

Activity report of COST Action TU0905 Working Group 3 – Post-fracture performance and integrated design methods

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ABSTRACT: This report is a summary of the activities undertaken during the European Research Network on Structural Glass (TU0905) supported by the European Office for Cooperation in Science and Technology. It primarily includes the work within two Task Groups Structural Design Philosophy (TG08) and Learning from Failures (TG09). It also includes work done in conjunction with other Working and Task groups as well as activities supported by the Short Term Scientific Missions and the development of the relevant parts of the Education Pack.

1 INTRODUCTION

Glass is inherently brittle and has a relatively low tensile strength. As a result the overarching design philosophy is to ensure adequate strength and stability for normal actions and to provide safe failure or adequate residual post-fracture capacity thereby minimising the risk of human injury. This fundamental ‘fail-safe’ concept is yet to be formally embedded in to the design process, largely due the lack of quantitative methods for assessing the post-fracture performance of glass. This shortcoming was the principal motivation for establishing Working Group 3 (WG3). It was recognised that the activities in this area required:

1. A deeper understanding of materials, component and system characteristics such as the effects of time / temperature / relative humidity on delamination; crack branching and fragmentation of glass, fail-safe connections etc.
2. A better understanding of the state-of-the-art approaches in mitigating failure in practice.

This paper describes the work undertaken in this area by WG3. This is subdivided into work related to the core activities of WG3; work done in collaboration with other working groups; and participation in the other activities of this COST action such as short term scientific missions, development of the education pack and training school / workshops.

2 CORE ACTIVITIES

The first task undertaken by WG3 was to collate all relevant existing research in this area. This included the on-going research projects in this field of research. The latter is summarised in (Overend, 2010).

The second task was to identify the specific needs and expectation within this field and to establish which of these would be pursued further by WG3 and what methods would be adopted to do so (Table 1). The ensuing sections describe the progress made in these areas.

Table 1: Needs and expectations. Topics pursued in this COST action (shown shaded)

Needs & expectations	Method
1. Sharing experimental “know-how”	Dissemination; presentations at Cost Action meetings; STSMs.
2. Sharing numerical “know-how”	
3. Design data / guidelines (new structures)	Collate and define and describe steps in integrated structural design
4. Learning from failure	
5. Structural design philosophy (safety + robustness)	
6. Mechanical post-fracture characteristics of laminated glass	Experimental, numerical and analytical research
7. Common language research – industry	
8. Validate numerical work	
9. Future ‘tangible’ research projects	

2.1 *Learning from failures – current practice*

This work was led by Daniel Honfi who collected data on the existing design philosophy and glass failure cases. The investigation included a survey about how practicing structural engineers deal with different design aspects of glass with a special focus on robustness and serviceability. This was undertaken by means of semi-structured interviews with leading practitioners. The first round of findings of this work was published at mid-term conference of this COST action (Honfi & Overend, 2013).

2.2 *Unified design approach Integrating risk analysis, normal service conditions and exceptional actions.*

The efforts in this area were led by Mauro Overend and Richard Green. The former produced a unified method for the structural design of glass elements in buildings based on the limit state design philosophy (Overend, 2012). The approach firstly identifies the structural performance requirements as function of the intended application and secondly provides advice on the calculations and prototype testing required for assessing the performance of the candidate design. A simple risk analysis / performance requirement matrix is shown in Figure 1. The document produced also provides advice on material selection and connection design. Further useful sources of information for detailed design and specification are provided.

The work in this area involved interaction with the work undertaken by the American Society of Testing Materials’ in its development of the standard for glass in buildings ASTM E1300 (ASTM, 2009). A very useful insight of the work going into the re-structuring of the forthcoming versions of this standard have been published at mid-term conference of this COST action and elsewhere (Green 2013a, b).

2.3 *Post-fracture performance of laminated glass*

Work in this area was led by Didier Delince and Caroline Butchart. The work focuses on gaining a better understanding of the mechanical performance of fracture laminated glass including the effects of strain rate, type of interlayer, angle of peel and relative humidity. The work involves carefully executed experimental investigations and corresponding analytical work (Delincé & Belis, 2013; Butchart & Overend, 2013).

3 WORK IN COLLABORATION WITH OTHER GROUPS

There were several interactions with other groups. These included:

- Mapping of the façade design and construction process (Voss & Overend, 2012; Voss et al. 2012). This research is not exclusively developed for glass components, but is relevant to a wide range of materials of component used in facades, of which glass is one. This work is useful for identifying possible improvements to the design and construction process.

	Location	Consequence of potential failure				
		Severe	High	Medium	Low	Very Low
Risk analysis	Primary structure (e.g. load bearing columns, beams, floors and walls)	Key elements that determine the stability of the structure	Primary structural elements whose failure would result in localised collapse			
	Secondary structure (e.g. glass fins and top hung bolted glass facades)			Secondary structural elements whose failure would be contained within the secondary structure		
	Infill panel (including glass partitions and balustrades)			Glass members in critical locations where failure is limited to the member in question, but there is a potential for injury	Infill panels in non-critical locations	Infill glass elements in locations where people do not normally enter
Special performance requirements		Design as key element with adequate reserve strength and protect occupants from glass fragments	Provide adequate reserve strength and protect occupants from glass fragments OR Provide alternative load paths and protect occupants from glass fragments		none	none

Figure 1 Simple risk analysis and corresponding special measures

- Research on crack branching and fragmentation of glass (Zaccaria & Overend, 2012). This work is useful for determining the size of the glass fragments upon fracture which is in turn essential for predicting the post-fracture strength and stiffness of laminated glass.
- Fracture mechanics and design methods. This work completed in collaboration with TG05 (Glass Strength) involves practical recommendations for using either the deterministic fracture mechanics approach or the stochastic random flaw population in order to determine the strength (or probability of failure) of a glass component, The design recommendations are summarised in the Education Pack.
- Sub-critical Crack Growth & Crack Healing of Glass. This involves research undertaken jointly since the start of this COST Action between the University of Cambridge, Darmstadt University and Ghent University. The research involved the mechanical performance of as-received, naturally weathered and artificially scratched glass and the effect of coatings on the strength of these glass plates. The work completed to date includes an extensive literature review and testing of over 250 specimens, the findings are currently being written up for publication in a high impact journal.
- Non-destructive evaluation & repair. This involves preliminary carried out collaboratively between the University of Cambridge and Darmstadt University on a mobile flaw-scanning device and a corresponding damage tolerant procedure for improving the reliability and reducing the cost of: (1) locating and assessing the fracture strength and the lifetime of new glass components; and (2) assessing the remaining fracture strength and remaining lifetime of existing glass components in-situ. A research proposal was submitted to a space call in the EU 7th Research Framework. The proposal was well received by the reviewers, but was not ranked highly enough to be funded. Both universities are pursuing alternative means of funding this project.
- Characterisation of Interlayer properties. This was undertaken in conjunction with TG06 – Interlayer Properties and is fundamental to the work on post-fracture performance. This work was published at mid-term conference of this COST action and elsewhere (Savineau et al. 2013).

4 CONTRIBUTION OF WG3 TO OTHER ACTIVITIES WITHIN THIS COST ACTION

WG3 has actively contributed to and supported a range of activities such as short term scientific missions and the training school / workshop events.

4.1 *Short term scientific missions*

- Hybrid glass beams: Mr. Michal Netusil (Technical University of Prague) visiting the Glass and Façade Technology research Group at the University of Cambridge in Jan 2011.
- Glass structures – learning from failure: Mr Daniel Honfi (Lund University) visiting the Glass and Façade Technology research Group at the University of Cambridge in Aug-Sept 2012.
- Non-destructive testing and repair of glass: Dr Mauro Overend (University of Cambridge) visiting the Technical University of Darmstadt in Sept 2012.
- Mechanical characteristics and design norms and directives: Mr Marc Vandebroek (Ghent University) visiting the Glass and Façade Technology research Group at the University of Cambridge in March 2013.
- Adhesives for Hybrid Glass-Steel Facade Elements: Mr Vlad Silvestru (Graz University) visiting the Glass and Façade Technology research Group at the University of Cambridge in June 2013.

4.2 *Education Pack and training school workshops*

The major contributions were made in the Design Guidelines and Fracture Mechanics sections of the education pack. These were originally developed and presented at the 1st training school in Ghent held in April 2012. The sections were developed further and presented at the second training school in Darmstadt in March 2013 and at the Glass Processing Days workshops in Finland in June 2013.

5 CONCLUSIONS

The post-fracture performance is an essential consideration when designing structural glass components. Failure to deal with this adequately would lead to a high risk of glass-related human injuries particularly in extreme events. The mechanisms that provide the post-fracture strength and stiffness are complex and are sensitive to strain rate, environmental conditions, glass fragmentation pattern, boundary conditions etc. A universal analytical model for predicting post-fracture performance has yet to be established, but this working group has made significant contributions to this area of research by bringing together established and young researchers. The working group has also successfully captured the design and construction process involving glass elements in facades and has collated the valuable advice and engineering intuition on robustness and serviceability of practicing engineers. Based on this information the working group has also produced a stand-alone document on the design of glass based and the findings of the working group are being actively used in the development of future national and international standards.

ACKNOWLEDGEMENTS

Several individuals and institutions have contributed to the activities within working group 3. These are too numerous to list here and they can be found in the individual references at the end of this documents, In addition the active members of working group 3 are duly acknowledged. A list of names and contact details is available at <http://www.glassnetwork.org/working-groups/working-group-3>

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