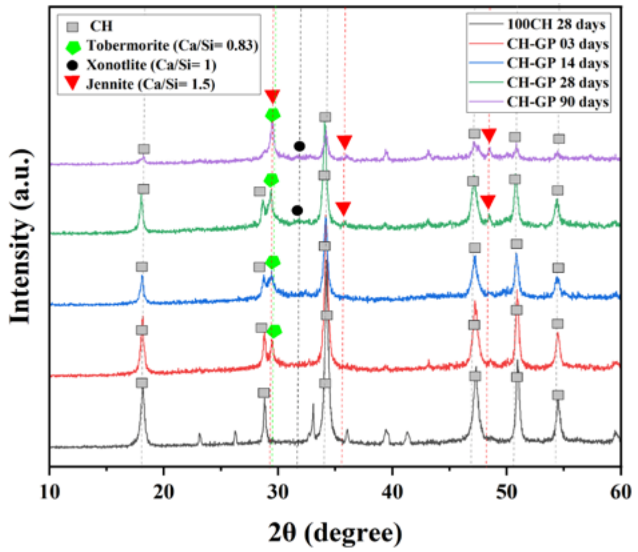

Fig 2 XRD diffractograms for CH-GP mixes and 100CH mix at different days of curing.

The typical range of Ca/Si ratio in C-S-H varies from 0.66 to 2. The optimal Ca/Si ratio of 1.5 (Jennite- a C-S-H mineral with Ca/Si=1.5) in C-S-H is often considered a reasonable target for well-balanced hydration and strength development. The C-S-H with Ca/Si ratio 1.5 (Jennite) have more crystalline structure of C-S-H compared to C-S-H with Ca/Si ratio lesser than 1.5. The reason for the same is attributed to the hydration process because of which the OH bond in between CaO and silica atoms decreases leading to the formation of crystalline structure of C-S-H (Mehta and Monteiro, 2014 and Taylor, 1997). The Ca/Si ratio in C-S-H on the product side in Eqn. (1) is 1.5. Therefore, it can be determined that the molar ratio of SiO2 (S) and Ca(OH)2 (CH) should be at least 0.54 (S/CH ratio) in order to result in Ca/Si ratio of 1.5 in C-S-H on product side.

The mix design of calcium hydroxide powder and glass powder with particle sizes less than 75 microns (content of SiO2 and CaO in glass powder are 70% and 10% respectively based on the X-ray fluorescence (XRF) analysis) was 54:46, to ensure the S/CH ratio of 0.54. Subsequently, three samples of 20mm cubes were cast and water-cured for 3, 7, 28 and 90 days. In addition, a reference 100% CEM-I cement paste and 100% calcium hydroxide paste were also casted and cured for the same number of days.

The compressive strength test was displacement controlled at a rate of 0.3mm/min because it is suggested that at this loading rate minimizes sudden shocks or dynamic effects during the test, providing a more stable testing environment. The compressive strength of calcium hydroxide (CH) and glass powder (GP) mix named as CH-GP were experimentally determined to be 3.8, 4.9, 7.8 and 12.2MPa at 3, 14, 28 and 90 days, respectively. As expected, the compressive strength of 100% CEM-I cement paste named as 100CEM-I were much higher (32.1, 41.6, 56.1 and 65.4MPa at 3, 14, 28 and 90 days respectively) than CH-GP mixes at same number of days. Although, the 90 days compressive strength of CH-GP mixes is 57% higher than its own 28 days compressive strength, whereas, for 100CEM-I, the 90 days compressive strength is 16% higher than its own 28 days compressive strength which implies that rate of gain of compressive strength in CH-GP mixes is more significant compared to that of 100CEM-I mixes after 28 days of curing. Furthermore, at 28 days, the after crushing images of 100CEM-I shows a failure pattern which is identified as brittle failure and similarly the 28 days CH-GP specimen after crushing images show same proper brittle failure pattern suggesting the development of proper microstructure as shown in Fig.1.

The XRD analysis was conducted using Bruker D8 Autochanger + X-ray diffractometer with graphite-monochromatised Cu Kα radiation generated at 40 kV and 100 mA at continuous scanning rate with 2θ ranging from 50 to 750 and a speed of 20 min-1 for CH-GP specimen at all curing days and 100% calcium hydroxide paste named as 100CH at 28 days. Fig. 2 shows that the 100CH specimen shows no peak of C-S-H formation even until 28 days which establishes that there is no or negligible strength contribution in CH-GP specimen from calcium hydroxide reaction with water. Further, the CH-GP specimen shows the evident peaks of C-S-H which keeps on increasing as the curing period increases. On and after 28 days of curing, the XRD peaks of jennite (C-S-H with Ca/Si ratio 1.5) are clearly noticed which confirms that the later stage strength gain in CH-GP is due to the formation of jennite C-S-H in the mix (Taylor, 1997).

Potential for application of results

The successful demonstration of Ca/Si ratio optimisation in C-S-H formed during rection between calcium hydroxide and glass powder paste could be used to improve the current replacement percentage of cement with glass powder (20%) considering the findings that desired C-S-H (jennite) could be produced which can directly improve the mechanical strength of the concrete with glass powder. Increasing the replacement percentage of the cement with glass powder over the current replacement of 20% could significantly reduce the demand for cement leading to reduction in the carbon emissions.

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Material and structural behaviour of rubberised alkali-activated concrete

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Project objectives and goals

Advances in concrete research have led to the introduction of rubberised concrete (RuC) and alkali-activated concrete (AAC). RuC incorporates waste rubber in the form of crumbs as partial replacement for natural aggregates (Thomas and Gupta, 2016). This provides a recycling path for end-of-life tyres and enhances the deformation characteristics of concrete. AAC, meanwhile, employs aluminosilicate precursors and an alkaline activator to fully replace Portland cement, mainly for environmental benefits (Provis, 2018).

The present research combines the merits of both RuC and AAC to form rubberised alkali-activated concrete (RuAAC). An optimised RuAAC mix design is initially developed, and the aim is to characterise the mechanical properties and composite structural behaviour, mainly covering:

- The quasi-static mechanical properties and constitutive behaviour
- The rate-dependent cyclic constitutive response and impact properties
- The long-term compressive strength development and creep response
- The compressive behaviour of RuAAC confined with fibre-reinforced polymer (FRP) sheets
- The compressive and lateral cyclic response of steel tubes infilled with RuAAC

Description of methods and results

The constituent materials used to form RuAAC are shown in Fig 1. The aluminosilicate precursors employed are blast furnace slag and fly ash. Anhydrous sodium metasilicate (Na_2SiO_3) is used as a solid activator, while sodium tetraborate decahydrate-borax ($Na_2B_4O_7{\cdot}10H_2O$) is added as a solid admixture. River sand and crushed gravel are used as the fine and coarse natural aggregates, respectively. Crumb rubber particles of different sizes, as depicted in Fig 1, are used to replace up to 60% of the total natural aggregates by volume.

The quasi-static mechanical properties are examined first. This includes the compressive strength, splitting tensile strength, flexural strength, and compressive stress-strain response. The findings indicate a degradation in the mechanical properties in proportion to the rubber content. The ductility and normalised energy dissipation, however, increase as the rubber content increases. The rate-dependent constitutive response of RuAAC is also investigated under cyclic loading, covering quasi-static, moderate seismic, and severe seismic conditions. The results highlight an increase in the mechanical properties as the loading rate increases. The unloading modulus is shown to be sensitive to the unloading strain, rubber content and applied strain-rate, while the plastic residual strain is mainly influenced by the unloading strain.

The response to low-velocity impact under compression and splitting tension is also examined. The findings show that a high rubber content leads to an increase in the impact duration and a higher dynamic increase factor for a given strain-rate. Specimens loaded in splitting tension are shown to be more sensitive to the strain-rate when compared to specimens loaded in compression. The creep response of RuAAC under sustained load levels of 10% and 20% of the 28-day compressive strength is monitored for a period of 1 year. The observed creep coefficients and specific creep values increase with higher rubber content. The rate of creep development also varies from that given by various design codes for conventional concrete.

The axial compressive behaviour of RuAAC confined with unidirectional FRP sheets is investigated using experimental and numerical methods. The experimental parameters investigated are the rubber content (0-60% replacement ratios) and number of aramid FRP sheets (1-3 layers). The numerical study is mainly carried out to determine the effect of different FRP materials, concrete grades, rubber contents, and FRP layers on the confined constitutive behaviour. The results highlight that the rubberised specimens benefit largely from confinement, resulting in higher confined-to-unconfined compressive strength ratios when compared to their non-rubberised counterparts.

Experimental and numerical methods are also utilised to characterise the axial compressive behaviour of steel tubes infilled with RuAAC. The experimental programme covers circular and square cross-sections, and up to 60% volumetric rubber replacement ratio. The numerical study expands on the experimental results, covering the influence of a wide range of practical design parameters on the axial behaviour. The results highlight an increase in ductility with higher rubber content in the concrete infill, and significantly lower reduction in axial strength and stiffness due to rubber addition when compared to similar unconfined specimens.

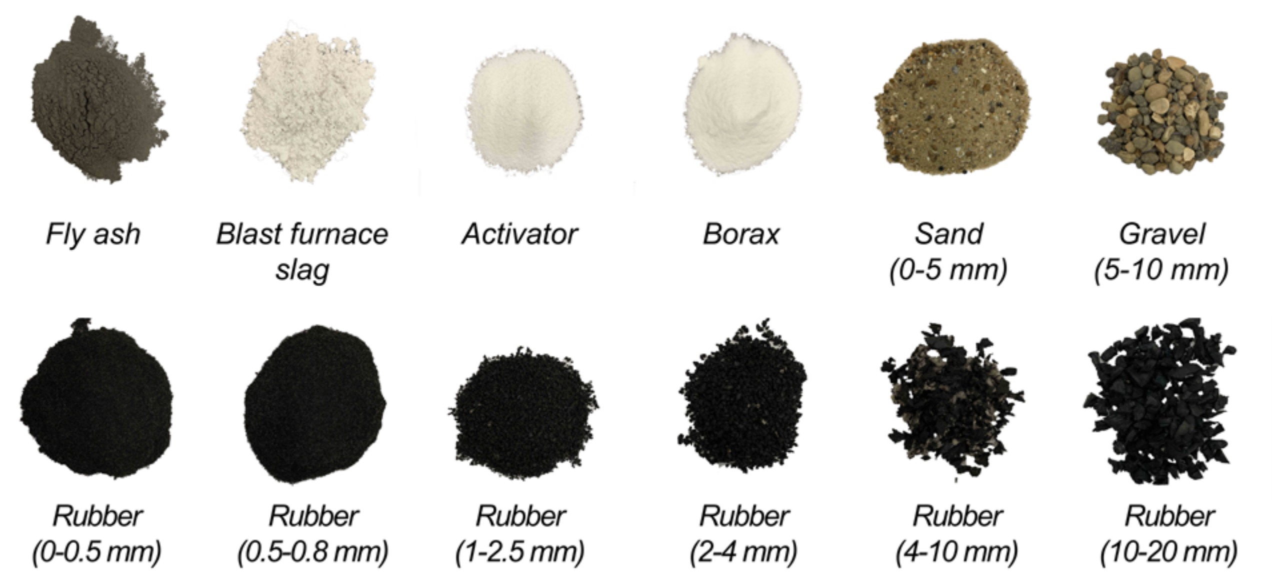

***Fig 1** Constituent materials.*

The inelastic cyclic response of square steel tubes infilled with RuAAC is also investigated as depicted in Fig 2. Specimens are tested under lateral cyclic loading with a co-existing axial load of up to 20% of the cross-sectional capacity, and complementary numerical assessments are also performed. The results illustrate that the RuAAC-infilled specimens have significantly improved ductility and energy dissipation when compared to comparative hollow steel tubes. However, square concrete-filled steel tubes (CFSTs) do not benefit largely from rubber addition as is the case for circular CFSTs.

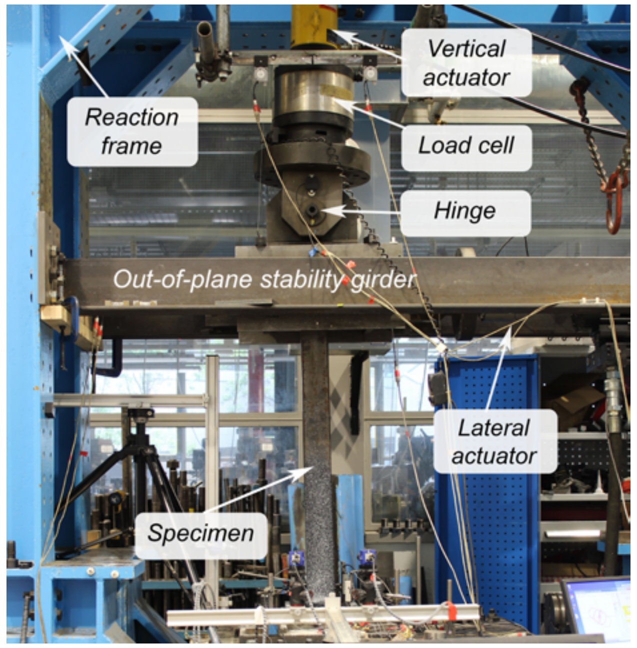

***Fig 2** Lateral cyclic test setup of steel tubes infilled with RuAAC.*

Potential for application of results

The results are used to derive detailed expressions for the mechanical properties, monotonic and cyclic constitutive behaviour, and dynamic increase factor at varying strain-rates, which are all useful for practical design. The results from the FRP-confined specimens allow for the introduction of simple design-oriented constitutive models and FRP stiffness limits to ensure sufficient confinement. The results from the RuAAC-infilled steel tubes are used to recommend modifications to the axial capacity prediction approaches in Eurocode 4 and AISC 360 to factor in the effect of rubber addition on confinement. The lateral cyclic loading results of the RuAAC-infilled CFSTs allow for quantifying the stiffness, plastic hinge length, and critical strains corresponding to the onset of local buckling, which are all important for characterising the seismic response.

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ArchIMEDES: The Development of computer vision based structural health monitoring methods for predicting scour at bridges

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Project objectives and goals

ArchIMEDES: Arch **I**mage **M**easurement for the **E**valuation of **D**isplacement by **E**rosion due to **S**cour is the computer vision program which has been developed to remotely record load-induced displacements across a masonry arch bridge. It is built from the ground up specifically for the FlexiArch but has applications outside of this system.

Scour-induced failure of masonry arch bridges is a common cause of bridge collapse, especially during extreme flood events. Over recent years there has been a significant increase in the numbers of documented scour induced failures of this bridge stock across Europe and the USA. The extent of the scour can erode the supporting soil or sediment around the bridge piers or abutments, leading to a loss of support for the structure. As the foundation becomes unstable, it can result in settlement or tilting of the bridge, potentially causing structural damage, while the ongoing nature of scour can result in the progressive deterioration of the bridge's ability to safely transfer load. Traditional hydraulic adjustments, such as streamlining abutments with wing walls and using cutwaters on piers, do not significantly reduce scour depth for masonry arch bridges (Sloan et al., 2019). This project aims to link the changes of response under load to the easement of support at the bridge foundation due to scour. Scale experiments on the FlexiArch under loading with realistic scour conditions is contributing to the development of an algorithm based on the relationship between the structural response of the FlexiArch and prevailing scour conditions. The computer vision-based monitoring package, ArchIMEDES, developed as part of the research, will use this algorithm to predict current bridge scour conditions at any given time. This will allow for potential scour development to be identified and investigated before the bridge collapses, ensuring the security and safety of these vital pieces of infrastructure.

The intended outcomes are to develop:

- **ArchIMEDES** - A computer vision displacement and hinge formation measurement system building on a study by Lydon et al (2019).
- **Scale experiments** with realistic scour conditions to build a bank of structural response and behaviour data under load.
- **Finite element models** which can be used to predict bridge behaviour beyond the limits of the current run of experiments in a similar way to McNulty (2013)
- **A bridge management program** which will directly predict current scour conditions from a combination of observed data (deformation and load) and comparing this with the bank of data produced by experimentation.

Description of method and results

ArchIMEDES captures salient points across a defined region. By defining scale properties and relating them to pixel displacements, ArchIMEDES can report sub-millimetre deflections of any region along the arch. (Fig. 1)

A 1:10 scale model of a typical FlexiArch bridge, built in both the heavy structures laboratory to extract displacement data under loading and inside the flume tank in the hydraulics research laboratory to derive scour patterns.

Load testing takes place under a calibrated hydraulic actuator, with ArchIMEDES used to extract displacement data. Simulated scouring under the foundations was modelled between 0mm and 60mm in 10mm increments as well as fractionally at each increment at ¼, ½ and ¾ scour of the foundation area. The flume will be used to subject the bridge and bed sediment to various flow conditions. The realistic scour holes generated in the flume will be 3D scanned and the 3D printed in inverse to create a scour mould. This mould will then be used to produce an accurate replication of the scour hole which

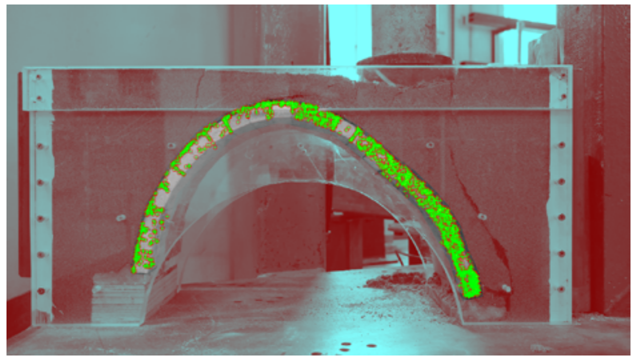

Fig 1 An example of the scale experiment set up with ArchIMEDES recognised features.

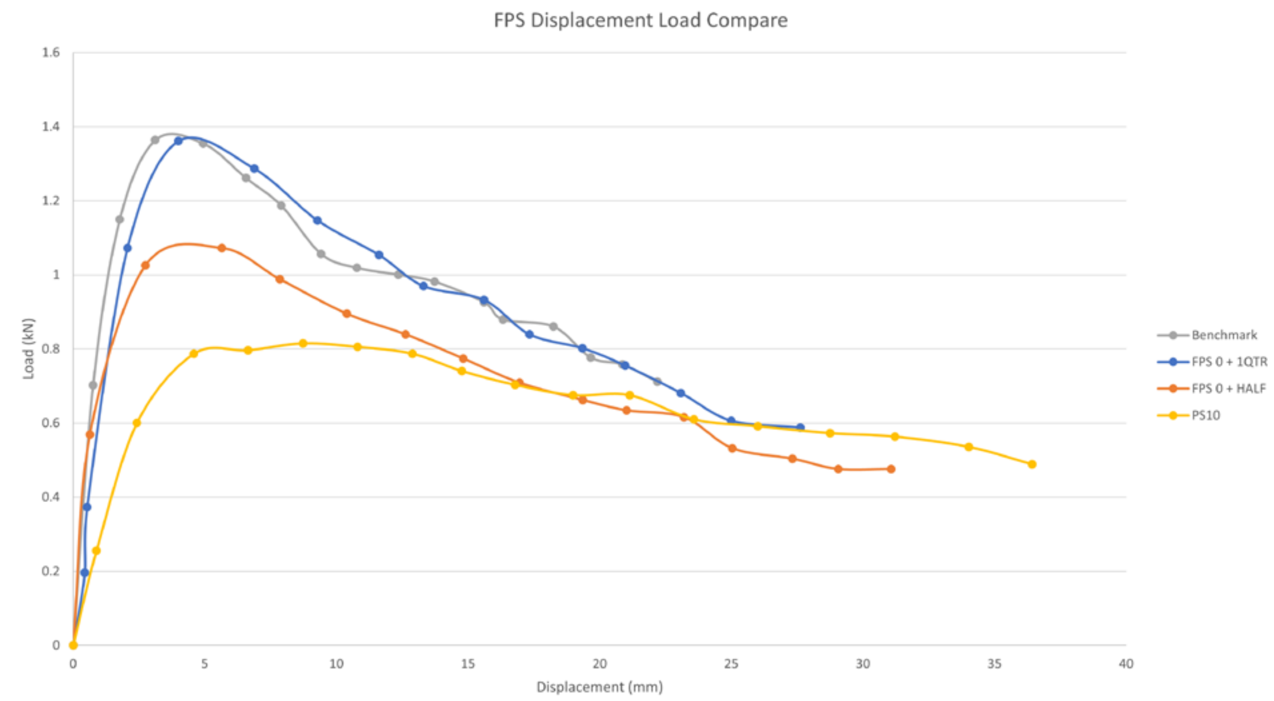

Fig 2 An example of the load/displacement curves obtained for a selection of the experiments undertaken.

can be used in the structures lab and tested in the same way as the simulated scour experiments. This will further refine the ability of the ArchIMEDES bridge management program to predict current scour conditions from observed displacement under load.

The results of the experiments to date show ArchIMEDES to be capable to extracting meaningful response data. The bank of data is currently being built with only a few experiments remaining to be conducted. As expected, the data shows that with increasing scour, the load required to induce a mechanism in the arch decreases, Fig 2. illustrates this. The load/displacement pattern of each scour scenario has been captured and presents a strong base for ArchIMEDES bridge management to work from. The finite element model presents data in line with the experiments and will be used in a parametric study shortly.

Potential for application of results

Although this project is primarily focused on the unique FlexiArch system (Long et al, 2013), it could also be extended to traditional masonry arch bridges.

In Northern Ireland alone, Sloan et al (2020) identifies that arch bridges make up 50% of our bridge stock, this is therefore of critical importance. Equating to approximately 3000 bridges. Their age and condition make them a priority for monitoring. ArchIMEDES can help make this process more effective and efficient.

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Unveiling the potential of scaling in progressive collapse studies

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Project Objectives and Goals

Progressive collapse poses a severe threat to different types of structures. In this type of collapse, local failure propagates through a structure resulting in widespread and often disproportionate damage (Adam et al., 2018). In many cases, this leads to significant financial losses and, tragically, life losses. Recognising the urgency of this issue, researchers have diligently explored it in recent years. However, they have faced various challenges, primarily due to the expensive, unrepresentative, and impractical testing methods commonly used. The dynamic and large-scale nature of progressive collapse studies contributes to these challenges. In response, researchers have suggested alternative methods, such as subassembly testing or employing numerical and analytical approaches. While these methods offer advantages, they also present unique challenges, often leading to inaccurate results. Addressing these issues is crucial to advancing the general understanding and fortifying structures against the severe threat of progressive collapse.

To overcome the issues related to current testing methods, this research aims to validate the applicability of dynamic scaling on subassemblies of framed structures. This method facilitates the utilisation of scaled models to replicate the behaviour of large-scale structures during progressive collapse events. To achieve this goal, the following objectives were set:

- Adopting dynamic similitude laws to create scaled models
- Testing the created scale models under quasi-static loading to simulate column loss scenarios
- Examining the behaviour of the samples concerning collapse resistance
- Validating the applicability of scaling laws utilising experimental results obtained from large-scale prototypes and the tested scaled models.

Description of Methods and Results

Initially, a large-scale prototype model was selected, and dynamic scaling laws were applied to create the scaled models. The benchmark model represents a two-bay beam-column subassembly extracted from a building, with loading focused on the middle joint to simulate a potential progressive collapse due to middle column loss (Alogla et al., 2016). Various critical aspects, including geometric properties, material properties, boundary conditions, and loading rates, were considered in the scaling process. The careful consideration of factors contributing to collapse resistance behaviour ensures the production of scaled samples that accurately represent the prototype model. For each of these aspects, the scales were calculated based on the chosen geometric and material elastic modulus scale factors (Moncarz and Krawinkler, 1981). A total of 13 samples, all adhering to the same boundary conditions and a geometric scale of 1:4, were created and tested in this study. Figure 1 provides a visual depiction of the sub-assembly scaling process. To assess the sensitivity to deviations from similitude laws, different properties of the samples were systematically altered one at a time.

Specimen	CAA		CTA	
	Load	Displacement	Load	Displacement
	kN	mm	kN	mm
Prototype sample (Alogla et al., 2016)	34.9	89.3	33.2	477.3
Scaled up results from tested sample	31.8	71.2	33.6	550.2
Difference in %	-8.9	-20.2	1.2	15.3

Table 1: Comparison between the results acquired from the prototype model and a specimen highly compliant with the scaling laws (where load and displacement refer to maximum applied load and middle joint displacement, respectively)

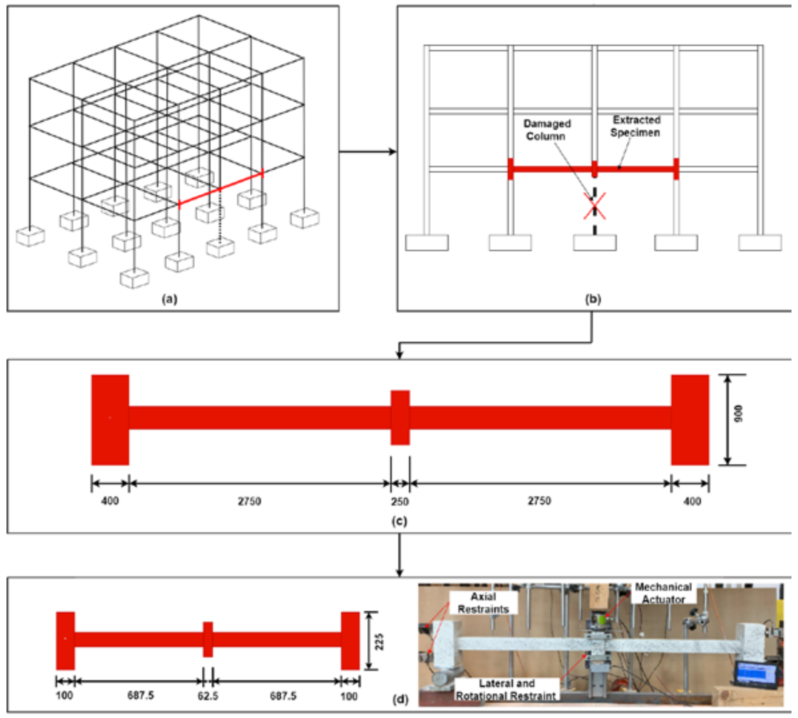

Fig 1 Sub-assembly scaling process: (a) Full structure considered, (b) 2D Frame extract, (c) Full-scale sub-assembly (Alogla et al., 2016) and (d) Scaled sub-assembly.

Concrete and reinforcement bar properties were the primary aspects modified, with each variation leading to the testing of two samples, thereby enhancing the comprehensiveness of the study.

Instruments such as load cells and linear variable differential transformers (LVDTs) were positioned on the scaled models in adherence to the configuration observed in the large-scale prototype. The boundary conditions and frame stiffness of the test rig were methodically downscaled in accordance with the prescribed scaling law. The test samples were subjected to displacement-controlled testing, which synchronised the loading rate to ensure its compliance with the scaling laws based on the loading rate adopted in the large-scale test. As with the large-scale prototype, displacement to the middle column of the beam-column sub-assembly was applied to ensure that the testing conditions adequately represent the real-life situation. Acquired data from the scaled models were compared against the prototype model for validation.

The main criteria used to assess the performance of the samples were their load-carrying capacity and undergone deformation throughout the testing procedure. The samples with the highest level of compliance with the scaling laws concerning the material properties of concrete and reinforcement produced the most compliant outcomes. This finding confirmed that the scaling laws can be applied to progressive collapse studies. The higher variation in the outcomes was caused by distortion in any of the parameters of the concrete or steel reinforcement. Table 1 presents some critical results for one of the highly compliant samples. As noted, a high correlation is present between the load-carrying capacity of the prototype sample and the scaled model in both the compressive arch action (CAA) and catenary tensile action (CTA) stages. CAA and CTA refer to the main collapse-resisting mechanisms that develop in beams during progressive collapse events.

Future Applications

This study's findings reveal that scaled models effectively predict the behaviour of full-scale sub-assemblies in progressive collapse events. Further validation with diverse full-scale structures is needed to enhance its credibility. Adopting this experimental approach offers a reliable and cost-efficient testing technique, significantly alleviating the usual time and space constraints related to progressive collapse testing. With a reliable method that helps to efficiently acquire data, researchers can expedite the resolution of knowledge gaps in progressive collapse. This acceleration will aid in improving existing international codes and addressing their current shortcomings.

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Timber vault floors for low-embodied carbon buildings

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Project objectives and goals

Buildings need to become more environmentally friendly. Currently, construction is responsible for about 10% of all greenhouse gas emissions with the majority of embodied carbon existing within floors (United Nations Environment Programme, 2022). As an alternative to traditional materials like steel and concrete, which has high embodied carbon, timber provides a more sustainable option (Hart et al., 2021). Timber's benefits include a high strength to weight ratio and lower embodied carbon. However, timber's low stiffness often results in the serviceability limit state governing the design, particularly at long spans. In contrast, vaults structures provide high geometric stiffness and are lightweight due to the primary load transfer mechanism being shifted from bending to compression.

Hawkins et al., (2020) found that concrete vaults, due to membrane action, can reduce embodied carbon by 43-53% when compared to traditional flat slabs, which do not fully utilise the full capacity of the material. Despite these benefits, these vaults still require the use of concrete. In contrast, timber is increasingly seen as a more sustainable construction material when compared to concrete (De Wolf et al., 2016). However, timber is perceived to be expensive and even though timber has the benefit of sequestering carbon, it remains a finite resource (Pramreiter et al., 2023) and with global floor area projected to double by 2060 (United Nations Environment Programme, 2022) ensuring the sustainable use of timber is critical for its competitiveness against concrete and steel.

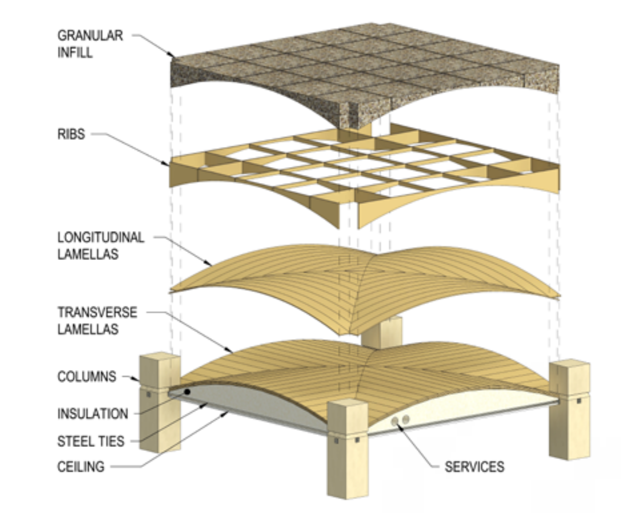

Fig 1 Isometric exploded view of proposed groin vault floor system prototype test setup.

This study aims to develop a low-carbon floor system that combines the structural efficiency of vaults with the strength and renewability of timber. The objectives are:

- Develop an economical vaulted flooring system. The system will consider life cycle impacts, stress history, timber availability, manufacturing, cost, constructability, and end-of-life considerations.
- Establish a reliable, repeatable, and robust design methodology for timber vaults.
- Identify the most cost-effective and low-embodied-carbon solution and compare it with other flooring systems.
- Construct and test a prototype timber vault flooring system to validate the design approach.

Proposed structural system

This study investigates two vault systems: a barrel vault spanning between support beams and a groin vault spanning between columns (Fig 1). Both systems use thin, glue-laminated curved timber for the vaulted floors. The inclusion of ribs (Fig 1) is expected to increase the stiffness of the system and provide a level surface for floor panels. Granular infill of earth, gravel or rubble will be used to provide a level surface, which may also improve vibration and acoustic performance.

The steel ties in the groin vault (spanning between the columns) and the barrel vault (spanning between beams) are used to counter the thrust forces of the vaults. The voids created below the vaults allow for the integration of services, insulation, and ceiling panels. This design aims to achieve a structural depth comparable to a typical CLT built up structural system.

Description of method and results

A computational optimisation study was conducted to find the optimal vault design using typical office floor loadings to BS EN 1991-1-1 (2002). A two-dimensional barrel vault was analysed using a MATLAB, (2021) script using beam elements and the three-dimensional groin vault was modelled in Grasshopper, (2022) and analysed

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with shell elements in Karamba3D (Preisinger, 2022) using linear finite element analysis. The analysis considered member utilisation under ultimate limit state (ULS) design, accounting for axial, bending and shear loads, and serviceability limit states (SLS) including deflection and vibration. A genetic algorithm was adopted to optimise the vaults as it is capable of handling both discrete and continuous variables. A penalty term was added to the objective function to transform the unconstrained problem to a constrained one that includes the ULS and SLS member utilisation (Khan and Mir, 2017). Fig 2 presents the preliminary outcomes of the barrel vault optimisation, showing a 32% reduction in embodied carbon at a vault rise of 0.6m. These results indicate that the groin vault solution could yield higher embodied carbon savings by removing the support beams used in the barrel vaults.

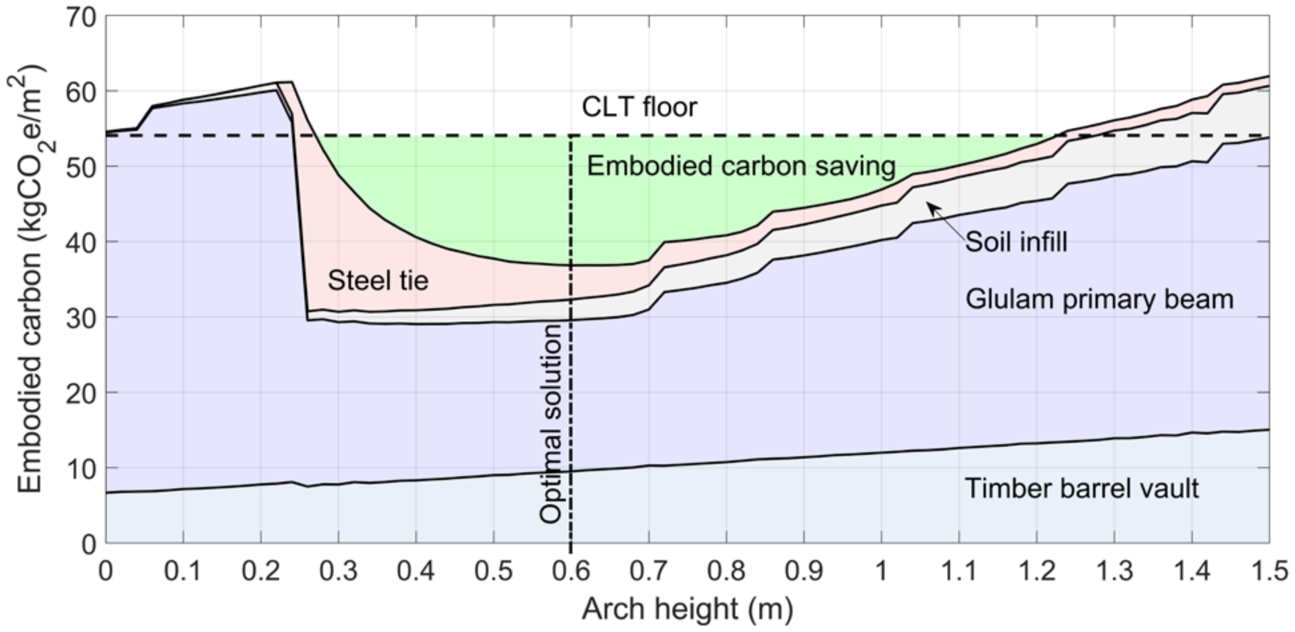

Fig 2 Embodied carbon vs height for an 8m span barrel vault timber floor.

Potential for application of results

The results show that timber vaults offer substantial reductions in embodied carbon compared to cross laminated timber (CLT) floor systems, presenting a more sustainable alternative. This design approach not only lowers the embodied carbon impact but also enhances the competitiveness of timber against concrete and steel, potentially increasing the uptake of timber in more buildings. Additionally, a programme of physical prototyping and structural testing is also being undertaken to validate and verify the numerical model by investigating the vaults' ultimate failure mechanisms, vibration performance, and the damping properties of the granular infill.

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Investigating the durability performance of seawater-mixed concrete

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Project objectives and goals

This project aims to contribute to the sustainable development of the world by directly using seawater (SW) without desalination and to contribute to the application of seawater concrete by addressing the key underlying issues. Seawater with huge reserves is being considered as an alternative to fresh water for concrete mixing to relieve water pressure, which is especially significant in coastal regions and islands where fresh water is limited. Desalination is expensive and energy-intensive, and it also has adverse impacts on the environment (Elimelech and Phillip, 2011). The fresh properties and strength of plain seawater concrete without reinforcement are comparable to concrete mixed with tap water (Younis et al., 2018) (Li et al., 2021) (Ebead et al., 2022). However, there is very limited research on the durability performances of seawater concrete.

The goal of this project is to answer three questions regarding the application of seawater concrete. Firstly, will seawater induce durability issues such as sulfate attack and alkali-silica reaction in plain concrete without steel reinforcement? If so, how can this problem be solved? Lastly, how serious is the steel corrosion caused by mixed seawater?

Description of method and results

1) Resistance of cement paste to sulfate attack from seawater
The resistance of cement paste to sulfate attack from mixed seawater or external seawater environment was studied by analyzing the expansion, mass loss, strength development, and erosion products of cement paste. Deionized water (DW) and saturated limewater (LW) were used as standard mixing water and standard curing water, respectively. After 360 days of curing, quantitative XRD analysis was performed to measure the erosion products that induce expansion, such as ettringite and gypsum, along the following depths of one cement paste bar: 0–2, 2–4, 4–6, 6–8, 8–10, 10–14 mm. Backscattered scanning electron microscopy (BSEM) combined with energy spectrum analysis (EDS) was used to observe element distribution.

As shown in Fig 1, both internal and external seawater attacks induced the highest expansion of cement paste, which was 0.107% at 6 months, slightly higher than the limit value of the moderately sulfate-resistant mortar sample. The erosion depth is limited to 2 mm according to the ettringite distribution. GGBS blended paste experienced more severe damage than ordinary Portlandite cement (OPC) paste in seawater due to the magnesium attack on Portlandite and C-S-H. The degradation mode of GGBS blended paste is mainly surface debonding rather than high bulk expansion, which is different from OPC paste.

2) Risk of alkali-silica reaction in seawater-mixed cement mortar
Accelerated mortar bar test (ASTM C1260, ASTM C1567) for 28 days and long-term expansion test (ASTM C227) for 360 days were conducted. The expansion and strength of cement mortar samples mixed with different water (distilled water or seawater) and different types of sand (non-reactive sand (NA) or reactive sand (RA)) were monitored with time. At 360 days of moisture curing, hydration products of cement mortar were analyzed by XRD. The compositions of ASR products in cement paste mixed with deionized water or seawater were identified by BSEM-EDS.

Fig 2 indicates that seawater did not cause ASR expansion when non-reactive sand was used, since the expansion value was below the limit. Seawater increased ASR expansion and caused more cracks and larger strength reduction in the presence of reactive aggregates. However, replacing cement (represented by C in Fig 2) with 70% GGBS (represented by 70G in Fig 2) prevented expansion and cracking.

3) Risk of steel corrosion in seawater-mixed concrete
The wet (in NaCl solution) and dry (in air) cycles method was used to accelerate steel corrosion in reinforced concrete and to simulate the splash zone. A low water-to-cement ratio of 0.4 was used. One steel bar was embedded in concrete with a cover depth of 30 mm for corrosion study, and one stainless mesh was embedded for the electric connection purpose. The corrosion rate of rebar in concrete was monitored frequently using electrochemical measurement technologies, including half-cell potential, linear polarization resistance, and electrochemical impedance spectroscopy tests.

Corrosion rate results indicate that both tap water-mixed reinforced concrete and seawater-mixed reinforced concrete underwent negligible corrosion up to 40 cycles.

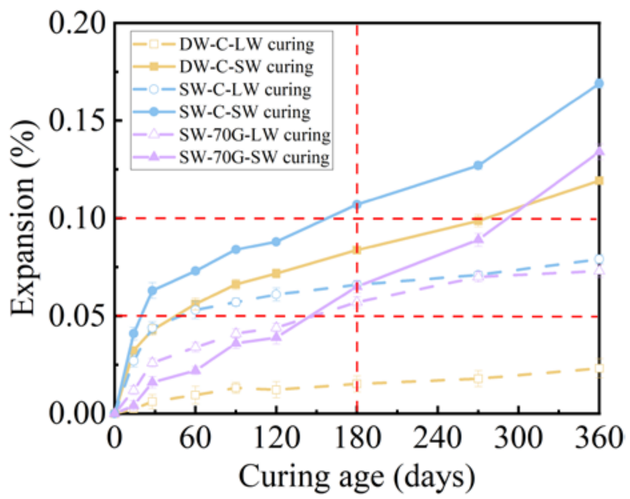

Fig 1 Expansion of cement paste bars cured in saturated limewater or seawater.

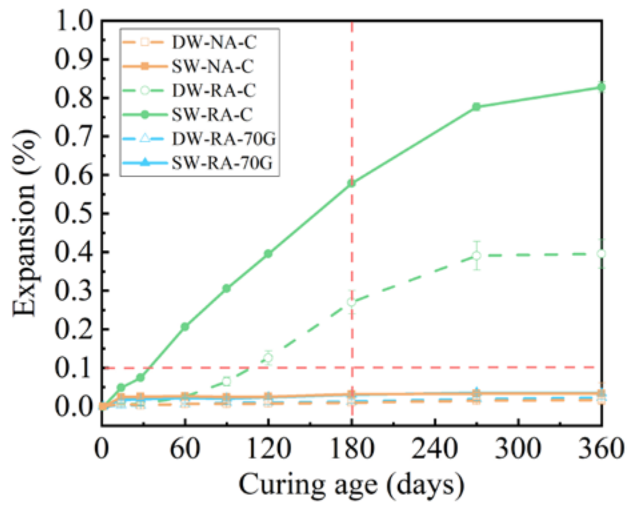

Fig 2 Expansion of mortar bars cured in the moist environment at 38°C.

Potential for application of results

Seawater-mixed concrete includes plain seawater concrete and reinforced seawater concrete, so their application should be discussed separately. For plain seawater concrete, it is possible to use it to produce non-structural elements such as storm drains, curbs, and pedestrian slabs if non-reactive aggregates are used.

For reinforced seawater concrete, it may be possible to use it to construct temporary structures that require a relatively short service life compared to reinforced concrete mixed with tap water. A low water-to-binder ratio is necessary in seawater-mixed concrete to keep the corrosion rate low.

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Exploring Optimal Geometries for Reinforced Concrete Piles

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Introduction

Construction materials, particularly cement and steel, significantly contribute to embodied carbon due to their energy-intensive manufacturing processes, a concern emphasised by the UN report (2022). The construction industry is under heightened scrutiny to curtail its overall embodied carbon as part of the global imperative to combat climate change. Consequently, optimising the environmental impact of structures has become a pressing focus for researchers. Foundations, although responsible for a substantial portion of a structure's total embodied carbon, have received limited attention in research, creating a notable research gap. This lack of attention may be attributed to various factors such as a lack of understanding of the soil-structure interference and a lack of reliable site data as highlighted by Senanayake et al. (2017). Addressing this research gap is crucial for developing more sustainable construction practices and achieving the ambitious carbon reduction goals set for the construction industry to be NetZero by 2050.

Project objectives and goals

This research aims at optimising the environmental impact of piles and discovering the optimal pile geometry that achieves minimal embodied carbon. The research aim is fulfilled through the following objectives:

- Developing an optimisation algorithm that is capable of allocating optimal geometries under various construction constraints.
- Comparing the performance of the different pile geometries at the same capacity and in different soil conditions.

Description of method and results

A genetic- algorithm-based optimisation tool was built and validated to compare the performance of the different pile geometries at different load capacities. Four different pile geometries were tested including solid piles, hollow cylindrical piles, tapered piles and hollow tapered piles, these four geometries were compared to common industrial pile designs to assess the embodied carbon savings Fig 1 shows a schematic of the algorithm and Fig 2 shows a direct comparison between the values of embodied carbon resulting from the different tested geometries at different pile capacities. The following are the main concluded points:

- While optimal solid piles exhibit lower embodied carbon compared to typical industrial pile designs, various alternative geometries have demonstrated superior carbon savings. It's important to note that optimal solid piles are significantly slender in comparison to other geometries, leading to practicality concerns. The authors have previously explored the impact of the slenderness ratio on pile embodied carbon in a separate study.
- Hollow tapered piles proved to be the optimal pile geometry and correspond to significant carbon savings when compared to other pile geometries, however, achieving a tapered outer geometry requires a fundamental change to standard augering methods, requiring contractors to look for novel pile construction methods (Khan et al., 2008).
- Hollow cylindrical piles serve as excellent alternatives to optimal hollow tapered piles, as they offer the advantages of both reducing embodied carbon and being constructible using a standard auger.
- Solid taper piles emerge as highly viable choices for low-capacity piles, demonstrating the capability to meet the necessary pile capacities with a (40-52) % reduction in embodied carbon compared to commercial pile designs.

Potential for application of results

The proposed optimisation algorithm and research results are believed to be excellent guidance for all designers and contractors interested in optimising the cost and the environmental carbon of piled foundations. Employing the optimal pile geometry and design parameters can lead to a substantial 72% reduction in total embodied carbon, showcasing promising prospects for widespread adoption. This emphasises the potential of pile optimisation as a significant avenue for carbon savings within the built environment.

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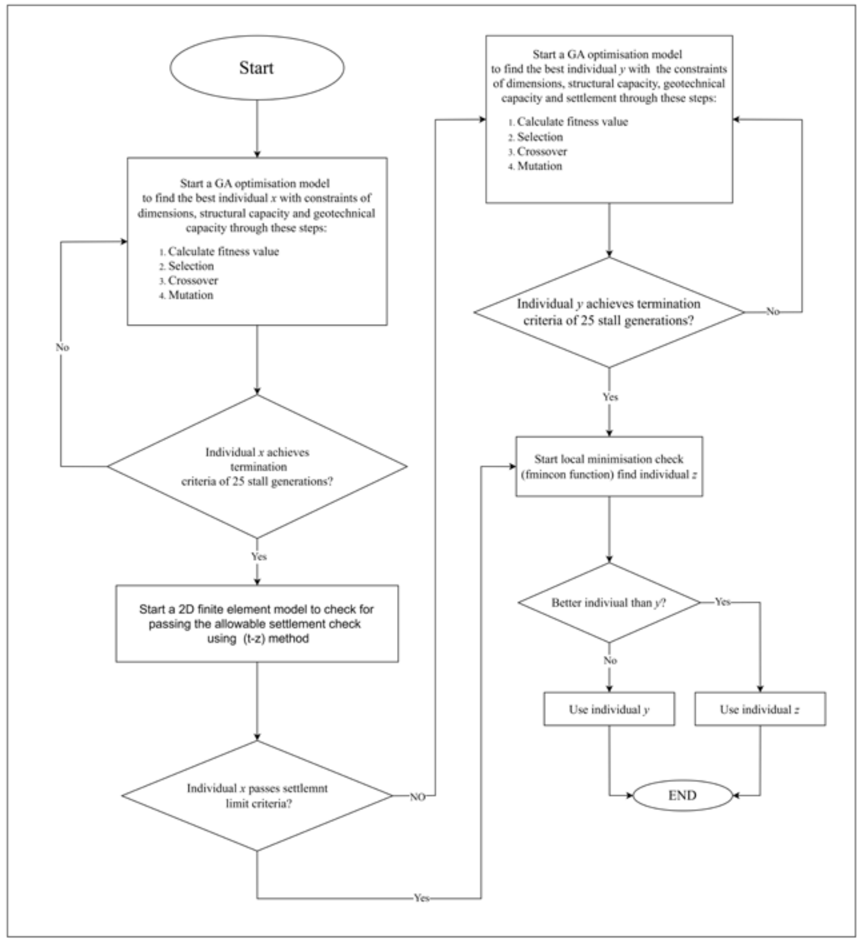

Fig 1 A schematic of the proposed optimisation algorithm.

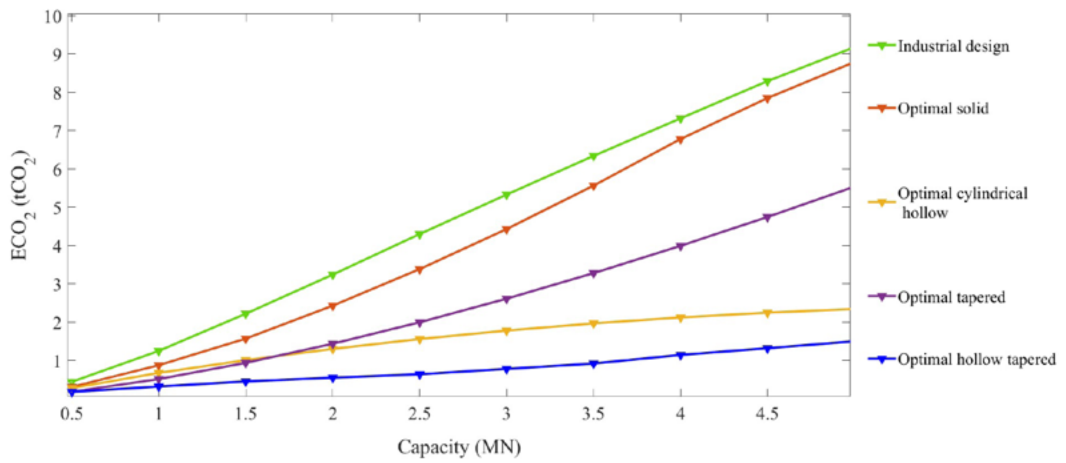

Fig 2 Optimisation results for the different pile geometries.

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Web crippling behaviour of aluminium sigma sections

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Project objectives and goals

The construction industry is shifting towards sustainable construction methods to achieve the sustainability targets. On that note, innovative sections have been introduced to the cold-formed industry to improve the material efficiency. Sigma sections are introduced in the industry with several advantages including enhanced stiffness. Fig. 1 presents the cross-section illustration of sigma sections. This research intends to analyse the web crippling behaviour of aluminium sigma sections to explore the applicability of aluminium sigma sections in modular buildings. Hence, the following objectives are set.

- Development of Finite Element models
- Validation of modelling approach
- Parametric plan development
- Development of design guidelines

Description of method and results

Numerical approach was opted in the study to explore the web crippling behaviour of aluminium sigma sections under EOF and IOF loading conditions. ABAQUS/CAE (2017) was employed as a Finite Element (FE) modelling and Analysis (FEA) software. Overall, three structural elements, (1) sigma section; (2) loading/ supporting plate (bearing plate) and (3) web side plate were modelled and then assembled according to the actual loading setup. The ABAQUS/ Explicit analysis method was employed in this study for its proven credibility of being efficient in solving quasi-static problems. To check the reliability of the numerical models, the verification process was conducted with experiment studies. Hence, experiment studies on CF aluminium LCBs by Husam et al (2021). were considered for validation study. The numerical models were generated and validated with experiment results. Comparisons indicated that numerical models were coordinated well with the experimental results under IOF and EOF loading conditions.

Section 140							Section 200						
			Web crippling capacity (kN)							Web crippling capacity (kN)			
t	b_l	r	EOF		IOF		t	b_l	r	EOF		IOF	
			f_y(MPa)		f_y(MPa)					f_y(MPa)		f_y(MPa)	
mm	mm	mm	180	220	180	220	mm	mm	mm	180	220	180	220
1	50	3	1.10	1.26	2.50	2.81	1	50	3	0.88	0.83	2.31	2.60
1	50	5	1.03	1.17	2.50	2.77	1	50	5	0.92	0.78	2.24	2.50
1	100	3	1.20	1.32	2.88	3.29	1	100	3	0.95	1.05	2.69	3.06
1	100	5	1.14	1.26	2.74	3.07	1	100	5	0.92	1.02	2.54	2.87
1	150	3	1.35	1.50	3.07	3.50	1	150	3	1.09	1.22	2.91	3.30
1	150	5	1.25	1.38	2.90	3.31	1	150	5	1.02	1.13	2.73	3.09
2	50	3	3.65	4.16	8.34	9.53	2	50	3	3.25	3.66	7.84	8.83
2	50	5	3.52	4.00	8.16	8.99	2	50	5	3.11	3.54	7.57	8.45
2	100	3	4.46	4.97	9.47	10.79	2	100	3	3.80	4.26	9.05	10.25
2	100	5	4.24	4.72	8.94	10.22	2	100	5	3.65	4.07	8.66	8.96
2	150	3	5.27	5.92	10.27	11.71	2	150	3	4.51	5.14	9.77	10.99
2	150	5	4.75	6.93	9.06	10.33	2	150	5	4.18	4.71	9.28	9.69

Table 1: Results.

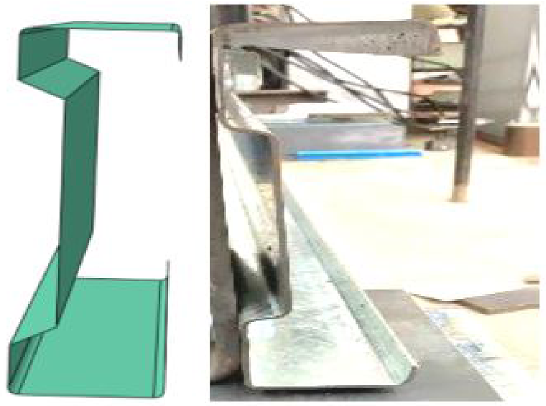

Fig 1 Sigma section.

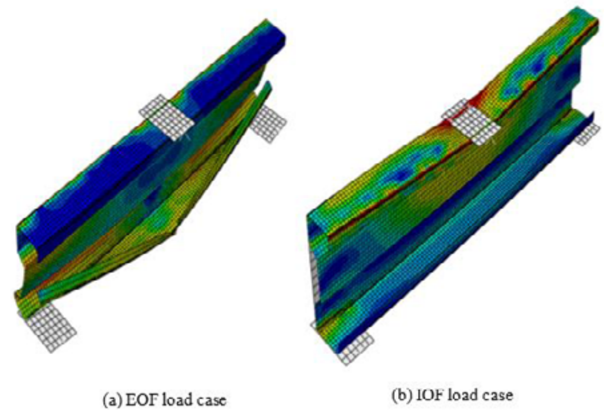

Fig 2 Failure pattern under one flange load cases.

Key parameters such as section depth, thickness, yield strength, radius, and bearing length were selected based on the industry requirements. Two section depths (140 mm, and 200 mm), two thicknesses (1 mm, and 2 mm), two different yield strengths (180 MPa and 220 MPa), two radii (3 mm, and 5 mm) and three bearing lengths (50 mm, 100 mm, and 150 mm) were included in the parametric plan. Overall, 96 numerical models were generated for both load cases.

Parametric study results were obtained from the numerical study which was carried out using ABAQUS/CAE (2017) and results were analyzed with key parameters to study their effect on web crippling behaviour of sigma sections under one flange loading conditions. Fig 2 illustrates the failure pattern of aluminium sigma sections under both load cases and Table 2 presents the obtained numerical results of section 140 and section 200 under one flange loading conditions.

AS/NZS 4600 (2018) reports a unified web crippling capacity equation under one flange load cases. The parametric study results of aluminium sigma sections under one flange loading conditions were compared with the existing design equation from the standard and the equation was modified according to the numerical results. A modified equation (Eqn 1) was proposed to accurately predict the web crippling capacity of aluminium sigma sections under IOF loading conditions. Table 2 presents the proposed coefficient values.

$$P_{proposed} = Ct^2\sqrt{Ef_y}\sin\theta\left(1 - C_R\sqrt{r_i/t}\right)\left(1 + C_N\sqrt{N/t}\right)\left(1 - C_h\sqrt{h/t}\right) \quad (1)$$

Where: fy - Yield strength; E- Elastic modulus; N- Bearing length; r_i- Radius; t- Thickness; h- Section effective depth; C, CR, CN and Ch- Geometrical coefficients

Load case	C	CR	CN	Ch
EOF	0.16	0.09	0.26	0.03
IOF	0.33	0.04	0.18	0.01

Table 2: Proposed coefficients.

Potential for application of results

Aluminium sigma sections are one of the best options to be employed in modular sections to provide maximum structural ability with light weight. However, their web crippling nature should be identified to avoid localized failures. On that note, the proposed equation becomes significant to fill the knowledge gap in the design procedure and ensure the design is safer and efficient.

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Full-scale fire test of non-load bearing hemp block wall

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Project objectives and goals

Hemp blocks, also referred to as hempcrete, are environmentally friendly and sustainable construction materials. They consist of a hemp plant shiv, lime binder, and water, making them a natural and renewable option. Owing to their carbon-negative properties, these blocks contribute to the reduction of carbon emissions and are notable for their excellent thermal insulation capabilities (Barbhuiya and Bhusan, 2022) (Jami et al., 2019). Their adoption has gained traction globally, with recent approvals for their use in construction projects across the United States and various other countries. Construction using hemp blocks is presently occurring in multiple countries, and consistent techniques are being utilised. Nevertheless, guidelines or standards that regulate the incorporation of hemp blocks in building construction are scarce. Furthermore, there is a substantial lack of information regarding its fire-resistance properties. The focus of this study is to examine the fire resistance of non-load-bearing walls constructed using hemp blocks, shedding light on their fire safety and suitability in diverse building applications.

Description of method and results

The fire resistance behaviour of a non-load-bearing wall made of hempcrete blocks was investigated using a fire-resistance furnace test apparatus. The test was performed to assess the structural stability, integrity, and insulation properties of the walls. The test was performed according to the SANS 10177 (2005), which follows ISO 834 (1999). The hemp block wall was built using commercially available hemp blocks, measuring 390 mm in length, 110 mm in width, and 110 mm in thickness. A wall measuring 2200 mm × 2400 mm was built, set up, and assessed 31 days following its installation. These blocks have a compressive strength of less than 1 MPa. Fig 1 shows the non-load-bearing hemp block wall layout and thermocouple arrangements, where R1 to R5 refer to the thermocouples located on the right and L1 to L5 are those situated on the left. The temperature in the furnace was controlled by the average of ten plate K-type thermocouples. High-temperature 10 × 1200 mm plate-type stainless-steel K-type thermocouples were used. The surface (exposed and unexposed) temperatures of the walls were measured using two groups of five thermocouples. Additional temperature measurements were taken at distances of 27.5 mm, 55 mm, and 82.5 mm from the exposed face of the blocks to determine the temperature gradient. The furnace test was conducted for 2 h. The hemp block walls maintained their structural stability and integrity after 2 h of the standard fire testing. The maximum deflection measured was 15 mm from the outside, and it was observed that the deflection occurred gradually.

Potential for application of results

The results of the standard furnace test on the hemp block wall system indicated that the system could withstand exposure for the duration of the 2 h furnace test. The maximum recorded unexposed surface temperature was 75 °C, as shown in Fig 2. After 2 h of exposure, the blocks remained intact and maintained their structure. After being exposed to the furnace heating, the hemp blocks exhibited different discolouration, including white, grey, brown, and cream layers. These layers accounted for varying proportions of the total thickness of the hemp blocks, with approximately 74 % of the blocks affected (complete burn and char) by the applied heat. However, no significant holes or damage were observed, and a high exposure temperature of 1050 °C resulted in the hemp block glowing by the end of the test. The results indicated that the system exhibited good fire resistance characteristics, including stability, integrity, and insulation properties. After 24 h, the wall system showed minimal deflection and negligible impact on stability, suggesting its suitability as a partitioning component for non-load-bearing walls. This suggests that the hemp block wall system has potential as a building material because it can provide fire resistance in addition to other desirable properties, such as thermal insulation and sustainability. Further research is needed to investigate the long-term durability of hemp as a construction material and to assess its suitability for various construction applications. Moreover, plastering hemp blocks can further improve fire resistance properties. This additional plaster layer offers further protection against ignition and reduces the risk of fire spreading. Consequently, the fire-resistance performance of hemp blocks is likely to be more reliable and robust in construction applications than that indicated here when plastered.

Fig 1 Non-load bearing hemp block wall layout and thermocouple arrangement.

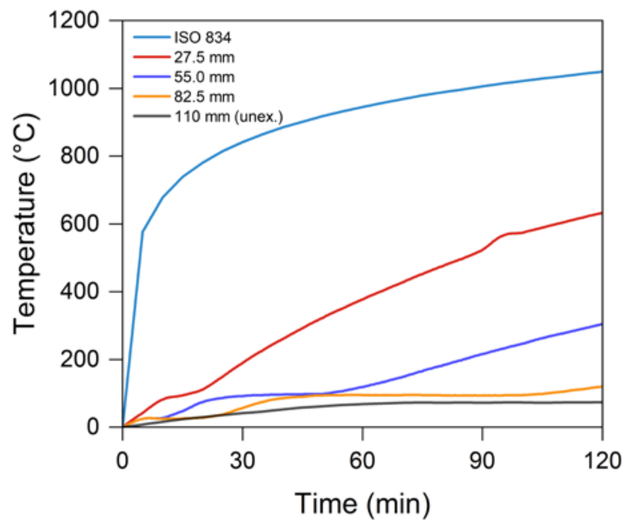

Fig 2 Temperatures recorded at specific thermocouple locations from the exposed face.

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Funding body

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Publication

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Disproportionate collapse resistance of timber beam-column connections

13 **L M Milindu B Jayasekara**
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Project objectives and goals

Timber beam-column connections are typically multi-material assemblages combining metals with engineered timber. In addition to providing a load path between members, they are the main source of ductility in timber post-and-beam structures. Appropriately designed, they sustain large deformations without loss of capacity, providing energy dissipation through plastic deformation and enabling kinematics required to form alternative load paths in the event of element removal, thereby avoiding a disproportionate or progressive collapse. A full understanding of timber connection ductility and capacities under large deformations and combined loading is crucial for safe design. Experimental and numerical studies on the performance of increasingly sophisticated contemporary timber beam-column connections are limited. This project aims to investigate the disproportionate collapse resistance of hanger-type timber beam-column connections to inform design guidance. The following are the key objectives.

- Develop a computational modelling technique to capture complex pre- and post-failure behaviour of multi-material timber connections under combined loading and at strain rates ranging from quasi-static to fully dynamic.
- Investigate, experimentally and numerically, the flexural and shear behaviour including failure modes of hanger-type timber beam-column connections under large deformations.
- Investigate, experimentally and numerically, the resistance of sub-frames using hanger-type timber beam-column connections under combined moment, axial and shear loads resulting from column removal.

Description of method and results

A computational modelling technique was developed for complex simulations of multi-material timber connections. Continuum damage modelling was used to replicate post-yield damage initiation and damage evolution for metal components. Two widely used single-surface failure criteria, two recent multi-surface failure criteria, and two new composite failure criteria proposed in this study were compared to select a suitable constitutive law to capture the complex failure behaviour of timber that can include both plastic yield and brittle fracture. Implementation in the finite element (FE) domain using explicit integration with the forward Euler method enabled the application of these failure criteria in highly nonlinear complex analyses. Combined with appropriate modelling techniques and solving tools, this enables accurate and efficient simulation of complex multi-material connections through large deformations. Comparison of model predictions with experimental results in the literature indicates that a Hill-Gharib composite failure criteria provides the most realistic simulation of actual behaviour.

A timber beam-column connection composed of “L” shaped steel brackets bolted through columns was designed according to Eurocodes to investigate the flexural and shear performance of combining a multi-dowel slotted-in T-plate with a bearing plate. A limitation of previous studies has been the difficulty of obtaining a full true stress-strain profile for the bolts post-necking. Therefore, a novel uniaxial tensile testing procedure was developed in this study using computer vision and Python for ductile metals to derive material true stress-strain relationships required for accurate numerical simulation of post-necking responses. Experiments were conducted on a reduced-scale L-connection through large deformations and were compared against FE predictions obtained using the developed computational model. The connection exhibited ductile shear and flexural failure modes showing large deformation capacities without loss of strength. FE predictions, including failure modes, agree well with experiments, and the moment-rotation behaviour of the connection is depicted in Fig 1a. The flexural and shear behaviour of a “C” shaped steel bracket was also predicted using the numerical model.

Combined moment, axial and shear loading resistance of the L- and C-connections under column removal was explored conducting reduced scale experiments on a two-bay sub-frame. Displacement control loading applied on the unsupported middle column was used to replicate quasi-static, and two fast load rates of 200 mms-1 and 400 mms-1. The results suggest that no significant strain rate effect on the overall load-displacement response exists for the selected load rates. Both the connectors demonstrate the ability to develop alternative load paths through catenary action. True dynamic tests using sudden column removal were also performed for each connection type. These displayed a significant capacity reduction with displacement and resistance dynamic amplification factors of about 1.5 and 2 respectively. FE predictions agree well with quasi-static, fast load rates, and dynamic experimental results. Fig 1b illustrates the numerical results of the quasi-static load-displacement response compared to experiments, and Fig 2 presents failure modes.

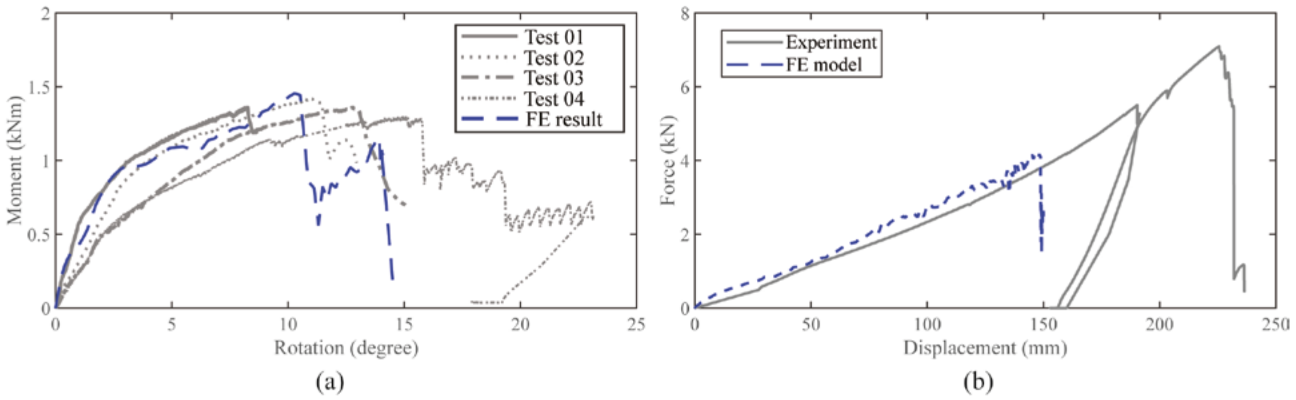

Fig 1 (a) Moment-rotation and (b) column removal load-displacement responses of L-connection.

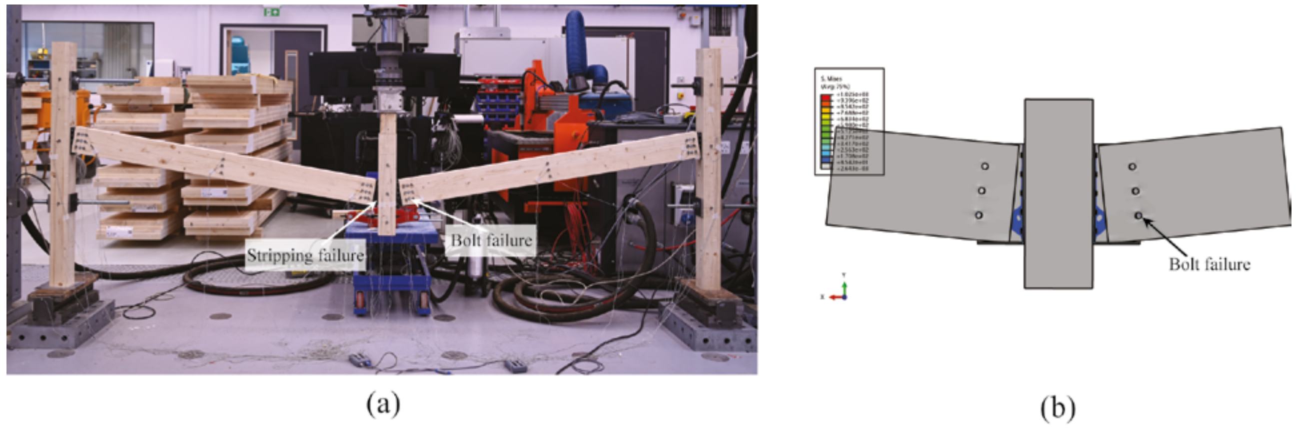

Fig 2 (a) Experimental and (b) numerical failure modes of L-connection column removal test.

Potential for application of results

- The computational modelling technique developed and the proposed Hill-Gharib composite failure criterion using explicit integration methods can be used to capture complex pre- and post-failure behaviour of multi-material timber connections under diverse loads including dynamic loads.
- Both “L” and “C” connections exhibit a ductile behaviour indicating their potential to provide adequate strength and rotational capacity that may be exploited in design against disproportionate collapse, seismic actions or in fire.
- The novel tensile testing procedure that uses computer vision techniques with Python is a simple, cost-effective, and accurate method for obtaining true stress-strain relationships of ductile metal specimens to numerically simulate realistic post-necking behaviour.
- The connections designed to satisfy Eurocode tie force requirements were able to form catenary action, but the realised capacity may not be sufficient in all design cases. Dynamic situations reduce load capacity, requiring connection design methods that explicitly account for dynamic and combined loading effects.
- The experimental and numerical analyses conducted provide insights into possible collapse-resisting behaviours, including failure modes, of the timber beam-column connections investigated. The methods developed will also enable more accurate modelling and prediction of the behaviour of complex multi-material timber connections more generally, enabling the design of more efficient, reliable and robust timber structures.

Funding body

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Shielding History: Protection of Historical Buildings against Explosions

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Objectives and goals

Blasts can occur due to accidental events, such as industrial explosions and accidental truck bursts, or due to deliberate malicious actions. Regardless of their cause, their effects can jeopardise the integrity of vulnerable structures as the risk of malicious explosions increases with the advancement and accessibility of technology, geopolitical tensions, and domestic political instability.

Historical buildings, which have not been built to either survive extreme events or to meet the requirements of modern construction standards, are in need of efficient protective strategies against blast loads. This need is heightened by the unique quality of historical constructions to stand for generations to come as ambassadors of their nation's legacy. In this context, masonry, commonly used in historical constructions (Lourenco 1996), poses a unique challenge for preservation efforts due to its fragile nature. To safeguard an important historical building from potential blast threats, protective measures are usually taken to enforce a safe distance between the structure and the potential sources of danger and consequently minimise the potential ensuing loads on that building. Examples of these measures are bollards, strong peripheral walls and/or controlling the accessibility to the structure (Yandzio and Gough 1999). To implement these measures, sufficient space is needed around the building. However, many historical buildings are vulnerable and space does not exist that allow for such protective measures, highlighting the need to strengthen the building itself against the effects of extreme blasts.

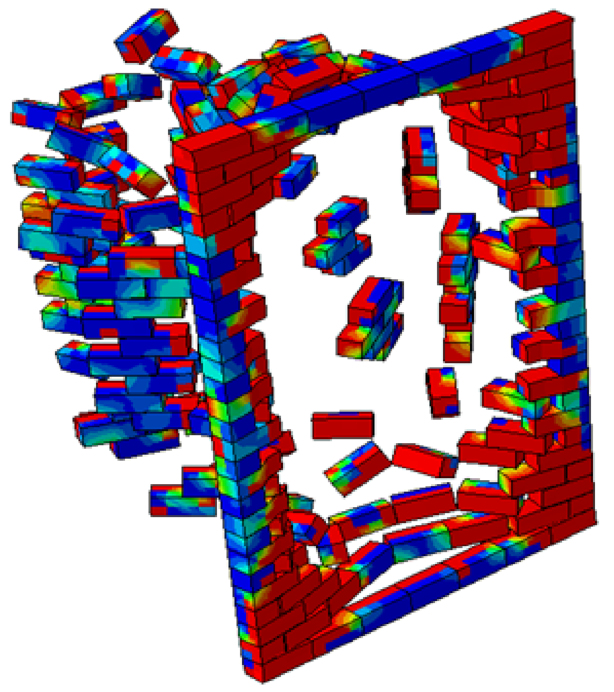

Fig 1 Damage mechanism of a single-leaf URM panel under blast scenario.

The available scientific literature presents several traditional methods of masonry strengthening such as FRP sheets/laminates (Myers et al., 2004), sprayed polyurea (Davidson et al., 2005), and RC jackets (Abd-Mooty et al., 2017). These methods involve permanently bonding new materials to the masonry, which can be incompatible with the nature of a historical building. These strengthening methods also alter the structural characteristics of the building and consequently change its behaviour under other extreme risks such as earthquakes. In this context, the goal of this project is to device a temporary lightweight sacrificial cladding with high energy absorption capacity. These new cladding components will be placed in contact with the existing building to act as a sacrificial façade and a first line of defence against explosions, but could be easily removed if required. This cladding is intended to absorb the blast energy and keep the transmitted stresses to the shielded masonry within safe limits.

Method and results

This research adopts a combination of numerical and experimental studies. Nonlinear high-fidelity mesoscale numerical simulations are conducted to better understand the behaviour of various historical masonry constructions (such as single- and multi-leaf constructions) under blast loads. Brick/stone units are expanded to include mortar dimensions (if present) and modelled as continuum elements with plasticity-based damage material laws. On the other hand, the bond between units and mortar is represented by surface-based mixed-mode cohesive contact, hard penalty stiffness, and Coulomb friction failure criteria. Blast loads due to free-air and ground detonations are simulated using the Conventional Weapons software (ConWep). Moreover, recognizing the higher mechanical properties exhibited by materials under high loading rates, like blasts, compared to low rates, the effects of high-strain rates are considered in this research.

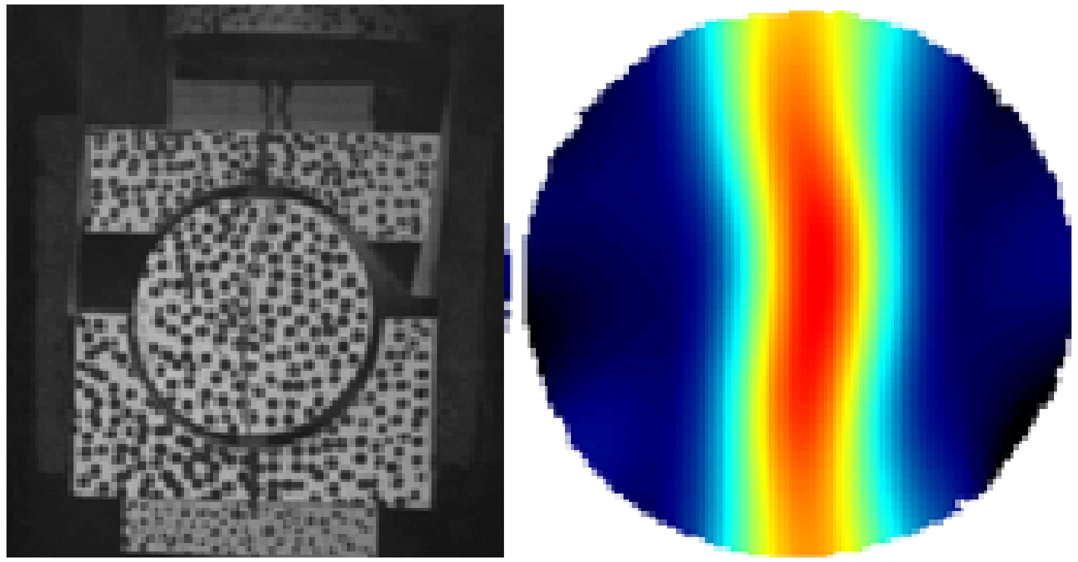

Fig 2 Mortar specimen under impact: left) splitted specimen; right) DIC strain map.

However, existing work on the high strain rate sensitivity of masonry materials is limited and there is no work on the sensitivity of historical mortars. To this end, experiments are conducted to characterise the strain-rate sensitivity of various masonry elements, with a specific focus on typical historical materials. High-speed impact tests are carried out on various pure lime mortars under compressive and and splitting tension stresses and the sensitivity of various mechanical properties is investigated. Two high-speed cameras oriented in stereo position were used to measure strains on the surfaces of the samples via digital image correlation (DIC). Experimental investigation of dynamic strengths and strain rate sensitivity of tensile bond strength and shear bond strength of masonry joints, and compressive strength of masonry is ongoing. Fig 1 shows the damage of a single-leaf URM panel under blast and Fig 2 presents the development of a splitting crack in a mortar specimen along with the strain map obtained with DIC.

Potential for application of results

The research outputs of this study will play an important role in the preservation of vulnerable historical buildings during periods of high blast risks without compromising their heritage value. This research also promotes a wider reuse of lime, typically found in historical mortars, in modern constructions as a replacement for cement due to the lower carbon footprint of lime. The work on lime mortars and other masonry materials provides new understanding which is expressed in practical equations for determining their strain rate sensitivity suitable for standards and guidelines.

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The hypothesis of massless structure in computing the waterborne debris impact forces on structures is not accurate when the structure-to-debris mass ratio is higher than a critical value

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Project objectives and goals

Waterborne debris impacts on structures cause significant damage in extreme hydrodynamic events like floods or tsunamis (Korswagen et al., 2022). The equivalent force approach is commonly used to simulate the structural behaviour in these scenarios. Here, the impact load is represented through a force-time (F-t) diagram and used to define a time-dependent force. These F-t diagrams depend on the debris velocity v_d, mass m_d and stiffness k_d and structural stiffness k_s (Piran Aghl et al., 2014). In particular, k_s determines the occurrence of flexible or rigid impacts by influencing the resistance opposed by the structure to the debris (Paczkowski et al., 2012). In rigid impacts, the structure behaves as a rigid body and the F-t diagram is rectangular. In flexible impacts, the structure is displaced significantly, and the F-t diagram is sinusoidal. Given the same debris properties, the impact force is more severe in rigid impacts. However, the structural resistance might also depend on the structural mass m_s (Haehnel and Daly, 2004), but this has never been investigated. The F-t diagrams are computed with analytical models, but many of them ignore m_s due to the lack of information about its role. As such, they assume a massless structure. This is the case of the one-dimensional wave propagation (1DWP) model by Paczkowski et al. (2012) and of the design prescription by ASCE/SEI 7-22 (ASCE, 2022), which are a simplified version of the 1DWP.

Based on the information reported in the previous paragraph, it is unknown whether m_s affects the F-t diagram, and if this happens, the 1DWP and ASCE models might be inaccurate. Therefore, considering a log debris impact, the objectives of this study are:

- To investigate the effects of m_s across a range of structure-to-debris mass ratios.
- To assess the accuracy of the 1DWP and ASCE models to compute the F-t diagrams in such a range.

Description of method and results

The numerical F-t diagrams used as a reference are obtained with a solid debris impact model, where the structure and debris are represented as interacting solid bodies (Fig 1). The simulations are carried out using the FE software Abaqus/CAE (Abaqus, 2018). The mass and stiffness ratio, computed as:

$$\mu = \frac{m_s}{m_d}, \qquad \delta = \frac{\delta_s}{\delta_d} \qquad (1)$$

respectively, are defined. The impact force F is measured at the contact area as a function of the time t. The nondimensional force and time, computed as:

$$F_{nodim} = \frac{F}{v_d\sqrt{m_d k_d}}, \qquad t_{nodim} = \frac{t}{2\sqrt{\frac{m_d}{k_d}}} \qquad (2)$$

respectively, are presented to compare different cases. k_d is the longitudinal debris stiffness. k_s is the transversal structural stiffness. The model is validated against the results by Paczkowski et al. (2012). The log properties are those given by ASCE/SEI 7-22 as minimum design demand, i.e. m_d=450 kg and k_d=61300 kN/m. v_d=1.8 m/s is chosen in the range tested by Piran Aghl et al. (2014). The structure is a simply supported elastic square plate with edge length of 3 m and thickness 0.1 m. The target values of μ and δ are obtained by varying m_s and k_s (by adapting the density ρ_s and Young's modulus E_s). To understand the contribution to structural resistance given by m_s, a low k_s is used. As such, δ=0.3 is chosen to have a flexible impact under the massless structure hypothesis (Paczkowski et al., 2012). μ is varied between 0.001 and 20. The wall studied in De Iasio et al. (2023) has δ=0.25 and μ=5.3, therefore, the studied range is realistic.

Results are shown in Fig 2. The massless structure hypothesis is valid for low μ as strong similarities are observed between the numerical F-t diagrams and the 1DWP model for 0.001<μ<1. Here, the impact is flexible and follows the sinusoidal 1DWP diagram. Conversely, the shape of the F-t diagrams becomes rectangular with plateau force proportional to μ for μ>2. Therefore, μ=2 is the critical value μ_{cr} for which the effects of m_s are significant, and the hypothesis of massless structure is not more valid. The rectangular shape conveys that a rigid impact happens

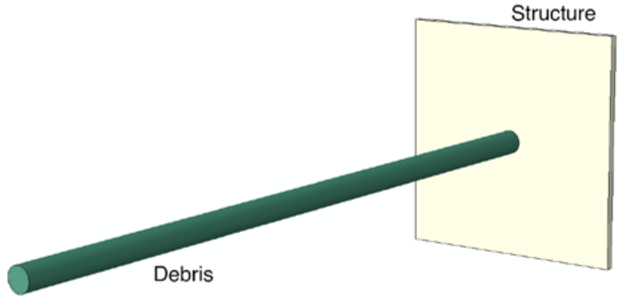

Fig 1 Representation of the solid debris impact model.

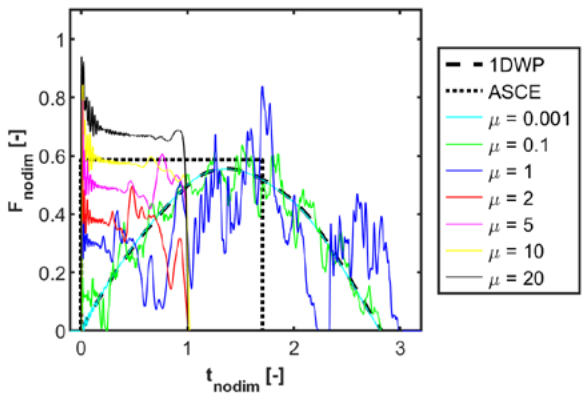

Fig 2 Numerical F-t diagrams for different values of μ compared against those computed using the 1DWP and ASCE models.

due to the effect of m_s instead of the flexible impact predicted assuming m_s=0. In such circumstances, the 1DWP and ASCE models are significantly inaccurate. It is worth noting that the design prescriptions by ASCE always overestimate the impact duration and either underestimate or overestimate the plateau force based on the value of μ.

Potential for application of results

The findings demonstrate that m_s significantly affects the debris impact F-t diagram if μ>μ_{cr}. In these scenarios, the hypothesis of massless structure becomes inaccurate. As such, the 1DWP model, based on this hypothesis, fails. The design prescription by ASCE/SEI 7-22, based on the 1DWP model, are also inaccurate. Therefore, these results indicate that m_s needs to be accounted for in updated design prescriptions to consider waterborne debris impacts on structures accurately. To work on this update is a valuable future research project.

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3D Modelling of Masonry Arch Bridges

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Project objectives and goals

Masonry arch bridges play a paramount role within the UK's transport network for both railway and roadway traffic. Owing to their deterioration due to both environmental effects and increasing traffic demands, the assessment of their structural safety has become an insistent need. However, this need has always been hindered by their complex nature, resulting into a lack of confidence regarding their structural reliability. This problem becomes further amplified when considering the large proportion of these bridges in the UK, as well as the economic and environmental cost for their replacement. Such cost can only be evaded through reliable assessment tools, which can effectively contribute to making informed decisions regarding these bridges.

Masonry bridges are mainly composed of an arch barrel and spandrel walls, confining the backfill which the bridge deck rests on. Based on the bridge orientation, the arch barrel could be square or skew, affecting the construction method for the barrel. Such variability in the details of the bridge components and the mutual interaction between these components lead to a complex behaviour, which is predominantly three-dimensional under the effects of asymmetric traffic loads. However, most of the current assessment methods are two-dimensional ignoring any 3D effects. Moreover, these methods mainly focus on the ultimate response of these bridges despite the importance of the response under service loads, which is more critical to avoid further deterioration for these bridges. These shortcomings are addressed in this study through 3D detailed models as outlined in the next section.

The objectives of this study are to:

- Adopt a consistent procedure to calibrate the 3D detailed models based on material tests.
- Validate the calibrated models against previous experimental tests on masonry arch bridges.
- Use the validated models to explore the 3D characteristics for the behaviour of masonry arch bridges through extensive parametric studies to improve the understanding for their complex behaviour.
- Utilise the results of the parametric studies to calibrate practical lower-level assessment tools.

Description of method and results

In this study, a 3D modelling strategy that can capture cracks and plastic deformations within the structure up to collapse is adopted, as described in (Grosman et al., 2021). This strategy accounts for the nonlinear behaviour of different bridge components, as well as their mutual interaction. This is achieved by using a discrete 3D mesoscale modelling approach to model the masonry components, allowing for the actual masonry bond. This approach utilises 3D elastic solid elements to model masonry units and 2D nonlinear interface elements to model both mortar joints and potential fracture planes within bricks. The material nonlinearity in masonry is lumped within the interfaces using a cohesive-frictional material model. This is complemented with a continuous elastoplastic modelling approach for backfill, where the plastic response for backfill is defined by a modified Drucker-Prager yield criterion.

In addition, the interaction between the bridge components is considered using nonlinear interface elements at their mutual physical interfaces, where a mesh tying approach, based on the mortar method, is adopted to allow for the connectivity between the non-conforming meshes for the arch barrel, backfill, and spandrel walls. Such detailed models are associated with a significant computational cost which is efficiently reduced using a domain partitioning technique, where the bridge is subdivided into smaller partitions linked together using a parent structure, allowing for an efficient parallel computation. The proposed methodology is implemented in the nonlinear finite element program ADAPTIC (Izzuddin, 1991).

The adopted modelling strategy has been validated against the experimental tests carried out on both square (Melbourne and Gilbert, 1995) and skew bridges (Hodgson, 1996), where the 3D models managed to efficiently predict both the experimental load-displacement response and failure modes as highlighted in Fig 1 and 2. The validated models have then been used to perform extensive parametric studies on both square and skew masonry arch bridges under the effect of patch loads, to contribute to the development of a more profound understanding of the 3D behaviour of masonry arch bridges.

Potential for application of results

Due to the limitations associated with the experimental testing for masonry bridges, the only means to reach an improved understanding for their behaviour is through accurately validated numerical models. These models are extended to investigate both square and skew bridges

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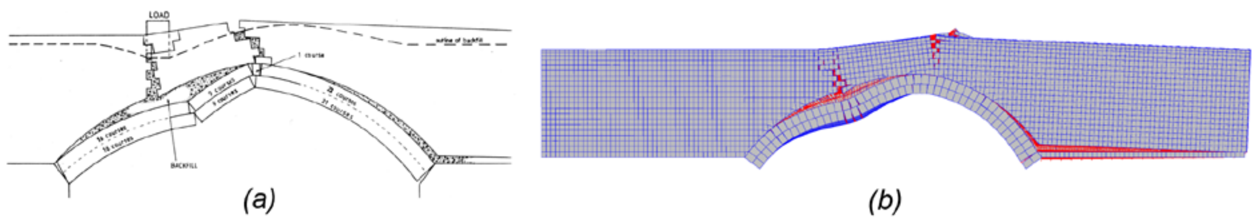

Fig 1 (a) Experimental failure mode; (b) Numerical deformed shape at failure for square bridge "Bridge 3-3" (Melbourne and Gilbert, 1995).

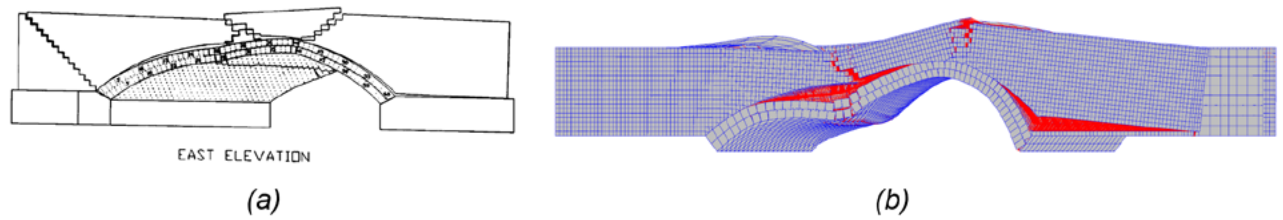

Fig 2 (a) Experimental failure mode; (b) Numerical deformed shape at failure for skew bridge "Bridge 3-3" (Hodgson, 1996).

under traffic patch loading, identifying the most critical load locations. In addition, different geometries are considered including bridges with various dimensions and bond patterns. The contributions of the bridge components are also investigated, showing how spandrel walls can influence the bridge overall performance. Moreover, the load distribution through backfill is explored for different backfill types. Such large stock of models with various characteristics enriches the understanding for masonry bridges, allowing for the development of reliable assessment tools that can be implemented in future standards.

The high computational cost for these detailed models renders them inconvenient for practical assessments. However, they can be used to calibrate simplified 2D strip models by deriving an appropriate effective width that can account for the 3D effects in the full bridge models. In another perspective, simplification can be directed towards the scale of material modelling, where relaxed mesoscale, or even macroscale models can be adopted. Despite the reduced computational effort for these models, their accuracy is only guaranteed through proper calibration which can be performed based on the detailed models. Finally, the aim of these simplifications is to reach practical assessment tools for masonry bridges without violating the accuracy of such assessments.

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Innovative optimization method for internally voided concrete building elements

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Project objectives and goals

The use of voided slabs commercially in buildings has become widespread over the past three decades and the use of voided beam and columns has garnered significant interest. One of the main advantages of void formers applied in practice have been to reduce the environmental and economic cost while maintaining the overall depth of the element.

Several experimental and numerical studies have also been done to assess the performance of voided beams and columns with mixed results. Simplified approaches in literature typically involves homogenization methods which are appropriate to assess the global behavior of the voided concrete. Several homogenization methods do not consider local effects such as local punching shear failure and the stress distribution through the concrete which are critical in the evaluation of internally voided concrete in discontinuity regions. There is also a lack of research into void former shape design and optimization.
To address the existing research gap, the focal point of this research is to develop analysis methods to evaluate the effect of the layout and shape of void formers and apply optimization techniques to internally voided concrete building elements.

Description of method and results

The project method includes a validated micromechanical model based on previous experiments. In order to assess optimization objectives, a novel methodology, vertical fiber analysis (VFA) is put forward for the design of internally voided concrete elements. In VFA, the design force is distributed to each vertical fiber based on the width of the fiber. Each fiber should be able to resist the applied load for it to meet the requirements of the design. For design purposes, it is not necessary to distribute the reinforcement equally to each fiber. As indicated in Fig 1, each fiber is designed based on the required reinforcement, where A_(st,i) is the reinforcement at a location i and n is the number of fibers. VFA is used to design concrete elements using 2D calculation methods such as compatible stress field method (CSFM) and strut-and-tie model (STM) to assess and tabulate the capacity of each vertical fiber across a void former.

VFA is applicable to internally voided D-regions and has the advantage of being able to consider local effects and assess the results of void former optimization. VFA is applicable to void formers spaced through a concrete element and give conservative design results. The accuracy of VFA is dependent on the number and distribution of fibers. The width of the vertical fiber should be small enough to account for relevant local effects.

For computational efficiency, CSFM is used for the calculation of the strength of each fiber. CSFM is particularly suitable for discontinuity regions, which uses both the advantages of stress fields and strut-and-tie models (Kaufmann, et al. 2020). CSFM is used to perform

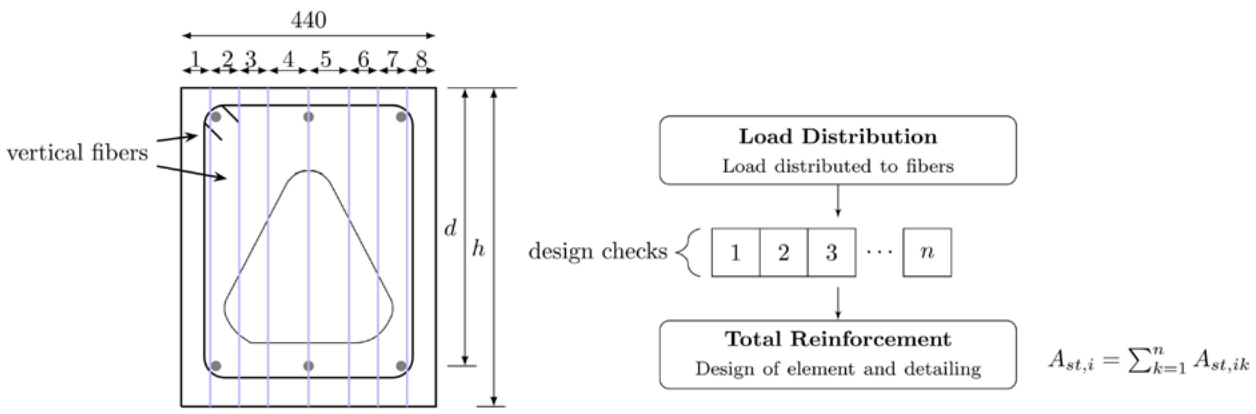

Fig 1 Vertical fibers for design checks.

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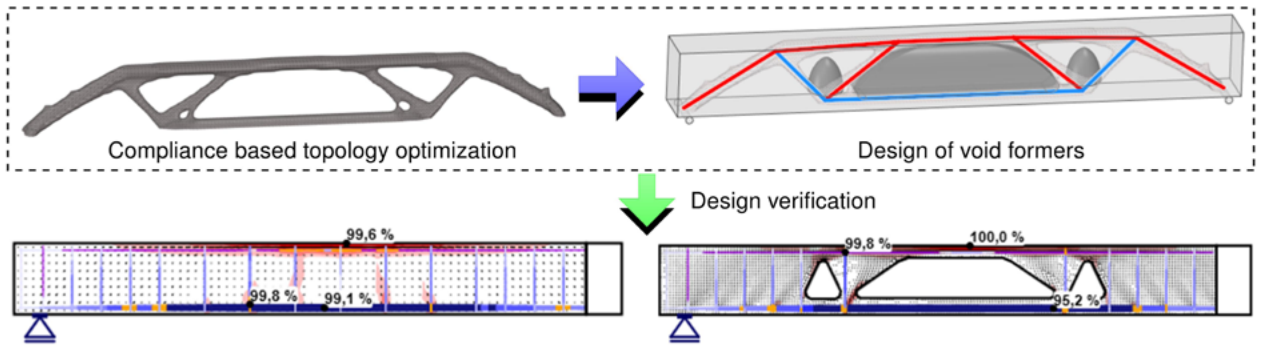

Fig 2 Topology Optimization and Design Verification.

analyses based on assumed, rotating, stress-free cracks that open without slip and take into account equilibrium at cracks and average strains of the reinforcement (Kaufmann, et al. 2020).

The results of VFA with CSFM are comparable to that of the micromechanical models validated in Ansys Structural Static 2023 for cases with beneficial void former configuration, and produces conservative results when void formers are placed in regions dominated by local effects. To corroborate the research findings, the study incorporates experimental testing of voided beams primarily subjected to flexural and shear forces under cyclic loading conditions.

VFA has been used to verify void former shape design obtained from compliance-based topology optimization. Fig 2 shows vertical fibers with similar reinforcements subjected to a uniformly distributed load. The configuration of the void formers in this arrangement is considered as beneficial. From the results, novel void former shapes have been put forward such as the pear and trapezoidal shaped void formers. From analysis results, pear shaped void formers perform better than spheres when subjected to point loads. In previous experimental results, the most comparable void former shape to a pear was a cone for which a voided slab had a greater ultimate capacity when compared to the solid slab (Bhamare, et al. 2019).
Potential for application of results

With a global push towards conservation, the research findings can be used for design optimization of internally voided concrete and determine safe void former configurations without impacting the ultimate load capacity. The research methods can be applied to internally voided concrete to minimize self-weight and reduce overall costs. VFA can also be used to detect problems in void former shapes and layout; verify optimization results and determine the required reinforcement detailing around void formers.

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Designing auxetic structures through topology optimization

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Project objectives and goals

This research project aims to revolutionize the field of materials by focusing on the design of auxetic structures through the application of topology optimization techniques. Mechanical metamaterials are manufactured structures with extreme mechanical properties that do not exist in nature (Saurabh et al., 2023). It is the array of microstructures designed to provide specific properties with unique geometrical configurations of the unit cell instead of the material properties (see Fig. 1). Unlike most materials that contract when stretched and expand when compressed, auxetic structures exhibit the opposite behaviour—they expand when stretched and contract when compressed. The primary objectives include delving into the principles and applications of auxetic materials, establishing a solid foundation in topology optimization methodologies, and evaluating materials for their suitability in creating innovative structures. The project seeks to define specific design criteria, develop a computational model, and implement optimization algorithms to iteratively refine the topology of auxetic structures. The ultimate goal is to create novel auxetic designs with superior mechanical properties and wide-ranging applicability across industries.

By achieving these objectives and goals, this project aspires to contribute groundbreaking advancements in materials science. The envisioned outcomes include the creation of efficient auxetic structures surpassing existing designs, optimization of mechanical properties for enhanced performance, and the exploration of diverse applications in aerospace, automotive, biomedical, and consumer goods industries. The research aims to bridge the gap between theoretical design and practical implementation, ensuring manufacturability and promoting sustainability through eco-friendly materials and optimized designs. Ultimately, this project seeks to not only advance the understanding of auxetic structures but also to provide tangible solutions and innovations with real-world applications, pushing the boundaries of materials engineering and topology optimization.

Description of method and results

The conventional density-based Topology Optimization (TO) method aims to discover the optimal configuration of material distribution within a defined domain. In this methodology, the density of each finite element serves as the design variable. The SIMP (Solid Isotropic Material with Penalization) method utilizes a power-law formulation to establish the relationship between this density variable and material properties. It imposes a penalty on the existence of material within an element, compelling the density to approach values of either 1 or 0. The optimization challenge for TO in micro-structure design, with the goal of maximizing the elastic modulus, can be expressed as follows:

$$\begin{aligned} &\underset{\rho}{\text{minimize}}: -\eta(\rho_e)\left(C^H_{1122} - \delta^l\left(C^H_{1111} + C^H_{2222}\right)\right) \\ &\text{subject to}: \boldsymbol{KU}^{(jj)} = \boldsymbol{F}^{jj}, j = 1, \dots, d \\ &\qquad : \textstyle\sum_{e=1}^{N} v_e \rho_e \le \mathcal{V}_f \\ &\qquad : 0 \le \rho_e \le 1, e = 1, \dots, N. \end{aligned} \qquad (10)$$

Here, C^H_{ijij} represents the homogenized stiffness tensor. In the provided equation, K represents the global stiffness matrix, while $U^{(jj)}$ and F^{jj} stand for the global displacement and external force vectors corresponding to the specified test case (*jj*). The symbols d and v_e represent the spatial dimension and elemental volume, respectively, and V_f denotes the permissible material volume fraction. δ is a fixed parameter specified by the user, and the exponent l indicates the number of design iterations. As per the modified SIMP approach, the element elastic modulus $\eta(\rho_e)$ can be defined as [9]:

$$\eta(\rho_e) = E_{\min} + (\rho_e)^p (E_0 - E_{\min}), \quad \rho_e \in [0,1] \qquad (11)$$

where ρ_e is the elemental density, Young's modulus of solid material is represented by E_0, while Young's modulus of the Ersatz material is represented by $E_{\min}$.
The python code developed by (Gupta et al., 2020) using the open-source scientific computing platform FEniCS has been adapted and modified for the current study. The results of numerical implementation are presented in Fig. 2. The results of this study showcase novel auxetic designs with superior mechanical properties achieved through topology optimization. These optimized structures will demonstrate enhanced flexibility, resilience, and load-bearing capabilities compared to traditional materials.

Potential for application of results

The results of this project have the potential to revolutionize a multitude of industries through the application of optimized auxetic structures designed using topology optimization techniques. In the aerospace sector, these structures could lead to the creation of lighter yet more resilient components, improving fuel efficiency in aircraft.

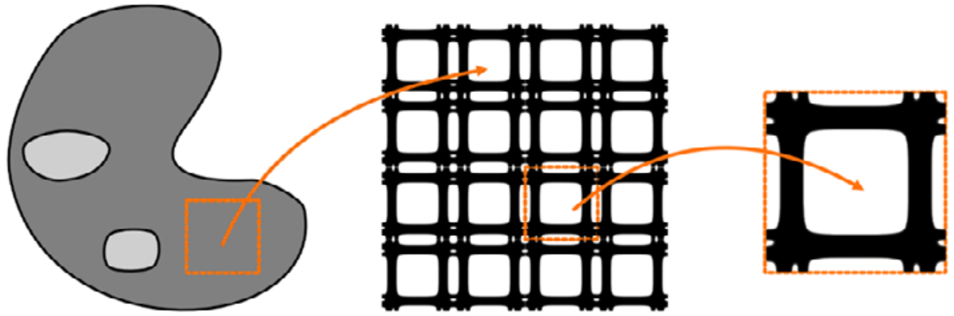


Fig. 1 Depiction of a material constituted by periodically arranged unit cells.

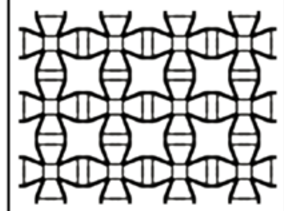
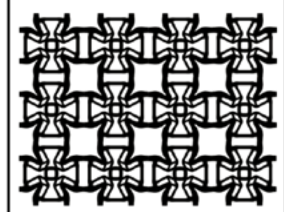
Topological parameters	Unit cell	3 × 4 structure	Homogenized Poisson's ratio
initial design = 1 $nel_x = 75$ $r_{min} = 3$ $\mathcal{V}_f = 0.3$ $p = 4$			$\overline{\nu} = -0.33$
initial design = 1 $nel_x = 100$ $r_{min} = 3$ $\mathcal{V}_f = 0.5$ $p = 5$			$\overline{\nu} = -0.62$

Fig. 2 : Optimum designs of auxetic structures for different topological parameters.

The automotive industry stands to benefit from enhanced impact absorption and increased safety by integrating auxetic materials into vehicle components. Biomedical engineering could see improved implants and prosthetics with increased comfort and functionality, while the consumer goods sector may witness innovative designs in sportswear, protective gear, and ergonomic furniture. The designed auxetic structures will not only surpass existing designs but also find diverse applications across industries, thereby establishing a new paradigm in materials engineering through the fusion of auxetics and topology optimization.

Furthermore, the construction industry could leverage the project's findings to create more resilient and earthquake-resistant structures. The adaptability of auxetic materials under stress makes them ideal for enhancing the durability of construction materials. The project's impact extends to advanced manufacturing processes, where optimized designs can be seamlessly integrated into 3D printing and other manufacturing technologies, streamlining production and reducing costs. Moreover, the focus on sustainability and eco-friendly materials contributes to environmental conservation efforts, potentially reducing the overall environmental impact of manufacturing processes. The research aims to yield a comprehensive understanding of the impact of material variations and design parameters on auxetic structures' performance, providing valuable insights for future advancements. In essence, the transformative potential of these results is poised to significantly influence diverse facets of modern industry and scientific exploration.

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BIM-based Circularity Assessment for Sustainable Construction

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Project objectives and goals

The research aim is to investigate how to leverage building information modelling (BIM) to develop a comprehensive and integrated framework for building circularity and sustainability assessment at the early design stage to inform design decisions. The following objectives were set to achieve the aim of this study:

- Identify existing indicators for assessing building circularity and BIM integration approaches.
- Develop a comprehensive and integrated assessment framework to inform design decisions from a technical circularity and sustainability perspective.
- Implement the proposed framework in a BIM-based tool.
- Demonstrate and validate the framework by using the prototype in a case study.

The current BIM-based tools are still in their infancy and use different calculation methods. Current tools do not provide a comprehensive assessment for decision-making support effectively and no approach simultaneously accounts for circularity and sustainability aspects in decision-making for the trade-off of different aspects and informs design decisions. Most studies focus on linking to a custom external database, not on the inclusion of circularity information in BIM objects (elements and materials). In the case of the addition of information in objects, still, the addition of information in objects is limited only to the elements (thus, not materials) and does not align with the material passports (MP). The need for this integrated assessment and practical tool is emphasized in several studies.

Description of method and results

The design science research methodology was adopted to develop an artefact to address a problem (Hevner et al., 2004). The artifact produced is a framework expressed through a software prototype as proof of concept. It is identified that building circularity indicator (BCI) for the technical circularity adapted from (Verberne, 2016) (Cottafava & Ritzen, 2021) (Khadim et al., 2023) and life cycle sustainability assessment (LCSA) were most suitable for developing the integrated assessment framework. The proposed framework is based on the four steps recommended by ISO 14040 and 14044 standards on LCA and the identified and adopted indicators and BIM integration approach. This research adopts the second integration approach suggested by (Díaz & Antön, 2014) and the fifth strategy identified by (Wastiels & Decuypere, 2019), which are related to the addition of information into the BIM. This leverages BIM potential in information management and acts as a data repository for information throughout the project's life cycle (Santos et al., 2019). Moreover, this will facilitate the generation and documentation of material passports and data traceability for the material bank.

The proposed prototype tool follows the three steps of input, processing, and output as shown in Fig 1.

The proposed framework is implemented into a BIM-based prototype tool as an add-in (plugin) within Autodesk Revit using C# programming language and Revit API. MySQL was used to develop the database for semantic enrichment and Airtable was used as a cloud-based database for the material passport. The Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) was chosen as a multi-criteria decision analysis method to select the optimal design solution among various design alternatives. The three criteria (circularity, embodied carbon, and cost) can be assigned equal weights of importance, or users can specify weights based on their preferences and project objectives as shown in Fig 2.

The proposed prototype provides circularity and sustainability insights within a colour-coded BIM model (green to red scale), graphical charts, tabular, and parameters in elements properties and project information. The tabular result represents the material passports (MP) including the life cycle information. The user can export it to Microsoft Excel. MP serves as an optimization tool and decision support tool at the early design stage while it serves as documentation and inventory for an urban material cadastre at the end-of-life stage of existing buildings (Honic et al., 2019). The results can be exported to a material bank that includes information regarding existing reclaimed stock.

Potential for application of results

Implementing the proposed framework and prototype tool will facilitate informed decision-making by identifying the most circular and sustainable materials for buildings at early design stages. Moreover, it will contribute positively to optimising material use and resources efficiently, decarbonization in the building stocks, and the transition toward a sustainable circular economy. Future work will include a demonstration by implementing a case study.

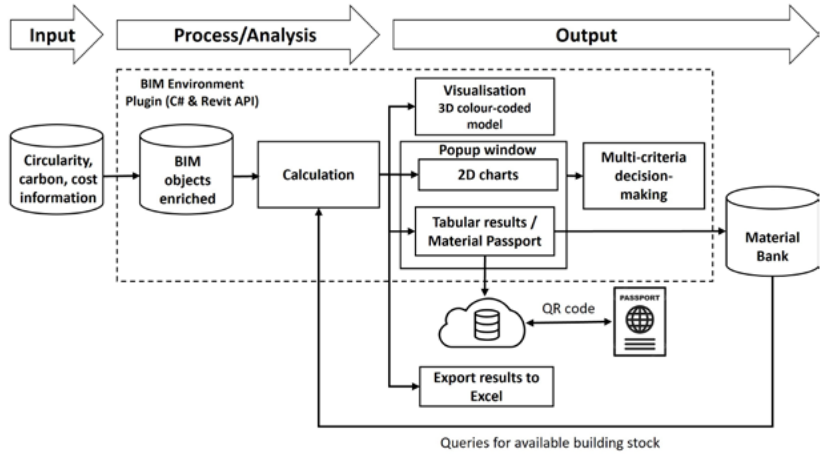

Fig 1 System Architecture.

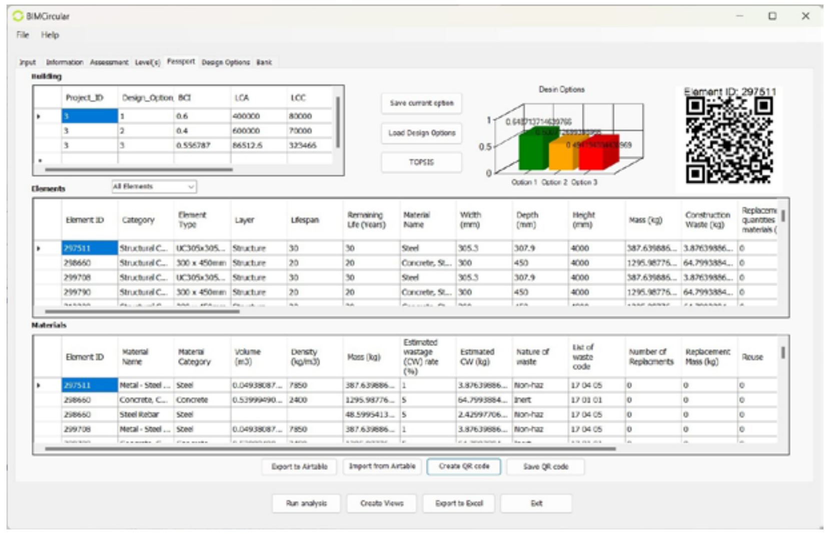

Fig 2 Design options analysis at the building level.

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Physics-informed neural networks for structural health monitoring applications

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Project objectives and goals

Physics-informed neural networks (PINNs), an approach that directly integrates physics-based principles (e.g., boundary conditions for displacement and force, and governing equations) into neural network architecture or loss functions, have significant potential for initiating digital twins of physical systems and processes. By integrating physics-based principles, engineers can use PINNs to predict structural responses and/or force quantities at locations not physically equipped with sensors, a process referred to as virtual sensing (Al-Adly and Kripakaran, 2024). This technique can be also used for damage detection. Therefore, PINNs hold promise in supporting decision-makers with maintenance and optimisation processes. This project explores the implementation of PINNs for structural health monitoring (SHM) applications by applying PINNs to a simply supported reinforced concrete floor slab, aiming to achieve the following objectives.

- Objective 1: Investigate the performance of PINNs that enforce the structure's boundary conditions can accurately model the structural system despite not explicitly including the governing PDE.
- Objective 2: Examine a PINN's ability to predict deflections and internal forces (moments) for loads that have not been included in the training datasets.
- Objective 3: Evaluate PINNs in real-world conditions with measurement noise and deviations from idealised boundary conditions.

Description of method and results

Fig 1 outlines processes utilised to achieve each objective.

The PINNs setup included:

- Stage 1: Involves defining the problem by modelling a reinforced concrete floor slab (4x4 meters and 200 mm thick), subjected to a uniformly distributed load of 9840 N/m2, Young's modulus of 31,724 MPa, and a Poisson's ratio of 0.20, using a PINN based on the Kirchhoff-Love plate theory for stress and deflection analysis under load.
- Stage 2: focuses on configuring PINNs with key hyperparameters: four hidden layers, 64 neurons per layer, Tanh activation function, and the Adam optimizer for training.
- Stage 3: Optimization of loss function components, including data loss (LD), displacement data loss (Lw), force loss (Lm), and PDE loss (Lf), through weight adjustments.
- Stage 4: Table 1 outlines the scenarios and cases explored, corresponding to the loss function terms of PINNs.

Results

PINNs were trained and evaluated for scenarios listed in Table 1, with results for achieving project objective 1 shown in Fig 2. Their performance was measured using metrics such as root mean square error (RMSE), coefficient of variation (CV) of RMSE, and normalized mean bias error (NMBE) for deflection (w) and moments (Mx, My). For different uniformly distributed load (UDL) conditions, PINNs were adapted to include UDL as an input, reflecting real-world situations with variable loads, as detailed in Table 2. This modification aligns with practical scenarios assuming known loads, addressing objective 2. Table 3 evaluates PINNs' performance under varying noise levels, using signal-to-noise ratios (SNRs) and boundary condition deviations, relating to objective 3.

Potential for application of results

This study investigates PINN model development methods that meet structural physical constraints and observations to assess predictive accuracy. Accurate structural behaviour prediction supports maintenance, repair, and optimisation decisions, benefiting structural health monitoring, digital twin technologies, and virtual sensing applications. The next step involves using PINNs to monitor fatigue stress on steel girder bridges. We are validating the proposed approach using measured data from a bridge under a known load.

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Further information

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Scenario (SN)	Loss Function Terms	Investigated Cases	Sensor No.	Sensor Coordinates (x, y) (m)
Performance of NNs -SN1	L_d	Case 0	No measured data included	---
NNs informed with displacement constrains – SN2	$L_w + L_d$	Case 1	S1	(2,2)
NNs informed with Force Constrains – SN3	$L_m + L_d$	Case 2	S1, S2, S3, S4, S5	(2,2), (1,1), (3,1), (1,3), and (3,3)
Displacement and force constrain informed NNs – SN4	$Lw + L_m + L_d$	Case 3	S1, S2, S3, S4, S5, S5, S6, S7, S8, S9	(2,2), (1,1), (3,1), (1,3), (3,3), (2,1), (2,3), (1,2) and (3,2)
PINNs – SN5	$L_f + L_w + L_m + L_d$	---	---	---

Table 1: Summary of the loss function scenarios and cases employed in the study.

UDL (N/m²)	Cases	w (mm)			Mx (N.m/m)			My (N.m/m)		
		RMSE	CV (%)	NBME (%)	RMSE	CV (%)	NBME (%)	RMSE	CV (%)	NBME (%)
150,000	Case 1	0.2741	8.61	-2.55	15165	27.68	3.08	12031	21.96	2.64
	Case 2	0.1701	5.35	-2.82	7131	13.02	2.91	9801	17.89	3.30
	Case 3	0.1211	3.81	-0.44	8478	15.47	6.15	8302	15.15	6.14
450,000	Case 1	0.8132	8.84	-5.45	36093	21.00	8.68	32162	18.71	8.68
	Case 2	0.8251	8.97	-6.58	28614	16.65	7.79	30993	18.03	7.89
	Case 3	0.5382	5.85	-3.89	33249	19.35	11.05	32573	18.95	10.96

Table 2: Error metric results for PINNs model with varying uniformly distributed load.

SN	SNR	w (mm)			Mx (N.m/m)			My (N.m/m)		
		RMSE	CV (%)	NBME (%)	RMSE	CV (%)	NBME (%)	RMSE	CV (%)	NBME (%)
SN4	10 dB	0.0443	26.87	3.07	1150	43	33	1182	45	30.32
	20 dB	0.0312	18.93	6.33	798	29.85	23.93	808	31	20.24
	30 dB	0.0147	8.91	1.37	876	32.78	5.61	639	24.52	4.06
	Ref.	0.0068	4.11	0.56	804	29.62	11.97	778	30.65	-8.27
SN5	10 dB	0.0245	14.86	-4.72	719	26.88	-13.59	723	27.73	-16.45
	20 dB	0.0178	10.78	-3.74	743	27.78	-13.80	729	27.96	-16.47
	30 dB	0.0132	8.03	-3.87	383	14.31	4.50	478	18.32	0.37
	Ref.	0.0092	5.56	0.65	308	11.55	7.25	380	14.6	4.687

Table 3: Error metrics for the PINNs subjected to different SNRs.

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