Structural behaviour of laminated glass elements – a step towards standardization


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Abstract

Various research projects were undertaken last years to study the mechanical properties and behaviour of laminated glass elements for use in structural applications, with as principal aim the development of design rules adapted to this particular kind of material. However, up till now design rules of commonly used standards or other reference documents do not sufficiently take into account the specific properties of the interlayer material for the calculation of the stiffness of laminated glass.

The Belgian Building Research Institute (BBRI) carried out a research project between 2004 and 2006 in collaboration with the Laboratory for Research on Structural Models of Ghent University, with as main objective the development of standardization to support the use of laminated glass products and associated design rules for specific, essentially “structural”, applications.

This paper presents the main outcomes of this research project, focusing on the following aspects: characterization of mechanical properties of different interlayer materials, effect of weathering on the design values of those properties (durability of the mechanical properties), bending behaviour of laminated glass plates, buckling of laminated glass beams, and discussion on the influence of tolerances of laminated glass layers thickness.

Introduction

One main concern when studying the mechanical behaviour of laminated glass is the modelling of the shear-bond between the glass plies provided by the polymer interlayer, and the evaluation of the higher flexural stiffness it provides to the laminated glass element. It has been shown by many authors that common interlayer polymer materials have a visco-elastic behaviour, pointing out its dependence on temperature T and duration t of the applied load. The stiffness provided by the interlayer is often expressed by its shear modulus G, so:

$$ G = G(t) $$

Most experimental studies were done for the most common interlayer material products, known as “PVB” (polyvinyl butyral). Figure 1 compares the shear modulus G at room temperature in function of the load duration t, given by 2 different models for PVB interlayers.

Bennison’s model [9, 10] was established on the basis of relaxation shear tests on cylindrical samples, obtained by hollow drilling in laminated glass units. This model is assumed to be valid for any laminated glass with PVB interlayer. Other authors showed that this model gives very safe results to calculate bending and flexural resistance of laminated glass.

Sobek’s model [9, 10] was established on the basis of relaxation shear tests on cylindrical samples, and serve to calibrate a rheologic model of traction tests on interlayer samples, and to establish a rheologic model for thermoplastics. This model gives a higher value of G and is valid for any interlayer material. SentryGlass® Plus of DuPont de Nemours (referred hereafter as SGP) is one of those; but other products (e.g. some cast resins,…) are also pointing up their attractive properties.

A major problem with such advanced material behaviour models for practical use is the lack of validation and control methods, and as a consequence a lack of confidence from controlling authorities. European harmonised product standard (hEN) for laminating glass products, EN 14449 [7], published by CEN in 2005 and aimed to serve as basis for CE-marking of laminated glass products, refers to the previous published standards series ISO 12543. Main contributions of these standards regarding to mechanical behaviour are general rules for tolerances on laminated glass layers thickness, and testing methods to assess the product quality, i.e. the laminating process. Various safety performances can be assessed by standardized testing methods, but none of these allow the use of advanced calculation models for structural design.

Another matter is to define corresponding design values of load duration t and temperature T, in function of the specific application and

![Figure 1](image)

**Figure 1**

Comparison of material models for PVB interlayer at room temperature (20°C)
associated performance requirements. Current design codes usually do not give guidelines to define these values independently of the used material. General design rules of European codes for structural design, the Eurocodes, however, might serve as a basis to define such design values.

Finally, the durability of the mechanical properties against environmental influences is also of importance to ensure the suitability of such advanced models for safe practical design purposes.

To underline the interest to have a better knowledge of reliability (statistical) and representativeness (application field) of shear-bond models for laminated glass, it is probably useful to remind that the flexural resistance of laminated glass is highly dependent on its out-of-plane deformation.

These aspects were studied in the context of a research project carried out by the Belgian Building Research Institute (BBRI) in collaboration with the Laboratory for Research on Structural Models of Ghent University. Beside the study of the characterization methods of interlayer properties, two types of applications were investigated experimentally: bending behaviour of laminated glass plates and lateral torsional buckling behaviour of laminated glass beams.

The present paper gives an overview of the research project, and some particular results are presented.

Objectives

The main objectives of the research project were the following:

1. Investigation and discussion of characterization methods for interlayer material properties, on the basis of a performance-based approach (independent of the interlayer material);

2. Investigation of the durability of the mechanical properties of the interlayer due to environmental conditions, in other words the effect of weathering on design values;

3. Experimental study of the influence of the interlayer material (stiffness) and glass type (with or without thermal tempering) on the lateral torsional buckling of laminated glass elements, and comparison to existing or developed models.

Overview of the research project

The first aspect - characterization methods of material properties was investigated by comparing different shear test methods on small cylindrical samples of laminated glass, and 4-point-bending tests on 1100x360 mm laminated glass plates. Shear tests were compressive shear tests (CST), usually used as quality control tests for measuring adhesion properties, and traction shear tests (TST), as used by Sobek for developing his model. Figure 2 gives an overview of the used testing
devices. The program was limited to tests at room temperature, since the prior objective was to compare reliability and representativeness aspects of shear test methods, and not to do a full characterization of some interlayer materials.

The second aspect — durability of the material properties — was experimentally investigated by mechanical tests on samples subjected to prior artificial weathering, compared to reference samples without prior weathering. Three types of mechanical tests were used: shear tests (CST and TST), and 4-point-bending tests. Two types of artificial weathering procedures were used according to standard EN ISO 12543-4 [6]:

- "UV exposure": samples were exposed to a standardised ultraviolet radiation source during 1000h, while the samples temperature was kept below 50°C.
- "Humidity exposure": samples were exposed to an environment with 100% relative humidity, at a temperature of 50°C, during 15 days (2 weeks).

The third aspect — buckling behaviour of laminated glass beams — was investigated by tests on 3 m long beams, of various height and thickness. The influence of the initial shape imperfections (planeness) of the beam on its buckling resistance \( F_b \) was investigated. Figure 3 shows how a laminated glass beam deforms in lateral buckling, with sliding between the 2 glass plies.

All experiments for studying those 3 aspects were done on laminated glass with PVB as well as SGP interlayers, referred to as "PVB-samples" and "SGP-samples" respectively.

**Results**

Only limited results are presented here. The interested reader will find more details in [1, 3].

**Methods of characterisation of the interlayer material properties**

Shear tests were done on series of 9 cylindrical samples, drilled in 3 similar 300x300 mm laminated glass plates; most of the samples had a diameter of 30 mm and a thickness of 1.52 mm. Details about testing procedures are given in [1]. Some series were not complete due to loss of samples during the drilling process, by breakage of the glass or delamination between the interlayer and one glass ply. The drilling appeared to be more difficult for SGP-samples than for PVB-samples: the loss of samples was about 40%, against 10% for PVB-samples.

Typical results of shear tests are shown in Figure 4 and Figure 5. On average, TST results show a slightly lower dispersion than CST ones (calculated dispersion on the shear stress \( \tau \) for a shear deformation \( \gamma = 0.5 \)).
Dispersion is higher for SGP-samples than for PVB-samples; however, dispersion at adhesion break value is lower.

Short term 4-point-bending tests were also conducted at room temperature to analyse the visco-elastic reaction of laminated glass units, on similar PVB and SGP-samples (“1010.4”: two 10 mm thick glass plies laminated with a 1.52 mm thick interlayer). Figure 6 shows typical results of relaxation bending tests, for a constant deflection w. An analytical sandwich model [8] can then be used to calculate the corresponding instantaneous value of the interlayer shear modulus G. Figure 7 and Figure 8 show calculated values of G corresponding to the measured load diagram of Figure 6.

This shows a much higher variability of the calculated values of shear modulus G for SGP-samples than for PVB-samples, while the dispersions on the value of F are similar. Figure 9 helps to understand the origin of this difference, showing the relation between deflection w and shear modulus G at a given value of the load F using the sandwich model. For the considered test conditions, PVB-samples show an intermediate behaviour between the two usually considered limits, monolithic (laminated glass behaves as a glass of equal thickness) and layered behaviour (no shear transfer between the 2 glass plies); while SGP-samples have a behaviour closer to the monolithic limit. Figure 10 shows the influence of the tolerances on glass plies thickness on the curve G – w of Figure 9.

These results draw the attention on the important influence of some uncertainties on calculated values with a sandwich model, which could be wrongly attributed to variations of interlayer material properties. In particular the influence of the glass plies thickness was highlighted.

However, after lamination an accurate measurement of the thickness of each laminated glass layer is difficult. For larger specimens as used for bending tests, the interlayer material was removed from the border, after melting it with a welding torch, allowing to measure the individual glass plies thicknesses.

Effect of weathering on durability of interlayer material properties

As explained above, the effect of artificial weathering on shear-bond properties of the interlayer was investigated using different types of mechanical tests. These parallel experiments aimed to compare local effects (shear tests) to observed effects on global behaviour (bending tests). Laminated glass plates of 300x300 mm were subjected to artificial weathering previous to drilling the cylindrical samples. Laminated glass plates of 1100x360 mm for bending tests...
were subjected to similar weathering exposures. For both types of artificial weathering (UV and humidity exposures), evaluation of samples was made not less than 24h after the end of the weathering process, according to the ISO standard guidelines: a visual evaluation of signs of delamination was done in all cases, and a measurement of the light transmittance before and after exposure to UV radiation (this evaluation was done only for 300x300 mm samples). No defect according to evaluation criteria of the standard was noticed for the tested samples.

Two aspects of weathering effect can be compared based on the shear tests: adhesion level and strain-stress relation at lower strain rates. Figure 12 and Figure 13 show respective typical results for PVB-samples. The adhesion level appears to be slightly reduced by the 2 types of artificial weathering, while the stiffness appear to be slightly increased (calculated value of G-modulus at $\gamma = 0.5$ is higher).

Figure 14 shows the effect of the artificial weathering on calculated values of G-modulus with sandwich model for relaxation bending tests on PVB-samples. Comparing results from shear tests and bending tests, the effect of the artificial weathering on the stiffness properties appears to have a reversed trend. In addition, the observed failure-behaviour under static loads was qualitatively similar for PVB and SGP-samples in terms of adhesion of broken glass pieces to the interlayer.

The main conclusion to this point is that mechanical tests can be relevant to measure effects of weathering on shear-bond properties, complementary to visual evaluation prescribed in standards, to calibrate design values on the basis of a statistical analysis. For this purpose, it appears necessary to analyse further the representativeness of the chosen test method (definition of application field). Another point of interest is to discuss further the representativeness of the artificial weathering procedures regarding to assumed environmental design conditions.

**Lateral torsional buckling behaviour of laminated glass beams**

The influence of some parameters on the lateral torsional buckling behaviour of glass beams was presented previously [2, 4]. Experimental measurements of the initial shape imperfections of laminated glass beams have revealed a sinusoidal shape (see Figure 15). Design values are then proposed.

The influence of the interlayer stiffness on the lateral torsional buckling behaviour was investigated experimentally at room temperature for various beam heights and compositions. In addition, numerical buckling models have been developed, using a viscoelastic interlayer material law.

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Results from experiments show that the interlayer stiffness has a major influence on buckling behaviour, more specifically on the buckling load \( F_{cr} \) and ultimate resistance \( F_u \). Figure 16 shows results for laminated glass beam with different interlayer materials.

Conclusions

An overview of the objectives and associated experimental programs of the research project was presented. Three types of tests were used to conduct the analysis: different types of shear tests and bending tests on laminated glass plates, with or without prior weathering exposures, and buckling tests of laminated glass beams.

Analysing the different tests results were done with focus on reliability and representativeness of the test methods. The influence of some parameters in the analysis of test results, and more generally on the mechanical behaviour of laminated glass, was highlighted. In particular, the importance of the tolerances on the laminated glass layers thicknesses has been showed.

Further research in mechanical behaviour of laminated glass should distinguish the different types of uncertainties or variations in the analysis of test results and the assumptions for modelling.

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