Engineered Skins 2013

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

UNIVERSITY OF CAMBRIDGE
Department of Engineering

gFT glass & façade technology research group

Contents

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Welcome

Dear Guest,

Welcome to the 4th annual Engineered Skins symposium organised by the Glass and Façade Technology (gFT) Group at the University of Cambridge. This one-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.

This year's symposium will be followed by a dinner at Christ's College, which will give everyone an opportunity to continue the lively discussions in one of Cambridge's historic colleges.

We would like to thank Corning, Dow Corning, Interpane, Permasteelisa, and Seele 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 are happy to provide further information on our on-going research activities. A feedback form has provided for this at the back of the handout.

Best Wishes,

Dr. Mauro Overend

Research Group Coordinator
Glass & Façade Technology Research Group
www.gft.eu.com

Department of Engineering
University of Cambridge

Coffee & Registration	10:00
Welcome Address *Professor Robert Mair*	10:20
Keynote: Design Invention *Tim Macfarlane - Glass Light and Special Structures*	10:30
Coffee Break	11:30
A Façade Manufacturability Assessment Tool *Eleanor Voss*	11:50
Adaptive Building Skins for Future Zero Energy Buildings *Fabio Favoino*	12:10
The Structural Performance of Insulated Glazing Units *Kenneth Zammit*	12:30
Lunch	12:50
Keynote: Abu Dhabi Louvre *Rachel Witcherley - Buro Happold*	14:00
The Mechanical Performance of Steel-Glass Composite Panels *Shelton Nhamoinesu*	15:00
Post-Fracture Interlayer Delamination *Caroline Butchart*	15:20
Coffee Break	15:40
GFRP-Glass Composite Structures *Kenneth Zammit*	16:00
The influence of stress profile on strength and fragmentation of glass *Marco Zaccaria*	16:20
Closing Remarks *Dr Mauro Overend*	16:40
Dinner & Drinks *Christ's College, Cambridge*	18:10

glass & façade technology research group

UNIVERSITY OF CAMBRIDGE
Department of Engineering

Research Group Co-ordinator - Dr Mauro Overend

Mauro is a senior lecturer in Building Engineering Design at the Department of Engineering, University of Cambridge and is a Fellow of Christ's College.

He is a chartered engineer with several years of consulting engineering experience in the fields of structural engineering and façade engineering. He currently leads the Glass & Façade Technology Research Group (www.gft.eu.com) at the University of Cambridge, which undertakes research on the structural and environmental performance of glass and building envelope systems.

Mauro has more than 40 peer-reviewed publications to his credit and he serves on several national and international committees related to glass and façade engineering. In recognition of his research on glass and façade engineering he was awarded the 2011 Guthrie-Brown medal by the Institution of Structural Engineers and the 2013 IABSE Prize by the International Association of Bridge and Structural Engineers.

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:

(i) Smart/optimised skins
(ii) 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.

Opening & Keynote Speakers

Robert Mair

Opening Address

Robert Mair was appointed Professor of Geotechnical Engineering at Cambridge University in 1998. He is Head of Civil and Environmental Engineering and was Master of Jesus College 2001-2011. He was a Fellow of St John's College from 1998 to 2001. He is also one of the founding Directors of the Geotechnical Consulting Group (GCG), an international consulting company based in London, started in 1983. He was appointed Chief Engineering Adviser to the Laing O'Rourke Group in 2011.

Tim Macfarlane

Design Invention (What, Why, How)

Tim Macfarlane has been a principal of Glass Light and Special Structures since 2012. Prior to that he was the design Partner of Dewhurst Macfarlane and Partners a structural engineering consultant with an international reputation and offices in London New York and Trinidad.

His talk will focus on the challenge of developing design ideas within the litigious world of building construction.

Rachel Witcherley

Abu Dhabi Louvre

Rachel joined the Façade Engineering Group at Buro Happold as a graduate in 2002 and has developed with the group as it has grown into an international team. With a Master's degree in Architectural Engineering Rachel has utilised her multidisciplinary background to bring a holistic approach to façade engineering. She has delivered complex façade projects across the world from the Co-operative Headquarters Building, Manchester, to the Qatar Foundation Conference Centre, Doha. Rachel is the Buro Happold Façade Engineering lead for the Abu Dhabi Louvre Museum. She has a keen interest in the use of collaborative working to deliverer good design and believes that placing the needs of users at the centre of the design is critical to the success of a project.

gFT Research Group

Eleanor Voss

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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 RAMBOLL

A Façade Manufacturability Assessment Tool

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.

The application of knowledge based engineering and BIM like technologies in other industries has been found to be beneficial in design activities such as manufacturability assessments. The research project overall has looked for opportunities to exploit such technologies in the context of the facades sector.

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 further complicated by the increasing geometric complexity and diversity of elements required by architects.

The talk presents the testing of a tool to assist façade engineers in the capture, storage and use of such '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.

The tests compare the time taken to perform a manufacturability analysis using conventional methods adopted by façade consulting firms with the time required using the prototype assessment tool. In addition, a qualitative assessment of the tool is made to highlight the less easily measured aspects of using the tool. The tests focus on three real world case studies of geometrically and materially complex façades.

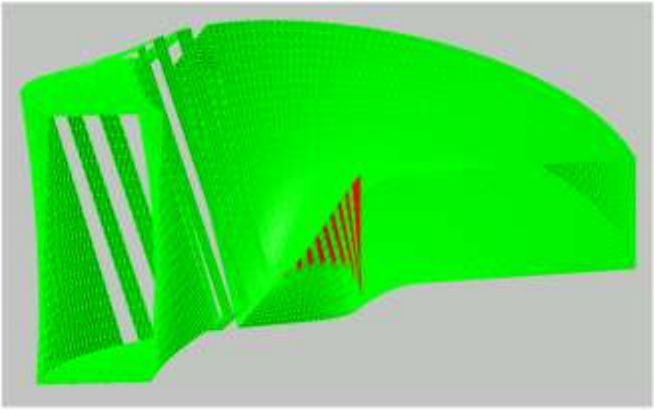

Figure: Astana Library, research project case study curtsey of RambollUK

Fabio Favoino

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Fabio Favoino joined the gFT research group in January 2013. He graduated (BSc and MSc) in Building Engineering at the Technical University of Torino, Italy in 2010, that included a 6 month student exchange period at TU Delft.

After the graduation he joined the TEBE research group, at the Energy Department of Technical University of Torino as a contract graduate researcher, working on the experimental evaluation of energy performance of dynamic building envelopes. His PhD project is about the energy and comfort performance of dynamic (smart) facades. His research is supervised by Dr. Mauro Overend and is funded by EPSRC and Wintech Ltd.

FUNDED BY:

EPSRC WINTECH

Adaptive Building Skins for Future Zero Energy Buildings

The efficiency of building envelopes has a direct influence on the space heating, cooling and lighting in buildings and on the levels of occupant comfort and well-being. The latter is particularly relevant in commercial buildings where the whole-life-value of the building asset is very sensitive to occupant comfort and productivity. Moreover the requirements for the façade elements are conflicting and transient, e.g. maximising natural light transmittance whilst minimising unwanted solar heat gain in the cooling season and minimising heat loss in the heating season. It is evident that a static facade cannot successfully satisfy all these conflicting and transient performance requirements.

The aim of this research project is therefore to investigate smart (or adaptive) facades that can outperform the current generation of high performance static facades. This builds on recent research activities within the group, particularly on the design optimization of (static) high-performance glazed façades which included a computational tool for performing multi-objective design optimisation of static facades. The current research project is funded by EPSRC and Wintech Ltd.

The presentation will describe the approach taken to evaluate and optimise the design and the operation of a dynamic façade. Firstly, developments in high performance buildings and building regulations will be discussed, in terms of energy performance, occupant comfort and productivity. Secondly, the potential of different adaptive façade technologies, which are able to regulate the heat and mass transfer through the building envelope, will be assessed. Finally the future work on the evaluation and selection of adaptive technologies will be presented and discussed.

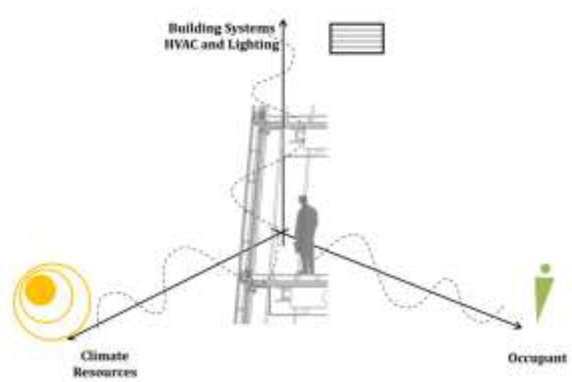

Figure: Domains of adaptiveness for high-performance (energy, IEQ, structural, architectural) facades

Kenneth Zammit

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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

PROJECT CONTRIBUTOR:

BMT Fluid Mechanics

The structural performance of insulated glazing units

The availability of ever increasing glass sizes and the development of stiff polymer interlayers provides opportunities for novel structural glass applications. As bolder designs are developed, some of the implicit assumptions in existing design recommendations for insulated glazing units (IGUs) and laminated glass do not always hold true and can lead to underestimation of stresses. Furthermore, there is a paucity of published research on the structural response of IGUs, particularly when these are subjected to load combinations or dynamic loading.

To address these shortcomings, the visco-elastic models for different interlayers were tested and results compared to available test results. Load testing of full size glass panels was also conducted using a sinusoidally varying central point load loading simulating the frequencies likely to be encountered on facades subject to wind loading. In order to isolate the different contributions to stiffness, a series of tests was carried out on IGUs both with and without laminated glass, as well as on a single laminated pane.

Using the above tests and models, a finite element model was developed which successfully captures the structural response of the units which includes: geometrical non-linearity due to large deflections; material non-linearity arising from the viscoelastic interlayer; and load-sharing between the glass plates across the sealed gas space. It was found that load sharing between monolithic glass plates is insensitive to loading frequency, however the existing simplified formulae given by design codes can lead to significant errors.

It is also shown that, in addition to temperature and load duration, the visco-elastic modelling of interlayers is also sensitive to the time-step considered in the analysis. Finally, recommendations for simplified analysis using an equivalent elastic stiffness approach and appropriate load durations for common load types and load combinations are suggested.

Figure: Pneumatic system used for cyclic loads

Shelton Nhamoinesu

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Shelton Nhamoinesu graduated from the University of Hertfordshire (Hatfield, UK) with a BEng (Hons) in Aerospace Engineering in 2009. For his final year project, Shelton designed and analysed the Structural Airframe of the University of Hertfordshire's 2009 Unmanned Aerial Vehicle.

Shelton joined the gFT group in January 2010 under the supervision of Dr Mauro Overend and is reading for a PhD at the University of Cambridge in Steel-Glass Composite Structures. The cost of his research project is met by an Industrial CASE studentship provided by EPSRC and a contribution from Corus Group PLC, the industrial partner.

FUNDED BY:

EPSRC TATA STEEL

Mechanical Performance of Steel-Glass Composite Panels

Glass is often used in conjunction with steel framing but the two materials rarely act in a fully composite manner; the in-plane and out-of-plane loads on the glazed structures are often resisted by the steel frame with the glass being used as infill or top hung panels. Such glazing systems are not only structurally inefficient due to their failure to fully utilize the load bearing potential of glass; they also lack aesthetical appeal due to the relatively large supporting frames. Steel-glass composite façade panels would therefore increase structural and material efficiency thereby making the façade more transparent and aesthetically pleasing. However, developing a steel-glass composite façade system presents a couple of engineering challenges: firstly, there are very few precedents on the use of glass as a primary load bearing material and secondly, there are no proven joining methods that allow efficient load transfer between glass and steel.

This presentation describes our recent efforts to investigate the mechanical performance of single-glazed and double-glazed (both one-way span and two-way span) medium-scale steel-glass composite panels subjected to flexural tests. The glass panels (dimensions: 700 mm x 300 mm) were linearly bonded to the reinforcing steel frames by Araldite 2047 adhesive, a two-part high strength acrylate selected from a previous study on potential candidates for steel-glass bonding. The presentation will also include a brief assessment of the validity of a non-linear numerical model developed to predict the mechanical behaviour of the composite panels. The experimental investigations show that (i) the steel-glass panels exhibit full composite structural action up to failure (ii) the mode of failure is glass fracture which in some cases is preceded by local adhesive plastic strain particularly near the joint ends and (iii) the double glazed panels achieve a post-fracture capacity of nearly 50% of the load to first fracture. The numerical model provides good predictions of the composite behaviour of the steel-glass composite panels. This model can be extended to predict the mechanical behaviour of more complex full-scale steel-glass composite façade systems.

Figure: Steel-Glass composite panel in four-point bending: a) before failure; b) after failure

Caroline Butchart

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Caroline Butchart graduated with a BEng and MEng in Architectural Engineering from the University of Leeds in 2010. She then joined the gFT group at the University of Cambridge in October 2010, where she is studying towards a PhD.

Her research focusses on the development of a method for estimating the post-fracture performance of laminated glass. She is supervised by Dr Mauro Overend and funded by the EPSRC.

FUNDED BY:

EPSRC

PROJECT CONTRIBUTOR:

EASTMAN

INTERPANE Glass for Life

Interlayer Delamintation Post-Glass-Fracture

One of the key factors affecting the post-glass-fracture load bearing capacity is the level of adhesion between the interlayer and glass. If the adhesion is too high, the interlayer is prone to tearing; if the adhesion is too low, glass fragments may not be held in place after fracture.

Upon glass fracture the interlayer delaminates; the delaminated interlayer is then free to stretch without the constraint of the glass on either side. It is the deformation in the delaminated interlayer that controls the post-glass-fracture load bearing, and the global deformation behaviour.

In order to accurately determine deformation in the interlayer, it is therefore essential that the delaminated length is known. Accordingly, a suitable method of determining the adhesion between the interlayer and glass is required, as well as an understanding of how different factors influence this adhesion. Lastly, a method of describing interlayer adhesion in a finite element analysis is also necessary.

To address this, peel tests were performed on specimens of Polyvinyl Butyral (PVB) laminated between a layer of glass and a flexible aluminium backing. The force required to peel the interlayer from the glass was recorded as a function of:

- i) rate of peel
- ii) angle of peel
- iii) presence of moisture

It was found that the peel force varied significantly with all three factors. Throughout the test, the point of delamination was recorded using a portable microscope. It was observed that the shape of the delaminating interlayer varied depending on rate of delamination.

This presentation discusses the peel tests performed and how the results might be used within a finite element model.

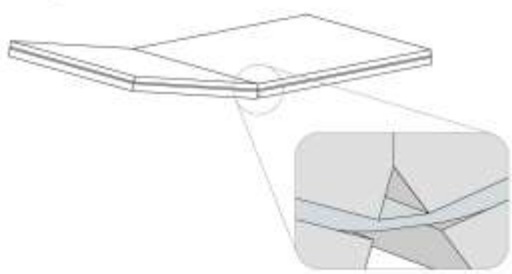

Figure: a) Interlayer delamination and deformation b) Peel test

Belarmino Cordero

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Belarmino is an architect with an interest in construction technology and environmental design. He has completed a MArch at Universidad Politécnica de Madrid (UPM) and an MSc in Environmental Design and Engineering at The Bartlett, University College of London (UCL). He first worked as an architect before joining the façade engineering team at Buro Happold, where he worked for four years.

Belarmino started his PhD on high performance facades in 2010 at UPM and joined the Glass and Façade Technologies (gFT) research group for six months as visiting researcher. After winning pump priming grants from the Engineering and Physical Sciences Research Council (EPSRC) and the Institution of Structural Engineers (IStructE), he now collaborates with gFT to develop a research project on GFRP-Glass composite structures.

GFRP-Glass Composite Structures

The recent research on glass bonding at the University of Cambridge and the availability of new high-performance adhesives provide an opportunity to develop Glass Fibre Reinforced Polymer (GFRP)-Glass composite units that are structurally and thermally efficient. The aim of this project is to investigate the composite structural behaviour between glass and FRP. The work will involve three overlapping stages:

- Stage 1: Selection of suitable candidate glass-GFRP adhesives and bond thickness.
The selection criteria will be driven by the capacity of the adhesives to transfer shear and accommodate differential thermal expansion between the substrates. The bond thickness will be governed by: (i) manufacturing flatness tolerances of the glass and GFRP; and (ii) the strength and shear stiffness required to mobilise composite action between the glass and the GFRP including a provision for differential thermal expansion. Suitable adhesives will be selected from a pool of silicones, epoxies and acrylates most of which have been previously investigated at the University of Cambridge.

-Stage 2: Analytical and numerical modelling of typical GFRP-glass joints
The mechanical behaviour of GFRP-glass joints will be simulated by using analytical and numerical (finite element) models of single-lap shear joints. Information from these preliminary predictions will be useful in the setting up of experimental tests.

-Stage 3: Experimental tests on GFRP-glass joints
(i) Single-lap shear and accelerated UV tests
Adhesively connected GFRP-glass lap joints will be assembled and tested in SLS to investigate the shear strength and failure mode. Some of the specimens will be subjected to accelerated UV testing prior to the SLS test. The test results will also be used to validate the numerical models of the SLS joints (performed in Stage 2).
(ii) Four point bending tests
Small scale adhesively bonded glass-GFRP panels will be subjected to 4-point bending tests to investigate composite behaviour of the panel as well as the post-fracture characteristics.

Marco Zaccaria

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Marco Zaccaria joined the gFT research group in October 2011. He graduated in Building Engineering at the Technical University of Bari in 2010 and subsequently worked Italian institute of technology where he undertook research on the enhancement of mechanical properties of nanostructural materials. In 2009 he spent 6 months as a visiting research student within the gFT research group where he investigated steel-to-glass adhesives connections and the strength of naturally weathered glass. His PhD project on Novel Fire Resistant Glass is supervised by Dr. Mauro Overend and is funded by EPSRC and Trend Marine Ltd.

FUNDED BY:

EPSRC

TREND MARINE

Stress profile influence on strength and fragmentation of glass

Toughening and lamination processes produce a stronger and more reliable material. However, the strongest glass currently available is chemically toughened which does not produce a safe fracture pattern. An ideal toughened glass would have the high strength of chemically toughened glass (CTG), and a safe breakage, typical of fully toughened glass (FTG).

Attempts to produce such a glass were made by combining the two toughening methods. This was termed bi-toughened glass (BTG) and was toughened either thermally and then chemically (T+C) or vice-versa (C +T).Specimens of BTG were inspected using a scattered light polariscope (SCALP) to determine the residual stress profile. The specimens were then tested on a coaxial double ring (CDR) and the number of fragments was recorded. Control tests on conventional CTG, FTG and annealed glass (AG) were also undertaken.

Test results showed that CTG is the strongest, followed by BTG (T+C), FTG, BTG (C+T) and finally AG. However, there is a mismatch between ranking the specimens from the highest residual surface stress to the lowest, as read from the SCALP (CTG, BTG (C+T), BTG (T+C), FTG and AG) and the ranking obtained from test data. Safe fragmentation complying with EN12150-1 was seen for FTG and BTG (C+T) only. This agrees with the SCALP readings as these types of glass had a considerably higher value of tensile stress in the core of the pane as well as a higher stored energy than the other glass types.

At this stage it can be concluded that BTG is neither stronger nor safer than existing toughened glass. In order to produce a BTG which actually fulfills these requirements the following steps will be undertaken:

(i) Use an existing numerical model to predict transient stresses during the manufacture of FTG;

(ii) Develop an empirical model that predicts the stress profile in CTG as a function of time, temperature and salt bath contents;

(iii) Combine the two models to optimise and control the BTG production process.

This presentation will show the results of the photo-elastic analysis, the destructive tests and the fragmentation analysis. Future work will also be described.

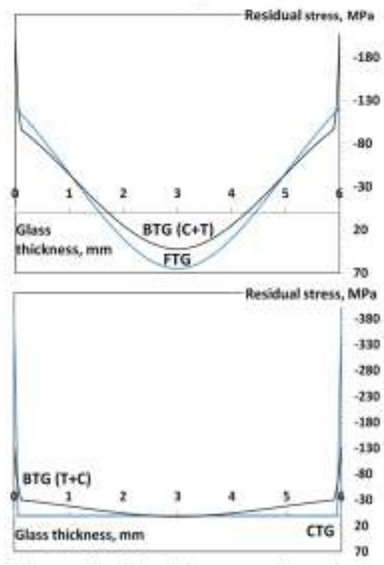

Figure: Residual stress profiles a) BTG (C+T) and FTG; b) BTG (T+C) and CTG

Kyriaki Datsiou

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Kyriaki Datsiou joined the gFT research group in June 2013. She received her Diploma in Civil Engineering, specializing in Structural Engineering, from the Aristotle University of Thessaloniki, Thessaloniki, Greece in 2012. Her Diploma Thesis concerned the use of by-products in alkali-activated mortars and their possible industrial applications. After graduation she worked for four months as a research assistant at the Laboratory of Building Materials of the Aristotle University of Thessaloniki. Her PhD project concentrates on stressed-skin glass structures and is supervised by Dr. Overend. Her research is funded by EPSRC and Eckersley O'Callaghan.

FUNDED BY:

EPSRC

eckersley o'callaghan
structural and facade engineers

Stressed-Skin Glass Structures

During the last decade, the role of glass in the construction industry has evolved from functional and decorative to structural giving emphasis to its load bearing capacity. Nonetheless, utilizing glass structurally poses several challenges as a result of its brittle nature indicating the need to use high strength glass that is either chemically strengthened or heat treated.

The latest architectural trends require the use of free form geometry and curvature in glass design in conjunction with high standards of optical and visual quality. Therefore, new challenges emerge in relation to the development of curved surfaces concerning both structural performance and economical production of the glass units.

Kyriaki's research project focuses on developing novel, lightweight, stressed-skin glass units. This will be achieved by deforming thin chemically strengthened or tempered glass at ambient temperatures in order to improve the out-of-plane stiffness of the glass and to simultaneously accomplish the desired curvature. Due to their form and lightweight nature, these glass units, will have the potential to be applied in the architectural, automotive and aerospace industries.

In more detail, the first stage of the project comprises the investigation of the salient properties of chemically strengthened glass, which until now remain insufficiently documented. In particular, the durability of the glass i.e. the natural surface weathering of the units due to environmental conditions and wind borne debris as well as their edge strength are the properties to be examined. The second stage will focus on the investigation of the stability (i.e. the buckling behaviour) of monolithic and laminated stressed skin glass units using both numerical models and experimental methods. Finally, the last stage contains the development of some empirical models for the prediction of the unit's structural performance.

Evening Dinner

For those guests attending dinner

Dinner will be held at Christ's College Cambridge. Starting with drinks at 18:10, followed by dinner in The Hall at 18:30.

On arrival please report to the Porters' Lodge, where you will be directed to the dinner.

Menu

Wild Mushrooms in a Cream & Garlic Sauce

~

Supreme of Duck in Cherry & Port Sauce

or

Aubergine & Fig Moussaka with Apricots & Prunes

~

Cambridge Burnt Cream with Raspberries

~

Coffee

Attendees

Name	Company	Email Address
Andrea Marston	AGC Glass UK	andrea.marston@eu.agc.com
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Feedback

Thank you for attending Engineered Skins 2013.

We would appreciate it if you could take the time to leave us feedback on both the symposium and the work presented by the research group.

Please Share your opinion on the direction of the research and the individual projects.
Running of the day:
1) Organisation and Structure: poor 1 2 3 4 5 excellent Comments:____________________ 2) Catering and Location: poor 1 2 3 4 5 excellent Comments:____________________ 3) Quality of presentations: poor 1 2 3 4 5 excellent Comments:____________________
If you have any further comments, please provide them below:
Would you like any addional information on any of the research projects? If so, please specify which and leave contact details below: