COST Action TU0905, Mid-term Conference on Structural Glass – Belis, Louter & Mocibob (Eds)

Characterization of interlayer properties – TG06 Status Report

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ABSTRACT: The material characterization and material improvement of glass elements by lamination with different interlayer materials are within the focus of COST TU0905/WG2/TG06. The Task Group “TG06 Interlayer properties” comprises 10 members from academia and industry. The main objectives, state-of-work, issues and concerns, next steps, perspectives & development within TG06 are presented in this paper. TG06 members are working on the 4 following goals: 1) to create a shared list of references (scientific, academic works, conference papers); 2) to collect, discuss and develop experimental and numerical methods allowing characterization and modelling of the mechanical behaviour of viscoelastic interlayers for the unfractured (SLS) and fractured (ULS) states of laminated glass; 3) to contribute to European Standards (CEN TC129/WG08 - Mechanical Strength) and Eurocodes (CEN TC250/WG3-Structural Glass) works; and 4) to contribute to the Educational Pack and COST Training School.

1 CONTEXT

1.1 *About COST*

Founded in 1971, COST is one of the longest-running European instruments supporting cooperation among scientists and researchers across Europe. COST is an intergovernmental framework for European Cooperation in Science and Technology (COST), allowing the coordination of nationally-funded research on a European level.

More information can be obtained through the website www.cost.eu, section “About COST” and links to Related Documents “About COST 2012-2013 (PDF, 2MB)” and “COST overview September 2012 (PDF, 3MB)”.

1.2 *About COST Action TU 0905*

Structural glass is gaining importance in building practice at a fast pace. However, in spite of Europe’s pole position in research and new developments in this field, structural glass is not yet incorporated in engineering and architectural engineering academic education. Knowledge transfer is required on different levels, educational and professional. One of the key targets of COST Action TU0905 “Structural Glass – Novel design methods and next generation products” on an educational level, is to develop an Education Pack to help educate students and researchers in this field. These aims are channelled through activities within four working groups:

WG1 Predicting complex loads on glass structures
WG2 Material characterization and material improvement
WG3 Post-fracture performance
WG4 Novel glass assemblies

More information can be obtained through the website: www.glassnetwork.com

1.3 *About WG2: Material Characterization and Material Improvement*

The research network focuses on the development of improved design methods and novel high performance structural glass products that will lead to a safer and more energy efficient use of glass in buildings. Within WG 2, different sub-themes are addressed and in February 2011 Task Groups were formed accordingly. One of the three task groups attached to WG2 is the TG06: Interlayer Properties.

1.4 *About TG06: Interlayer Properties*

The focus of the TG06 is the material characterization and material improvement of glass by lamination with different interlayer materials. The goals within the Task Group are to discuss and develop experimental and numerical methods to classify the mechanical behaviour of visco-elastic interlayer materials for the unfractured and fractured glass states.

Ten members have joined since initiation of the Action and participate regularly at meetings. They represent four European Universities - Ghent (Belgium), Darmstadt (Germany), Vilnius (Lithuania) and Cambridge (United Kingdom); - and three PVB/EVA interlayer manufacturers (Eastman Saflex®; Kuraray Trosifol®, Sekisui S-LEC®). Interactions with WG1 (Predicting complex loads on glass structures) and WG3 (Post fracture performance) have started and would be reinforced in the future. Additional contacts were also established with other interlayer manufacturers and with others universities, but none of them expressed so far their intention to join TG06.

1.5 *TG06 Identified fields of interest*

At the initial task group meeting in Madrid (February 2011), attendees, all active in academic research at a relative early stage, stated that a first major problem to the advancement of this field is the lack of comprehensive overview. In particular there is no review of issues relating to the determination of material properties and material models of interlayers, especially for the use of laminated glass products beyond traditional framed glazing. This was particularly relevant since a large amount of research in this field was either on-going or had recently been completed under the initiative of a variety of stakeholders, from both research institutions and industry. In particular, three fields of interest were identified as being significant to determining the influence of interlayers on the structural performances of laminated glass elements:

- the influence of the shear transfer ability and viscoelastic properties of interlayers on the stiffness of laminated glass elements;
- the influence of interlayers on the dynamic behaviour of laminated glass elements; dynamic behaviour is understood here as opposite to quasi-static one, and therefore encompasses cyclic loading (wind, vibrations,…) and short-term high strain rate loading (impact, blast,…);
- the contribution of the interlayer to post-fracture behaviour and corresponding residual load-bearing performances of fractured laminated glass elements.

Besides these three fields of interest, a major point of attention has been identified which concerns the identification and management of uncertainties. It is important to be able to make clear and correct distinction between the different types of uncertainties present, in particular experimental, numerical and material uncertainties.

The scope of structural glass applications is perceived, deservedly, as a limited market in comparison to that of ‘traditional’ glazing products. However, the conceptual barrier between standard and non-standard, and structural and non-structural use of laminated glass as a building product still remains ambiguous. Various opinions on the location of this barrier still exist amongst involved stakeholders and experts, some of them driven by conceptual thoughts, others by more practical considerations.

In a similar way, the three fields of interest identified here are not fully independent of each other (Fig. 1). Questions arising about comprehension and modelling of involved mechanisms in the structural response and resistance of laminated glass components are largely similar in nature, regardless of the specific requirements and aspects ruling the final design and the developed solution.

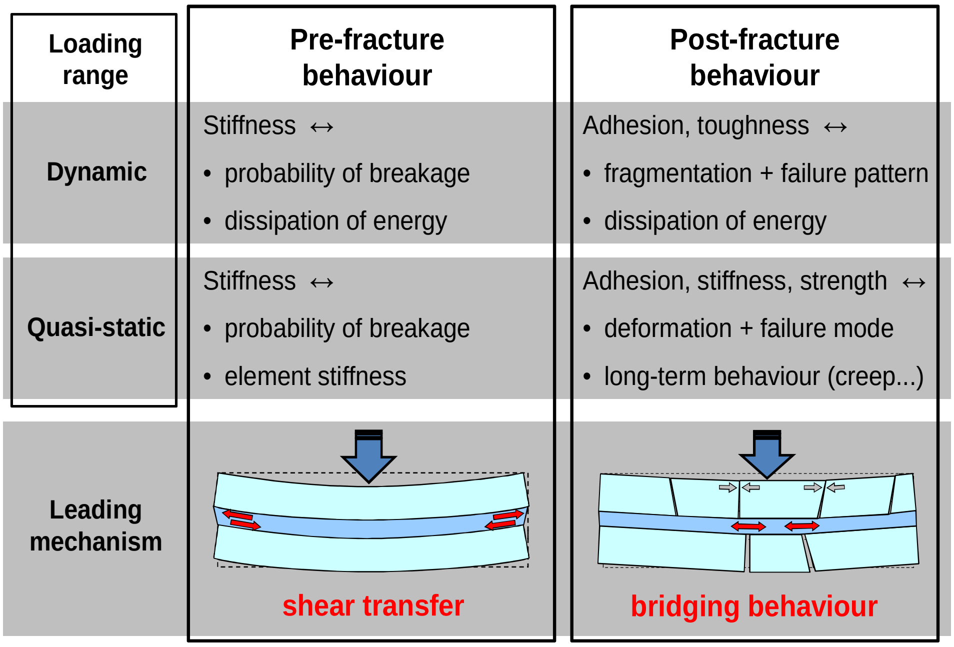

Figure 1. Contribution of interlayer to structural properties of laminated glass elements: schematic articulations between identified fields of interest.

The *shear-transfer ability* of an interlayer, namely its ability to transfer stress between glass plies of a laminated element subjected to bending, has been studied previously. Investigation was initially motivated by the possibility to reduce the design thickness of laminated glass units, when considering deformation and probability of breakage under wind action. A move towards the use of sloped glazing, and an increase in the use of glazing as a (quasi-) permanent load bearing element, extended the field of interest to the contribution of the interlayer to the bending stiffness under static load. This highlighted the possible time-delayed deformation due to creep behaviour of the polymer. It has been also demonstrated more than once that the influence of shear-transfer ability varies with geometry, connection type and associated boundary conditions, and loading situations considered. The issue of modelling and taking into account the shear-transfer ability of the interlayer in calculation tools is in an advanced stage of development. From a structural perspective, in most cases the probability of glass breakage is still the governing design parameter, followed by deflection limits. Consideration of the shear-transfer ability in design leads to an improvement in behaviour in both cases.

Shear-transfer behaviour is clearly also an important factor when modelling the *dynamic behaviour* of laminated glass elements. Unlike wind loading, when other dynamic ranges are considered, such as resistance to impact and explosion, the risk of glass breakage is often no longer the governing design criterion: instead, criteria concerning behaviour and performances after initiation of glass cracking often dominate. It is therefore necessary to gain insight into post-fracture behaviour, as a necessary complement to pre-fracture behaviour, when considering more demanding dynamic performances. Many different experimental configurations have been developed for assessing performances under a variety of impact events, however the development of appropriate and reliable design tools for building applications is still a challenge. Inclusion of glass breakage and crack propagation in modelling the dynamic response of an element requires the development of advanced numerical models (see §2.2.2), which however are not easy to use in practice, for different reasons. An important one is related to different design philosophies balancing the relative importance of probability of glass breakage and of post-fracture performances, each design philosophy leading to different design criteria.

The conceptual debates here about are complicated by the intrinsically complex contribution of the interlayer to the overall performances. Accordingly striking the balance between interlayer product on one side and laminated glass configuration on the other side is difficult when trying to satisfy the different performance requirements defined in the dynamic range.

In summary, the contribution of the interlayer to the overall dynamic performances is related to its capacity to dissipate energy in shear-transfer mode on one side, and to limit crack propagation between glass plies on the other side. Additionally, it is also expected that spalling of glass fragments during an impact event is kept to a minimum. Dynamic behaviour of laminated glass elements is dependent on both global parameters (geometry, layers composition, fixing conditions,…) as well as local ones (interlayer bulk material properties, adhesion to glass and eventual other lamination materials).

The interest in processes ruling the *post-fracture response* of laminated glass elements is not limited to the dynamic range anymore: with the development of structural applications, interest is growing in modelling the residual resistance of fractured elements in static loading ranges. The mechanisms involved in the response of cracked elements in dynamic and static loading ranges are not fundamentally different, but the interlayer properties can vary significantly with considered loading rate and temperature ranges. This implies that complementary experimental investigations are necessary to extend possible fields of use of existing laminated glass products.

The field of interest of post-fracture response is also concerned with the adaptation and development of safety concepts for structural use of laminated glass products. Accordingly it is also concerned with the identification of preferred failure modes which should govern the design. Interest in post-fracture performances lead amongst other things to consider, from a structural safety perspective, that the breakage of glass components of a laminated glass unit is not anymore the ultimate failure event. Instead it is thought of as a preferred localization of first damage, leading to intermediate design situations with the interlayer taking over a more important role, that of the transfer of efforts between glass fragments of the fractured element. As such redundant mechanisms are considered, increasing the robustness of the laminated glass element. A practical consequence is that, besides the lower limit usually considered in calculations, also an *upper limit of glass strength* should be determined for glass components used in structural laminated products.

For all three identified fields of interest, questions exist regarding the durability of the products and the life-time stability of the involved material properties, due to the presence of ageing phenomena.

1.6 *TG06 Mission Statement*

To stay focused on the aims and objectives of TG06, a mission statement was agreed upon: “Eliminate or reduce the risk of injuries or casualties due to glass-related failure in case of accidental (earthquake, hurricane, wind load, snow load, self-weight, localized load, fire, chemical/gas explosion) or malevolent (terrorist bomb blast, vandalism, burglar, fire arm) breakage of the laminated glass. This will directly result in safer products and risk analysis-based design methods taking into account environmental factors and ageing properties of the interlayers whilst enabling selection of the right interlayer for the right laminated glass at the right place in building applications.”

2 TG06 GOALS AND STATE OF WORK

Considering each of these, four main goals were identified. The TG06 goals and progress of each of these are presented hereafter :

1. to create a shared list of technical references (scientific, academic works and conference papers);
2. to collect, discuss and develop experimental and numerical methods allowing characterization and modelling of the mechanical behaviour of viscoelastic interlayers for the unfractured (SLS) and fractured (ULS) states of laminated glass;
3. to contribute to European standardization works (CEN TC129 /WG08 - Glass Strength) and Eurocodes (CEN TC250/WG3 - Structural Glass);
4. to contribute to the COST TU0905 Educational Pack and Training School.

2.1 *Goal #1: Collection of references in Mendeley*

The objective of this first goal is to create a shared list of technical references (scientific, academic works and conference papers) in a common interface.

2.1.1 *Status*

During the initial meeting of TG06 (February 2011), it was established that one of the recurring barriers to the advancement of this field was a lack of comprehensive review of the subject. Existing information on the properties of interlayers is scattered, and approaches the problem from a wide range of angles. In response to this, a centralized database of work relating to the properties of interlayer materials was proposed. The database was planned with three ultimate aims : publishing a review of the field, publishing a ‘bibliography’ of relevant works, and summarizing existing technical data on the properties of interlayers.

Mendeley (www.mendeley.org) was selected as a working tool. The proposed database is a collection of PDF documents relating to the properties of interlayers. These documents come from a wide range of sources including, academic research, commercial product data sheets, and existing codes and standards. To aid processing and collaboration, it was required that the database system had the ability to annotate PDF files directly, as well as a suitable system for sorting and labelling. Mendeley is a web-based referencing software with a desktop application for offline working. It includes a facility for academic collaboration ‘groups’, either public - in which case the facility to upload PDF files is removed (but references can include a DOI or URL-shortcut to extern portals) - or private - with the ability to share and annotate PDF-files. A private group has been established within Mendeley in order to start the completion of the proposed database.

Hitherto, the database has been populated with selection of documents and articles from identified ‘reference collections’ including Glass Performance Days (GPD), ISAAG, Challenging Glass, and Engineered Transparency conference proceedings, in addition to a selection of references from the IABSE SED 10 book ‘Structural Glass’ (IABSE, 2008). Furthermore, a preliminary directory system has been created for sorting the collected documents.

2.1.2 *Issues and Concerns*

Private groups are limited in size in terms of both document storage space and available member spaces. The basic free-of-charge features comprise the possibility to manage a maximum of five private groups, each of 10 members and 1GB of web storage (500MB personal, 500MB shared). The TG06 group already has 10 members. Should TG06 continue to expand, the current solution will no longer be viable free of charge. Limitations attached to the use of public groups may appear to be less constraining; however some useful functionalities are then not available.

The method of document categorization has not been finalized, and with many documents fitting into several categories, it is anticipated that this will be a large job.

Copyrights remain a major concern. Indeed, papers may come from Non-partners (issue) conference proceedings such as GPD Conference (www.glassfiles.com), ISAAG (www.isaag.com), or Partner conference papers (no issue) such as Challenging Glass (www.challengingglass.com), Engineered Transparency (www.engineered-transparency.eu), A.T.I.V. conferences (www.ativ-online.it) and ICSA 2013 (www.icsa2013.com).

The recently introduced “Glass Academy” project (presented at Glasstec 2012 by the GPD organizers) may be seen as a concern or an opportunity for the Mendeley database and/or the Educational Package.

2.1.3 *Next Steps*

To advance this project the next stages of work include :

1) Continuous updating of the database with new reference collections;
2) The addition of relevant product data sheets from interlayer manufacturers;
3) The addition of relevant standards;
4) Provision of a suitable organization system within the Mendeley database.

It is the opinion of TG06 that this database is a useful tool, and that it is worthwhile to continue with its development. It is believed to be of most use to early stage researchers, consequently they would receive priority access. At the current stage the database is incomplete and its organization requires improvements; as such, for the time being it should remain a ‘private group’.

2.2 *Goal #2: Interlayer Properties and Characterization Methods*

To collect, discuss and develop experimental and numerical modelling methods to identify typical interlayer properties and associated mechanical/rheological models, and to classify the mechanical behaviour of viscoelastic interlayers for the unfractured, or Serviceability Limit State (SLS), and fractured, or Ultimate Limit State (ULS) of laminated glass.

2.2.1 *Experimental Test Methods and Typical Properties*

2.2.1.1 Status

Technical data sheets are available from interlayer and/or laminated glass manufacturer’s websites. These data sheets encompass the visual, physical, mechanical, chemical, thermal, solar and electrical properties along with the test methods used to determine each property. The test methods generally refer to national, European (CEN) or international (ISO) standards. Some test methods such as the ‘Pummel adhesion test’ or the ‘Tenacity test’ have been developed by interlayer producers or by laminated glass manufacturers and are referred to as “industry standards”.

2.2.1.2 Issues and Concerns

When comparing typical values of interlayer properties, it is important to keep in mind the test methods used and the different test method procedures/conditions. Typical values are strongly dependent on the test method and testing conditions. The tensile properties of standard PVB illustrate this concern: variation of up to 20% of the nominal tensile strength can be seen and variation of more than 40% can be seen for elongation (see table 1). Such differences can be explained by the fact that the standards prescribe or allow the use of different loading rates and different specimen geometries. Other studies have shown that the total elongation decreases with increasing loading rate; this is a normal phenomenon for viscoelastic polymers. Another potential source of confusion is that these typical values generally correspond to nominal values of stress and strain. Deviations with values of true (local) stress and strain can be large since the corresponding deformations are situated within the large strain deformation field out of the small strain field usually considered in structural engineering.

Tensile strength and elongation at failure of different interlayers films are compared according to JIS K6771 (see table 2). These interlayer characteristics allow comparisons of the product stiffness.

Interlayer manufacturers are beginning to disclose viscoelastic data for their product range. For example, the shear modulus (G) and the Young’s modulus (E) of the interlayer for a given load duration and temperature is provided for use in calculation of the structural capacity of glass laminated with this product. In this case, published values may also be influenced by test method and comparing values without taking this into account could be misleading.

2.2.1.3 Next steps

Compare current test methods and make recommendations on how to resolve experimental uncertainties.

Collect and add to Mendeley the most recent datasheets published by the interlayer manufacturers and report accordingly within the group.

Table 1. Variation of typical values of mechanical properties for a "standard" PVB according to different uniaxial test methods.

Mechanical property	Unit	Test method	Testing conditions	Typical value
Tensile strength (at break)	MPa (kg/cm²)	JIS K6771	23°C, 20 cm/min 50% RH	25 (250)
	MPa (kg/cm²)	ASTM D412-83	23°C, 51 cm/min	22.6 (226)
	MPa (kg/cm²)	DIN 53455-4-5 / ISO 527-3	23°C, 20 cm/min	20.8 (208)
Tensile elongation (at break)	%	JIS K6771	23°C, 20 cm/min 50% RH	250
	%	ASTM D412-83	23°C, 51 cm/min	190
	%	DIN 53455-4-5 / ISO 527-3	23°C, 20 cm/min	313

Table 2. Typical values of mechanical properties for different interlayers.

Property	Unit	Test method	PVB standard	PVB acoustical	PVB structural	Ionoplast	TPU	EVA
Tensile strength	kg/cm²	JIS K6771	250	120	330	≥350	≥375	≥210
Tensile elongation	%	JIS K6771	200-250	300-360	190	≥500	≥400	≥415

2.2.2 *Numerical calculation methods*

2.2.2.1 Status

Several software packages suitable for the design or finite element modelling (FEM) of the behaviour of laminated glass elements have been identified from different publications: ABAQUS, ANSYS – FEM-packages mainly used in research – and COSMOS and SJ Mepla – design oriented FEM-software.

The FEM software packages are used to predict deformation and stresses arising within laminated glass systems under different loading types (wind, snow, self-weight and permanent load) and/or different boundary conditions (temperature, load duration, installations/fixings). Under different conditions the predicted values of deformation have been compared to experimental data. The degree of correlation depends on the rheological model used. These FE programs also allow calculation of the interlayer shear transfer coefficient ($0 < \omega < 1$) which is one means for expressing the degree of shear connection between glass sheets, compared to full shear transfer ($\omega = 1$) and zero shear transfer ($\omega = 0$). It was demonstrated that this is dependent on temperature, load duration, viscoelastic properties and relative thickness of the interlayer.

2.2.2.2 Issues and concerns

Interlayer shear-transfer behaviour clearly has a critical influence on modelling *dynamic behaviour* of laminated glass elements. Modelling the dynamic response involving glass breakage and crack propagation requires development of advanced numerical models, which are often difficult to implement for a variety of reasons. One important reason being the existence of different design philosophies which lead to different design criteria, namely by balancing the relative importance of probability of glass breakage and of post-fracture performances.

2.2.2.3 Next steps

There is a clear need for close collaboration between WG2/TG06, WG3/TG07 (Post fracture performances / numerical know how and validation of numerical work) and WG3/TG08 (Post-fracture performances / Structural design philosophy) to improve the know-how in using numerical methods and managing the associated uncertainties.

2.3 *Goal #3: European Standards and Eurocodes Developments.*

To contribute, and participate in development of European Standards (CEN/TC 129/WG08-Glass Strength) and Eurocodes (CEN TC 250/WG3-Structural Glass).

2.3.1 *Status*

The TG06 group members present at Prague meeting (October 2012) contributed to the half-day brainstorming exercise dedicated to CEN/TC250/WG3 “Structural Glass” and completed the questionnaire proposed by its chairman, Professor Feldmann. One TG06 member was proposed as the “Official TG06 COST Liaison Officer” with CEN/TC129/WG8 (Glass Strength) and CEN/TC250/WG3 (Eurocodes). However he has not yet been officially appointed.

A new draft prEN 13474 “Glass in building - Determination of the load resistance of glass panes by calculation and testing” (CEN/TC129/WG8/N312, 2012) is now circulated through the national bodies for comments. The former three parts of the prEN13474 have been reworked and fused into one single document.

2.3.2 *Issues and Concerns*

TG06 “Official Liaison Agent” should be approved by both CEN/TC129/WG8 and CEN/TC250/WG3 in order to be able to attend the meetings and participate to their ongoing works.

2.3.3 *Next Steps*

Continue to provide (upon request) expertise, assistance and comments on current working documents submitted by CEN/TC129/WG8 (prEN 13474) and CEN/TC250/WG3 (SaT-report, February 2013).

Learn from equivalent non-European Standards (e.g. ASTM E 1300, AS 1288-2006…) and Building Codes.

2.4 *Goal # 4: Knowledge Transfer (Educational Pack) and Training School*

To contribute to the Educational Pack and COST Training School “Structural Glass”.

2.4.1 *Status*

TG06 has been contributing to the Educational Pack and COST Training School “Structural Glass” by taking leadership of the Laminated Glass Section part A1.2 (Interlayers) & A.1.3 (Glass Product: Laminated Glass). This topic was presented during the two first editions of the Training School at Ghent University (Belgium) in April 2012, and at TU Darmstadt in March 2013 by the TG06 Team leader.

2.4.2 *Concerns and issues*

The duration of each presentation prepared for the training school is limited to 45 min. This is an appropriate duration providing the speaker does not have to combine two presentations in one.

2.4.3 *Next steps*

The TG06 will continue to contribute towards the developments of the Educational Package.

3 PERSPECTIVE & DEVELOPMENT

In summary, three main fields of interest were identified in regard to the contribution of interlayer to the structural performances of laminated glass elements. For each of these, ageing is likely to play an important role. The magnitude of ageing effects and the importance of taking these into account may vary according to product and application considered, and these are probably about the most constraining in terms of experimental assessment. The presence of ageing phenomena raises questions about the representativeness of results from tests performed on reference configurations, in order to clarify safe design. Aspects related to ageing are certainly important when dealing with the general management and estimation of uncertainties, and in particular for a fairly correct identification of the different types of uncertainties, and for the conception of adapted test facilities and experimental protocols. Identification, distinction and estimation of all uncertainties present deserve attention, but in the same time it seems useful to state that it does not always involve a necessity to reduce any single experimental, production or design uncertainty. Finally, reference methods used for other materials might appear as less relevant for laminated glass products and applications, at it seems that dealing with these aspects of ageing and other types of uncertainties are a necessary prerequisite for developing design methods and tools leading to safe design.

4 CONCLUSION

The COST TU0905/WG2/TG06 has put in place a team of dedicated experts both from academia and industry. All members have a strong background, experience and know how in the use of laminated glass in building applications. In 2012, they have been very active and making tremendous progress with regards of material characterization (experimental test methods and numerical methods) and have been addressing the current uncertainties concerning these methods. They have created a shared list of references in a common interface (Mendeley). In spite of some issues such as the limitation in free storage space and members' spaces, this data bank is a "gold mine" for new researchers and enables knowledge transfer on both educational and professional levels. This has been demonstrated through the collection of first Education Pack and the launch of the first Training School at the Ghent University in April 2012. With the appointment of an "official COST Liaison Officer" with the concerned CEN working groups, TG06 expects to take his share and contribute to the current developments of European Standards related to design and assessment, by means of calculations or tests of "Structural Glass" works. As TG06 Team Leader, I am convinced we will achieve our goals on time in spite of some remaining critical issues. In 2013 we will need, in particular, the support of WG3/TG07 & TG08 to validate our works and findings.

5 REFERENCES

IABSE (International Association for Bridge and Structural Engineering, eds.). 2008. *Structural Engineering Documents SED 10: Structural use of glass*. Zürich: IABSE / ETH Zürich.