Proceedings of the
17th YOUNG RESEARCHERS’ CONFERENCE
14 April 2015
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Conference sponsors

Arup
As one of the world’s leading building consultancies, Arup offers clients the creativity and technical know-how to deliver innovative projects across the globe. For over 65 years we have continued to pioneer distinctive structural designs, maintaining our reputation through investment in attracting and developing the most inventive structural engineers.

www.arup.com

Flint & Neill:
Flint & Neill is an engineering consultancy specialising in the design of unique and innovative bridges and structures. The practice has been involved in the high quality complex projects, large and small, all over the world and is currently leading the detailed design of Mersey Gateway Bridge Project.

www.flintneill.com

IABSE
IABSE (International Association for Bridge and Structural Engineering) is the pre-eminent international Association dedicated to sharing and disseminating structural engineering knowledge and expertise among its members. The British Group is those members currently working in the UK, and we organise local events.

www.iabse.org and www.iabse.org.uk

Oasys
Oasys is a leading developer of structural and geotechnical engineering software, with a long-standing reputation for providing high-quality solutions and unrivalled support. Established in 1979 as part of Arup, Oasys software is used by leading engineering organisations and reputable research and teaching Universities across the globe. Our extensive product range includes heavily discounted University bundles for structural and geotechnical engineers - helping to develop the future of engineering.

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Ramboll
Ramboll is a leading global engineering and design consultancy offering services in the UK in buildings, environment, transport and energy. Innovation – and a commitment to sustainable development – informs all our work. We test the limits of design and construction technology because we have a continual appetite for improvement.

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The Institution of Civil Engineers

ICE is an international membership organisation that promotes and advances civil engineering around the world. Its purpose is to qualify professionals engaged in civil engineering, exchange knowledge and best practice, and promote their contribution to society.

www.ice.org.uk

The Institution of Structural Engineers Research Fund

The Institution of Structural Engineers Research Fund supports the Undergraduate Research Grant Scheme, the MSc Research Grant Scheme, the Young Researchers’ Conference and The Institution of Structural Engineers’ Research Award. The fund occasionally awards other research grants. Details of all these schemes are available on our website. www.istructe.org/about-us/donate/research-fund

www.istructe.org

TRADA

TRADA is an internationally recognised centre of excellence with over 80 years of experience in the specification and use of timber and wood products. We aim to provide the highest quality information and through the TRADA University Engagement Programme support teaching of timber and timber research in UK universities.

www.trada.co.uk
Welcome

Welcome to The Institution of Structural Engineers’ Young Researchers’ Conference. The membership of this institution represents collectively the world’s foremost body of structural engineering innovators. Our members do extraordinary things, daily, to delight users of buildings and bridges all over the world.

All great professions are fuelled by research findings which allow boundaries to be pushed. Structural engineering is a wonderful example of such a profession, and The Institution of Structural Engineers is central to ensuring that vibrant research underpins our members’ continual innovation.

The Young Researchers’ Conference is now in its 17th year, and its success simply multiplies year on year. It celebrates the greatest research being conducted by the future leaders of our profession, and it suggests important paths which could lead to successful innovation. You will experience first-hand today research of potentially great significance and impact to structural engineering.

And what a wonderful way to enter this profession! Conducting research at the limits of our knowledge is both exciting and crucial. You are the chosen few, for whom the privilege and responsibility in delivering world-class research findings come in equal measure. Thank you for wanting to tell your profession about your research. This is a deep responsibility, and we all look forward immensely to hearing your stories.

It might be that after your research degree you become an academic, thereby helping to lead future generations of researchers in structural engineering. Or it might be that you enter practice, and become a highly-skilled member of a design or construction team. Whatever you end up doing, the skills which you acquire as an inquisitive, rigorous researcher will ensure that you have an extremely rewarding and successful career. And, of course, the biggest winner will be structural engineering.

Professor Tim Ibell
President of The Institution of Structural Engineers
Conference team

Chairman:
Professor Tim Ibell
FR Eng CEng BSc(Eng) PhD FIStructE FICE FHEA
President of the Institution and Associate Dean for Research, Faculty of Engineering and Design, University of Bath

Tim Ibell is a structural engineering academic who is passionate about the importance of research and education in order to underpin creativity and innovation in our profession. After graduating with a First-Class Honours Civil Engineering degree from the University of Cape Town, he subsequently graduated with a PhD from the University of Cambridge in 1992 and, after a couple of years design experience, completed a post-doc at Cambridge before joining the Department of Architecture and Civil Engineering at the University of Bath in 1997. Tim was promoted to Professor (2003), Head of Department (2005) and Associate Dean of the Faculty (2008). In 2002, Tim spent a year in the US on a Fulbright Distinguished Scholar Award. Since 2006, Tim has been a member of the EPSRC Peer Review College. He is an Associate Editor of the Institution’s research journal Structures, and has sat on several Institution committees, including the Board of Trustees, Council, Membership, Nominations, Resources, Education Project Steering Committee, Academic Qualifications Panel and the Joint Board of Moderators. He is a Senator and Councillor at the University of Bath and a Fellow of the Royal Academy of Engineering.

For many years, Tim has had a strong research interest in the structural behaviour and retrofit of concrete bridges and structures. In particular, he has been interested in the realistic structural assessment of existing concrete bridges and he has had a succession of research students looking at the use of fibre-reinforced polymer (FRP) materials to reinforce and/or strengthen concrete structures. While FRP strengthening remains a key research field for him, more recently he has concentrated his efforts on fabric-formed concrete structures. Such structures are architecturally interesting and efficient, and they lend themselves to innovative building typologies. Tim and his team have been the recipients of five best journal-paper awards, including two from The Institution of Civil Engineers and three from The Institution of Structural Engineers. This team has also been the recipient of the Institution’s Award for Teaching Excellence in Structural Engineering Education.

Oral judges:
Steve Matthews - Chair of oral presentation judges
Carl Brockas
Dr Antony Darby
Prof Leroy Gardner
Prof Costas Georgopoulos
Susan Giahi-Broadbent

Poster judges:
Team A
Dr Roger Singleton Escofet – Chair of poster judges
Tim Hetherington
Dr Messaoud Saidani

Team B
Prof Toby Mottram - Team leader
Dr David Martin
Dr Keerthi Ranasinghe
“Smart Skin…structures that feel”

Lydia Hyde
Senior Scientist

Lydia is a senior scientist within BAE Systems research hub, Applied Intelligence Labs, whose role focuses on research and innovation of novel sensing systems. Primarily this is for the defence industry (MoD, dstl, the European Defence Agency, BAE Systems internal product streams), but occasionally she works with completely different industries, such as a current project with the GB Equestrian Team under a UK Sport partnership.

Lydia has been working for the industry for just over five years, with two years spent on the BAE Systems graduate scheme. Prior to that she completed a Masters degree in Physics at Durham University, with her final year project being joint between the Physics and Electrical Engineering departments.

Despite being relatively early in her career, for the last two years, Lydia has been nurturing the concept of a ‘Smart Skin’. The concept creates intelligent sensing materials and structures by embedding tiny, mm-scale computers. This work has gained significant attention, with the work featuring in a variety of media, including national and international newspapers, internet articles, radio, and television.
Research Panel

The Institution of Structural Engineer’s 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 a number of research grant and award schemes, 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:

- MSc research Grant scheme (http://www.istructe.org/education/scholarships-grants-and-bursaries/msc-research-grants).
- Research Award scheme (http://www.istructe.org/events-awards/research-award).

More information on the Research Fund can be found at: http://www.istructe.org/about-us/funds-and-donations/research-fund.

The Young Researchers’ Conference was instigated by the Research Panel to provide PhD students 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 judges the presentations on the day.

Professor Leroy Gardner
Research Panel Chair
Panel members

**Profess Prof L Gardner (Chairman)**  
CEng MICE FIStructE

Leroy is Professor of Structural Engineering at Imperial College London. He is engaged in teaching at both undergraduate and postgraduate level, specialist advisory work and leading an active research group in the area of steel structures. His principal research interests, in respect of which he has co-authored four textbooks and some 200 papers, lie in the areas of structural testing, numerical modelling and the development of design guidance for steel structures. He is a member of the European and BSI Committees responsible for Eurocode 3 and Fellow of both the Institutions of Civil (FICE) and Structural (FIStructE) Engineers. He is also Chair of the Research Panel and Editor-in-Chief of the new Research Journal of The Institution of Structural Engineers - *Structures*.

**Chris Walker (Vice-Chairman)**  
CEng MStructE

Chris is a Principal Engineer at Flint & Neill Limited which he joined after graduation in 2004 and his experience to date reflects the capability of Flint & Neill to tackle complex and technically ambitious structural engineering projects. Chris holds Master’s degrees from the University of Cambridge and Imperial College and his recent projects include detailed design of the cable systems for the 3,300m bridge across the Messina Strait between Italy and Sicily (2010-2011) and deck design for the 1,550m Izmit Bay suspension bridge, due for completion in 2016. He is currently leading a team working on erection engineering for the transformation of the London 2012 Olympic Stadium.

**Susan Giahi-Broadbent**  
MSc(Eng) CEng FIStructE MICEL MCIHT

Susan has over 25 years experience in civil and structural engineering projects (rail, highways and building) involving management, design and construction in the UK and overseas. As a structures project manager, a discipline lead and coordinator she has wide experience on highly prestigious projects. She has been an active member of the Institution since 2007. This includes Member of Council, Board, Membership Committee, Research Panel, Health & Safety Panel and Chair for Midland Counties Regional Group.

**Alan Burr**  
BSc MSc DIC CEng MStructE PE

Alan is a principal of the firm of Murphy Burr Curry, Structural Engineers in San Francisco, which he co-founded in 1997. He and his firm specialized in structural engineering services and building design, including commercial, retail, residential and educational facilities, with an emphasis on seismic design and retrofit. Before moving to San Francisco in 1991, Alan worked in London, Cardiff and Hong Kong for Ove Arup and Partners. Alan has a Master’s Degree from Imperial College London and is a licensed structural engineer in California and Hawaii, as well as a member of The Institution of Structural Engineers.

**Dr Antony Darby**  
BSc(Hons) PhD CEng MStructE

Antony is a Reader in Structural Engineering and Head of Civil Engineering at the University of Bath, where he has worked for the last 16 years. He has also worked for petrochemical contractor, M.W. Kellogg, and Matra-Marconi Space. His research interests follow two main themes; the use of advanced composites in construction and structural dynamics. He led the authorship of the Concrete Society’s TR55, (the UK Design Guidance for strengthening concrete structures) and is the UK’s principal expert on Task Group 1 of CEN TC250/SC2/WG1, responsible for incorporating strengthening and reinforcing with FRPs into Eurocode 2.

**Professor John. P. Forth**  
PhD CEng MStructE

John is the Chair of Concrete Engineering and Structures in the School of Civil Engineering at the University of Leeds. He was awarded his first degree, a BEng (Hons) in Civil and Structural Engineering from the University of Sheffield. He received his PhD from the University of Leeds. 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.
Professor Costas Georgopoulos  
MEng MSc CEng FHEA FCS FInstStructE FICE

Costas is Chair in Structural Engineering Practice at Kingston University London, he has a unique multi-sector experience comprising consulting engineering, academia and professional bodies in the UK and overseas. Costas has particular expertise on concrete (manager of education for The Concrete Centre), earthquake-resistant structures (tutor of the ICE 1-day CPD course on Seismic Design to EC8 for practicing engineers) and sustainability (author of the book ‘Sustainable Concrete Solutions’ by Wiley). Prof Georgopoulos’ contribution to the Institution includes: chairman of the Southern Regional Group, member of Academic Qualifications Panel & Research Panel and member of the Council.

Tim Hetherington  
MEng CEng MInstS

Tim graduated from Leeds in 1992 and worked for Mott MacDonald on land regeneration and general structures/civils projects before focussing fully on progressively more advanced structural engineering at Bison Structures, Buro Happold, then at special structures company Fenton Holloway. In 2004 he moved to Edinburgh and worked on taller steel and concrete buildings at Upton McGougan before moving to SKM Anthony Hunts as senior engineer then structural lead, where he was responsible for several award winning cultural, educational and sports facilities up to £25M. Tim now runs his own expanding practice Applied Engineering Design, with offices in Edinburgh and Glasgow.

Professor Jason Ingham  
BE (Hons) ME (Dist) PhD MBA

Jason is a professor of structural engineering at the University of Auckland. He obtained his PhD from the University of California San Diego and an MBA from the University of Auckland, and his research interests primarily focus on the seismic assessment and improvement of existing masonry and concrete buildings. Jason also undertakes research on the seismic response of precast concrete components and concrete materials technology. Recently Jason’s primary focus has been associated with the performance of masonry buildings in the Canterbury earthquakes and the development of a detailed seismic assessment methodology for unreinforced masonry buildings.

Professor Abdy Kermani  
BSc MSc CEng FInstS

Abdy is Professor of Timber Engineering and Director of the UK’s Centre for Timber Engineering at Edinburgh Napier University. He is a Chartered Engineer, Fellow of The Institution of Structural Engineers and Fellow of the Institute of Wood Science. He has served on the organising committees and editorial technical advisory boards of international journals and conferences on timber engineering and the innovative use of construction materials. He is the appointed principal consultant to several UK and European structural and timber engineering firms and manufacturing industries. He has led numerous research and development programmes on the structural use of timber and its reconstituted products. His research work in timber engineering is internationally recognised and published widely.

Professor Dennis Lam  
BEng(Hons) MPhil PhD CEng FInstS MICE MIMgt

Dennis is the Chair of Structural Engineering and the Director of Bradford Centre for Sustainable Environments at the University of Bradford. He is a Chartered Engineer, Fellow of The Institution of Structural Engineers and Member of the Institution of Civil Engineers. Before joining the academia, he has spent more than ten years in engineering practices and had extensive experience in structural design, especially in schools and public buildings using steel, concrete and composite frames. He holds visiting professorship at Tsinghua University, China and Hong Kong Polytechnic University and is a member of the European Committee on Standardization (CEN) responsible for the development of the Eurocode 4.

Dr David M Martin  
BSc PhD CEng FInstS FIMechE

David is a graduate of the Universities Glasgow and Dundee. He has worked in the construction and engineering industries for over 30 years and has particular experience in managing large multidisciplinary design & engineering teams for major capital projects. David is a Chief Engineer with ATKINS and is accountable for the quality of design and engineering work undertaken across a broad range of projects in two highly regulated, high hazard market sectors.
Panel members cont’d

Dr. Keerthi Ranasinghe
BSc (Eng. Hons. 1st) PhD

Keerthi is the Principal Structural Engineer & Eurocodes Consultant for BM TRADA. He is the author of the Eurocode 5 version of the popular TRADA publication, Span Tables and is also the developer behind the TRADA Eurocode 5 online software suite. Keerthi sits on BSI committees B/525/5 (Timber), B/525/1 (Actions) and B/525/-/32 (Fire). He also sits on the European Committee CEN/TC250/SC 5 (Timber) and the Working Group 4 (Fire). He is also the current expert commentator for Eurocode 5 on the BSI Eurocodes Online website. Keerthi has served the Research Panel at the Institution for the last two years.

Dr Robin Sham
BSc PhD DIC CEng FICE FiHT FHKIE

Robin has an illustrious career that spans nearly four decades and several continents. He is a leading international authority in bridge engineering, whose pioneering contributions have helped realize the largest and the most complicated bridges in the world. He is a Gold Medallist of the Institution of Civil Engineers, and a Fellow of the City and Guilds of London Institute. He is the Global Long Span and Specialty Bridges Director of AECOM. His recent projects included the Taizhou Bridge, which received The Institution of Structural Engineers 2013 Structural Award in the Highway or Railway category, and also the Supreme Award for Structural Engineering Excellence.

Dr Roger Singleton Escofet
BSc PhD

Roger is currently Portfolio Manager at EPSRC; having previously completed a PhD in Biology at UCL and a degree in Biochemistry – so he will not be quizzing you about stresses and strains. His role involves managing research in civil engineering which gives him a privileged position in understanding the future trends and challenges within structural engineering research.
Dr Ahmer Wadee
BEng PhD MSc DIC ACGI

Ahmer is currently Reader in Nonlinear Mechanics in the Structural Engineering Section at Imperial College London. He is a leading expert on structural stability having published over 100 articles in international journals and conference proceedings. In 2014, he was listed as one of the UK’s top 100 practising scientists by The Science Council and was also a co-editor of the book “50 Visions of Mathematics” published by Oxford University Press. He is a Chartered Mathematician and Scientist, a Fellow of the Institute of Mathematics and its Applications and a Graduate Member of The Institution of Structural Engineers.

Professor Chien Ming Wang
BEng(Hons) MEngSc PhD FIstructE FIES

Chien is the Director of the Engineering Science Programme, National University of Singapore. He is a Fellow of Academy of Engineering Singapore, a Fellow of Institution of Engineers Singapore, a Fellow of The Institution of Structural Engineers and Chairman of the Singapore Regional Group. He is also Adjunct Professor in Monash University, Australia. His research interests are in the areas of structural stability, vibration, optimization, nanostructures, plated structures and Mega Floats. He has published over 400 papers and authored several books. He is the Editor in Chief of International Journal of Structural Stability and Dynamics and IES Journal Part A: Civil and Structural Engineering and an Editorial Board Member of several journals. His awards include Lewis Kent Award, Keith Eaton Award, IES Prestigious Engineering Achievement Award, and IES/IStructE Best Structural Paper Award.

Ron Watermeyer
CEng PhD FIStructE

Ron is a director of Infrastructure Options (Pty) Ltd. He has been at the forefront of many development initiatives in South Africa since the early 1990s including the development of housing standards for a structural warranty scheme, the reinterpretation of national building regulations, the classification of sites in terms of geotechnical characteristics and building practice and procurement and delivery management. In 2009 he was awarded a Doctor of Engineering from the University of the Witwatersrand for his published work on Contributions to the delivery of infrastructure for the advancement of a changing South African society.

Dr Pete Winslow
PhD CEng MIStructE

Following the completion of his PhD on longspan, free-form structures, Pete joined Expedition Engineering whereupon 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 is currently working on range of unusual structures including refurbishment of a historic building, a tensegrity sculpture and the acoustically-sculpted Soundforms shells. Pete is also responsible for Expedition’s R&D programs, working with universities and industry to explore advanced materials, pedestrian induced vibrations and prototyping adaptive structures.
Programme

09.30 Registration and coffee
10.00 Welcome by Martin Powell - Chief Executive of The Institution of Structural Engineers
10.10 Research matters
10.15 Keynote address by Lydia Hyde – Senior Scientist at BAE Systems
10.45 Chairman’s introduction
10.55 Session 1
10.55 A validated model to incorporate the effects of residual stresses in glass structures (Abstract No. 6)
Bogdan Balan – University of Southampton
11.10 Design and performance of cold bent glass (Abstract No. 9)
Kyriaki (Corinna) Datsiou – University of Cambridge
11.25 Discussion
11.35 Coffee
12.00 Session 2
12.00 A new design method for circular hollow sections (Abstract No. 8)
Craig Buchanan – Imperial College London
12.15 Behaviour of welded tubular structures in fire (Abstract No. 32)
Emre Ozyurt – Manchester University
12.30 Discussion
12.40 Key research areas for structural engineering
13.00 Lunch
13.45 Poster presentation
14.20 Session 3
14.20 Tuning and shaping semi-active tuned mass dampers for use on high-rise wind excited structures (Abstract No. 11)
Demetris Demetriou – University of Leeds
14.35 Structural behaviour of beam to concrete-filled elliptical steel tubular column connections (Abstract No. 39)
Jie Yang – University of Bradford
14.50 Reinforced concrete crack analysis (Abstract No. 14)
Taheer Fayyad – University of Cambridge
15.05 The effect of post-tensioning force magnitude on the NFs of post-tensioned concrete structures (Abstract No. 30)
Darragh Noble – Trinity College Dublin
15.20 Discussion
15.40 Tea & judging
16.05 Membership matters
16.15 Prize giving & closing remarks
16.30 Close
Poster presentations

Use of electromagnetic damping for mitigation of human-induced vibration (Abstract No. 2)
Wai Kei Ao – University of Exeter

Improving the seismic performance of non-structural systems using viscous fluid dampers (Abstract No. 10)
Giuseppe Del Gobbo – University of Oxford

Shear strengthening of RC slab-on-beam structures using externally bonded FRP fabrics (Abstract No. 16)
Robert Foster – University of Cambridge

Modelling of crack propagation of brittle heterogeneous materials (Abstract No. 17)
Elia Gironacci – University of Warwick

Study of mechanical properties of bamboo for designing lightweight structures (Abstract No. 18)
Martha Godina – University College London

Shaking table tests on steel and reinforced concrete precast buildings with and without buckling-restrained braces (Abstract No. 19)
Hector Guerrero – University of Manchester

Performance of textile reinforced concrete retrofitted RC beams under cyclic actions (Abstract No. 21)
Georgios Kampisios – University of Leeds

Performance-based design of secondary substructures (Abstract No. 22)
Stavros Kasinos – Loughborough University

Design of a FRP-reinforced concrete beam system for fire performance (Abstract No. 24)
Mohamed Kiar – University of Edinburgh

Improved structural efficiency of steel single storey industrial buildings using sandwich panels (Abstract No. 29)
Dimitrios Moutafsis – Oxford Brookes University

Pull-out capacity of BFRP rods in Irish grown Sitka Spruce (Abstract No. 31)
Caoimhe O’Neill – Queen’s University Belfast

Improving the out-of-plane behaviours of masonry infill walls using a partially debonded engineered cementitious composite layer (Abstract No. 33)
Saeed Pourfalah Bazkiani – Heriot-Watt University

Behaviour of demountable shear connectors in composite beams (Abstract No. 35)
Naveed Rehman – University of Bradford

Stress and moisture effects on the durability of CFRP tendons in pre-stressed concrete (Abstract No. 36)
Shobana Sivanandran – University of Cambridge

Serviceability of fabric-formed concrete structures (Abstract No. 37)
Yadgar Tayfur – University of Bath

Performance-based optimisation of an innovative cold-formed steel wall-frame system for lightweight multi-storey structures (Abstract No. 40)
Jun Ye – University of Sheffield

This booklet contains synopses from researchers taking part in the 17th Young Researchers’ Conference, organised by The Institution of Structural Engineers. The Institution bears no responsibility for the presentation or technical accuracy of the content in these synopses.
An assessment of the severity of exposure of RC structures to airborne chlorides in the Cape Peninsula

Olukayode O. Alao
University of Cape Town

Project objectives and goals
The distance of reinforced concrete (RC) structures from the sea (coast) is an important aspect to consider when studying the deleterious effect of airborne salinity in a marine exposure environment. This study provides first-hand experimental information as foundation for in-depth research, and guidance for practising civil and structural engineers to consider in design and construction of RC structures in airborne chloride exposure zones in South Africa. The evaluation of this aggressiveness potential of the environment due to deposition of marine salts on reinforced concrete structures is the objective of this study. The vector of development of principal cities in South Africa is located in coastal regions where the action of sea spray is favourable for the creation of an aggressive atmosphere toward construction materials and products. This study anticipates to aid in the design of durable and maintenance-free reinforced concrete structures given due knowledge of the prevailing microclimate.

Similar studies were carried out in Chittagong, Bangladesh and Joao Pessoa, Brazil, by Hossain et al. (2009) and Meira et al. (2010) and their effects on specimens made from five different types of mortars normally used as external renders for built infrastructures such as buildings and bridges. Mortar specimens were exposed to atmospheric environment at 12 monitoring stations scattered around Chittagong’s metropolitan area. Mortars were made using combinations of cement, lime, volcanic ash, and fly ash respectively. Meira et al. (2010) found that the airborne chloride concentration decreased with increasing distance from the sea (see Fig 1).

Description of method and results
Five sampling stations were chosen with major criteria relating to their varying distances from the coast and presence of existing reinforced concrete infrastructure. The wet candle device an ASTM (G140) standard method (shown in Fig 2) was used to monitor the chloride deposition rate at each location. The sampling stations were geographically referenced and identified by their distance from the coast, varying from 50 m to approximately 13.5 km. The final choice of the location of each sampling station depended on the availability of an open but secured area, free of interference from walls, trees or other obstructions, thus permitting wind circulation. In addition to this, it was necessary to provide safety for the exposed material.

Potential for application of results
The major shortcoming of the current marine exposure classifications in the SANS 10100-2 and EN 206-1:2013 is their generalist approach. RC structures exposed to airborne chlorides are identified as being within a distance of up to 30 km from the coastline in the current SANS design code (SANS 10100-2). Chloride deposition rate measured from the wet candle device would be used to infer possible exposure distance of RC structures to airborne chloride attack.

The assessment in this study should inform and modify the design method of RC structures that are not in direct contact with seawater but are within the marine environment. The evaluation of the severity of the exposure environment will enable an informed design of concrete structures that satisfies their desired service life and durability performance.

References

Funding body
The Concrete Institute (TCI), South Africa and Concrete Materials and Structural Integrity Unit (CoMSIRU), University of Cape Town.

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Figure 1. Chloride deposition on the wet candle device at varying distances at Joao Pessoa, Brazil

Figure 2. a) Wet candle device setup

Figure 2. b) Wet candle dimensions
Use of electromagnetic damping for mitigation of human-induced vibration

Wai Kei Ao
University of Exeter

Project objectives and goals
Vibrations can cause problems in many engineering scenarios such as aircraft systems, building structural systems and mechanical systems. This study is focused on civil engineering floor structures subject to human-induced dynamic loading. The study of floor vibrations has become increasingly important because new construction technologies have facilitated structural designs of floors to be long-span, slender and lightweight. In addition, many office buildings are adopting more open plan floor layouts with less inherent damping.

In civil structures, when the vibration magnitude is large then serviceability becomes a problem. To try to deal with this, researchers have proposed several solutions. The tuned mass damper (TMD) has commonly been used for vibration control for structures subject to earthquake and wind excitation. The TMD consists of a mass, spring and dashpot. Alternatively, a viscous damper can be directly attached to the structure by itself to provide extra damping.

The aforementioned improvements originated in mechanical engineering and are now more commonly used in civil engineering. However, electrodynamic actuators and electromagnetic dampers (EMD) are also used extensively in mechanical systems but these are not yet commonly used in civil structures. These utilise the electromagnetic induction concept to generate eddy current and Lorentz forces to provide vibration suppression forces. In this research, these principles will be developed for vibration serviceability control of a civil engineering structure.

An extension of the EMD is to combine it with a shunt circuit to generate the dynamic force, referred to as an EMDS. The shunt circuit consists of a resistor, inductor and capacitor (RLC), which is a fundamental circuit oscillator. The $H_\infty$ and $H_2$ optimisation methods have been adopted for use with the RLC resonant circuit (or EMDS) and utilised in an analytical implementation study for comparison against an equivalent TMD. From the frequency response, the peak magnitude of frequency response function (FRF) of the bare structure can be reduced by adding the RLC resonant circuit as seen in Fig 1. The cascaded RLC resonant circuit can have an equivalent TMD dynamic behaviour. It is observed that the uncontrolled peak of the FRF curve is reduced to the two lower peaks, and that the $H_2$ FRF has lightly lower peak than $H_\infty$.

The eddy current problem usually depends on the geometry of the moving conductive material and the magnetic pole direction, which can be either unidirectional magnetic pole projection or alternating magnetic pole projection. The ECD is proposed to develop and perform in floor vibration control. There is no short cut to tackle the results of analysis and design. Coulomb’s law is used to analyse the eddy current in a time-invariant situation and calculate the induced electromotive force (EMF) and eddy current density, assuming the infinite dimension of the conductive plate for boundary condition. A mathematical model has been developed and shown to correspond with the finite element model simulation as can be seen in Fig 2. It is shown that a damping force was generated when the copper plate moves within magnetic poles.

Description of method and results
In order to carry out an analysis of the potential performance of both TMD and EMDS devices, the properties of a laboratory slab strip structure were used. The structure is an in-situ cast post-tensioned slab strip that is simply supported between knife-edge supports. The slab strip has span 10.8 m, width 2 m and depth 0.275 m. The measured first dynamic mode is a pure bending mode, with frequency of 4.6 Hz, damping ratio of 2.4% and corresponding modal mass of 6610 kg.

The objective of the first part of this study is to examine the use of an electromagnetic actuator or motor for vibration control of a civil engineering structure (the aforementioned structure properties are used) with an EMDS. The shunt circuit consists of a resistor, inductor and capacitor (RLC), which is a fundamental circuit oscillator. The $H_\infty$ and $H_2$ optimisation methods have been adopted for use with the RLC resonant circuit (or EMDS) and utilised in an analytical implementation study for comparison against an equivalent TMD. From the frequency response, the peak magnitude of frequency response function (FRF) of the bare structure can be reduced by adding the RLC resonant circuit as seen in Fig 1. The cascaded RLC resonant circuit can have an equivalent TMD dynamic behaviour. It is observed that the uncontrolled peak of the FRF curve is reduced to the two lower peaks, and that the $H_2$ FRF has lightly lower peak than $H_\infty$.

The eddy current problem usually depends on the geometry of the moving conductive material and the magnetic pole direction, which can be either unidirectional magnetic pole projection or alternating magnetic pole projection. The ECD is proposed to develop and perform in floor vibration control. There is no short cut to tackle the results of analysis and design. Coulomb's law is used to analyse the eddy current in a time-invariant situation and calculate the induced electromotive force (EMF) and eddy current density, assuming the infinite dimension of the conductive plate for boundary condition. A mathematical model has been developed and shown to correspond with the finite element model simulation as can be seen in Fig 2. It is shown that a damping force was generated when the copper plate moves within magnetic poles.
Potential for application of results

The EMDS does not involve any extra moving mass in the suppression system. Theoretically, the EMDS can achieve a substantial virtual mass from circuit components (capacitance) in which relevant optimal circuit components (resistor and inductor) are functions of the capacitance. However, it is known that larger TMD mass ratios results in better controlling performance and, in a comparative sense, increasing the equivalent virtual mass ratio of the EMDS can also have a better controlling result. In a real application case, the equivalent mass ratio is dependent on the capacity of the force actuator. In the first part of this study a SDOF system was selected and vibration control of the single mode was carried out, which represented the first bending mode of the actual system. The approach pursued here can be extended to control of multiple modes by using multiple RLC resonant circuits with the system.

The second part of this study will focus on the ECD. The performance from initial analytical results has showed that the unidirectional magnetic pole projection can create a larger damping force in the vertical direction which was the same as the finite element analysis results. The analytical results show that the unidirectional poles can generate almost ten times the force of the alternating poles projection. The analytically calculated damping force (Lorentz’s force) was always larger than FEA. The reason can be concluded from two assumptions of the analytical method that relate to a time-invariant uniform magnetic field and the infinite boundary condition of the conductive plate.

The authors plan to carry out a practical implementation of the system, which will be presented in later publications.

References


Funding body
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Figure 1. Comparison of acceleration frequency response under $H_\infty$ and $H_2$ with machine constant $K_{emN} \neq K_{emV}$

Figure 2. Lorentz’s force of unidirectional magnetic pole projection under $v=0.02$ m/s
Hybrid FRP-steel reinforced continuous beams

Almahdi Araba
University of Bradford

Introduction
Deterioration, reduced serviceability and failure of concrete structures reinforced with steel bars are inevitably the most common consequences of corrosion of steel reinforcement in aggressive and corrosive environments. Hence, this phenomenon has become a major concern in the construction industry due to a substantial increase of maintenance and repair costs. The use of fibre reinforced polymer (FRP) as an alternative reinforcement in concrete structures has emerged as an innovative solution owing to their non-corrosive and non-magnetic properties, making them ideal for severe environments and situations where magnetic transparency is required. However, due to the linear-elastic behaviour of FRP composite materials up to rupture, continuous concrete beams reinforced with FRP rebars generally exhibit less ability to redistribute stresses between critical sections compared to those reinforced with steel rebars (Ashour and Habeeb, 2008; Mahroug et al. 2014). As a result, a sudden failure is expected to occur with little or no ample warning, calling for the implementation of a new method of construction to avoid such problems that is durable and cost effective, and exhibits some ductility. Hence, a hybrid system consisting of both FRP and steel reinforcement is proposed in this project; such reinforcement system show improved serviceability and ductility, and enhancement of load-carrying capacity compared to traditional reinforcement (Aiello and Ombres. 2002; and Qu et al. 2009).

Project objectives and goals
The research aim is to study in depth the behaviour of continuously supported concrete beams reinforced with hybrid steel and FRP bars. More specifically, the objectives of this research are:

- To experimentally study the structural behaviour of the simply and continuously supported hybrid reinforced concrete beams in comparison with concrete beams reinforced with either FRP or steel bars.
- To develop an analytical technique for predicting the behaviour of simply and continuously supported concrete beams reinforced with hybrid reinforcement.
- To study the extent of moment-redistribution in continuous concrete beams reinforced with hybrid reinforcement.
- To examine the applicability of design guidelines against the experimental results of continuous hybrid reinforced concrete beams

Description of method and results
To achieve the above mentioned objectives, parametric studies have been conducted using non-linear finite element analysis (FEA) software, ABAQUS and an analytical modelling program developed by the author using Matlab-2013 to investigate the potential behaviour of hybrid indeterminate beams. Figure 1 and Figure 2 show results obtained from parametric study using the aforementioned tools. In addition, experimental tests will be carried out on a number of reinforced concrete beams continuous over two spans to observe the real behaviour of hybrid-reinforced continuous concrete beams. Based on the parametric studies results, some parameters such as the type of FRP reinforcement, amount of reinforcement, and concrete compressive strength influence the flexural behaviour of hybrid-reinforced beams.

Potential for application of results
The outcome of this investigation will provide valuable experimental results on continuous beams reinforced with a hybrid system consisting of both FRP and steel reinforcement. The experimental results on simply and continuous beams can be used for design guidelines development and validation. Moreover, structural engineers will be provided with new knowledge and understanding of the behaviour of concrete beams reinforced with hybrid reinforcement, consequently making this system a more viable option. The developed numerical technique and FE model can be used for further parametric studies to provide more insight into the behaviour of continuous concrete beams reinforced with a hybrid combination of FRP and steel rebar.

References
Funding body
Higher Education Ministry-Libya

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Figure 1: Moment-Curvature of concrete section reinforced with different reinforcement

Figure 2: FRP reinforcement ratio vs steel reinforcement ratio, indicating the different flexural failures
Steel CBF-MRF dual system with energy dissipating braces and replaceable fuses

Marco Baiguera
Heriot-Watt University

Project objectives and goals

This project develops a novel steel concentrically braced frame-moment resisting frame (CBF-MRF) dual seismic-resistant system. The structure is comprised of concentric braces (CBs) with energy dissipation devices (EDs), and an MRF with ductile fuses, as shown in Fig 1. The high stiffness of the resulting system provides low inter-story drifts under the design earthquake. Yielding EDs with hourglass shape (named WHPs) are placed in parallel with the braces and activate before the brace yields. WHPs made of stainless steel have been recently proposed and evaluated by Vasdravellis et al. (2014). It was shown that they possess excellent energy dissipation capacity while being cost-effective and easily replaceable after a strong earthquake. The MRF acts as a backup system that: provides restoring forces at low drifts, hence drastically reducing residual drifts; protects the gusset plate and beams from being damaged; and enhances the collapse capacity of the dual system. The replaceable link concept proposed by Shen et al. (2011) was considered as a first step for the design of the beam fuse.

Conventional seismic resistant structures are effective to provide life safety under strong earthquakes, but they do not avoid damage in structural elements and they result in large residual drifts. Losses due to damaged structures and indirect losses due to downtime can be significant from a socio-economic perspective. The proposed system is designed to achieve greater resilience by minimizing residual drifts, and thus to enable a quick recovery in the aftermath of a major earthquake strike.

The research project has the following objectives:

- To evaluate the seismic performance of the proposed dual frame by means of numerical simulations
- To optimize the geometry of the beam fuses in order to maximise their fracture capacity and increase the collapse capacity of the system
- To evaluate a novel beam fuse by means of large scale experimental tests
- To develop reliable numerical models for collapse simulations, including deterioration and fracture hysteretic models of the WHPs and the fuse, calibrated against the experimental results
- To assess the collapse potential of the proposed system

Description of method and results

A typical steel frame office building was chosen to compare the response of the CBF-MRF dual system with a conventional dual system with buckling-restrained braces (BRBs) and MRF. The prototype is a six-story building, square in plan with three equal bays in each direction. The bay width and the storey height are 6m and 3m, respectively. The lateral load resisting systems are located along the perimeter of the building and a chevron configuration is used for the braces. The BRB-MRF system sections were designed in accordance with EC8, assuming a behaviour factor q equal to 6, a seismic action with a return period of 475 years (PGA=0.36 g), and inter-story drift limit equal to 0.5% under the frequently occurring earthquake (half of the intensity of the design earthquake). The CBF-MRF beam and column sections are identical to the ones used for the BRB-MRF system. Bracing members with WHPs have a similar stiffness to BRBs and are capacity-designed to ensure that only the WHPs yield.

A detailed three-dimensional FE model was created using the commercial software Abaqus (Hibbit et al., 2013) to study the local behaviour and the failure modes of the frame by means of nonlinear (NL) pushover analysis. A more simplified 3D model consisting of beam type elements was developed in order to provide a practical tool for parametric studies. In the latter model, NL springs were used in place of WHPs. Additionally, a beam-column subassembly model with beam fuses was calibrated and validated against the experimental results presented by Shen et al. (2011). NL time-history dynamic analyses were performed using a 2D numerical model constructed in OpenSees (McKenna, 2000), which incorporated deterioration and fracture models for both WHPs and beam fuses.

Fig 2 shows the pushover curves of the proposed CBF-MRF and the conventional BRB-MRF dual systems. CBF-MRF system provides the intended seismic performance levels and numerical results correlate well with analytical predictions. Under large drifts, the damage is limited to the replaceable devices (WHPs and beam fuses), whereas the main structural components are damage-free. The results also show that the simplified and the detailed FE models were in good agreement. In addition, NL dynamic analyses performed in OpenSees have shown that the proposed frame provides a seismic performance similar to a conventional one, but it drastically reduces the residual drifts under the design earthquake and eliminates the damage in main structural components.
Potential for application of results

This project will provide fundamental knowledge on the seismic performance of the proposed system, along with a reliable design methodology in accordance with Eurocodes 3 and 8. An extensive experimental database on fracture capacity of the replaceable fuses will be created. Furthermore, it will be used to assess the collapse of the proposed structural system by means of fragility curves. Loss estimation study will be conducted to evaluate the seismic performance and economic impact of the innovative dual system, which is a key aspect for its practical application.

References


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Figure 1. The proposed steel CBF-MRF dual system geometry

Figure 2. Base shear-roof drift behaviour from nonlinear monotonic (pushover) analyses
Aeroelastic control of long-span suspension bridges

Konstantinos-Nikolaos Bakis  
University of Oxford

Project objectives and goals
Recent development in structural materials and construction technology has contributed to the increase in span length, flexibility and slenderness ratio of bridge design trends. It is widely appreciated that long-span bridges are prone to aerodynamic instabilities with the now iconic Tacoma Narrows bridge disaster (1940) serving as a reminder of the importance of efficient aerodynamic design. The increasing use of flat box girders to the alternative massy truss deck solution justifies the use of traditionally inappropriate classic thin airfoil theory for flutter analysis (Wilde and Fujino, 1998), as was formulated in Theodorsen’s original work (1934). This theory also exposes a non-oscillatory instability known as torsional divergence, caused by loss of torsional rigidity.

The main thrust of this work is to build on previous work (Graham et al., 2011) by extending into a full bridge aeroelastic model the analysis described therein with respect to suppression of aerodynamic instabilities making use of control theoretic means. The motivation for this is that a complete structural model is necessary for evaluating the bridge’s multimodal behavior and for uncovering the modal interplay which drives the structure in flutter instability. Another reason is that a full bridge model enables investigating different flap configurations and accounting for limited flap length along the deck.

Description of method and results
The structural part of this work is based on Abdel Ghaffar’s FE formulation (1980) tailored for suspension bridges. The methodological described therein was altered to account for the closed box girder deck as well for modelling the bridge construction phase. Flutter aeroelastic instability during the early erection stages of the deck are more dangerous because the fundamental torsional mode is closer to the fundamental vertical mode and hence they couple at lower wind speeds. The low flutter speed limit observed during the early stages of erection justifies the use of controlled surfaces of the type shown in ‘Fig 1’ as a mean for making the bridge more aerodynamically stable. The control strategy followed in this paper aims at stabilizing the system while achieving maximum stability margins or in other words better robustness to uncertainty. In setting up the optimization problem we make use of a model reduction procedure in order to bring the system in a manageable size for the task at hand.

The lift and moment on a system with a leading and trailing edge flaps is based on a transformation of the wing-flap-tab formulation. As opposed to following a frequency based approach for modelling the unsteady forces a high fidelity quartic rational function approximation (RFA) of the Theodorsen function is implemented (Bakis et al.) and the aerodynamic loading is cast FE framework, which allows the equations of motion to be expressed through a generalized eigenvalue problem approach. The extra states due to flap dynamics are implemented in the FE model resulting in a closed loop system of the form given in ‘Fig 2’. The uncontrolled system is described by the plant $P(s)$ containing the structural dynamics and the non-circulatory part of the fluid mechanics. The controllers for the leading – and trailing edge flaps are $K(s)$ and $L(s)$. Both controllers receive the pitch angle of the corresponding element as input.

Potential for application of results
The presented research addresses the issue of modelling and validating the aeroelastic behaviour of suspension bridges in their final form as well as during the erection process. A leading-trailing flap mechanism is then used to suppress aerodynamic instabilities especially during the early construction phase. Our results show that good aerodynamic performance can be achieved throughout the erection process and the methodology for designing passive compensators with maximum robustness margins is outlined. The implementation of a passive flap mechanism during the erection of long span suspension bridges as well as in their final form might prove to be a cost-effective solution for wind design as well as enabling the construction of even lengthier spans.

References


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**Figure 1.** Cross section of a streamlined long-span suspension bridge with flutter suppression winglets.

**Figure 2.** Block diagram of the aeroelastic control system.
A validated model to incorporate the effects of residual stresses in glass structures

Bogdan Balan  
University of Southampton

Background
Although glass offers great potential to be used in the built environment, design of glass structures is challenging for structural engineers due to its brittle material behaviour. In glass, high localised stresses cannot be redistributed (IStructE, 2014) and therefore conventional structural design approaches of steel and concrete are not appropriate for design of glass structures. Most of the design recommendations are based on rules of thumb (IStructE, 2014); the allowable stress design approaches focus on external loads only, neglecting the effect of residual stresses which inherently are present in glass. The misfit strains (i.e. eigenstrains) developed during the cooling process of glass in the manufacturing process, generate residual stresses and there is no method currently used in practical designs to incorporate these residual stresses.

Project objectives / outputs
- Development of an accurate analytical / numerical tool to characterise residual stress in glass.
- Establishment of a validated technique to incorporate the effect of residual stresses in designs.
- Prediction of the structural response of practical structural glass elements.

Description of method and results
A simple and convenient way of incorporating the effect of residual stress in designs is needed and the eigenstrain concept provides a good solution (Achintha and Nowell, 2011). The new hybrid contour method/eigenstrain method (Balan and Achintha, 2014) proposed here is able to construct residual stresses in glass using the knowledge of the misfit strains (i.e. eigenstrains). The results obtained based on the surface deformation (due to stress relaxation) in the contour method are used in an inverse analysis to determine the eigenstrain profile of glass elements. The step by step procedure of the proposed method is shown in Fig 1.

The residual stresses determined using the hybrid method were validated against experimental results of a scattered light polariscope. For the study glass samples of float and tempered glass with surface dimensions of 150 mm x 100 mm and varying in thickness from 4 mm to 10 mm were investigated. Due to space limitation only the results for 4 mm and 10 mm are presented here in Table 1. The table compares the residual stress values in the glass samples obtained using the hybrid method with those using the scattered light polariscope. The first two columns of the table show the results obtained from the hybrid model at surface and mid-depth, while the last two columns show the experimental results at the surface and respectively mid-depth.

The findings show that glass has a parabolic stress distribution, with surface compression on each side balanced by mid-thickness tension. The surface compression represent on average ~ 20 % of the thickness, while the middle tension zone represent on average ~ 60 %, irrespective of the type of glass (i.e. float or tempered). Moreover, the present results agree with the data available in the literature (IStructE, 2014). Fig 2 compares the stress depth profile (σxx) along a 10 mm thick float glass sample obtained using the hybrid method and experimental procedure. As can be seen there is a good agreement between the two profiles.

Potential for application of results
- Correct prediction of failure. Combined effects of residual stresses and applied stresses represent a cause of premature failure in structural elements, thus the knowledge of residual stresses play a significant role towards safe designs of glass structures. Investigations have shown that by failing to consider the correct amount of initial residual stress in analysis of glass elements can result in under-designing the element with ~ 50 %.
- Determine high areas of stress concentrations. The lack of yielding capacity suggests that areas of high localised stress concentrations should be avoided. By correctly incorporating residual stresses in glass analysis this can be accomplished. For example, results have shown that in order to avoid high localised stress concentrations around holes in glass plates, the hole’s diameter should be higher or equal with the thickness of the glass plate.
- Determine the safe distance of the connection away from elements edges. The investigations of an in-plane loaded pinned joint connection has shown that even when the connection is not loaded the compressive surface stress is decreasing as the hole is closer to the free edge of the element. The results suggest that the hole should be at a distance of at least three times the thickness of the glass plate to ensure that it offers the requested reliability.

Benefits to structural engineering profession
- The proposed method offers a robust tool that allows incorporating residual stresses in structural design.
- The complex multi-physics problem behind residual stresses is simply and efficiently accounted so that engineers can determine residual stresses in new glass elements without experimental procedures or daunting FE procedures.
- Safe and sustainable designs can be achieved if residual stresses are correctly implemented.
Summary
The hybrid modelling approach works well to model residual stresses in glass, providing validated results. The current method enables modelling of residual stresses in new geometries (e.g. stress concentrations around hole) and or during subsequent loading. This allows correctly predicting the structural behaviour of glass elements and in terms a safe, reliable and sustainable design.

References

Table 1. Comparison of residual stress results ($\sigma_{xx}$) in different glass samples

<table>
<thead>
<tr>
<th>Glass type/thickness</th>
<th>Hybrid Surface (MPa)</th>
<th>Hybrid Mid-depth (MPa)</th>
<th>Experimental Surface (MPa)</th>
<th>Experimental Mid-depth (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Float / 4 mm</td>
<td>- 3.0</td>
<td>1.5</td>
<td>- 4.0</td>
<td>1.8</td>
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<tr>
<td>Float / 10 mm</td>
<td>- 8.0</td>
<td>3.5</td>
<td>- 5.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Tempered / 4 mm</td>
<td>- 96.0</td>
<td>48.0</td>
<td>- 96.0</td>
<td>51.0</td>
</tr>
<tr>
<td>Tempered / 10 mm</td>
<td>- 88.0</td>
<td>50.0</td>
<td>- 84.0</td>
<td>48.0</td>
</tr>
</tbody>
</table>

Figure 1. Step-by-step procedure of proposed method

Figure 2. Comparison of stress profiles ($\sigma_{xx}$) for a 10 mm thick float glass sample
Seismic design and evaluation of moment resisting frames using elastomeric dampers

Christos Basagiannis
University of Oxford

Project objectives and goals

Passive dissipative devices, such as elastomeric dampers, can enhance the seismic behaviour of structures, by reducing the inelastic deformation demand of the primary elements (beams and columns). This reduction is directly related with the target performance criteria of the building. If these criteria indicate that the structure should remain linear or have minimal damage, then an alternative earthquake approach has to be adopted.

Therefore, the main aim of the current research is the evaluation of the effect of elastomeric dampers on the seismic behaviour of steel moment resisting frames (MRFs). Elastomeric dampers consist of a rubbery material bonded between two steel plates and have similar characteristics to viscoelastic dampers, but are less sensitive to frequency and temperature, a fact which potentially makes them even more effective. Both numerical and experimental research will be carried out in order to fully examine their effect on structures under earthquake conditions.

Description of methods and results

In order to numerically evaluate the effect of elastomeric dampers, a prototype 10 storey, 4x3 bay steel Moment Resisting Frame (MRF) was designed according to Eurocode 8 for seismic zone 3, using the Finite Element (FE) software SAP2000. However, some assumptions had to be adopted in order to proceed with the design of the structure. Firstly, the building was characterised as DCM (Ductility Class Medium), and a behaviour factor, q equal to four was used in both directions.

Subsequently, only the perimeter frames of the longest direction (4 bays) of the prototype building were used for non-linear analysis (SMRF). Non-linear time history analyses were carried out based on three different ground motions: a) El Centro, b) Chi Chi/CHY029-V, and c) Loma Prieta/ WAH000. These ground motions were scaled based on a method proposed by Fahjan and Ozdemir (2008), in order to represent the Design Basis Earthquake (DBE), and the Maximum Considered Earthquake (MCE). A bilinear model was assumed for the steel material of the main elements of the building with a yielding stress 275 MPa, while the FE software used for the non-linear analyses was OpenSees.

Regarding the elastomeric dampers, one of their main characteristic is their ability to provide both stiffness and damping. Hence, a Kelvin-Voigt model was applied, based on the characterization tests of Antonucci et al. (2001) (equivalent stiffness \( k_{eq} = 7.4 kN/mm \), and equivalent damping \( c_{eq} = 2.66 \times 10^{-3} kN/(m/s) \)). Two dampers were implemented in each floor, at the first and the fourth bay of the perimeter frame. However, additional diagonal braces had to be assigned to every damper location, which were designed so as not to buckle under the forces transmitted by the dampers. At the same time they will not significantly increase the total weight of the structure. This way, the deformation demand of each floor is dissipated by the dampers, and hence they become even more efficient.

The addition of the diagonal braces along with the elastomeric dampers (DMRF), led to a 22% decrease of the natural period of the structure, while at the same time all the interstorey drifts, floor accelerations, interstorey shear, and base shear were greatly reduced (see Figure 1 and Table 1). More specifically, the residual drifts were almost eliminated for both DBE and MCE, while the maximum displacements were reduced by 35% for the DBE with no yielding at any element, and 40% for the MCE with only the base columns and a few beams at the first three floors to be yielding. With regard to the shear forces, while the base shear only reduces by 21% for DBE, and 7.1% for MCE, the interstorey shear forces decrease up to 84%.

Potential for application of results

Two elastomeric dampers have been provided by Tun Abdul Razak Research Centre (TARRC) in order to be tested in the dynamic lab of the Engineering Department of Oxford University. Once characterization tests have been carried out, equivalent stiffness and damping values should be determined and will be implemented into the aforementioned numerical analyses. Moreover, a more sophisticated model will be adopted in the non-linear analyses based on a complex Zener model.

Subsequently, multiple parametric analyses will be carried out, optimizing the main characteristics of the diagonal braces, elastomeric dampers compared with the storeys’ stiffness and the dynamic properties of the structure. These analyses should lead to the proposal of a new design procedure for buildings using elastomeric dampers.

References


Table 1. Summary and variation of the basic parameters examined in this study

<table>
<thead>
<tr>
<th></th>
<th>DBE (SMRF)</th>
<th>MCE (DMRF)</th>
<th>%</th>
<th>DBE (SMRF)</th>
<th>MCE (DMRF)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Shear (kN)</td>
<td>1267</td>
<td>992</td>
<td>-21.7</td>
<td>1429</td>
<td>1328</td>
<td>-7.1</td>
</tr>
<tr>
<td>Roof Displacement (cm)</td>
<td>54.64</td>
<td>19.15</td>
<td>-65</td>
<td>72.14</td>
<td>28.8</td>
<td>-60.1</td>
</tr>
<tr>
<td>Roof Acceleration (g)</td>
<td>0.88</td>
<td>0.73</td>
<td>-17</td>
<td>1.33</td>
<td>0.82</td>
<td>-38.3</td>
</tr>
<tr>
<td>Residual Displacement (cm)</td>
<td>16</td>
<td>0.008</td>
<td>-100</td>
<td>36</td>
<td>1</td>
<td>-97.2</td>
</tr>
</tbody>
</table>

Figure 1. Roof displacement of SMRF and DMRF for DBE
A new design method for circular hollow sections

Project objectives and goals
Circular hollow sections (CHS) have been used as structural elements since the early 1800s (Dutta 2002). Design codes, such as Eurocode 3 and AISC 360, currently use cross-section classification and linear elastic, perfectly-plastic material models in predicting cross-section compression and flexural resistances. Comparison with experimental data has shown these traditional design methods to be overly conservative in estimating cross-section capacity (Gardner 2008).

A new design method, called the continuous strength method (CSM), has been developed to better predict the cross-section resistance of metallic plated sections. The aim of this project is to extend the CSM to cover structural steel, stainless steel and aluminium CHSs, resulting in a design process that is more accurate and that has less scatter than current methods.

Description of method and results
The CSM features two key differences compared with traditional design methods. Firstly the concept of cross-section classification is replaced with a continuous relationship between local slenderness and deformation capacity. This better reflects the observed continuous nature of section capacity reducing with increasing local slenderness, rather than the discontinuous nature that section classification currently suggests. Secondly strain hardening material models are utilised, allowing the limiting material stress to exceed the yield stress as witnessed in coupon tests. Previous work on the CSM has focussed on plated cross-sections in structural steel (Gardner 2008, Gardner et al. 2011 and Foster 2014), stainless steel (Afshan and Gardner 2013) and aluminium (Su et al. 2014).

In order to extend the CSM to cover metallic CHS a comprehensive dataset was collated, comprising of over 300 existing stub column and four-point bending experimental results. The dataset was firstly used to identify the local slenderness limit below which there is significant benefit from strain hardening. Then the continuous relationship between local slenderness and deformation capacity (called the base curve) was then determined. This relationship is used to estimate the extent to which the cross-section can deform before its resistance decreases. The material limiting stresses and strain hardening moduli are predicted using material models that incorporate strain hardening. The cross-section compressive and flexural resistances of the CHS dataset are finally determined through appropriate resistance expressions, using the estimated deformation capacities and material properties.

A graphical comparison between the ultimate compressive experimental loads and the CSM and Eurocode capacity predictions is provided in Fig 1. The graph shows the over conservatism of current design methods, with ultimate capacities exceeding the Eurocode predictions by a significant margin. It is evident that, on average, the CSM is more accurate and consistent than existing design methods, with the ultimate experimental capacities being closer to the CSM predictions and also having reduced scatter. There are a small number of over predictions of CSM resistance, and these are being investigated, along with using new experimental results to further validate the design method and the undertaking of reliability analyses.

Another benefit of the improved capacity prediction is that cross-sections benefit from enhanced resistance. Table 1 shows the extra capacity that the CSM provides over the Eurocodes for both compression, \(N\), and bending, \(M\). It can be seen that for the same cross-section, the CSM offers on average up to 9% additional compressive resistance and 14% further flexural capacity over current design methods.

Potential for application of results
Traditional design methods have been observed to be overly conservative in estimating the compressive and flexural cross-section resistances of CHSs. The design expressions determined through the extension of the CSM to cover CHSs can be used by structural engineers to design and build more efficient, cheaper, lighter metallic structures. Designers can specify a more locally slender cross-section, where previously a stockier cross-section would have been required. The ultimate aim is for the CSM CHS extension to be incorporated into international structural steel, stainless steel and aluminium design standards. There are also environmental benefits through the adoption of the CSM, with reduced carbon emissions through more efficient material use, leading to more sustainable construction.
References


Foster, A. (2014). Stability and design of steel beams in the strain-hardening range. Imperial College London


Funding bodies

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Figure 1. CSM and Eurocode compression predictions compared with test data
Design and performance of cold bent glass

Kyriaki (Corinna) Datsiou
University of Cambridge

Project objectives and rationale
A significant increase of the use of glass in buildings has been observed lately due to architectural trends that require lightness, transparency and curvilinear forms. Glass is no longer confined to small rectangular infill panels but can be used as a load bearing material in large span applications even in curved forms in order to fulfill modern architectural ideas.

The principal challenges that arise from the above are: 1) to cost effectively form the curved shape and 2) to ensure its efficient long term performance. Cold bending is an energy efficient method of creating curved glass surfaces based on the elastic deformation of glass at ambient conditions. The recent availability of high strength and thin glass in the form of chemically toughened glass (CTG) provides an opportunity to address the first challenge by developing a new generation of lightweight stressed-skin glass surfaces. The concept is to introduce a controlled amount of strain (and associated stress) into the chemically toughened glass panels at ambient temperatures which will produce the curvature required. However, the durability of chemically toughened glass is not well documented. Therefore, besides the need to investigate the cold bending behaviour of CTG, its long term performance should also be evaluated.

Description of method and results
The first part of the project comprises the understanding of cold bending of glass; this will be developed by means of numerical and analytical investigations validated by experimental testing. The available literature showed that there is a change in the deformation mode when applying an out of plane load on one corner of the plate in order to create a curved shape. At this point, the plate buckles causing one diagonal to straighten and the edges to suddenly become curved. This behaviour was described as snap through buckling (Galuppi et al., 2014).

Up to now, the project’s research focused on the cold bending investigation of rectangular monolithic plates with the application of an out of plane load on one of its corners (Fig 1). Experimental and numerical results showed that by preventing in-plane translation at two opposite corners of the plate, a change in the deformation mode occurs, comprising two phenomena under increasing applied displacement (Fig 2). The centre of the plate snaps in the opposite direction as the supported diagonal becomes stiffer confining significant vertical deflection to the loaded diagonal. This phenomenon is followed by the appearance of rippling along the length of the supported diagonal. The occurrence of the ripple is attributed to local buckling and can be referred to as “cold bending distortion”. The amplitude of the ripple may exceed the maximum allowable limit of roller wave distortion of thermally toughened glass (0.5 mm over a length of 300 mm) that is set in EN 12150-1:2000. The occurrence of the “cold bending distortion” does not indicate failure of the panel but poses a serviceability limit as it can cause unwanted visual distortions on the cold bent glass panels.

The influence of different boundary conditions and geometrical characteristics of the plate on the aforementioned instability were investigated (Datsiou and Overend, 2014). Table 1 presents the maximum values of the ripple amplitude for plates with different boundary conditions. The thickness of the plate has also a significant effect; the ripple amplitude increases with increasing plate thickness e.g., for a 1000 x 1000 x 8 mm plate that corresponds to the first case of boundary conditions of Table 1, the maximum amplitude becomes 0.5 mm.

Research will continue on laminated glass. Interlayers are viscoelastic materials i.e., their properties are temperature and time dependent. The influence of the interlayer will be investigated during the shaping process and the service life of the panel taking the interlayer’s material properties into account.

The second part of the project comprises the evaluation of the long term performance of CTG with a series of non-destructive and destructive testing. Tests will be implemented on artificially aged CTG since it is not commonly used in structural applications and there is a lack of naturally aged specimens. Therefore, the first step of the process is to establish a suitable artificial ageing method using naturally aged annealed glass as a reference. A combination of different artificial ageing methods will be trialled inducing random damage (sand trickling method - ASTM D968-05) and deliberate damage (using indenters and scratching devices) on the surface of the as received specimens.

Potential for application of results
The main practical advantage of this research will be the conversion of the acquired results in a set of guidelines that will have the potential to be adapted to different case studies that involve cold bent glass.
Table 1. Maximum ripple amplitude for glass plates with different boundary conditions

<table>
<thead>
<tr>
<th>Boundary conditions at the corners of the plate (plate dimensions: 1000 x 1000 x 5 mm)</th>
<th>Max ripple amplitude (mm)</th>
<th>Applied displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Restrained translation and rotation</td>
<td>0.33</td>
<td>141</td>
</tr>
<tr>
<td>Restrained translation and allowed rotation</td>
<td>0.24</td>
<td>121</td>
</tr>
<tr>
<td>Restrained translation and partially allowed rotation</td>
<td>0.31</td>
<td>142</td>
</tr>
<tr>
<td>Allowed translation and rotation</td>
<td>0.00</td>
<td>-</td>
</tr>
</tbody>
</table>

References


Funding body

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Figure 1. Test setup

Figure 2. Shape of the supported diagonal in consecutive steps during the bending process
Improving the seismic performance of nonstructural systems using viscous fluid dampers

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Problem objectives and goals
Buildings designed to modern standards are able to withstand earthquakes while undergoing only minimal structural damage. Although this suggests that a quick recovery from earthquakes may be possible, this outcome is not always achieved. Recent earthquakes such as the 2010 Canterbury earthquake and the 2010 Chile earthquake have demonstrated that buildings which do not experience structural damage may still incur extensive nonstructural damage (Dhakal, 2010; Miranda et al., 2012). The consequences of poor nonstructural seismic performance are substantial, as nonstructural systems make up the majority of building investments and are essential to building operations (Taghavi and Miranda, 2003). Inadequate nonstructural seismic performance has led to enormous repair costs and lengthy functional disruptions. Nonstructural damage accounted for billions of dollars of losses in 2010 alone (Fierro et al., 2011).

Attaining a target level of seismic performance mandates the harmonization of structural and nonstructural performance levels. However, both analytical and experimental research on nonstructural systems have been scarce compared to primary structural systems. This study investigates the role that viscous fluid dampers can have in enhancing nonstructural seismic performance and how these devices can contribute to the achievement of resilient structures.

Despite having the potential to be effective and economically viable solutions (Dicleli and Mehta, 2007; Pavlou and Constantinou, 2006; Wanitkorkul and Filiatrault, 2008), research focusing on viscous fluid damper applications for nonstructural enhancement has been very limited. Studies have concentrated on applications in low-rise and mid-rise buildings at the expense of high-rise structures. There have also been minimal attempts to maximize nonstructural performance using viscous fluid dampers. Parametric studies on nonlinear viscous damper coefficients and examinations on the optimization of damper placement have been restricted to structural objectives.

This project will examine the effectiveness of several different viscous fluid dampers and the effect of damper placement on nonstructural response. Expected nonstructural damages from retrofitted designs will be compared to code conforming buildings. Probable damage levels will be estimated for buildings with different nonstructural configurations and for varying earthquake intensities. The final aim of the project is to develop a viscous fluid damper placement strategy that will minimize nonstructural repair costs and service disruptions.

Description of methods and results
A Eurocode compliant 16 storey steel building design was created in order to evaluate the nonstructural seismic performance of standard structures. The lateral load resisting system consists of concentric braced frames located around the perimeter of the structure. Seismic design was conducted through modal response spectrum analysis in SAP2000.

The structure was modelled in the finite element program OpenSees and subjected to nonlinear time history analysis incorporating several ground motions. Engineering demand parameters (EDPs) used to characterize demands on nonstructural systems such as peak acceleration and interstorey drift ratios were recorded. Fragility curves were used to relate the EDPs to expected damage costs. The results of this analysis provide a benchmark on which to compare the effectiveness of alternative designs employing viscous fluid dampers.

Interstorey drift ratios were evaluated using fragility data corresponding to partition walls common in commercial and institutional buildings. It was determined that partition walls at several storeys can be expected to sustain damage during seismic events. It was also determined that the Eurocode interstorey drift ratio limit of 1% is inadequate in preventing partition wall damage.

Following the completion of the benchmark examination, viscous fluid dampers will be accurately represented and incorporated into the nonlinear building model. Several levels of earthquake intensity will be tested and multiple nonstructural component categories will be considered. The effectiveness of the viscous fluid dampers in improving nonstructural seismic performance will be assessed by comparing the fragility results to the standard building results. Damper placement optimization will then be explored. The enhanced placement procedure will be confirmed through testing in both the office building model and several other representative structures.

Potential for application of results
The results of this research will contribute towards meeting the societal demands of today. The viscous damper placement strategy will minimize earthquake-induced nonstructural damage and allow for a rapid return to building occupancy. Expectations are shifting in modern earthquake engineering, as clients are requesting that a rapid return to occupancy be possible after an earthquake event (May, 2007). The economic impact of nonstructural seismic response is substantial, as it has been shown that the majority of costs associated with earthquake damage in developed areas result from nonstructural systems (Filiatrault et al., 2001). These direct economic losses from damages are compounded by large indirect costs due to downtime and disruptions.
The interstorey drift measurements indicate that nonstructural damage and downtime can be expected in modern high-rise structures following an earthquake. This suggests that modern building standards still do not accomplish the ability of a community to quickly recover after an earthquake. The limitations of the Eurocode damage mitigation methodology were also revealed as the prescribed interstorey drift ratio limit did not prevent partition wall damage. These results highlight the need for design procedures which enhance nonstructural seismic performance. Viscous fluid dampers are a promising solution, and a damper placement strategy will enable engineers to harness this potential. The application of the project results will minimize the societal impacts of earthquakes and accelerate community recovery.

References


Funding body

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Tuning and shaping semi-active tuned mass dampers for use on high-rise wind excited structures

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Introduction
Semi-active tuned mass dampers (STMD) are control devices that can be used to enhance the vibration mitigation capacity of structures subjected to dynamic loading such as earthquakes and strong winds, enhancing structural safety and occupant comfort. Such devices operate on the basis of online altering their damping and/or stiffness properties for maximum energy dissipation. The manner that these parameters change depends explicitly on the chosen control algorithm which is in a sense the brain of the control system. In this regard, the selection of an appropriate control algorithm becomes an integral part of the control system design process and can indubitably affect to a great extend the vibration attenuation performance of the control system. To date, a large volume of advanced control algorithms has been developed and reviewed for the case of semi-active control (Liedes, 2009), however, a comparison of different control algorithms for the control device (STMD) and the problem specific (high-rise structure) case has yet to be considered.

In this paper, the most famous feedback controllers, namely proportional-integral-derivative (PID), groundhook (both displacement based (DBG) and velocity based (VBG)) and linear-quadratic-regulator (LQR) are examined for the case of wind excited high-rise structures comprising a variable damping STMD, discussing both quantitatively and qualitatively the gains of the use of each control algorithm. It is believed that such an investigation is important so as to direct future research efforts in the most promising directions by providing a frame of reference to both practicing engineers and researchers interested in the area of STMD control of high-rise structures.

Methodology
To illustrate the effectiveness of different controllers at alleviating structural response, the 76-storey wind-excited benchmark structure proposed by Yang et al. (2004) was considered. Three alternatives, namely: passive, semi-active, and active controlled structures that comprise a tuned mass damper (TMD), an STMD and an active mass damper (AMD) respectively were used for the investigation of the relative performance gains of the semi-actively controlled system at different control algorithm configurations (figure 1).

For the fairness of the comparison, particular emphasis was given on the tuning of the damping ratios of the TMD so as to optimize its performance while at the same time not exceed strict device limitation such as maximum stroke etc. On the contrary, the optimum minimum and maximum achievable damping ratios by the STMD were found using the cumulative energy dissipated by the auxiliary device at different damping (min/max) configurations.

Concluding remarks
Through the numerical analyses it was shown that the choice of a control algorithm has considerable effects on the performance of the STMD controlled structure. This is evident by the fact that only two of the semi-active control algorithms managed to bring the system’s acceleration response within the allowable limit (<15mg) (Yang et al., 2004). Yet, regardless of the choice of algorithm, the STMD as expected is shown to outperform the purely passive system, achieving behaviour similar to the actively controlled one (figure 2). Some additional interesting findings from the analysis include:

- DBG compared to VBG by default yield a better vibration attenuation performance for a given min/max damping ratio, however the latter algorithms can attain similar performance to the first when the maximum damping ratio of the device is reduced and the mass of the damper is allowed to move further (without exceeding the maximum stroke). Similar observations can be made for the case of PID controlled STMD.

- LQR controllers although being more complex to design (i.e. need of observers, full state feedback) by default yield a better performance compared to the other algorithms. Additionally LQR controllers allow the designer to choose the states to minimise, which implies that more control is obtained in terms of stroke minimization and vibration attenuation at certain locations.

References


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Figure 1. Structural configurations of the 76-storey building (a) TMD, (b) AMD, (c) VD-STMD

Figure 2. Peak and RMS response of the STMD equipped structure using different algorithms
Multi-axial long duration blast response of column sections

Jack William Denny
University of Southampton

Project objectives and goals
Long duration blast pressures are characteristic of very large explosions, typically associated with nuclear detonations and hydrocarbon vapour cloud explosions. In comparison to conventional explosives, the positive phase duration typically exceeds 100ms. The complexity of analysing long duration blasts is increased due to the relatively long duration of drag loading associated with the dynamic pressures. Currently no results or design procedures exist for the effects of long duration blast pressures interacting multiple times with undamaged and damaged load-carrying column sections from oblique angles.

This project aims to investigate the transient dynamic response and subsequent damage states of axially loaded column sections to multiple, consecutive long duration blast loads acting laterally from a range of oblique axes. After an initial blast event, the damage accumulation and therefore remaining structural resilience becomes a function of the modified harmonic properties, material strain-rate effects, and residual local and global resistance of the system.

In particular, I-shape Universal Column sections will be investigated; the cross-section shape gives rise to complex blast wave diffraction and drag loading when considering shock waves interacting from various angles of incidence (Fig 1).

Description of method and results
Given the occurrence of multiple detonations, this project seeks to investigate the effect of progressive damage accumulation on structural response. Additionally, the effects of multi-axis blast wave interactions on column structural response and subsequent damage will be investigated. Quantifying the structural response and damage accumulation of the columns throughout each blast event will be measured in terms of:

- Residual axial load capacity
- Maximum lateral deflections
- Harmonic response (natural frequency)

Numerical models will be developed to predict the structural dynamic response of column sections subjected to axial compression and multiple, consecutive long duration lateral blast loads acting from a range of oblique axes. Parametric studies using non-linear finite element analysis software, LUSAS (see extract in Fig 2) and computational fluid dynamics code, Air3d (Rose, 2011) together with a series of experimental trials are being undertaken to investigate the structural response described above. The parametric study will examine a range of oblique angles of incidence of the shock wave, explosion size and shock off distances. Following parametric studies, it is intended to define critical performance envelopes for specific column sections, from which, the loading regimes in the experimental trials will be based. Mesh sensitivity, element and solver suitability studies will be performed to ensure the most accurate computational results are ratified.

A series of experimental trials are planned for the future to investigate the structural response described. Long duration planar blast waves will be recreated within the Air Blast Tunnel (ABT); the researcher has been given privileged access by the sponsor for use of the ABT at the national testing facility on Foulness Island, Essex. The ABT is capable of creating blast pressures characteristic of a long duration explosion; overpressures of 110kPa with positive phase durations of approximately 200ms are attainable, in comparison to durations of 10-20ms typical of conventional explosions. Column specimens will be orientated at a range of oblique angles inside the ABT to investigate the effects of multi-axis blast wave interaction. The column specimens will also be subjected to repeat blast loadings (at comparatively different orientations) to replicate multiple detonations acting from different axes. The subsequent damage will be recorded in terms of lateral deflections and deformed shape.

For each blast regime, duplicate column specimens will also undergo further, parallel experimental trials to determine the harmonic properties and residual axial load capacity after each blast event. The harmonic properties of the columns, in particular, the natural frequencies will be verified separately utilising a pull down rig at Foulness Island. In addition, specimens will undergo compressive load testing, thus recording the residual axial load capacity and damage state of a column throughout the successive blast events.

Potential for application of results
Steel column sections subjected to long duration blast loads are of interest due to increased security demands and the occurrence of intentional or accidental explosive events, such as the 2005 ‘Buncefield Disaster’ and the more recent 2013 ‘Texas Fertilizer Plant Disaster’. There are circumstances in which multiple blast loads from different axes is of interest. These include columns where the direction of a potential blast is known, such as industrial operations involving volatile, explosive materials confined to certain areas of a facility. Multi-axial behaviour of columns is also important when designing security perimeters; it is important to limit structural columns’ exposure to blasts from known ‘vulnerable’ axes given the occurrence of multiple detonations.

It is the objective that the experimental trials and parametric studies will be used to draw significant conclusions regarding the structural response of steel columns to multiple long duration detonations, both in terms of the progressive damage accumulation and the effects of blast wave interaction from various angles. These conclusions will define key resistance functions for Universal Columns undergoing successive blast loading by reference to the explosion size, the progressive damage state and the respective angles of incidence concerning blast wave interaction.
References

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![Figure 1. Air3d modelling of 45° blast wave interaction with Universal Column cross section](image1)

![Figure 2. LUSAS extract of Universal Column section subjected to multiple, oblique angle blast loads](image2)
Project objectives and goals

Within the building industry, approximately 45% of the total material usage arises from the consumption of steel and concrete in construction. Therefore, it is crucial to understand the flow of interactions between materials, processes and activities within buildings’ lifecycle in order to meet national and global environmental emissions’ targets (Ibn-Mohammed et al, 2013). The present research investigates the potential to reduce the environmental impacts of structural systems through a more efficient use of materials. The main objective of this study is to explore and to develop a novel approach that utilises Building Information Modelling’s (BIM) capabilities combined with advanced structural analysis and Life Cycle Assessment (LCA) as well as with a two-staged automated search engine that considers structural efficient and environmentally responsible steel I-beams.

Description of method and results

A prototypical steel framed structural system under certain loads has been analysed. Four input parameters of the I-section have been assumed: web thickness, flange thickness, section’s width and depth. The obtained optimal solution is the one that makes more sustainable use of materials - minimises the weight of the structure - without compromising its structural performance - maximises the efficiency of the tested frame. The system’s architecture utilises the Application Programming Interface (API) of Robot and the .NET framework of C#, and it inherits several structural functionalities based on Robot Finite Element Method (FEM) engine. The main functionalities that have been implemented within the developed Graphical User Interface (GUI) are:

- Developing a parametric, 3D computer model of a prototypical steel framed structural system;
- Verifying the structural elements according to Eurocode BS-EN 1993-1:2005/NA: 2008/AC: 2009, Performing sensitivity analysis in order to identify the correlation matrices between input and output parameters;
- Establishing a custom constraint genetic algorithm that interacts with the developed computer design model;
- Executing calculations and carrying out validation of the developed 3D models with the optimised steel sections

In the Monte Carlo analysis, multiple simulations have been performed using randomly generated values based on the specified range (Table 1). From the Pearson correlation of the parametric structural model after 900 simulations, it has been observed that within the tested sample the web thickness appears to have the highest negative correlation with the efficiency ratio (-0.8354) (Fig 1) and the highest positive correlation with the structural weight (0.6338). On the other hand, the width of the section appears to have the highest negative correlation with the slenderness ratio Lamy (-0.9253), whereas the depth of the section has the highest negative correlation with the slenderness ratio Lamy (-0.9385).

The Genetic Algorithm’s (GA) conceptual theory, developed by John Holland in the 1960’s and 1970’s (Holland, 1992) mimics the evolutionary processes in nature by populations, reproduction and heredity, with the inherent ability for the designer to alter several parameters within the method such as population size, crossover technique and mutation rate. The beam’s parameters represent the four genes of the GA, which comprise of the algorithm’s inputs. In particular, the section’s Depth d and Width B, as well as the flange’s Thickness T and the Web’s Thickness t are allowed to vary between the ranges displayed in the Table 1.

The fitness function is linked to the overall weight of the structure, and it appears to have a constant declining trend while the algorithm is searching the entire design space for the optimum solution. A constraint method that penalises the infeasible solutions has been implemented: a constant penalty to the solutions that violate the Eurocode’s slenderness constraints is being applied. The penalty function for the minimisation problem with m constraints is shown in Eq 1.

\[ f_p(x) = f(x) + \sum_{i=1}^{m} \epsilon_i \delta_i \]  

Eq 1

The effectiveness of the penalty function can be seen in Fig 2, where the efficiency ratio sporadically exceeds the maximum value of (1) during the early generations, and the algorithm, after approximately 350 generations, converges to the maximum ratio of 0.999, which is equivalent to a minimum structural weight of 380kg. In that way the algorithm develops an “intelligent” behaviour by penalising the solutions with efficiency ratio greater than 1 and gradually eliminating them from the final population. The obtained section details from the GA are: Depth d = 152.6 mm, Width B = 90.4mm, Web t = 4.2mm, Flange T = 4.1mm collectively forming a decent estimation of the design problem. The reduction in weight compared to the next available standardised UB 152x89x16 section is 21%. In regards to the equivalent LCA environmental indicators the largest reduction of approximately 20.7% has been observed in the Global Warming Potential (GWP) measurements, whereas the smallest reduction has been detected for the Acidification Potential (AP) with 19% reduction compared to the UB152x89x16 section.
Potential for application of results

Preliminary validation trials of the model have been conducted within Price & Myers. The proposed framework could be utilised as a design tool to inform early stage solutions that improve the environmental and structural indicators of steel design systems. The implementation of BIM platform allows the system to automatically update the 3D geometry based on the custom steel sections. In addition the global search engine of the evolutionary algorithm is an expandable model and the conflicting nature of structural engineering problems can be further analysed. Cost-efficiency and value-engineering parameters can also be implemented within the fitness function of the configuration and a multi-objective examination of the structural system will allow designers to assess the Pareto front for trade-offs between potential solutions that not only reduce environmental impacts but also reduce construction-fabrication costs.

References


Funding body

Engineering and Physical Sciences Research Council (EPSRC)

Price & Myers

Table 1. Steel beam sections specified ranges for genetic algorithm

<table>
<thead>
<tr>
<th>Design Inputs</th>
<th>Genes</th>
<th>Minimum (mm)</th>
<th>Maximum (mm)</th>
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<tr>
<td>Depth d</td>
<td>1</td>
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<td>175</td>
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<tr>
<td>Width B</td>
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<td>90</td>
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<tr>
<td>Flange thickness T</td>
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<td>4</td>
<td>6.5</td>
</tr>
<tr>
<td>Web thickness t</td>
<td>4</td>
<td>4</td>
<td>6.5</td>
</tr>
</tbody>
</table>

Figure 1. Correlation between efficiency ratio and web thickness

Figure 2. Optimisation results with penalisation – structural weight

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Reinforced concrete crack analysis

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Project objectives and goals
Due to rapid advances in the development of techniques for monitoring and retrofitting concrete, there is a need to revisit and generalise classical theories in order to better assess the strength of existing reinforced concrete (RC) structures and to inform the design of strengthening systems. An improved understanding of concrete cracking is an implicit requirement to achieve these aims. This requires the consideration of local phenomena such as tensile and compressive concrete softening as well as the interaction between the reinforcement and the concrete. This can give a better understanding of cracking in reinforced concrete beams and how to model new reinforcing systems such as fibre reinforced polymers (FRPs).

This research aims to carry out an in-depth investigation of the crack propagation in concrete beams and to undertake an experimental and theoretical study of crack bridging in reinforced concrete structures. More specifically, the objectives of this research are:

– To investigate the mode of crack propagation in RC using Digital Image Correlation (DIC).
– To develop an integrated fracture-based model to describe the cracking process in RC
– To study crack bridging and the associated high localized stresses and strains in the cracked regions in reinforced concrete structures and measure the fracture process zone in reinforced concrete.
– To study the effect of using FRP reinforcement on the fracture parameters of reinforced concrete.
– To study the ductility of RC beams and suggest more rational minimum reinforcement formula to avoid brittle failure.

Description of method and results
The laboratory experimental work includes the casting and testing of concrete beams with longitudinal reinforcement and the monitoring of the crack development. The main test parameters are the geometrical and material properties of the concrete and reinforcement. These parameters influence the fracture behavior and provide insight into the stresses at the crack tip and the forces generated in the reinforcement bridging the crack. Fig 1 shows the test rig set up. Images of the crack propagation during the tests were recorded using a high resolution digital camera. A Digital Image Correlation technique (DIC) was subsequently used to analyze the images taken at different loading stages.

The theoretical investigation includes the development of a general closed-form model for reinforced concrete fracture to study the effect of the interaction of the stress localisation in the tension and compression zones. A Bond-slip model is used to simulate the interface between concrete and reinforcement. The model results show a good correlation with the experimental data obtained from test specimens. It was noted that:

– The cracking process of reinforced concrete can be broadly divided into two phases: crack propagation phase and a crack rotation phase. The crack propagation phase includes tensile softening and then when these stresses diminish, crack rotation around the crack tip follows.
– The cracking process depends strongly on the reinforcement properties including the reinforcement type, strength and modulus of elasticity.
– The cracking process is unstable at low reinforcement ratios, and this instability depends on factors such as the concrete compressive strength, beam depth and reinforcement shear stresses.
– Based on the results of the model, a minimum reinforcement ratio associated with given geometrical and material properties to avoid instability. This minimum reinforcement requirement is found to be inversely proportional to the beam size (Fig 2) and this contradicts many code provisions.
– Revisions to the prevailing code provisions that define the minimum reinforcement in flexural members (ACI318 (2011), EC2 (2004)) since it appears that these were derived based on empirical formulas and without considering the size effect.

Potential for application of results
– Understanding of crack propagation and fracture is important for the safety assessment and renovation of existing structures. This study provides a better understanding of the cracking process of RC beams.
– The DIC technique enabled the visualisation and quantification of the fracture properties in reinforced concrete. The exploitation of new advances in digital imaging and high resolution cameras can provide advanced tools to measure fracture and monitor crack profiles.
– Relatively few fracture-oriented experimental studies have been conducted on concrete that is reinforced. Knowledge of concrete fracture processes can help in deciding suitable analysis approaches to be used for detailed crack analysis.
References

ACI 318M-11: Building Code Requirements for Structural Concrete and Commentary. American Concrete Institute, 2011


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Figure 1. Test rig set up

Figure 2. Minimum longitudinal reinforcement requirements for different beam depths and concrete strengths
Project objectives and goals

The study proposes the design of a freestanding, biomimetically inspired, deployable canopy. A review of the key features characterising deployable structures along with an investigation into the biological world was applied to the modelling of a foldable structure inspired by the blooming of a Morning Glory flower (Ipomoea Violacea). Through freezing the geometry at set deployment stages, a time-stepped analysis was created, showing the structure at various stages of deployment. The freezing of the structure allowed a parametric investigation of the most suitable deployment sequence to be developed.

Biomimetics, also known as biomimicry, is defined by Santulli (2012) as the approach to finding the solution to a problem through the observation of Nature. It is commonly known that Nature is never static. On the contrary, it is in continuous motion: evolving in response to its environment. Thus, in the sphere of structural engineering, where everything is per definition fixed in place, biomimetics introduces the notion of movement. Hence, the need for deployability to confer the power to vary the form and function of a system by a series of motions and manipulations (Chiesa, 2010) that must occur in an autonomous and safe manner (Pellegrino, 2001).

The advantages of mimicking a swirl flower for the design of a deployable awning are:

- The lesser number of petals allows for the creation of a simple and effective geometry, bypassing surplus of members, thus increasing the ability for the structure to pack tighter.
- The continuity of the petals avoids issues caused by them working as single elements. The deployed structure being continuous above the covered area will offer more efficient protection from the environment’s conditions once opened.
- The additional twisting characteristic of the deployment enables more compact packing, leading towards the design of a structure being relatively small when folded.

Consequently, this research has focused on a member of the Ipomoea family: the Morning Glory Flower shown in Fig 1. The main characteristic of such a flower is the way in which the petals are joined together to form a trumpet (Stern, Jansky et al., 2003).

Description of method and results

The observation of fast motion videos showing the flower blooming allowed gaining a more precise understanding of the mechanism that the model was to perform. Therefore, it was possible to generate a physical and digital model of the deployable structure that would reproduce the motion synthesized by the flower’s unfolding process through the creation of a moving structure with three distinct degrees of mechanical freedom (Fig. 1):

1. The rotation of the lower plate $\theta$,
2. The vertical translation of the plate $D$, and
3. The change in length of the pistons $R_2$.

Through varying the geometrical parameters of the structure it was possible to optimise the structure in relation to key functions that were:
- to gain maximum coverage,
- to minimise the forces for the deployment mechanisms,
- to minimise the compaction of the closed configuration.

The time-stepping of the deployment sequence allowed a comparison between the various deployment stages, assuming a steady and controlled deployment sequence to avoid the effects of sudden accelerations and decelerations. The extremities of the deployment sequence, from fully packed to fully deployed, were established and subsequently divided into six equivalent static stages from 0% to 100%. The plate starts off at 0% rotation and 0% lift and ends up at 100% for a total of 36 combinations. The 36 distinct stages of deployment were analysed for four piston dimensions varying in relation to the radius of the lower plate with the following ratios of the lower plate radius to the upper piston length ($R_1$ to $R_2$): 0.5, 1, 1.5 and 2.

The post-processing methodology used to investigate the vast amount of data created was to plot contour maps of force, stress and displacement for each plate radius ($R_1$) to piston length ($R_2$) ratio. The contour maps show the variation of the structural behaviour at every possible deployment situation considered in the time-stepped stages.

In order to verify the effectiveness of the deployable structure, the purpose of which is to have the capacity to fold to a small compact state and unfold creating a sheltering canopy, coverage is a fundamental characteristic. The benefit of the third degree of freedom stands out when observing Fig 2. Maximum coverage is reached with the ratio $R_2=2R_1$ and minimum coverage when $R_2=0.5R_1$. Thus, the variation of the piston's length enables the benefit of reaching a quicker and greater coverage and a tight, compact and small folded state.
Potential for application of results

The mechanism governing flower blooming is relevant to the creation of biomimetically inspired deployable structures, but requires an innovative and unique analysis approach in order to be successful for determining the most efficient deployment routine. The methodology developed is applicable to any deployable structure that can be held in a controlled and balanced temporary state. Due to the type of analysis carried out, there is scope for expansion through the nesting of the contour graphs to identify increasingly efficient structures. The deployment sequence causing the minimum deployment force, maximum coverage and deflections could be determined through plotting a deployment path connecting the minima within the contour plots and consequently minimizing the energy required during deployment and/or its in service forces.

References


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Shear strengthening of reinforced concrete slab-on-beam structures using externally bonded FRP fabrics

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Project objectives and goals
The project investigates the behaviour of reinforced concrete slab-on-beam structures strengthened in shear by externally bonded fibre reinforced polymer (FRP) fabrics. Recent work (Dirar et al, 2012) has indicated that current guidelines for strengthening may overestimate the contribution of externally bonded FRP fabrics leading to the possibility of unconservative design in practice. The latest edition of The Concrete Society Technical Report 55 (2012) has taken some steps to accommodate these findings but further work is needed to ensure that current design methodologies are appropriately conservative. The objective of this project is to improve upon our current understanding of strengthened concrete behaviour and provide a more rational design method validated using sound empirical evidence.

Description of method and results
The behaviour of concrete slab-on-beam structures strengthened in shear by externally U-wrapped and bonded FRP fabrics have been investigated experimentally by carrying out a series of push-off tests. As part of this research, a modified push-off specimen that generates a combination of shear and tension on the shear plane was developed. This has been used to investigate the effect of varying reinforcement ratios, FRP thicknesses and FRP end conditions. Of particular interest has been the load sharing behaviour between the concrete, the internal steel reinforcement and the external FRP strengthening.

The second experimental phase has involved three point bending tests on a series of 360mm and 540mm deep FRP strengthened concrete T-beams. These test results will ultimately be combined with a coordinated test series being carried out at the University of Bath, to provide a data set of geometrically scaled, strengthened T-beams of three different depths. This will allow scale and other effects to be investigated, and the implications for design assessed.

Potential for application of results
The conclusions from the experimental and analytical programme are expected to inform technical guidance in future editions of TR55 and design codes addressing the use of FRPs to strengthen existing concrete structures. Conclusions with regard to failure mechanisms associated with the de-bonding of the external FRP reinforcement and incipient near-surface failure of the concrete are thought to be of particular relevance in explaining the possible lack of conservatism in the current guidance.

The push-off testing approach provides a method for investigating shear transfer across a dominant crack and the test results for realistic scale strengthened T-beams will be valuable in extending the currently limited data set. Improved understanding of the possible scaling effects will be critical in bridging the gap between the understanding gained from small scale experimental work in a research environment and its application to full size structures in practice.

Detailed modelling of strengthened T-beams, benchmarked against the experimental data from the full scale beam tests, will improve and validate the accuracy of numerical modelling of full scale beam behaviour. This will provide confidence in assessing the capabilities and limitations of computational analytical approaches to support the design of strengthened elements in practice.
References


Funding body
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Modelling of crack propagation of brittle heterogeneous materials

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Project objectives and goals
Modelling of crack propagation is a crucial aspect in engineering field, as it involves safety, reliability and integrity of civil engineering structures and components. Most of engineering materials, like concrete and rock, exhibit a heterogeneous nature due to their composition, and homogeneous-based models may lead to unrealistic and unreliable results, as smooth crack paths, while, in reality, fractures propagate along the paths of least resistance, showing more tortuous patterns. Uncertainty in the location of the crack initiation point, flaws and possible manufacturing defects contributes to confer a non-deterministic nature to materials.

Multiscale modelling is a very powerful and elegant approach widely used to incorporate effect of heterogeneity in computational models; nevertheless, materials with a very high degree of heterogeneity would require a too high degree of precision to be modelled with such technique. Stochastic approaches can provide several advantages over multi-scale approach. Furthermore, when simulation involves large-scale problems (i.e. embankments), for material located in depth might be impossible to extract a sample providing the needed information, and values to insert in a model can only be defined probabilistically.

In this work, results for the implementation of a theoretical and computational framework for modelling of crack propagation on brittle heterogeneous materials are presented. Heterogeneity is incorporated in a homogeneous based code using advanced and computationally feasible stochastic tools, capable to opportunely simulate randomness in the mechanical properties. Monte Carlo method is employed to reach an acceptable convergence of the results. Model validation is achieved through comparison with experimental results.

Description of method and results
To include effect of heterogeneity on crack path and material strength evaluation, stochastic finite element method is adopted. A theoretical model for crack propagation in homogeneous brittle materials is implemented with a statistical procedure able to sample random values for the chosen mechanical property.

Validation of results is achieved by comparing them with experimental data from an intact brazilian disc test conducted on a rock specimen. Fracture toughness, which describes the resistance of a body to damage from an existing crack, is estimated from experimental data. Literature provides several expressions for calculating stress intensity factor; nevertheless, almost all of them consider notched specimens to localize stress concentrations and crack initiation point, as stress intensity factor is function of specimen geometry, loading condition and size and position of the initial notch (Romlay et al, 2010). In case of intact specimen, conclusions from Li and Wang (2013) are employed in order to locate crack initiation point in a specified zone of the disc, corresponding with the zone of maximum tensile strain.

Approximations and assumptions done to calculate the value of plane strain fracture toughness are the reason for choosing it as random parameter. Random values are assigned to each finite element node following the lognormal Weibull distribution; Gorjan and Ambrožič (2012) proved that, if an adequate degree of heterogeneity is considered, it well reproduces brittle behaviour of materials like concrete and rocks. Maximum Likelihood Estimation technique has been adopted to sample a value from the given distribution. Monte Carlo method is used for tensile strength final estimation. Preliminary results from simulation with homogeneous model and the mean from MCS of 50 heterogeneous models are compared with experimental results and shown in Fig 1.

In presence of a suitable number of simulations, stochastic approaches provide valid results. Additional advantage of considering material heterogeneity is in the possibility to evaluate realistic crack paths and to estimate the probability of failure: its estimation can provide useful information that may be considered during design and planning phase of engineering works, in order to suitably consider the realistic limit state of a material and consequently provide the best solution to conduct them safely and in economically sustainable way.

Potential for application of results
Incorporation of effect of heterogeneity of materials in computational models spreads the range of applicability, as this allows predicting behaviour of materials more realistically.
References


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Engineering and Physical Science Research Council (EPSRC)

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Figure 1. Stress-strain plot from homogeneous and heterogeneous models: comparison with experimental data.
Study of mechanical properties of bamboo for designing lightweight structures

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Project objectives and goals
Bamboo as a structural material has many advantages; it is lightweight due to its hollow shape and its fibre and matrix composition. The mechanical properties of bamboo culms in the longitudinal direction are remarkably good, its stiffness to weight ratio is better than that of steel. Moreover, it is a natural material with a fast growing rate. One of the main challenges is that its mechanical properties are difficult to obtain and to understand, as it is an anisotropic material with a complex structure and high levels of variability along and across the culm. Nonetheless, many projects around the world have shown the potential of bamboo as a structural material, as it is one of the oldest building materials along with wood. Despite this, very little technical knowledge of the material is known.

The main goal of the research is to encourage the usage of bamboo as a suitable alternative of sustainable structural material. In order to do so, two main objectives have been established:

1. Devise an appropriate method to determine the axial and flexural properties of bamboo using small coupons based on a simpler and more accessible testing procedure.
2. Develop a design methodology that exploits bamboo in lightweight structures under predominantly compressive axial forces.

Description of method and results
This synopsis describes the methodology to determine the axial stiffness (EA). This methodology is based on codified experimental compressive tests of small coupons (JG/T 199-2007), and theoretical analysis based on macromechanical analysis of a composite material model of a transversely isotropic laminate (Fig. 1). The material model takes into account the geometrical shape of the cross-section as well as the variability of the culm wall across the thickness. In order to determine the respective plies of the laminate, through-thickness volume fraction was calculated by image analysis as it is assumed that fibre content is proportional to the stiffness of the bamboo, as shown by Amada et al. (1995), Nogata et al. (1995) among others. Experimental tests on both full culms (ISO 22157-1:2004) and small coupons have been carried out in order to validate the composite material model.

The composite model is based on the following assumptions: i) bamboo is constituted of several unidirectional laminas of material; ii) three laminas are bonded together to form a laminate, which represents the variation across the wall thickness; iii) the model takes the laminate properties into a hollow cylindrical beam in order to consider the cross-section geometry of the element. The four engineering constants of a transversely isotropic material are , , , , and the stiffness matrix is (Kollar and Springer, 2003):

\[
\begin{align*}
A_{ij} &= \frac{1}{2} \sum_{k=1}^{\infty} (\tilde{Q}_{ik})_x (x_k - x_{k-1}) \\
B_{ij} &= \frac{1}{2} \sum_{k=1}^{\infty} (\tilde{Q}_{ik})_y (y_k - y_{k-1}) \\
C_{ij} &= \frac{1}{2} \sum_{k=1}^{\infty} (\tilde{Q}_{ik})_z (z_k - z_{k-1})
\end{align*}
\] (1)

where is the stiffness matrix of each lamina, and is the distance from the mid-plane to both surfaces of each lamina. The respective axial stiffness is:

\[
EA = 2\pi \frac{1}{\tilde{a}_{11}}
\]

 is an element from the compliance matrix (inverse of the stiffness matrix), analysed at the neutral plane.

To determine the volume fraction of each of the three laminas we defined the thicknesses based on an average distribution of fibres in each of the laminas as shown in Fig. 2. A set of sixteen coupons of the species Moso (Phyllostachys Pubescens) were taken from bottom to top along the bamboo culm to record the variability in properties in the longitudinal direction. Strain measurements were taken using both strain gauges and Digital Image Correlation (DIC); the latter was used on the side wall of the culm to observe the strains distributions through the thickness. The validation process for the composite material model is currently undergoing.

Potential for application of results
The research is intended to contribute to develop a better material model to enable the rigorous analysis and design of lightweight and efficient bamboo structures, through the adoption of composite materials theory.

References
Funding Body
Engineering and Physical Sciences Research Council (EPSRC)

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Figure 1. Transversely isotropic section of bamboo

Figure 2. Volume fraction distribution in through-thickness wall
Shaking table tests on steel and reinforced concrete precast buildings with and without buckling-restrained braces

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Background
Experimental tests of individual BRB members (e.g. Merrit et al. 2003) have demonstrated their high energy dissipation capacity. However, experimental evidence of their dissipation capacity when fitted in actual structures is limited. In this project, the effects/benefits of introducing BRBs on structures located in soft soils are studied in terms of global responses (displacements, floor velocities and floor accelerations).

Aim and objectives
The project aims to examine experimentally and theoretically the behaviour of model structures with and without Buckling-Restrained Braces (BRBs). The objectives are:

– Conduct test on individual BRB members subjected to cyclic loading
– Conduct shaking table tests on a steel frame model structure with and without BRBs using seven earthquake inputs recorded in Mexico City
– Conduct shaking table tests on two concrete precast building models with and without BRBs using the similar ground input as above.
– Examine the damping effect of the BRB members on the models due to the inclusion of BRBs
– Calibration of a displacement-based methodology for seismic design of structures fitted with BRBs

Method and results
Fig 1 shows one of three structures tested on a shaking table at the National Autonomous University of Mexico. The first tested structure consisted of a five-storey steel frame with a total height of 1450 mm. It has one bay on each direction with 600 mm in the longer one and 300mm in the shorter one. The BRBs were located in the longer direction as diagonals. Then, two RC precast models, geometrically identical but with different levels of steel reinforcement, were tested. They were one-bay and four-storey frames with the inter-storey height of 1.10 m. The square plane has a side length of 3.30 m. The first precast model was designed according to the Mexico City building code to fully-resist the lateral loads imposed by the ground motion. The second precast model and the steel model were designed to resist gravity loads only; while BRBs were provided and designed to resist the lateral loads. A displacement-based methodology, proposed in this study (see Guerrero and Ji, 2012), was used in these models for design purposes. All three models were assumed to be located in the seismic zone IIIb of Mexico City characterised by very soft soils. The models were subjected to the SCT-EW record of the 19/09/1985 Mexico Earthquake.

The results of the steel model have already been processed and they show the benefits of introducing BRBs in building frames; i.e. the global responses significantly reduced while the damping ratios increased. For example, Fig 2 shows the time history of the relative displacement, absolute floor velocity and absolute floor acceleration at the top floor of the steel model. As observed, the reductions of these responses were about 59%, 35% and 27% respectively. The results of the two precast models are in process and they will be available in two months.

Potential application
The inclusion of BRBs in building structures has demonstrated to be beneficial (at least) for the steel model because the global responses significantly reduced. In this sense, the damages after earthquakes in buildings equipped with BRBs would be significantly less than those without BRBs. In addition, BRBs act as structural fuses which, if damaged, can be replaced after a severe event. This will remain the main structural systems without (or suffering significantly reduced) damage.

The design methodology proposed in this study has one important advantage: selecting the amount of capacity provided by the main structural system and the capacity provided by the BRBs. In this context, designers have the freedom of selecting the best balance between economy and participation of the BRBs in the performance of the structural system. It is also recognised that each project is different; however, less than 50% capacity provided by the BRBs is advised so that the connections and other elements are capacity protected. It is important to remark that the proposed methodology utilises multiple sets of seismic records; the same records which are used in the Performance-Based Assessment of the structure. Therefore, the proposed methodology has been developed in a Performance-Based approach and is fully compatible with it.

References
Funding body
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Figure 1. Precast model equipped with BRBs tested on a shaking table

Figure 2. Global responses on the steel model with vs. without BRBs
Vibration serviceability of lightweight floors

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Project objectives and goals
Economical and architectural demands are pushing construction industry towards building more slender and lightweight structures. The need for less material usage and column-free spaces is implemented with the advances in material technology and construction quality control. Slender buildings that meet strength and deflection criteria, might fail to fulfill the vibration requirements. Lightweight floors, in many different construction types, are common examples of slender structures in buildings. They are also expected to be more widely used in future.

Lightweight floors are frequently reported as having annoying and intolerable vibration levels (Li et al., (2011), Tigli, (2014)). Those excessive vibration levels can affect the comfort of humans occupying the floor or the functionality of sensitive equipment accommodated on the floor. Despite the increasing efforts to understand and deal better with vibration serviceability of lightweight floors (Parnell et al., (2010), Nguyen et al., (2014)), many issues are still not fully resolved.

One of these under-researched aspects is the nonlinearities introduced to the structure from structural components supporting or connected to the lightweight floor. Unbolted column supporting lightweight floor is an example of those nonlinearities which the study will focus on. This column is not firmly connected to the foundations, hence unbolted column. The aim is to propose the best linear model describing nonlinear behaviour of a real-life floor. This is supported by the fact that linear models are easier to deal with in terms of required resources and time.

Description of methods and results
A systematic approach will be adopted to achieve the goals of the research outlined in the previous section.

Analytical model of the floor under investigation is to be created to get a basic idea about the expected results of the experimental tests. After that, experimental test should be designed, and full experimental modal test is to be performed to extract the modal properties of the floor. The next step is to update and correlate the analytical model to perform more investigations. At the same time, floor vibration serviceability assessment is to be conducted. The analysis of experimental results will quantify the effects of the nonlinearity presented by unbolted column on vibration serviceability of lightweight floor under investigation.

The new in the UK unique reconfigurable full-scale lab floor panel structure at the University of Exeter (Fig. 1) will be used to conduct most of the experimental work, while other data will be obtained from testing real-life structures. ANSYS® and MATLAB® will be used to process the results.

Potential of application of results
Using the best linear approximation of the nonlinear structure can save unnecessary expenses in resources and time spent for its analysis. In addition, investigating this issue will highlight the effect of unbolted columns on vibration serviceability of lightweight floor.

References

Funding body
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Figure 1. The unique reconfigurable full-scale lab floor panel structure at the University of Exeter during modal test.
Performance of textile reinforced concrete retrofitted RC beams under cyclic actions

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Project objectives and goals
In the past, many researchers conducted experimental and numerical studies in designing and retrofitting structural members and structures. Meanwhile, the upgrading of novel materials is another advantage because offers the potential for designing sustainable structures efficiently and cost effectively. The main idea of this project is to provide novel knowledge on how to retrofit existing structural beams under cyclic actions in order to upgrade existing structures and codes, with novel materials with potential to replace existing materials. The performance of most common strengthening methods, such as the carbon reinforced polymer (CFRP) method have some drawbacks, such as the high cost and non-friendly environmental behaviour. Meanwhile, even if fibre reinforced polymer (FRP) composites, are very desirable materials because of their properties, such as high strength-to-weight ratio, the adhesive material between FRP and the old substrate concrete is epoxy paste adhesive, which has some drawbacks; some of them are diffusion tightness, poor thermal compatibility with the base concrete, poor fire resistance and susceptibility to UV radiation. In order to avoid these problems, cement based composite systems consisting of FRP and a cementitious mortar has been used. Meanwhile, the bond of FRP in the cementitious mortar is unable to penetrate and wet individual composite fibres, therefore alternative methods have been developed to improve the enhancement of the bond, by using fabric meshes into cementitious mortar.

One of the solutions proposed for designing cement based strengthening systems for concrete structures are Textile Reinforced Concrete (TRC), consisting multi-axial textile fabrics bonded to concrete surfaces with a fine-grained, high strength concrete. The effectiveness of TRC system was presented by authors such as Brückner et al. (2006), and is widely analysed in the literature. Although many researches were studied monotonic loading conditions, there is a lack in the literature regarding the behaviour of TRC-strengthened RC beams under cyclic loading. One of the main objectives is the evaluation of the performance of strengthened beams in terms of stiffness and strength by measuring the stiffness degradation after each cycle and by hysteretic testing. One of the parameters influencing the behaviour of reinforced members is the shear span-to-reinforcement depth (a/d) ratio which is the distance between the applied load and the support. Another important parameter is energy dissipation capacity, which will be used as a criterion for the measurement of the capacity of a structural member to cyclic inelastic loading or as a damage indicator. Energy dissipation is based on parameters such as reinforcement, configuration of reinforcement, geometrical characteristics of members and therefore empirical formulas are not accurate even if this parameter is important for economical purposes and seismic safety.

Description of methods and results
In this study experimental and numerical investigation will be conducted and the cyclic load will be imposed based on Protocol I-quasi static by FEMA-461 (2007). The size effect is considered by creating full scale rectangular beams with different shear span-to-depth ratio tested until failure. Four beams with a ratio of 2.8 (2m long, 150 mm beam width, 250 mm beam height) will be casted, strengthened by TRC and tested under four-point bending as simply supported beam. Two large beams with shear-span-to-depth ratio of 4.6 (4m long, 250 mm beam width, 350 mm beam height) reinforced with similar way will be compared in terms of size effects. The externally bonded TRC will be plated as a side bonded plate and the amount of TRC, layers and thickness are the same for all the beams. An un-strengthened control beam will be included for both large and short beams for comparisons in terms of energy dissipation. Meanwhile the transverse steel reinforcement will be remained constant in all cases. Regarding the instrumentation, two strain gauges will be placed to steel reinforcements and three will be placed on the concrete. There is a need to locate them in different positions across the section of the member in order to define the location of the neutral axis. More strain gauges will be located in the surface between TRC and concrete for estimating the bond between the materials and displacements will be measured by LVDT’s at the middle of the beam. High definition camera will be used to record cracks, deflections and the flexure behaviour for the definition of mechanisms under which TRC strengthened beams reach the failure.

The nonlinear finite element analysis software ANSYS is used as a numerical tool to carry out further investigations such as a parametric study on flexural behaviour of RC beams by following methods known in the literature by Kachlakov and Thomas (2001). Numerical methods will take place in order to develop data useful for safe conclusions regarding the performance of TRC –strengthened beams in terms of energy dissipation.

Potential for application of results
This project will be the basis for conducting data for guidelines regarding TRC-strengthened reinforced concrete beams under cyclic actions. All these data will be useful for engineers who are willing to upgrade existing structures and codes by using knowledge on how to improve the performance of TRC-strengthened reinforced concrete beams. The accuracy of strain predictions of flexural performance of beams will provide the potential for improved design methods to avoid destructive forms caused by natural phenomena which can cause cyclic actions. Estimation of the transition actions from concrete, steel to TRC will be necessary for a better understanding of the strengthened system behaviour. The absence of guidelines on using TRC including the absence on cyclic loading is considered as an important reason for further research on this field.

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References


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Performance-based design of secondary substructures

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Project objectives and goals
The dynamic analysis and performance of secondary substructures in buildings and industrial constructions is a topic of broad engineering interest. Mechanical, electrical or architectural components must survive strong earthquakes to facilitate emergency and recovery services in the aftermath, limiting human and economic losses; while no damage should happen in case of less severe events. With current design methods lacking the necessary rigour and robustness, the project aims to develop new and more efficient analysis procedures for secondary substructures subjected to dynamic excitations. In particular, the following objectives are pursued:

- Establish a Performance-Based Design (PBD) framework for substructures exposed to seismic excitations;
- Assess the propagation of design uncertainties in primary and secondary components;
- Extend the improved modal correction method to the case of substructures (which in turn would allow reducing the computational effort);

Description of method and results
Aiming at the development of a PBD framework, seismic analyses are carried out using a commercial structural analysis program (SAP2000), coupled with numerical software (MATLAB) to assess the response of primary and secondary systems. In a first stage, the dynamic response of the primary system due to irregularities in plan (i.e. asymmetrical distributions of mass, stiffness and strength) and elevation (e.g. structural element discontinuities) is quantified. In a second stage secondary systems are analysed in conjunction with their supporting structure. This is achieved via:

i) cascade approximation i.e. floor response spectrum method, when subsystems are much lighter than the primary structure and their feedback can be neglected (Muscolino and Palmeri, 2007), and
ii) modal synthesis method, when the dynamic interaction needs to be adequately accounted for, through a combined system (Fig. 1). A wide spectrum of non-structural components is considered with attached and unattached components, modelled as linear or nonlinear (e.g. sliding, rocking behaviour) single degree of freedom (SDoF) oscillators as well as flexible ones, modelled as multi degree of freedom systems (MDoF), which can also be multiply attached.

The probabilistic seismic response, constitutes an intrinsic feature of PBD (FIB, 2012) and is thus of interest. Inherent uncertainties affect the seismic performance of structures, both in terms of ground shaking and structural properties (e.g. strength and stiffness of members and connections). In the current state of practice, these uncertainties are implicitly taken into account (i.e. through partial safety factors and characteristic values, known as “prescriptive paradigm”). In this study, the conditional mean spectrum method proposed by Baker (2011) is used as a tool to characterise the volatility of the hazard (i.e. ground motion histories). Similarly, the structural response is assessed with the propagation of design uncertainties from the primary to the secondary subsystem (Fig. 2), being quantified through various methods, namely Monte Carlo simulation, perturbation approach and surrogate models (i.e. response surface methodology). An interesting feature of the work under development is that uncertainty is characterised in the reduced modal space, rather than the full geometric space, so to significantly reduce the size of the dynamic problem and parameters. Notably, when this is coupled with a dynamic mode acceleration method (DyMAM), proposed by Palmeri and Lombardo (2011), a dynamic corrective term is introduced to further reduce the amount of modal information being used.

Potential for application of results
In the current state of practice, the analysis and design of secondary systems is hindered by inefficient procedures. The project aims to deliver recommendations for accurate and efficient analysis methods for secondary systems subjected to seismic excitations. This will allow for quantification of the impact for different seismic events, taking into account functionality. Implementation of the proposed methodology through a realistic case study (i.e. an industrial pipe bridge) will demonstrate its benefits and future application in the industry.
References


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Figure 1. Example of combined primary-secondary system

Figure 2. Uncertainty propagation in the time history of a secondary system due to El Centro earthquake (deterministic; thick red, stochastic; light red line)
Introduction

Self-compacting concrete (SCC), also known as self-consolidating concrete, is a relatively new type of concrete that was introduced to the civil engineering industry in the late 1980s in Japan in order to overcome the common durability problems associated with the use of normal concrete. SCC can be defined as a type of concrete that can flow and easily be placed in the moulds and formworks under its self-weight with no need for external vibration. It has the ability to completely fill the formworks and flow through the spaces within heavy reinforcement without mechanical vibration. It is considered as a revolution in concrete industry and becomes one of the most important concrete developments in recent decades. It can be employed in various civil engineering applications especially when normal concrete is difficult to be placed and vibrated such as pile caps, bridge girders and offshore structures.

Reinforced concrete deep beams have been very popular structural elements especially when construction requires free space of columns. They are used in different civil engineering applications such as stores, hotels, offshore structures, theatres, tanks, pile caps and others. They differ from shallow beams in terms of their small thickness when compared to their high depth and short span. In practice, continuously supported deep beams are mostly used in construction rather than simply supported ones. In case of deep beams made with SCC, all of the existence research has been conducted on simply supported beams. In contrast, there is almost no information about research on continuous deep beams made SCC.

Project objectives and goals

The main aim of this research is to evaluate the behaviour of continuously supported deep beams made with SCC. This can be achieved as follows:

a) Testing of different full-scale SCC continuously supported deep beams to study the influence of various parameters such as shear span-to-depth ratio and reinforcement ratios on the behaviour of SCC continuous deep beams including cracking load, load carrying capacity, deflection and shear strength.

b) Develop a non-linear finite element model using ABAQUS to analyse the effect of the different parameters considered in this research on the behaviour of SCC continuous deep beams.

c) Develop a mechanism analysis based on the upper bound theorem of the plasticity theory to predict the failure load of continuously supported deep beams made of SCC.

Description of method and results

In order to achieve the aims of the current research, eight different two spans SCC deep beams will be tested. All the specimens will have the same compressive strength of 30 MPa. The main parameters investigated in the current research are the shear span-to-depth (a/d) ratio, the longitudinal reinforcement ratio and the web reinforcement ratio. Two different a/d ratios will be used; 1.0 and 2.0. The beams will be subjected to a concentrated load at the middle of each span using a 250 Tons capacity PACT testing machine.

The failure load of continuously supported SCC deep beams will be predicted by the developing mechanism analysis based on the upper bound theorem of the plasticity theory. Also, a lower bound analysis using the strut-and-tie model will be developed to predict the load carrying capacity of continuous deep beams. In addition, a three dimensional non-linear finite element analysis using ABAQUS has been developed to investigate the behaviour of the test specimens. Figures 1 and 2 show some results obtained from the proposed ABAQUS model.

Potential for application of results

Up to the start of this research, there have been no research investigations on reinforced SCC continuous deep beams. This area of research is of special interest due to the high depth of deep beams, making it difficult for NC to be properly placed and vibrated. SCC offers unique characteristics in quality and economy. It provides significant quality, improves productivity and achieves engineering properties similar to those of NC with more durable structures. The use of SCC leads to the removal of vibration equipment which has a negative effect on the auditory sense of the workers and also people in the neighborhood surrounding the construction site. Therefore, SCC is the most preferable building material especially when the construction site is close to residential areas. In addition, SCC has high flowability and passing ability which allow the use of tight formworks with congested reinforcement in the construction of different structural elements. Moreover, the ease of placement and the elimination of external vibration make SCC the most preferable for deep beams which have tight dimensions, making it difficult for the compaction equipment to be used.

In spite of the fact that the literature shows some research on the use of SCC in simply supported deep beams, none of these research projects was carried out to investigate the structural behaviour of continuously supported deep beams made with SCC. In practice, continuously supported deep beams are mostly used in construction rather than simply supported ones. The structural behaviour and failure modes of continuously supported deep beams are considerably different from those of simply supported ones (Ashour and Morley, 1996). The failure in continuously supported deep beams usually takes place in the regions where the high
shear coincides with the high moment whereas in simply supported ones the region of high shear does not coincide with that of high moment (Yang and Ashour, 2008; Ashour, 1997). Therefore, it is vital to investigate the structural behaviour of continuously supported SCC deep beams. It is also important to examine that whether the models provided in the different design codes to analyse deep beams made with NC are also valid for those made with SCC.

References


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Figure 1. The effect of web reinforcement on load capacity of continuous deep beams

Figure 2. Load-deflection behaviour for the tested beams
Design of a FRP-reinforced concrete beam system for fire performance

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Problem statement
Concrete members that are reinforced with fibre-reinforced polymer (FRP) have many advantages over traditional steel reinforcement, such as the lack of corrosion, lightweight, and electromagnetic transparency. A substantial obstacle to their use, however, is the poor performance of an FRP-reinforced concrete member in fire. The bond between the FRP reinforcement and the concrete degrades due to softening of the resin, tensile forces in the reinforcement (FRP fibres) can still be resisted through the interlock and friction mechanisms of bond force transfer are lost due to softening of the resin, tensile forces in the reinforcement (FRP fibres) can still be resisted when the resin softening at temperatures around its glass transition temperature. As a consequence of this bond degradation, all means of force transfer between FRP bar and concrete are lost, the reinforced concrete member is unable to carry the required load, and a brittle failure results from the loss of the tension reinforcement.

Aim of research
This research project aims to enhance the fire performance of FRP-reinforced concrete by developing a new arrangement of internal reinforcement that does not rely only upon bond for load transfer. Instead of using straight separate FRP bars as reinforcement (an arrangement that has been copied from steel-reinforced concrete design), closed FRP loops will be utilised as the longitudinal reinforcement. These loops are filament wound from long continuous fibres. The proposed design takes advantage of the fact that the FRP fibres are capable of sustaining a large proportion of their original strength at relatively high temperature (up to 1000°C for CFRP). When the interlock and friction bond mechanisms of force transfer are lost due to softening of the resin, tensile forces in the reinforcement (FRP fibres) can still be resisted through the loops.

Research objectives
The following four objectives are required to meet the aim of this research:

- Produce closed continuous FRP loop reinforcement, by wrapping carbon fibre tows that are saturated with resin around a mould. Several windings will be required to create the reinforcement loops (typically Ø6mm).
- Conduct small-scale pull-off tests upon FRP loops reinforcement to understand and characterise its behaviour at both ambient and high temperatures. Push off tests are performed in which the ends of a reinforcement loop are embedded inside two concrete blocks, a hydraulic jack is used to push the concrete blocks apart so as to pull the reinforcement from the concrete (Figure 1).
- Conduct 4-point bending test upon beams with FRP loop reinforcement. These beams will be tested under load and temperature to demonstrate the viability of the new reinforcement method, and to validate the analytical modelling work.
- Develop analytical models that describe load-transfer within a concrete beam reinforced with FRP loops, and how this is affected by temperature. These models will utilise the results of the small-scale tests to predict failure of larger-scale beams. They are expected to be based upon established reinforced concrete design methods combined with new methods for modelling the degradation of FRP to concrete at high temperatures.

Research outcome
Push-off tests were performed on samples reinforced with CFRP loops, straight bars, and hooked bars. Results shows that at ambient temperature the FRP reinforcement in all but one specimen developed sufficient bond stress to give failure by rupture of the FRP outside the concrete block. The benefit of the CFRP loops became evident at elevated temperatures. Both straight and hooked reinforcement failed by pull-out at relatively low loads. Closed loops, however, retained strength up to three times more than the other specimens, and failed at a tensile strength that exceeded that of a steel reinforcing bar. The proposed design takes advantage of the fact that the FRP fibres are capable of sustaining a large proportion of their original strength at relatively high temperature (up to 1000°C for CFRP). When the interlock and friction mechanisms of bond force transfer are lost due to softening of the resin, tensile forces in the reinforcement (FRP fibres) can still be resisted through the loops (Figure 2). This new technology is promising and if developed might allow FRP reinforced concrete to be used in situations where its fire performance is important. It could help remove the last obstacle to its widespread use in buildings.

References
Figure 1. FRP loops as longitudinal reinforcement under test by hydraulic jack.

Figure 2. Load-slip response of specimens at temperature of 130°C.
On the robustness of ‘simple’ or ‘semi-rigid’ structural steel connections when subjected to blast loading

Matthew Kidd
University of Liverpool

Introduction
Following on from previous investigations by Stoddart et al. (2012), it is apparent that, when designing structural steel members to resist blast loading, a certain level of plasticity is permitted in accordance with the concept of energy absorption via plastic deformation. The level of which is generally related to the role and importance of the member in a structural system. The connections at the ends of a member can be the weakest point when the member is subjected to blast loading. Therefore, the connections must have a certain level of ductility and thus be able to transfer moments, shears and axial loads with sufficient strength, appropriate stiffness and adequate rotational capacity. This often results in the introduction of fabrication intensive and less economical connection solutions. However, most steel framed structures in the UK are designed and constructed using standard ‘simple’ or ‘semi-rigid’ connections (Fig 1) in accordance with prescribed industry guidance (i.e. SCI P358, Joints in steel construction; Simple joints to Eurocode 3 – usually referred as ‘The Green Book’). Such connections are generally acceptable for resisting applied shear and axial forces generated under the normal working load condition; however a great deal of uncertainty exists regarding the robustness of such connections when subjected to the end-rotations induced when an element enters its plastic phase under high transient loading conditions (e.g. blast loads). A similar uncertainty exists in the context of design against disproportionate collapse where the connections at the ends of a structural member are required to sustain the demands imposed by catenary action in the event of loss of an adjacent member, as is highlighted by Vlassis & Izzuddin et al (2008).

Project objectives and goals
This project will investigate how robust ‘simple’ or ‘semi-rigid’ structural steel connections are when subjected to large end-rotations induced by blast loads with the primary aims being to:

- Undertake a literature review on state-of-the-art research and current industry guidance to establish where the key knowledge gaps exist.
- Evaluate and determine the robustness of ‘simple’ or ‘semi-rigid’ structural steel connections when subjected to blast loading.
- Develop a strategy and associated guidance on the limits of use of such connections for incorporation into current industry design guidance for use in blast resistant design applications.

Description of method
Advanced numerical modelling using LS-DYNA coupled potentially with validation testing at University of Sheffield using the rig shown in Fig 2.

Potential for application of results
The outcome of the project could potentially provide industry with a robust assessment and design methodology which could be used by the practising engineer to achieve the required level of structural robustness if adopting ‘simple’ or ‘semi-rigid’ steel connections when blast loading needs to be considered in design.

References

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Figure 1. Example of simple or semi-rigid connections (Source: SCI P358, 2014).

Figure 2. Test rig set up (Source: Tyas et al 2012)
Estimating fatigue life of details in steel bridges using continuous response monitoring

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Project objectives

Fatigue is a type of material deterioration caused by cyclic loading. A survey conducted by the ASCE Committee on Fatigue and Fractures Reliability (Guo et al. 2008) showed that 80-90% of failures in steel structures are related to fatigue and fracture. Steel bridges, which are reaching or have exceeded their design life, are particularly vulnerable to fatigue damage since they experience increasing traffic volumes while suffering from significant age-related deterioration (Zhou, 2006). In the UK, there are 6000 metallic bridges, which are over 100 years old, and fatigue is highlighted as the major risk factor to bridge safety (Adasooriya & Sirawardane, 2014). Thus, the assessment of the remaining fatigue life of steel bridges is of great importance, especially when making decisions regarding rehabilitation and replacement of existing bridges.

Current approaches for fatigue life assessment focus on the use of design loads and stress distribution factors. For example, in the United States, the current AASHTO S-N approach uses a linear relationship between the number of allowable stress cycles and the stress range for predicting the fatigue life. The number of stress cycles corresponding to an equivalent stress-range that is chosen from a stress-range histogram computed for variable live loads forms the basis for fatigue life estimation. This approach, because of the variations in actual applied live loads and thereby the stress cycles, often results in overly conservative estimates of remaining fatigue life; in some cases, the approach even gives a negative remaining fatigue life, implying that the bridge that is in-service has survived beyond its design fatigue life (Soliman et al., 2013). The unnecessary retrofits or repairs undertaken based on current assessment procedures can significantly increase bridge maintenance costs (Kwon et al., 2012). A significant amount of research effort has therefore been directed towards the development of approaches for accurate fatigue life evaluation.

Recent developments in sensing technology offer a fundamentally different approach to fatigue life evaluation that is based on measured and therefore reliable data on real-life structural behaviour and loading. This alternative approach to determining the stress ranges through field measurement of structural response in place of estimating or predicting stress range using design loads can enable a safe and reliable assessment of the remaining fatigue life of steel bridges. However, relating the measured response to stress ranges is a challenging task. The stress range spectra for bridges are strongly site-specific depending upon vehicle types, range of vehicle speeds, road roughness conditions, ambient environment and bridge type (Laman & Nowak, 1996). The current study aims to investigate the relationship between fatigue damage and various bridge, environment and traffic related parameters, and propose a measurement-based methodology for determining the fatigue life of details in metallic bridges. The methodology will be evaluated on full-scale bridges to demonstrate that fatigue evaluation based on field measured data can prove to be a more accurate and efficient method for existing bridges than current approaches.

Description of method

The methodology employed in this study is shown in Figure 1. Strain measurements are used to determine the range of stresses experienced by parts of a bridge that are prone to failure by fatigue loading a potentially disastrous type of failure caused by repeated cycles of loading and unloading. Measuring strain histories for this purpose requires a modern data acquisition system with large storage capacity, rapid sampling rate, and the capability to provide a continuous record of strain profiles near various fatigue-prone structural components. While technologies that offer these capabilities are now widely available, there is no reliable approach to analyse the data for evaluating fatigue life. This research will provide that missing link.

The strain profiles are first analysed to determine the forces experienced by the components. This step requires a systematic consideration of the effects of the various loads on the structure including the static and dynamic effects of vehicular passage, temperature and other ambient conditions such as wind. The inferred forces are then applied to a detailed numerical model of the component (e.g. connection) to find the stresses at critical details such as a weld or a rivet. Stress predictions from the model are used to arrive at an estimate of the fatigue life of the component, i.e. the time remaining before the component or structure could be expected to fail by fatigue based on the current loading conditions.

Potential for application of results

The main area of application is for bridge management. Asset owners and operators will be able to track fatigue life of components in real-time based on in-situ measurements of deformations in structures.
References


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Figure 1. Research methodology
Crack localisation in frames using natural frequency measurements

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Project objectives and goals
A new computational method is devised for locating a single crack in a frame using natural frequency measurements. Accurate and noisy measurements corresponding to combinations of lower and higher vibration modes are considered. The method is based on the procedure formulated by Labib et al., (2014) for accurately calculating the natural frequencies of any order using the Wittrick-Williams algorithm (Wittrick and Williams, 1971). It advances the formulation of Greco and Pau (2012), and has the advantage of avoiding the use of finite elements (Hassiotis and Jeong, 1995, Bicanic and Chen, 1997, Nikolakopoulos et al., 1997).

Description of method and results
A rotational spring model is used to simulate the crack. Each frame member is discretised into a number of points representing possible crack locations. The first three natural frequencies are calculated accurately using the Wittrick-Williams algorithm in the uncracked case and when the crack is placed in turn at each discretisation point. Further natural frequencies are introduced iteratively by applying an optimisation procedure. Normalising the variation $\delta_i$ between the uncracked and cracked natural frequencies using Eqn 1:

$$\bar{\delta}_i(x/l) = \left[ 1 + \sum_{m=1}^{\infty} \delta^2_i(x/l) \right]^{-0.5}$$  \hspace{1cm} (1)

gives curves corresponding to the calculated natural frequencies. Here $\bar{\delta}_i$ is the normalised variation corresponding to frequency $i$ and $x/l$ is the dimensionless crack location in each frame member. The same normalisation is then carried out for the measured frequencies, giving $\bar{\delta}_m$. For exact measurements, point estimates of the crack location are obtained by searching for the point at which $\bar{\delta}_i$ equals $\bar{\delta}_m$ for all $i$. For symmetric frames, two such points are obtained. Using noisy measurements and applying the principles of interval arithmetic, Eqn 1 yields $\bar{\delta}_m$ in the form of crack location ranges $[\bar{\xi}_m^l, \bar{\xi}_m^u]$ where $\bar{\xi}_m^l$ and $\bar{\xi}_m^u$ are the lower and upper limits, respectively. Empirical probability distributions are used to provide a graphical representation of the combined ranges and their relative probabilities, as shown in the example frame in Fig 1, where the first three calculated natural frequencies are used as pseudo-experimental measurements. The numbers represent the relative probabilities of each range. Subsequent iterations involving higher order frequencies lead to the false ranges narrowing down or disappearing altogether, with the true range unchanged or narrowing down towards the actual crack location, as shown in Fig 2.

Potential for application of results
The method is a non-destructive technique for crack identification, accounting for measurement noise, based on that, new software can be incorporated in measurement instruments to produce the narrowest possible crack location ranges in each frame member. Efficient algorithms allow the fast computation and storage of the curves obtained by Eqn 1, even for large structures, for use in the crack detection procedure.

References

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Figure 1. Empirical probability distribution for the crack location when the first three natural frequencies are used assuming a measurement error of ±0.005 Hz. The actual crack location is shown in member A.

Figure 2. Empirical probability distribution for the crack location when the first, second, third, fifth and ninth natural frequencies are used assuming a measurement error of ±0.005 Hz. The actual crack location is shown in member A.
Behaviour of elliptical steel tube columns filled with self-compacting concrete

Munir Mahgub
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Project objectives and goals
A new elliptical shape of steel tube column has been used in few places, but is not yet popular. An elliptical hollow section can provide greater efficiency than a circular hollow section, particularly when subjected to eccentric loading (generating a bending moment about the stronger axis) or when differing end restraints or bracings exist about the two principal axes (alternative is the effective column buckling length) (Chan and Gardner, 2009).

The main goal of this research is to study the behavior of SCC-filled elliptical tube columns. The principal objectives are categorized into three phases as below:

- Concrete properties: In this stage, collected data from different researches in the literature will be used to predict the compressive strength of SCC design mix using ANNs.

- Experimental work: In this stage, the mix design of columns will be made by using ANN, then the fresh properties will be tested and the behavior of loaded SCC-filled elliptical columns will be investigated experimentally.

- Computational analysis: In this stage, results from experimental work and other researches will be collected and used to develop a computer simulation to predict the behavior of SCC-filled elliptical columns. The behavior of compressive strength of elliptical tube columns filled with SCC will be predicted by Column Deflection Curvature method.

Description of method and results
The behavior of SCC-filled elliptical tube columns will be investigated. 10 tube columns will be tested in a parametric study, where they are divided into two groups. Each group has different section. The same thickness of elliptical columns are used, 6.3mm, and two lengths 2m and 2.5m. Moreover, concrete compressive strength will be different. Elliptical tube column without concrete will be tested as control column for each group. The SCC specimens will be predicted by the ANN. Testing of the composite columns will be carried out using a 250 and 100 Tonn capacity PACT testing machine and the experimental set up. The specimens will be loaded at 20kN intervals at the beginning of the test (i.e. in the elastic region) and at a loading rate of 10kN intervals after the column began to yield, in order to have sufficient data points to delineate the “knee” of the stress-strain curve. A linear variable differential transducer (LVDT) will be used to monitor the vertical deformation. All of the operation and the change of loading rate will be operated manually and all the readings will be recorded when both load and strain stabilized. After the immediate drop of the load due to local buckling, the test continued until excessive deformation of the column will be observed. The purposes of this stage are, understand knowledge of the behavior of elements and add more data to the literature. The data from experimental will be used to validate the computational analysis. Figures 1 and 2 show the physical testing stages of elliptical columns.

Potential for application of results
Several researchers have introduced SCC to the construction industry as a new type of concrete used with tube columns. The overall success of this introduction paved the way for others to investigate the possibility of using SCC with different shapes of columns, including elliptical columns.

In comparison with the investigations carried out in this field, the current research will contribute the following:

- The limited number of previous researches in the field of using SCC with elliptical tube columns only investigated the behavior of short columns under varying loading. The present research project goes further in that the length of the column has been considered in investigating different behaviors of elliptical columns.

- Some designs mix of SCC technique are still not clear to follow; therefore, phase one of the project uses ANNs to predict the compressive strength of SCC.

- Elliptical columns enjoy more advantages than circular and square columns; these elliptical columns can carry loads and bending moments, more than circular columns. Moreover, elliptical columns use a smaller space compared with others and have an aesthetic appeal.

- The effect of elements such as different dimension of the section, length and compressive strength of concrete on the behavior of elliptical tube columns filled with SCC have not studied yet with regard to limited number of previous researches.

References

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Figure 1. Set the column under the jack and put the LvdI and strain gage

Figure 2. The column reached to the buckling load
Improved structural efficiency of steel single storey industrial buildings using sandwich panels

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Project objectives and goals

Since 2002, changes to Part L of the Building Regulations in England and Wales have resulted in a significant increase in the thickness of insulation within the building envelope and this trend looks set to continue. For composite insulated (sandwich) panels, the increase in depth has led to a considerable improvement in the structural capability of the envelope, which has hitherto been ignored in the design of the building structure. An opportunity exists to utilise this structural capability in order to reduce the steelwork and the associated embodied carbon within the building structure. The primary aims of the research are to quantify potential steelwork savings by exploiting the increased insulation depth of composite panel envelope systems and to address the technical barriers to the implementation of more efficient structure – envelope assemblies.

Description of methods and results

Feasibility studies were undertaken to investigate the opportunities for exploiting the structural capability of sandwich panel envelope systems. The primary areas of focus were:

- Building forms which accommodate the long span capabilities of the envelope (reducing number of supporting structural members and removing secondary steelwork).
- Building forms which exploit the diaphragm action capabilities of the envelope
- Frameless and semi-frameless buildings

The feasibility studies and structural reviews were carried out by an extensive series of structural analyses following the building design methodology of EN 1993-1-1 (CEN, 2004) and specialist literature particularly regarding the behaviour of sandwich panels and envelope systems under in-plane and out-of-plane load (Davies 2001, Davies and Bryan, 1982, Käpplein et al., 2010, Käpplein and Ummenhofer, 2011). For each frame option, the technical barriers that prevent the practical implementation of the research were assessed. The advantages and disadvantages of each option were evaluated and a decision was made whether to advance each opportunity.

The feasibility study concluded that the greatest potential benefit (38%-60% steelwork saving) arises from the use of long span envelope systems particularly for trussed roof frames with north light construction. There are only limited opportunities for the use of diaphragm action, primarily because diaphragm action was found beneficial for “sway” load combinations (for typical frame flexibilities) while “spread” load combinations typically dominate the design. Frameless buildings constructed from sandwich panels were found to be feasible but limited in size and challenging in terms of detailing.

Having identified the most promising opportunities for exploiting the structural capability of the building envelope, the research is currently set to address the most significant technical barriers to their implementation. While current sandwich panel technology can accommodate spans up to 6.6m, the optimised structural forms would require the envelope to span in the range of 8.00-10.00m. Furthermore, the panels would need to provide adequate restraint to the frames, a requirement that has not yet been experimentally proven. The methodology adopted to address these gaps is a mixture of testing and analysis:

- Engineering of long-span sandwich panels

The geometry and composition of sandwich panels are currently being revised in order to improve their spanning capability. The modelling of the structural behaviour is made according to constitutive equations for strength and stiffness (Davies et al., 2001, Pokharel and Mahendran, 2004), incorporating a defined range of geometrical and mechanical properties and design standard constraints. The development of new panel forms is based on a parametric study targeting a span of 10.00m at minimum cost and embodied carbon.

- Investigating the restraining ability of sandwich panels experimentally

Physical testing will be undertaken taking into account guidance from standards for shear panel assemblies (Davies and Bryan, 1982) to determine the in-plane performance of representative panel assemblies in terms of stiffness, failure mode(s) and reserve of strength. Comparisons of test results against analytically derived data will enable extrapolation to building scale assemblies and alternative panel geometries. Where appropriate, developments in the design guidance will be proposed.

Finally, the selected structure - envelope assemblies will be reviewed in terms of cost and embodied carbon with a view to evaluating the net benefit of the proposed building solutions. The cost appraisal will be carried out in terms of installed cost, while the carbon review will be based on established Life Cycle Assessment methods.
Potential application of results

The project will determine the feasibility of exploiting the increased insulation depth of sandwich panel envelope systems in order to deliver buildings with greater structural efficiency and, consequently, a reduced environmental impact. The study will quantify the saving made possible in terms of material, cost and embodied carbon. The associated technical barriers for the selected options will be addressed in order to justify the technical feasibility of the proposed solutions.

In the UK, almost 50% of the produced constructional steelwork is being used in single storey industrial buildings. The predicted steelwork savings of up to 60% by mass indicates that the practical impact of this research in terms of carbon emissions is likely to be considerable.

References


Pokharel N. and Mahendran M. (2004). ‘Finite element analysis and design of sandwich panels subject to local buckling effects’. Thin-Walled Structures, 42(4), pp589-611

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The effect of post-tensioning force magnitude on the natural bending frequencies of post-tensioned concrete structures

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Project objectives and goals
The main aim of the project is to determine empirically whether a relationship exists between the natural bending frequencies of post-tensioned concrete structures and the post-tensioning load magnitude. No agreement currently exists as to how prestress/post-tensioning force affects the natural bending frequencies of such structures. Currently, there are three distinct arguments:

- The natural bending frequencies ($\omega_n$) decrease with increasing prestress force magnitude ($N$). This is known as the “compression softening” effect and is based on classical Euler-Bernoulli beam theory of an externally axially loaded homogenous beam (Tse et al., 1978, Miyamoto et al., 2000).

- $\omega_n$ is unaffected by $N$. This argument has been taken to the fore by Hamed and Frostig (2006), who present a non-linear kinematic model and conclude that the final equation of motion for a vibrating beam system is independent of $N$.

- $\omega_n$ increases with $N$. Numerous empirical studies that have been conducted have found this to be the case (Saidi et al., 1994, Hop, 1991, Zhang et al., 2012) however, a satisfactory mathematical model predicting the increase in natural frequency ($\omega_n$) with increasing prestress force magnitude ($N$) has yet to be formulated despite some attempts.

Further research is required to determine the validity of the above models and their applicability to pre- and post-tensioned concrete structures.

Description of method and results
Dynamic impact testing has been conducted on nine post-tensioned concrete beams, each with a different straight profiled post-tension strand eccentricity, in the laboratory. The beams were instrumented with one accelerometer and three strain gauges. Dynamic impact testing and subsequent output-only determination of the natural bending frequencies has been determined using the accelerometer data. Sample results for Beam 2 are shown in Fig 1 and Fig 2. Fig 1 shows the normalised modal amplitude versus frequency and post-tensioning load in 3D space, clearly showing the dominance of the first bending mode of vibration in the structural dynamic response. Fig 2 shows a regression analysis of the change in first natural bending frequency with increasing post-tensioning load magnitude. It has been found that there is no statistically significant change in measured fundamental bending modes with increasing post-tensioning force for the nine uncracked concrete beams.

The beam sections were then loaded under four point bending until yield had occurred and the beam sections had undergone significant cracking. The dynamic impact tests were repeated on the cracked sections at increasing post-tensioning load magnitudes. It was found that the first mode of vibration no longer dominated the structural dynamic response of the cracked beams. The structural response was found to be a combination of many modes. Furthermore, when regression analysis was conducted on the change in fundamental natural bending frequency with increasing post-tensioning load magnitude, it was found that in each case a statistically significant decrease in fundamental frequency was observed, in contrast with the data from the uncracked concrete beams.

Potential for application of results
The application of the results are widespread. The Eurocode 2 equation for prestress loss as a function of time is well established. If the relationship(s) between prestress force and natural frequency for prestressed concrete structures can be established, then the variation of natural frequency over the design life of a prestressed concrete structure can be estimated. This problem is particularly pertinent in the field of post-tensioned concrete wind turbine towers and in the field of pre- and post-tensioned concrete girders in the bridge industry. The variation of natural frequency with prestress loss is of importance in dynamic design of structures to ensure extreme resonance effects are avoided over the design life of the structure and in the modal superposition method in time-history analysis for the prediction of structural response due to dynamic excitation. Given that no statistically significant change in fundamental bending frequencies were observed for the uncracked concrete beams and that changes in natural frequency due to environmental effects, lack of ideal support conditions and variability of concrete as a material are reported to be in the region of 14-18% (Peeters and De Roeck, 2001), the change in natural frequency with increasing pre- or post-tensioning force is not recommended to be considered in the dynamic design of pre- or post-tensioned concrete structures.
References


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Figure 1. Normalised modal amplitude versus frequency and post-tensioning load in 3D space, beam 2

Figure 2. Regression analysis; measured fundamental bending frequency vs. post-tensioning load; beam 2
Pull-out capacity of BFRP rods in Irish grown Sitka spruce

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Project objectives and goals
Bonded-in rods have great potential for reinforcement and restoration of timber structures. They have been used successfully to renovate roof and floor beams in buildings subject to decay and may be used for connections or reinforcement in new build construction. Over the past two decades there have been many national and international research projects commissioned on the use of bonded-in rods in timber construction however no universal standard exists for their design. There had been an informative annex proposed in BS ENV 1995-2 which provided limited coverage of the design of glued-in rods using steel bars however this document was replaced by BS EN 1995-2:2004 in which no guidance is included.

The three main elements to be considered when designing bonded-in rod connections are: the timber, rod and adhesive. The majority of research done in this area to date comprises steel rods glued-in to glued laminated (glulam) elements with lamellae of a high strength class timber. However other researchers have investigated the behaviour of bonded-in rods in lower grade timber and with some fibre reinforced polymer materials in place of the standard steel rods for example Alam, Ansell, & Smedley (2009) and Yeboah (2012).

This research is investigating the behaviour of Basalt Fibre Reinforced Polymer (BFRP) rods bonded-in to locally sourced Irish Sitka Spruce which has relatively poor strength and is of a low classification, typically C16. Embedded length of the bar, edge distance and durability performance of the bond are being investigated.

Description of method and results
To investigate the influence of embedded length on pull-out capacity a pull-bending test set-up was used as pictured in Fig. 1. This test required a hinge system to be developed that allowed transfer of load through the sample such that the bonded-in rod is under bending forces as well as axial forces.

Results of the pull-bending tests are summarised in Fig. 2. A clear increase in pull-out strength was observed with an increase in embedded length with the longest length of 330mm having a pull-out capacity 168% greater than that of the shortest embedded length of 80mm. Pull-out load was calculated from strain measured at mid-span on the rod. The most prevalent failure mode observed was a failure in shear of the timber with a total of 64% of all samples failing in this manner.

In order to simulate the deteriorative effects of long term moisture ingress on a bonded-in rod connection specimens were soaked in a pressure vessel to saturation, dried and tested to failure. Failure loads were compared to those without pressure soaking and any physical differences resulting from pressure soaking were noted including differences in failure mechanism. The pressure regime used was adapted from prEN 16351:2013 - Annex D and BS EN 14080:2013 - Annex C Cl. C.4.4 and had been used previously at NUIG to investigate bond quality in CLT specimens (Sikora, Harte, & McPolin, 2014).

Pull-out capacity of the specimens was tested by direct pull-out after being stored for 7 days in standard conditions of 20°C temperature and 65% relative humidity. The average pull-out force recorded for the nine pressure soaked specimens was 39.1kN. Comparing this to an average pull-out capacity of 50.4kN for nine similar untreated samples it can be clearly observed that the pressure soaking did have a significant influence on the pull-out capacity of the bonded-in rod with a 22% drop in pull-out capacity. The spread of results was found to be larger in the aged samples than in the results of those tested at ambient temperature with the coefficients of variation $c_{aged}=0.298$ and $c_{ambient}=0.149$. From observation of the failed specimens it was clear that some delamination had occurred by debonding of the epoxy and the BFRP bar. Other failure modes observed included pull-out (which accounted for 67% of failures in the specimens tested at ambient temperature) and failure of the timber by splitting.

Potential for application of results
From the results of the embedded length tests, an optimum embedded length has been chosen for further investigation. The influence of edge distance and glueline thickness can now be investigated for this embedded length. Further research will be carried out on the durability of this connection/reinforcement method with specimens undergoing moisture cycling to mimic a typical Irish climate over a period of 6 months after which the specimens will be tested to failure and the pull-out capacity compared with that of specimens tested at ambient temperature. The results from the project form part of a larger study in to the feasibility of using Irish timber for structural applications.

References


Yeboah, D. (2012). Rigid Connections in Structural Timber Assemblies. Queen’s University Belfast
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Figure 1. Pull-bending test setup

Figure 2. Influence of embedded length on pull-out capacity
Behaviour of welded tubular structures in fire

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Project objectives and goals
Currently, there is no design method to calculate the ultimate strength capacity of tubular joints at elevated temperatures. It may be possible to use the equations for ambient temperature design in design codes such as Eurocode EN 1993-1-8(CEN, 2005a) or design guide such as CIDECT guide No.1(CIDECT, 2010), and by replacing the yield stress of steel at ambient temperature by that at the elevated temperature. However, this approach may not be appropriate. These equations have been derived based on small deflections in the chord face. At elevated temperatures, as observed by Nguyen et al. (2010), the chord face may undergo large distortions and their effects should be considered.

Furthermore, the current method for truss member fire resistant design involves calculating the member force using static analysis at ambient temperature and then finding the critical temperature of the member using the ambient temperature member force. The member forces – critical temperature relationship can be evaluated using design methods such as those in BS 5950 Part 8(BSI, 2003) and EN 1993-1-2(CEN, 2005b). The member force is assumed to be unchanged in fire. However, the member force obtained from truss static analysis at ambient temperature may not be correct at elevated temperatures due to large deformation of the truss.

The objectives of this research are to understand these two aspects of truss behaviour in fire so as to develop simple and safe design methods for engineers.

Description of methods and results
Finite Element simulations of welded tubular joints with axially loaded brace members made of tubular sections at different elevated temperatures have been carried out using the commercial Finite Element software ABAQUS v6.10-1. When a T-joint is under brace compression load, the chord wall is in compression due to global bending and the side faces experience local deformation as shown in Fig 1. The combined effect of a flattened chord (due to side face deformation) and P-δ effect (due to chord compression from global bending) reduces the yield line capacity of the chord face compared to that based on the original undeformed chord face. Therefore, the joint failure loads decrease faster than the steel yield strength at elevated temperatures. The high temperature resistances of different types of truss joints have been investigated. A simplified design method has been developed.

For tubular truss member fire resistant design, numerical parametric studies have been carried out to examine the behaviour of different truss types, configurations, dimensions, and load levels. The results of the numerical parametric studies indicate that due to trusses undergoing large displacements at elevated temperatures, some truss members experience large increases in their forces at ambient temperature. Figure 2 summarises the increases in compressive forces of brace members from the parametric study cases.

A method has been developed to calculate the increased brace member forces due to large displacements at elevated temperatures.

Potential for application of results
For T-, Y- and X-joints with the brace member(s) in compression, the elevated temperature joint strength can be calculated by multiplying the ambient temperature strength by the steel Young's modulus reduction factor at elevated temperatures. For other joints, the steel Yield Strength reduction factor can be used to modify the ambient temperature values.

For truss member design, the following method may be used to calculate the increased compression forces in brace members at elevated temperatures. The total compressive force in the brace member may be calculated by adding the value of the vertical components of the compression chords. Based on the deformed geometry of the truss, a simple analytical method is developed to take into account this increase.

These methods can be used to give more accurate, and safer, results for truss member and joint design at elevated temperatures.

References

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Figure 1. Deformations of the T joints at elevated temperatures

Figure 2. Comparison for forces between ambient and elevated temperatures
Improving the out-of-plane behaviours of masonry infill walls using a partially debonded engineered cementitious composite layer

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Project objectives and goals
This article aims to introduce, for the first time, a novel retrofitting technique to improve the out-of-plane performance of unreinforced masonry (URM) walls using Engineered Cementitious Composite (ECC), or popularly known as bendable concrete. Results outlined below will be used to address the following specific objectives:

– To investigate the flexural strength and deformation capacity of un- and ECC-reinforced masonry beams;
– To study the influence of the bond between ECC and masonry on the flexural behaviour of small-scale masonry beams.

URM walls can be found in many places around the world, for instance, as infill walls in reinforced concrete or steel frame structures. While infill walls have been found useful in enhancing the resilience of structures under static and dynamic loading conditions (Griffith et al., 2007) (Cavaleri et al., 2009), it is the brittle nature of the material that often becomes the major concern, in particular the poor performance of URM walls in the direction orthogonal to the frame structures (the out-of-plane behaviour).

One way to strengthen the out-of-plane response of URM walls is using sprayable ECC (Kyriakides et al., 2008). ECC is a ductile fibre reinforced composite that has high tensile strain capacity (typically in the order of 3-5%) (Li, 2003) (Suryanto et al., 2010). Some studies have shown the effectiveness of ECC to improve the out-of-plane behaviours of masonry beams (Dehghani et al., 2013) (Kyriakides et al., 2008). They found that the ECC increased the ductility and load carrying capacity of the masonry beams dramatically and changed the failure mode from brittle to ductile. However, the microcracks in the ECC layer tended to be concentrated around the broken mortar-brick interfaces. This means that the full potential tensile capacity of the ECC has not been completely utilised. Building upon this background, this research focuses on the use of partially bonded ECC as a more effective means of enhancing the out-of-plane behaviour of URM walls.

Description of method and results
Six masonry beams were produced; two were unreinforced masonry beams made of 10 bricks, two were the same beams retrofitted with 15mm ECC that were fully bonded to the bottom surface of the beams; and two others were retrofitted by partially bonded ECC layer (Fig 1).

The ECC comprised of CEM I (52.5N), fine silica sand, fine fly-ash and Poly-Vinyl Alcohol fibres. The ratio of fly-ash to cement is 1.8, water-to-binder ratio 0.28, sand-to-cement 0.6. The fibre dosage was 2% by volume. The water-to-cement ratio of the mortar was 0.85 with sand-to-cement ratio of 3.0. Engineered bricks class B with dimensions of 210x100x65 were used throughout. The bricks were saturated in water for 24 hours and then used to build six 10-brick beams. The beams were covered by plastic sheet and cured for 14 days. The ECC was then casted on the top side of the beams, cured and covered by wet hessian and plastic film for 21 days. Plastic tape was used to provide unbonding length at the centre span of the partially bonded beams (Fig 1).

Fig 1 shows the flexural test set up. The load was applied monotonically to failure at rate of 1 mm per min. The vertical midspan deflection was monitored using two LVDTs located in both sides of each sample. The test results are shown in Fig 2. As can be seen, the two plain masonry beams showed very low load-carrying capacity (about 1.2 kN) with an average of vertical deflection of 0.07 mm. The failure was sudden and brittle. The other two ECC-retrofitted masonry beams showed a load capacity of approximately 12 kN (10 times higher) and a significant increase in ductility of about 4.5 mm (40 times higher). The last two masonry beams with partially bonded ECC layer had approximately the same load capacity to the fully bonded samples; however, it is interesting to note that the ductility of these specimens was about twice. The difference in the vertical deflection was due to the difference in the distribution of the microcracks in the ECC layer over the centre span. In the fully bonded ECC samples, as one would expect, microcracks were concentrated near the brick-mortar interfaces. In the partially bonded ECC samples, on the other hand, the microcracks were uniformly distributed throughout over the centre span.

Here, it can be argued that the beams failed when the ECC had achieved its maximum tensile capacity.

Potential for application results
This article has demonstrated a novel, innovative strengthening system for strengthening and protection system for URM infill walls. The system will be useful to enhance the out-of place load resistance and energy absorption of URM walls under extreme loading conditions such as earthquake and blast loading.
References


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Figure 1. Test setup

Figure 2. Load-displacement results
Deep embedment technique for strengthening of existing concrete structures deficient in shear

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Project objectives and goals
Deterioration and increased traffic load have brought an urgent need for strengthening of existing highway structures. It has become a global problem, and according to the results of recently assessed concrete bridges in the UK, a great number require urgent repair and rehabilitation in order to meet current standards.

When using conventional Carbon Fibre-Reinforced Polymer (CFRP) sheets for strengthening existing concrete structures in shear it is well known that size effect plays a significant role. Top compression chord must be connected to the bottom tension chord through the wrapping. This applies particularly to the prestressed concrete beams where bond strength represents the weakest point of these systems because CFRP sheets tend to peel and straighten due to the shape of the girders (non-rectangular beams). Furthermore, the larger the shear span-to-depth ratio is, the more likely debonding will occur.

Therefore this project is concerned with strengthening of existing concrete structures which are deficient in shear capacity by using the Bath-invented Deep Embedment technique. Deep Embedment (DE) strengthening (also known as Through Section Strengthening) is a novel, efficient retrofit technique, which involves inserting FRP or steel bars upwards into vertical holes which have been drilled from the soffit of concrete beams. This is often the case where closely-spaced precast beams form the structure, where the webs of the beams are not accessible.

Description of method and results
This research will be continued on the basis of previous studies that have proven deep embedment (DE) technique to be very efficient. It will be used to strengthen prestressed concrete T beams. These are the most commonly found bridge structures worldwide, and so far only reinforced concrete was considered.

In order to fully understand how these strengthened structures behave and how the load is transferred between steel, concrete and FRP bars, the following tests will be conducted:

- Material characterisation:
  - composite materials (GFRP and CFRP bars)
  - traditional materials (Steel and Concrete)
- Structural tests in order to fully understand mechanisms through which shear is transferred in prestressed structures strengthened with DE technique:
  - fully scaled prestressed T beams
- Bond performance tests in order to fully characterize bond and anchorage length requirements of FRP/Steel bars:
  - push-off specimens

Potential for application of results
It will not only be experimentation that is important. A suitable analytical tool which can predict the shear capacity of deep-embedment-strengthened structures will be developed. It is near certain that this analysis will be based on plasticity theory, as it has been found that deep-embedment-strengthened concrete structures show some ductility during failure. By developing such an analytical approach, and validating it through targeted tests, Civil Engineering Industry will be enriched for a codified approach for the safe use of deep embedment to strengthen concrete structures against catastrophic shear collapse. This project will therefore open up the possibilities of deep embedment to a vast array of bridge typologies.
References


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Behaviour of demountable shear connectors in composite beams

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Introduction
The increasing rate of carbon emissions in the environment has highlighted the issue of sustainability and reusing materials. This has led to intensive research for possible reuse of steel beams in a composite construction. However, these beams are difficult to reuse when welded studs are used for composite action as it is hard to dismantle the structure (Moynihan and Allwood, 2014). The subject of this research is to promote sustainability and to reduce carbon emissions by using Nelson demountable shear studs as an alternative to welded studs in a composite beam. This would allow the steel beam to be reused at the end of the structural design without the need of the recycling process. Bolted shear connectors have been rarely used in construction, actually just for rehabilitation work, because there is a lack of design recommendation (Pavlovic et al., 2013).

Pavlovic et al. (2013) studied the M16 Gr8.8 bolted as shear connectors through push-out in solid slabs using embedded nuts in concrete and compared the experimental results with welded headed studs in a solid slab. Moynihan and Allwood (2014) have recently reported beam tests using M20 Gr8.8 bolts as shear studs with embedded nuts and concluded that the beams have high strength as compared with the predicted value of Eurocode 4 for welded studs. Lam & Saveri (2012) carried out push-out tests using solid slabs and reported that the demountable studs have high ductility and similar behaviour to welded studs. The focus of this research is to assess the feasibility and capability of the Nelson demountable shear connectors in composite beams using metal decking.

Project objectives and goals
The primary goal of this research is to investigate the behaviour of traditional Nelson stud as demountable shear connectors in composite beams with metal decking. More specifically, the objectives of this research are:

(1). To check the strength, ductility and stiffness of demountable studs in a metal deck slabs through push-out tests and using different parameters of concrete strength, stud height and diameter, stud layout and positions of reinforcement to develop a modified push-out test.

(2). To carry out a beam test for the measurement of end slip, mid deflection and strains in a concrete slab and identify the mode of failure.

(3). To create a numerical model for parametric study and validating the laboratory experiment.

Description of method and results
The laboratory experimental work includes the casting of small scale concrete slabs and assembling the specimen with small steel sections through demountable shear connectors after curing the concrete. The push-out test technique (as shown in Figure 1) is used for testing the ductility, stiffness and shear capacity of the demountable shear connectors under maximum shear. The vertical downward load is applied by hydraulic jack on the steel beam. The slip between the steel beam and the composite slabs are measured against the load per stud by using LVDTs. The main test parameters are the concrete strength and number of studs in the specimen. The experimental results are compared in figure 2 with welded shear studs (Jayas and Hosain, 1988) to determine the feasibility of using this type of connectors in composite construction. The experimental results have revealed that the demountable shear connectors have very similar behaviour, shear resistance and high ductility compared to the welded studs through the metal deck slab (as shown in Figure 2).

Potential for application of results
Typical results obtained from the laboratory experiments indicate the ductile behaviour of demountable shear connectors and the viability of using demountable shear connectors as an alternative to welded studs. These experiments show that the studs can easily demount from the steel beam and also highlight the applicability of reusing the steel beam without the need of recycling process. This will also reduce carbon emissions caused by dismantling the structure and will save energy, used in dismantling and recycling. These modified push-out experiments will be used for developing a modified push-out test layout for demountable shear studs as there is no design recommendation for demountable studs with a metal deck slab in any code of practice.
References


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Figure 1. Push out set up

Figure 2. Comparison of demountable stud through metal deck with welded stud through metal deck
Stress and moisture effects on the durability of CFRP tendons in pre-stressed concrete

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Project objectives and goals
Carbon fibre reinforced polymer (CFRP) tendons are an alternative to steel reinforcement in pre-stressed concrete due to their good corrosion resistance and high strength to weight ratio. However, because CFRP is a relatively new construction material, further research is required to understand its long-term behaviour under prolonged exposure to various environmental and mechanical conditions. In this study, the particular characteristics pertaining to the interaction between CFRP and concrete when exposed to water and stress – conditions typical of that of pre-stressed reinforcement – are investigated.

Studies have shown that the imposition of external loading on fibre reinforced polymer (FRP) tendons will result in changes in the rate of moisture uptake whereby areas of tension experienced an increase in the moisture uptake rate and areas of compression experienced a decrease in uptake rate (Fahmy & Hurt 1980; Karbhari et al. 2007). Numerous studies have highlighted a positive correlation between stress and the rate of moisture diffusion in composite materials (Karbahi et al. 2007; Neumann & Marom 1985; Neumann & Marom 1987; Youssef et al. 2009; Henson & Weitsman 1986; Kasturiarachchi & Pritchard 1983). These results further highlight the need for a similar study to be undertaken on stressed CFRP rods in moisture to ascertain whether or not the effect of stress on moisture uptake is a factor that might affect the durability of the CFRP in pre-stressed concrete.

Description of method and results
In this study, a 3-point bending set-up is used. A simple rig with two end contact points and a moveable middle contact point in the y-direction has been designed such that the mid-span deflection δ can be varied to impose various levels of strain in the rods. A photograph of the rig is provided in Fig 1 below.

In the consideration of possible degradation of the material over time causing premature failure at a maximum strain lower than the given εf, it was decided to use δ values of 0,11mm, 22mm and 33mm to impose εmax values of 0%, 20%, 40% and 60% of εf respectively. Each rig bends two rods at a time; the rigs are immersed in distilled water at 20°C. These rods are removed from their water baths, blotted dry to remove residual surface moisture and measured on an Oertling balance at regular time intervals. From here, the mass uptake is calculated and plotted against time.

Potential for application of results
The diffusion rates and mass uptake values will be compared with that of the regular unstressed rods. It is expected that the difference in mass uptake rates and saturated mass uptake levels is a result of partial degradation of the material under long-term stress and moisture exposure. The magnitude of this will be determined from the results of the experiment through an Arrhenius plot of degradation for various stress levels. Following on from this, the levels of degradation of the tendons at tensile stresses commonly used in pre-stressed concrete (e.g. 60% of the ultimate tensile strength of the tendons) can be postulated as given by Eqn (1).

Eqn (1) was proposed by Karbhari et al (2007) as

\[(M_{\text{sat}})_{\text{st}} = (M_{\text{sat}})_{\text{u}} + \sigma \left( 1 - \frac{1}{2(1 + \alpha F)} \right)^{\frac{1}{\beta}} \left( 1 - \left( 1 - \frac{2\sigma f}{V_f} \right) \frac{M_{\text{sat}}}{\rho_w} \right) \]

(1)

where \((M_{\text{sat}})_{\text{st}}\) is the saturated mass uptake of a material when subjected to a constant longitudinal stress. \((M_{\text{sat}})_{\text{u}}\) is the saturated mass uptake in the unstressed material, \(m\) is the Weibull modulus, \(V_f\) and \(V_c\) are the volumes subjected to flexure and tension respectively. \(V_f\) is the volume fraction of fibre in the tendon. \(\nu_{12c}\) and \(E_{1c}\) are the longitudinal Poisson's ratio and Young's modulus of the composite. \(\rho_w\) and \(\rho_c\) are the densities of water and the composite respectively.

These results will provide a better understanding of the long term behaviour and limitations of CFRP tendons under stress and moisture, when used as pre-stressed reinforcement in concrete.
References


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Serviceability of fabric-formed concrete structures

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Fabric-form work is a technique for casting usually shaped concrete structural elements. In particular, this can allow structurally optimised beam sections to be easily constructed, potentially saving up to 40% of concrete material compared to an equivalent rectangular prismatic section beam (Orr et al., 2011; West, 2001; Garbett et al., 2010). However, while an optimised variable section structure beam can carry the ultimate loads more efficiently than a prismatic section, the reduction in cross section where it is not needed for bending or shear can lead to structures which fail to satisfy serviceability requirements.

Whilst great progress has been made in the study of fabric-formed optimised concrete structures at the ultimate limit state, there has been no research conducted on serviceability deflection of fabric-formed concrete structures. In order to peruse this method of forming concrete structures towards producing strong, durable and material efficient structural systems, it’s of vital importance that serviceability of fabric-formed concrete members to be thoroughly understood; otherwise excessive deflections and cracking may have undesirable consequences on their structural performance.

The main objectives of the current research project briefly outlined as follows:

2. Developing a method to simultaneously optimise for ultimate and serviceability limit states.
3. Investigation of factors affecting prediction of cracking and deflections of fabric-formed concrete beams such as tension-stiffening and bond-slip of the reinforcement.
5. Proposing an innovative fabric-formed structural system optimized for serviceability and strength.
6. Considering the whole assembly of members and the effects of deflection and cracking of members upon each other.

Description of the methods and results:

In order to develop a model that can efficiently predict load-deflection response of fabric-formed concrete members under service loads, a method of analysis is needed which can deal with variations in cross-section depth and shape, material properties, reinforcement ratio, loading type and arrangement and support conditions of fabric-formed concrete elements.

Finding deflection of reinforced concrete beams by integrating of curvatures has been proposed as an alternative to the effective second moment of area method and is considered to be a more accurate representation (Wickline et al., 2003). This method has been adopted in this study to predict deflections. This is because it’s a sectional approach which can easily adapt to changes in cross sectional geometry, unlike effective second moment of area methods. A computational model to predict load-deflection behaviour of fabric-formed concrete members has been formed. By applying this method reasonably good predictions for load-deflection behaviour have been achieved, although stiffness is slightly over-predicted due to the omission of bond-slip behaviour of the reinforcement.

A partial-interaction approach to study cracking behaviour of prismatic concrete members, which also accounts for slip between the reinforcement bars and concrete, was used by Viartin et al. (2013). This partial interaction method was preferred to be used to predict cracking behaviour as it does not rely on empirical relationships, which may be invalid for variable section fabric formed beams. The method can therefore account for variation in geometric properties of fabric formed concrete members while providing a good estimate of crack spacing and crack widths.

A sectional analysis procedure was used to optimize fabric-formed concrete structures. Each section of a member is first optimized to resist the applied bending moment and shear forces, and then based on minimum curvature values, optimization for serviceability was carried out to gradually add material to specific sections until serviceability and strength requirements are both satisfied in each section.

In order to validate the computational analysis adopted in this study, the load-deflection data of a number concrete beams taken from literature were compared to the data predicted by the program developed to stimulate load-deflection response of reinforced concrete beams. Aiming to assess the analysis program with a wide range of possibilities, the members considered in this work had various section geometries, reinforcement types and ratios, concrete compressive strengths and loading types. The members included simply supported and continuous beams, rectangular beams, prismatic T-beams, fabric-formed single and double T-beams with and without overhangs and one way slabs. The beams were singly or doubly reinforced with steel or FRP rebars and had low to high reinforcement ratios.
Results of the comparison indicate that, reinforcement type and ratio have a leading effect on the predictions. Predictions from the analytical program were satisfactory for moderately reinforced concrete beams and slabs. However, the assumption of perfect bond between the reinforcement and the surrounding concrete in analytical procedure, caused slight, moderate, and considerable over-prediction of flexural rigidity for members reinforced with high, moderate to low steel ratios respectively. For members reinforced with high FRP ratios, considerable over-estimation was noticed. The reason might have been bond slip which was caused by relatively low bond strength characteristics of the FRP.

Results achieved from the optimisation procedure showed that, flexural members that are optimised for ultimate limit state only are likely to undergo deflections larger than the limits provided by codes in many cases. For this reason, optimisation for serviceability limit was carried out and saving in material of up to about 35% was still possible.

References

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Experimental and numerical investigation of masonry walls retrofitted using the traditional collar-jointed technique

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Project objectives and goals
Masonry is a composite material made of units and mortar, which has been used for centuries in the construction of buildings. It is still widely used today as a global construction material and its popularity means that it is very often used in seismic-prone areas. It is especially useful in reinforced concrete or steel frames where it can be used to construct in-fill panels. Typically, masonry in-fill panels resist lateral loading due to wind but they can also make an important contribution to the structural behaviour of a frame during earthquakes. Even a moderate earthquake can cause a massive death toll and extensive economic loss; masonry is particularly susceptible to damage during earthquakes if not properly designed. Thus, masonry panels often need to be retrofitted following earthquake events or enhanced prior to seismic actions so as to ensure that it can deliver its highly sought and potentially underestimated energy absorption role (Ehsani et al. 1999).

During recent decades, researchers have investigated a number of different methods in order to enhance the seismic behaviour of unreinforced masonry walls; these include conventional techniques and modern retrofitting techniques. Ferrocement, shotcrete, gout and epoxy injection are found to be the most popular conventional strengthening methods. These methods enhance behaviour and are easy to implement; however, they are time consuming and also affect the aesthetics. Fibre-reinforced polymer (FRP) reinforcement is probably the most widely used modern approach to enhance the performance of masonry walls subjected to seismic loads. This method adds little mass and significantly improves the strength. However, the drawbacks of this method are the high cost, high technical skill and delamination problem.

In this paper, the author introduces a new retrofitting approach which uses a traditional masonry construction technique. The traditional method of building a wall parallel to an existing single-leaf wall and bonding the two walls together using a mortar (collar) joint is being considered as a possible strengthening and retrofitting technique. The method does not require sophisticated workmanship and it is potentially cost-effective. Theoretically, the method can be divided into two categories: pre-earthquake enhancement and post-earthquake retrofitting. For the pre-earthquake enhancement tests, the second wall was built parallel to the existing one and bonded to it using a 10mm-thick collar joint. For the case of post-earthquake retrofitted tests, the second wall was attached to the existing one after the existing wall had been tested (and as such partially damaged). Numerical validation has also been performed to help examine the experimental results. This numerical modelling has shown that it can significantly contribute to the understanding of the behaviour of the collar-jointed masonry walls.

Description of method and results
Method
The research uses both an experimental and an analytical approach. So far, seven experimental tests have been performed, investigating the performance of single-leaf walls (mostly for calibration purposes) and double-leaf masonry walls. The test configuration is illustrated in Fig 1. The walls are thirteen courses high and four bricks wide (900mmx975mm). The horizontal loading is applied in-plane to the top of the restricted panel; a vertical load cell is also used to suppress the restrained leaf from any uplift. The vertical load is pre-set at the beginning of the test; the horizontal load starts off from zero and increases gradually until the wall fails. For the numerical validation, a micro-scale model is developed using the commercial software, MIDAS. Lourenco’s (1996) and Van Zijl’s (2000) model is used; they propose that the bricks should be subdivided into a number of rigid elements and that the mortar joints are smeared into inelastic zero-thickness interfaces. The inelastic interface is simulated using a Mohr-Coulomb failure surface combined with a tension cut-off combined with a compression cap. The modelling approach for the single-leaf walls focuses on a two-dimensional representation, while the double-leaf walls are modelled using three-dimensional models. The interface model is presented in Fig 2.

Results
- The failure load of the masonry walls can be increased by 30%-60% using the collar-jointed masonry technique. As expected, the deflection of the walls decreases.
- The double-leaf wall can increase the equivalent diagonal strut width (the double-leaf wall has more cracks than the single-leaf wall), which means that the double-leaf wall can spread the stress more widely.
- The double-leaf wall can improve the integrity of the masonry wall. However, the initial attempt at post-damaged enhancement did not work as well as the pre-damaged enhancement. During the post-damaged enhancement test the collar joint separated when the wall fails.
- The numerical model can capture the different features of the nonlinear response of the masonry walls (i.e. maximum load, stiffness, and damage pattern) under combined loading.
Potential for application of results

The aim of this investigation is to provide engineers with an indication of the performance of double-leaf walls as a rehabilitation/reinforcement technique when used in structures within seismic areas. It also provides valuable experimental data which can be used to supplement the masonry database. It is notable that the strengthening/retrofitting method proposed in this paper is not costly and does not need advanced technology or workmanship; this makes it a viable solution for developing countries. The numerical validation agrees well with the experimental results and can give a better understanding of the behaviour of this retrofitting method.

References


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Structural behaviour of beam to concrete-filled elliptical steel tubular column connections

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Brief background
Elliptical hollow sections (EHS) have been increasingly adopted in construction practice recently. They provide an attractive appearance and potential structural efficiency due to the two different principle axes. Research on compressive behaviour of EHS and concrete-filled EHS columns has been conducted in recent years (Chan and Gardner, 2008, Sheehan et al, 2012). However, little information is available about design rules for steel beam to concrete-filled elliptical column connections. This might hinder the extensive application of EHS in framed construction as the connection plays a very important role to transfer loads from beams and slabs to columns. Lam and Dai (2012) investigated the structural behaviour of several easy-to-construct connections by numerical modelling, in which the beams were connected to the elliptical column via bolts and fin plates or a through plate welded to the column steel section.

Project objectives and goals
This project experimentally investigates the structural behaviour of typical beam to concrete-filled elliptical column connections and provides reliable information for similar connection design. The main objectives are:

- To detect the moment-rotation relationships of the connections and to observe their failure modes;
- To investigate the effect of in-filled concrete and stiffener plates on the rotation behaviour of these connections;
- To provide reliable data to validate numerical modelling methods and support parametric studies;
- To develop design rules for beam to elliptical column connections.

Description of method and results
A total of 10 specimens comprising hollow and concrete-filled columns were tested to failure at the University of Bradford. Fig 1 shows the typical connection types adopted in this research. Only one stiffener plate or through plate was welded either in the major or minor axis direction of the EHS column since this arrangement offered better constructability than using two stiffeners. The test setup is shown in Fig 2; a hydraulic actuator was fixed above the column to exert an axial compressive force equating to 40% of the column’s compressive resistance. Upward concentrated forces, representing the floor-slab loads, were then applied simultaneously at both beam ends through two other actuators. For connections with concrete-filled columns, the inward deformation was eliminated by the core concrete comparing with connections with hollow EHS columns; shear failure of the bolts governed the ultimate rotation capacity of the concrete-filled joints. Connections with concrete-filled columns have better moment capacity compared with their counterparts with EHSs; the enhancement in moment resistance for each connection type ranged from 1.91 to 5.19. The connection with the through-plate was found to have a higher stiffness and better moment capacity.

Subsequently, a finite element model (FEM) will be developed through ABAQUS software to capture the structural behaviour and failure modes of beam to elliptical column connections. After the modelling method being verified against experimental results, a parametric study will be conducted to extend the joint member dimensions and material properties and finally provide reliable data to develop appropriate design rules.

Potential for application of results
The results of this project will lead to a better understanding of the moment-rotation behaviour of beam to elliptical column connections. It will provide practical design guidance to improve the safety, economy and constructability of using EHS in constructions and provide references for further study on the structural behaviour of similar connections.
References


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Figure 1. Plan view of joint types

Figure 2. Typical test setup
Performance-based optimisation of an innovative cold-formed steel wall-frame system for lightweight multi-storey structures

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Project objectives and goals
Cold-formed steel (CFS) members are widely used in secondary systems or portal frames, stud wall panels, and storage racks. This popularity is particularly due to inherent advantages of CFS members including high strength, light weight, ease of erection, and simple manufacturing process. However, CFS sections are typically susceptible to local/distortional buckling and their connections possess a relatively low strength and stiffness. Thus, the application of CFS components in buildings is limited to stud-wall frames with low ductility and seismic energy dissipation capacity. In recent studies on CFS connections and beams at The University of Sheffield, Sabbagh et al. (2011) developed new CFS moment-resisting connections by using more efficient shape profiles and stiffeners at the connection zone, which eventually resulted in a higher moment capacity. Their results approved the efficiency of CFS elements to use in moment resistant frames in seismic areas (Sabbagh et al. 2012). However, still there is a lack of a practical performance-based design approach and optimization framework for CFS structural systems considering damage levels.

The aim of this research is to understand, predict, and optimize the strength and ductility of CFS members and moment-resisting connections. The optimised elements can be then included in full-structure modelling for performance-based seismic optimisation of multi-storey CFS frames. Specific objectives of the research are as follows:

More efficient cross-sectional prototypes will be developed and optimised by taking into account the design and manufacturing constraints. The efficiency of the optimised sections will be investigated compared with the predefined profiles in Eurocode 3.

Acceptable design criteria for CFS elements and moment-resisting connections will be developed to achieve specified performance levels.

High-ductility CFS moment-resisting connections will be combined with the optimised sections to develop a high performance frame system, which is suitable for multi-storey CFS structures in seismic areas. The suggested frame system can be integrated with structural wall panels to form a novel dual system (see Fig. 1) to improve the seismic performance of CFS structures.

A multi-criteria performance-based design frame work will be developed for optimum seismic design of CFS structural systems based on the previous work by Hajirasouliha and Pilakoutas (2012).

Research methodology

Software development
In order to facilitate the design of cold-formed steel sections, a program was developed in Matlab. The design approach followed the requirement of the effective width method suggested in Eurocode 3. By linking this software to Particle Swarm Optimization Algorithm, beam and column elements with different cross sections were optimised. Fig. 2 compares the results of an optimisation study with their corresponding FE models in ABAQUS. It's shown that there is a great potential for improvement the ultimate strength of CFS elements compared to industrial standard elements by using optimised shapes (up to 50% increment). This software will provide a base for the performance based seismic design of the multi-storey CFS moment resisting frames and dual wall-frame systems.

Full scale tests
The optimized CFS elements, connections and dual wall system will be subjected to monotonic and cyclic loads. The experimental results will be used to validate the FEA models to examine the efficiency of the proposed structural systems in providing high strength and ductility. The backbone curves of the cyclic moment-rotation responses will be used to find the plastic rotation limits (i.e. performance-based design criteria) for different damage levels.

Finite element modelling
Detailed FE modelling of CFS elements, connections and dual wall-frame systems will be set up with Python language of ABAQUS. To achieve reliable results, the non-linear material property and imperfections will be considered. A combination of verification and validation methods will be used to ensure the accuracy of the FE models.

Potential for application of results
The project will develop a novel CFS dual wall-frame system for light-weight resilient multi-storey buildings in both seismic and no-seismic areas. Optimisation of CFS beam and column elements has shown significant material saving compared to the standard sections. The research will also help improved understanding of non-linear behaviour of CFS moment-resisting connections, frames and dual wall-frame systems under static and dynamic loads. The outcomes of this research will lead to practical design recommendations for more efficient design of high-performance CFS structural systems to comply with modern performance-based design guidelines. The proposed performance-based design framework can act as a base for further research into other complex structural systems, such as space structures and new applications of CFS structures in modular systems and light-weight portal frames.
References


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Figure 1. CFS dual wall-frame system

Figure 2. Flexural strength of optimised CFS sections
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