UNIVERSITY OF CAMBRIDGE

ENGINEERED SKINS 2012

6th September, University of Cambridge

Proceedings

Recent Developments in Glass and Façade Engineering Research at the University of Cambridge

gFT glass & façade technology research group

Contents

Symposium Sponsors

PERMASTEELISA GROUP

DOW CORNING

seele

INTERPANE Glass for Life

UNIVERSITY OF CAMBRIDGE

gFT glass & façade technology research group

Dear Guest,

Welcome to the 3rd annual Engineered Skins symposium organised by the Glass and Façade Technology (gFT) Research Group at the University of Cambridge. The day event consists of keynote talks by eminent speakers and presentations on the recent research undertaken within gFT.

This is a free invitation-only event, to which a select group of industrial and academic partners have been invited.

We would like to thank Permasteelisa, Seele, Interpane, and Dow Corning for sponsoring this event. We would also like to thank the numerous funding bodies and industrial partners who are contributing to our research activities. These are acknowledged in the relevant project descriptions in this proceedings.

We would welcome any feedback and we are happy to provide further information on our on-going research activities. Please complete the feedback form at the back of the handout.

Best Regards,

Dr. Mauro Overend
Research Group Coordinator

glass & façade technology research group
www.gft.eu.com

Department of Engineering
University of Cambridge

Programme

6th September 2012

Department of Engineering
Trumpington Street, Cambridge CB2 1PZ

10:00 – 10:20 Coffee and Registration

Welcome Address
Prof. Dame Ann Dowling, Head of Department

Keynote Lecture: Doing More with Less: The London 2012 Olympic Velodrome
Pete Winslow & Jonathan Watts

11:20 – 11:40 Coffee Break

A Whole-life Value Based System For Façades
Qian Jin

Using BIM to Design Buildable Façades
Eleanor Voss

Transient Wind Loads on Complex Façades
Kenneth Zammit

12:55 – 14:00 Lunch

Keynote Lecture: Curtain Walling with High Performance Insulation
Mikkel Kragh

Fragmentation of Toughened Glass
Marco Zaccaria

Post-Fracture Behaviour of Laminated Glass
Caroline Butchart

15:30 – 15:50 Coffee Break

Adhesives For a Steel-Glass Composite Façade
Shelton Nhamoinesu

Long –Term Behaviour of Adhesive Joints
James Watson

Closing Remarks and Outlook
Mauro Overend

17:00 Drinks

About the Glass and Façade Technology Research Group

Aim
The Glass and Facade Technology (gFT) research group aims to address real-world challenges and disseminate knowledge in the field of glass structures and façade engineering by undertaking fundamental, application-driven and inter-disciplinary research.

Set-up
The research group consists of a core group of researchers within the Department of Engineering at the University of Cambridge. This core group is supported by a network of researchers in other centres of excellence worldwide.

This set-up allows the group to draw from the latest developments across several disciplines including: structural engineering; construction technology; wind engineering; computational mechanics; architectural materials; building physics; materials science and sustainability.

Most of our projects are grant-aided or industry-funded research and involve close collaboration with industrial partners such as glass producers and processors, cladding manufacturers, façade contractors, consulting engineers and architectural practices.

Research Priority Areas
The research undertaken by the gFT research group ranges from energy exchange through building envelopes to structural performance of glass and other façade components. The projects we undertake address one of the main research themes:

- Smart/optimised skins
- Transparent structures

Research Output & Other Activities
The group produces several publications and is involved in the development and writing of national and international standards. The group is represented at national and international professional societies and at major international conferences. The gFT research group also carries out contract research, development and testing.

Research Group Coordinator

Dr Mauro Overend is a lecturer in Building Engineering Design at the Department of Engineering in Cambridge and a Fellow of Christ's College. Before and immediately after completing his PhD on Structural Glass, he worked in consulting structural and façade engineering and obtained his chartered status, before moving back to full time teaching and research. He still maintains strong links with the construction industry. Mauro's current research interests in the structural and environmental performance of building envelopes are currently channelled through the Glass & Façade Technology Research group that he leads. He serves on the British Standards Committee for 'Glass and Glazing in Buildings' and the IABSE working commission on glass. Mauro is also the convenor of the Façade Engineering Study Group at the Institution of Structural Engineers and chairs the working group on the postfracture performance of glass within the recently established European Structural Glass Research Network.

KEYNOTE SPEAKERS

Doing More with Less: The London 2012 Olympic Velodrome

The 2012 Olympic Velodrome is a world-class venue which intelligently answers questions of function, beauty, sustainability, buildability and value. Inspired by the dynamism and geometry of the track and the engineering rigour of high performance bikes, the team set out to design a building that made no distinction between architecture and engineering. The 6,000 seat Velodrome has a 13,000 square metre roof which is supported by a light weight doubly curved cable net. Together with the careful integration of the environmental design and efficient use of materials throughout, the Velodrome has an extremely low embodied and operation energy performance, making it one of the most sustainable venues of its type. Described by six-time Olympic gold medal winner Chris Hoy as being “magnificent, better even than it looked on the drawing board”, the venue is testament to the success of client, design team and main contractor collaboration.

In this presentation Hopkins Architects and Expedition Engineering will describe the development project, from the initial brief to completion of the timber track. With a focus on the building envelope, it will discuss how to create a remarkable building within tight budgets and timescale: doing more with less.

Jonathan Watts

Jonathan studied architecture at the University of Bath and the Technical University of Munich with a particular focus on sustainable building design. He completed his education at the University of Greenwich London, where he was recipient of the Bennetts Prize for Best Part 3 Student. Since 2007, Jonathan has worked on a number of projects with Hopkins Architects, including the London 2012 Olympic Velodrome and legacy transformation of the VeloPark & North Parklands.The Velodrome has won numerous awards such as the RIBA Award for Architecture 2011, the AJ 100 ‘Building of the Year’, the BCIA Prime Minister's Better Public Building & the Stirling Prize ‘People’s Choice’.

Pete Winslow

Pete Winslow is structural engineer at Expedition Engineering, working on the design of special structures. He divides his time between Expedition Engineering and its sister research company MustRD. During the course of his PhD, awarded in 2009 by the University of Cambridge, Pete collaborated closely with the Buro Happold SMART group to develop new software tools for the design of free form structures.

After joining Expedition full time in 2009, Pete has worked on the London 2012 Olympic Velodrome which won the Institution of Structural Engineers Supreme Award in 2011 and was runaway winner of the Stirling Prize ‘People’s Choice’. Pete is currently working on Stavros Niarchos Foundation Cultural Centre .

Next Generation Curtain Walling with Vacuum Insulation Panels for High Performance Building

Energy consumption in buildings account for approximately 40 per cent of the global carbon emissions and energy regulations are getting ever stricter in an effort to meet targets set at international and national level. Ultimately, *near zero carbon emission buildings* will become the norm and this puts pressure on the building envelope to perform to higher standards than current practice. In a time of ever stricter energy codes, high performance is seen as a means to an end – Empowering the Designer to deliver high quality architecture with low environmental impact. We call it *Design Freedom*.

The fact that vacuum insulation panels offer the performance of a conventional insulated wall contained in a glazing unit opens up new architectural avenues and breaks down some of the barriers otherwise posed by stricter energy regulations. Examples of design freedom offered by high performance include the ability to increase the percentage of vision area, additional play with geometry such as layout and 3D form language – all due to enhanced performance in the insulated areas, offsetting the performance of vision area, increased transmission area, and linear thermal losses.

In a time where the energy performance of buildings needs to be addressed not only by visionary designers and clients, but across the board, the challenge is to not sacrifice high design freedom and quality architecture. The performance of curtain walling has been enhanced incrementally over the past decades and it is reaching certain limits mainly due to the need for vision area and the inevitable effect of the framing. A step change in insulation performance may quite possibly offer new opportunities for curtain walling in a world of *High Performance Building*.

Mikkel Kragh

Dr Mikkel Kragh is the Facade and Architectural Design Leader at Dow Corning. As part of the High Performance Building division he links the company's R&D and product development activities with the design community, including architects, engineers, façade systems manufacturers and specialist contractors. Dr Kragh's background spans Research, Specialist Contracting, and Consulting. He holds an MSc in Civil and Structural Engineering and a PhD in Building Physics. After chairing the Society of Façade Engineering for three consecutive terms he continues to promote façade engineering as a design discipline.

ABSTRCTS

Multi-objective optimisation of high-performance facades

High-performance façades, such as switchable glazing, have the potential to provide an optimal balance of performance, whole-life cost, and environmental impact, by responding to the variations in the outdoor environments and occupants' requirements. The major barrier to devising an optimal façade solution is the evaluation of the true values of alternative façade designs. Moreover, the lack of a systematic automated process makes the design process a time-consuming trial-and-error process.

Qian's research focuses on developing a multi-objective selection and design optimisation system, which integrates accurate simulation, systematic parametric analysis and automatic design optimisation. A comprehensive list of design criteria are populated, grouped, and linked to form three main objectives: social value, economic value, and environmental value. They form the basic elements of whole-life value.

The talk will describe the application of the multi-objective façade design and optimisation system on a real-world refacing project. The system was used during the initial design phase of the renovation of the Inglis building in the Department of Engineering, University of Cambridge. The façades earmarked for refurbishment is facing north and west. In-situ measurements were carried out to provide the basis for validating the computational simulation model. A preliminary computational simulation of several renovation strategies was performed to identify generic façade options with the largest improvement potential. A whole-life value based multi-objective optimisation approach was deployed to devise the optimal façade in terms of the three design objectives. The optimal renovation strategies were proposed, which significantly improve the indoor environment quality of the offices behind them with shorter carbon payback periods than the service life of the façades. The cash payback periods are in excess of 75 years.

1. Jin Q, Overend M. 'Façade renovation for a public building based on a whole-life value approach'. *Proceedings of the International Conference of Building Simulation and Optimisation, Loughborough*, UK. Sep 10-11, 2012.
2. Jin Q, Overend M, Thompson P. 'Towards productivity indicators for performance-based facade design in commercial buildings'. International Journal of Building and Environment, Volume 57, 271-281, 2012.
3. Jin Q, Overend M, Thompson P. 'A whole-life value based assessment and optimisation model for high-performance glazed facades', Proceedings of the Building Simulation 2011 Conference, Sydney, Australia. Nov 14-16, 2011.
4. Jin Q, Overend M. 'A thermal model for the design optimisation of high-performance glazed facades', Proceedings of the International Conference Engineered Transparency, Germany. September 2010.

Qian Jin

qj207@cam.ac.uk

Qian Jin graduated from Tongji University (Shanghai, China) with Bachelor Degree in Civil Engineering in 2008. She joined gFT under the supervision of Dr Mauro Overend in Oct 2008. After one year's study, she received her MPhil Degree in Engineering. She started her PhD program in Oct 2009. Her research is funded by Cambridge International Scholarships (CISS). Qian's research focuses on multi-objective optimisation of high-performance façade technologies.

Funded By:

UNIVERSITY OF CAMBRIDGE

Project Contributors:

Buro Happold

Using BIM to Design Buildable Façades

The increasing use of Building Information Modelling (BIM) across the construction industry opens new opportunities for interdisciplinary working. For the façade industry, BIM offers improved communication with members of the design and construction team, and fast access to increasingly complicated design information in a consistent digital format.

Modern façade design projects involve a wide range of materials whose manufacturing and installation impose many different constraints on the design. The façade engineer's role is to manage and apply these constraints to achieve an optimal design. This task is complicated by the increasing geometric complexity and diversity of elements required by architects. In other information rich industries, technologies similar to BIM are used to facilitate the design process.

The talk will present a tool to assist façade engineers in the capture, storage and use of 'downstream' design constraints. The tool captures and codifies expert knowledge of the geometric constraints placed on façade panels due to the manufacturing processes required to meet the design specification. Using the data stored in project BIM databases, the tool evaluates façade designs against constraints stored in the reusable expert knowledge database. The prototype tool facilitates the use of expert knowledge to perform manufacturability analysis of façades.

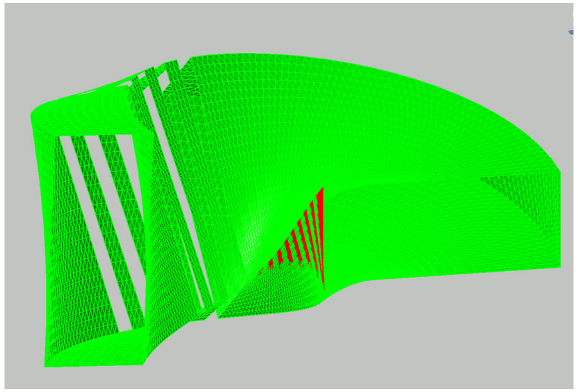


Figure: Visualisation of Manufacturability Analysis

As a demonstration, the tool is applied to a real-world façade project. The manufacturability of the design is assessed, assisting the façade engineer in the iterative development of the panelisation scheme by proving fast feedback on the implications of any modifications.

1. Voss E, Overend M. 'A tool that combines building information modeling and knowledge based engineering to assess facade manufacturability', Proceedings of the Advanced Building Skins 2012 Conference, Graz, Austria, Jun 14-15, 2012.
2. Voss E, Overend M, Stevens W. 'A building information modelling-based tool for heuristically assessing facade manufacturability', Proceedings of the IASS Annyal Symposium, Seoul, South Korea, May 21-24, 2012.

Eleanor Voss

ev236@cam.ac.uk

Eleanor Voss graduated from Cambridge University in 2009 having completed a BA and a MEng in Civil, Structural and Environmental Engineering. She then returned to Cambridge in October 2009 to start her PhD under the supervision of Dr Overend. Eleanor's research area is the use of Building Information Modelling within the facade industry as a tool for facade consultants to communicate effectively and work collaboratively with sub-contractors and manufacturers. The research is jointly funded by the EPSRC and the industrial partner Ramboll UK.

Funded By:

EPSRC
Engineering and Physical Sciences Research Council

RAMBØLL

Transient Wind Loads on Complex Façades

As the demand for energy efficient buildings increases, a significant number of high performance façades now use ventilated double skins, or include relatively small attachments such as external shading devices. These systems are often bespoke, giving each building its own distinguishing aesthetic, resulting in potentially different surface flow characteristics. There are several instances when the wind induced pressures on such facade elements cannot be obtained from codes of practice, or the façade elements are too small or complex to be included in conventional wind tunnel testing. Since wind-induced pressures often govern the sizing, detailing and performance of a façade, it is pertinent to investigate the wind-façade interaction in further detail.

When carrying out cladding pressure testing in the wind tunnel, the greatest challenge with achieving accuracy lies with modelling and instrumenting the small-scale features in sufficient detail. The research presented is the recent progress made in developing a more generally applicable method by combining the two approaches: (a) wind tunnel results for the entire simplified building surface and (b) Computational Fluid Dynamics (CFD) analysis to account for smaller façade details. The results from wind tunnel testing at a scale of 1:10 are presented which will be used to assess the accuracy of such a method.

It is envisaged that such a combined method could be used where it is impractical to model intricate facade details in the scaled wind tunnel models. The preliminary results indicate that it may be possible to validate CFD models for façade mean pressure computations and combine these with measurements of mean and peak pressures from wind tunnel testing using quasi-steady theory.

The wind tunnel spectra of fluctuating pressures measured across the façade elements are being compared to those measured on the external cube surfaces. It is hoped that consistently strong coherence can be identified between these spectra indicating the validity of this method, which provides a technique to assess pressures on most façade types.

1. Zammit K, Overend M, 'Transient wind loads on complex facades'. 10th Conference on Wind Engineering, Southampton, September 2012.

Kenneth Zammit

kz223@cam.ac.uk

Kenneth Zammit joined the gFT group in 2007 and is reading for a PhD at the University of Cambridge in Wind engineering on Glass Façades, while working as a façade engineering consultant at Thornton Tomasetti UK. Before joining the group, he studied Architecture and Civil Engineering at the University of Malta. He later worked as a structural engineer and obtained membership of the Malta Chamber of Architects. He then read for an MSc in Facade Engineering at the University of Bath before joining the gFT group under the supervision of Dr. Mauro Overend.

Part Funded By:

EPSRC

Engineering and Physical Sciences Research Council

Project Contributors:

BMT Fluid Mechanics

Fragmentation of Toughened Glass

There is a growing demand for curved monolithic glass panes that are toughened, fire-resistant and that also have a high optical clarity. No single type of glass can currently fulfil these requirements. For example chemically toughened shows good strength, fire-resistance, and it can be curved after the strengthening process, but it fails in large unsafe fragments; whereas fully toughened glass shows better fracture behaviour due to its residual stress profile. It is theoretically possible to combine the two toughening processes thereby producing a glass, called bi-toughened glass, with all the aforementioned properties. The research project is divided in two parts: the first is to develop a model for predicting the mechanical performance (e.g. strength, fracture toughness, slow crack growth, fragmentation) for any given stress profile. The second is to determine the relationship between the production process parameters of bi-toughened glass and the pre-determined mechanical performance. The outcome will be an optimal bi-toughened glass with applications in architecture as well as the marine industry.

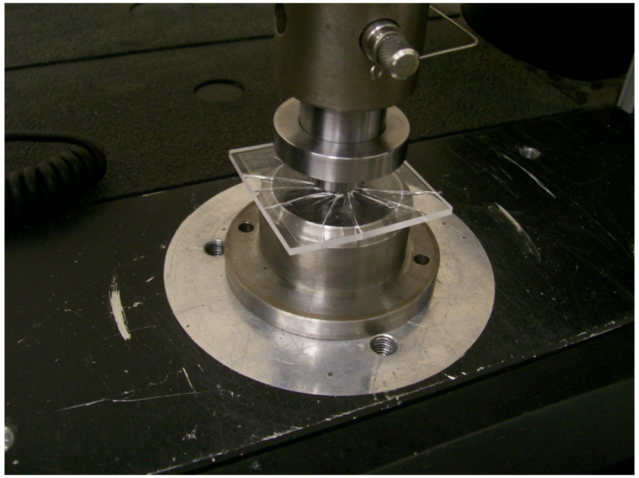


Figure: Equibiaxial strength testing on a Coaxial double ring

This presentation will show the work planned to achieve the goal and will focus on the preliminary work done so far, namely, investigations on the mechanical properties such as fragmentation, slow crack growth and fracture toughness in annealed glass and how these studies can be extended to toughened glass.

1. Zaccaria M., Overend M., 'Validation of a simple relationship between the fracture pattern and the fracture stress of glass'. Accepted for Engineered transparency, International Conference at glasstec, Dusseldorf, Germany, 25 and 26 October 2012.

Marco Zaccaria

mz287@cam.ac.uk

Marco Zaccaria joined the gFT research group in October 2011. He graduated in Building Engineering at the Technica University of Bari in 2010 and subsequently worked at the Italian Institute of Technology where he undertook research on the enhancement of mechanical properties of nanostructural materlis. In 2009 he spent 6 months as a visiting research student within the gFT research group where he investigated steel-to-glass adhesives connection as well as the strength of naturally weathered glass. His PhD project on Monolithic fire-resistant structural curved glass is supervised by Dr Mauro Overend and is funded by EPSRC and Trend Marine Ltd.

Funded By:

EPSRC
Engineering and Physical Sciences
Research Council

TREND MARINE

Post Fracture Behaviour of Laminated Glass

The deformation response of a fractured laminated glass plate can be described by the superposition of a number of micro-mechanisms. Each of these mechanisms must be understood, and characterised independently of one another before the global behaviour can be accurately described. The work here isolates two of these mechanisms: deformation in the polymer interlayer and delamination at the glass-polymer interface. These mechanisms are investigated by means of through-crack tension (TCT) tests.

Analyses of TCT tests to date have utilised an energy balance approach to calculate the interfacial adhesion between glass and polyvinyl butyral (PVB). The total applied energy can be equated to the sum of the energy dissipated during delamination, and the energy used in deformation of the interlayer. Force-displacement data gathered during TCT tests is used in combination with an appropriate material law for PVB to calculate the total energy used during deformation of the interlayer.

To date the material law used during these analyses has been elastic or hyperelastic. The consequence of this is the measured value of interfacial adhesion is valid only for the loading rate used in that particular experiment. This work employs a viscoelastic material law for PVB, which was determined from indentation tests on samples of Solutia's RB41 PVB. TCT tests were performed at two different strain rates. Images captured during the tests were analysed using digital image correlation in order to plot the variation in strain along the interlayer length. This strain profile was compared to that predicted using the viscoelastic material law. Values of interfacial adhesion were calculated from tests performed at both strain rates. The interfacial adhesion was found to vary with strain rate.

1. Butchart C, Overend M, 'Delamination in fractured laminated glass', Engineering Transparency Conference, Dusseldorf, October 2012

Caroline Butchart

cvb25@cam.ac.uk

Caroline Butchart joined the gFT group in October 2010 after having graduated from the University of Leeds with a BEng and MEng in Architectural Engineering in 2010. She joins the group reading towards a PhD at the University of Cambridge under the supervision of Dr Mauro Overend. Her research will focus on developing a model to help predict the post-fracture behaviour of glass elements, and is funded by the EPSRC.

Funded By:

EPSRC
Engineering and Physical Sciences Research Council

Project Contributors:

SAINT-GOBAIN GLASS

INTERPANE Glass for Life

Adhesives For a Steel-Glass Composite Façade

Despite the ubiquity of bolted connections in structural glazing systems, adhesive connections are becoming increasingly popular. Unlike bolted connections that weaken the glass in the vicinity of bolt-holes, adhesive bonding ensures a more uniform load transfer between glass and the supporting elements. As a result, efficient composite behaviour between glass and the supporting elements can be achieved. There is however a lack of confidence in the use of adhesives for structural applications partly because of a lack of reliable models that can accurately predict their transient and long-term mechanical behaviour.

As part of a broader on-going research aimed at developing a façade system in which both steel and glass form a composite load-bearing unit, this presentation describes experimental investigations undertaken to select suitable adhesives from short-listed epoxies and acrylates. The selection was based on mechanical performance of adhesive single-lap shear joints subjected to short-duration loads. An assessment of the validity of an analytical and a viscoelastic-plastic numerical model used for predicting the stress-state in adhesive joints was made. The investigation shows that three of the tested adhesives may be suitable for use in a steel-glass composite façade system. The analytical model provides good predictions at low strains but the accuracy decreases with increasing adhesive strains. The non-linear numerical model provides reasonable predictions but is sensitive to adhesive shear modulus history. Further research aimed at improving the adhesive constitutive model by accounting for effects of hysteresis and repeated cyclic loading is underway. It is hoped that the improved models can be used to predict the global adhesive joint performance in full-scale steel-glass composite façade modules.

Figure: Sample undergoing test

1. Nhamoinesu S, Overend M. 'The Mechanical Performance of adhesives for a steel-glass composite façade system', Proceedings of the Challenging Glass 3 conference, TU Delft, The Netherlands, June 28-29 2012.
2. Overend M, Nhamoinesu S, Watson J, 'The structural performance of bolted connections and adhesive bonded joints in glass structures' ASCE Journal of Structural Engineering. In press

Shelton Nhamoinesu

sn393@cam.ac.uk

Shelton Nhamoinesu graduated from the University of Hertfordshire (Hatfield, UK) with a BEng (Hons) in Aerospace Engineering in 2009. In January 2010, he enrolled at the University of Cambridge to study for a PhD in Engineering under the supervision of Dr Mauro Overend. Shelton's research within the gFT group is to develop a novel steel-glass composite facade system. The cost of his research project is met by an Industrial CASE studentship provided by EPSRC and a contribution from TATA Steel, the Industrial partner.

Funded by:

EPSRC
Engineering and Physical Sciences
Research Council

TATA

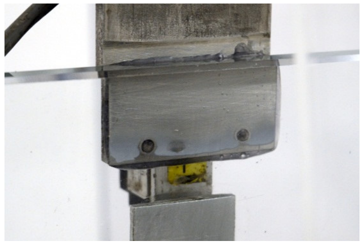
Long-Term Behaviour of Adhesive Joints

Traditionally the only option for joining glass in high stress structural applications was to use a bolted connection in fully toughened glass. However, adhesives have recently been growing in popularity as a solution as they distribute the stress more evenly and require very little surface preparation. However, there are concerns over the long-term behaviour of adhesives. This uncertainty is due to a lack of knowledge on the performance under long-term loading (both static and dynamic) as well as their ability to withstand environmental effects such as temperature/humidity. This doubt leads to very large safety factors which often rule them out as a possible option. This paper seeks to address some of these issues and to improve confidence in the use of adhesives for structural applications.

Experimental investigations have been undertaken to examine the long-term performance of adhesives which have excelled in short-term testing carried out in the department. Tests were designed to examine the static fatigue performance of the adhesive joints under various loads under controlled conditions. The loads were selected based upon industrial advice and a literature survey of similar testing. Joint displacements have been monitored continuously to measure the creep of the adhesives.

A combination of further experimental testing under various temperatures is also considered to predict the creep behaviour/master curve of these adhesives. The technique (stepped isothermal method) is based on time temperature superposition and has been revised as initial trials proved the original concept was unsuitable.

Dynamic fatigue testing is ongoing, where joints of the same geometry have been placed under sinusoidal load to examine the effect of a constantly changing load on crack growth and debonding.



1. Overend M, Jin Q, Watson J, 'The selection and performance of adhesives for a steel-glass connection'. International Journal of Adhesion and Adhesives 31,7 p 587-597, 2011

James Watson

jw484@cam.ac.uk

James Watson graduated from the University of Cambridge with a Ba MEng in Civil, Structural and Environmental Engineering in 2009. His final year project focussed on the design and modelling of a complex masonry façade in London and was completed in partnership with Ramboll UK.

James joined gFT under the supervision of Dr Mauro Overend in Oct 2009 when he began his PhD program. He is funded by Hourglass and the EPSRC through an Industrial CASE Studentship. James' research will focus on novel steel-to-glass and glass-to-glass connections for architectural applications.

Funded by:

EPSRC
Engineering and Physical Sciences
Research Council

HOURGLASS
GLASS ENGINEERING, BENDING & DECORATION

Thank you for attending Engineering Skins 2012.
We would appreciate it if you could take the time to complete this feedback form.

Please Share your opinion on the direction of the research and/or of the individual presentations

We would also welcome your thoughts on the running of the day:

Organisation and Structure of the day

Catering and Location

Quality of the presentations

If you have any further comments, please provide them below:

Would you like any further information on the research projects? e.g. electronic copies of publications
If so please provide contact details.

FEEDBACK FORM