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# Influence of Temperature on Post-Breakage Behaviour of Laminated Glass Beams : Experimental Approach

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The assessment of the post-breakage performances of laminated glass elements used in construction need to take into account the sensitivity to the temperature of the mechanical behaviour and properties of the product, in particular of the interlayer material. A general problem statement and an overview of different experimental approaches are firstly presented. Then results of specific orientation tests on pre-cracked laminated glass beams with a stiff interlayer of DuPont carried at three different temperatures (23, 45 and 60°C) are presented and commented. A comparison of the mechanical behaviour at the different temperatures is done, aiming to give a comprehensive order of magnitude of the sensitivity to temperature of the post-breakage behaviour observed during the tests.

**Keywords:** Laminated glass, Interlayer, Polymer, Post-breakage behaviour, Temperature, Structural application

## 1. Introduction

The post-breakage behaviour (or post-crack behaviour) is understood here as corresponding to the state in which one or more glass sheets are broken and the broken glass pieces are still bonded to the interlayer.

The various attempts of studying experimentally the post-breakage behaviour of construction parts including laminated glass elements highlights the difficulty to assess their post-breakage performances on basis of some generic experimental set-ups. Regarding the aspects of research or assessment approaches, there are obvious similarities between the study of the post-breakage performances and these of the impact performances. In fact, the evaluation of the impact performances includes most of the time some post-breakage performance of the laminated safety glass element; in other words, breakage (of the glass sheets) is allowed, not failure! However, not only impacts can cause the breakage of glass sheets of a laminated glass element leading to a post-breakage stage…

One could distinguish three approaches in the evaluation of the post-breakage performances of an application in laminated glass :

a) Assessment of the performances of the specific application most often by one full-scale test. This approach is in practice only reasonably affordable when the specific application is built in large series, like a series of cars of the same model, or a repetitive, modular construction. The focus in this kind of tests is the global behaviour and in particular the influence on it of the connection details between components. A typical example of this approach is the assessment by mean of a pendulum test of impact performances of balustrades, canopies, sound barriers [5],... for a specific construction project.
b) Assessment of the performances of a laminated glass product in a specific reference configuration, proved (but often only supposed…) to be representative of a range of similar applications, what can be identified as the application scope. The focus concerns the global behaviour as well, when the connection or support conditions don't have (or are not supposed to have…) a great influence on the global behaviour for the considered application scope. Typical examples are the classification of safety flat glass products based on a piece of three pendulum tests on laminated glass samples mounted in a specific frame, e.g. according to European standard EN 12600, the assessment of impact resistance of windows, doors, façade elements lines, or "kits" according to the terminology used in the assessment context of the Construction Products Directive. Experimental researches like these carried by Kott [6] and Feirabend [3] on plate configurations (load applied transversally to the plan of the glazing) and Louter [6] on beam configurations (load applied in the plan of the glazing) can be associated to this approach as well.
c) Assessment based on the determination of the material and mechanical properties needed to be used within mechanical models that can describe the post-breakage behaviour of laminated glass. The needed focus for this approach is on the comprehension, the distinction and the modelling of the different mechanisms occurring in the laminated glass element in post-breakage stage, as previously introduced [1] : 1) the stretching up to rupture of the interlayer under tensile (or shear) force, 2) the delamination (debonding) between the glass pieces and the interlayer under shear, 3) the cracks propagation in the glass sheets and the splitting up of the glass in the contact zones where the glass pieces scrape against each other. In this more fundamental approach, the necessity appears to make experimental works at different scales.

These three approaches are in fact complementary, as we can associate one or more testing scales to the different approaches. However, when thinking according to the third approach, one would generally like to make more detailed measurements and have a closer control of the testing conditions for similar testing configurations used in case of the other assessment approaches, in order to develop or validate numerical models.

One important aspect about post-breakage behaviour of laminated glass applications is the possibly important sensitivity to the temperature.

We can state that, in a very general way, the post-breakage performances of an application in laminated glass can be worse at a "high" temperature (higher than at an ambient temperature of reference), but also can eventually be worse at a "lower" temperature. The performances in function of the temperature are supposed to be mainly dependent on the specific properties of the interlayer's material, but also of the specific post-breakage performance considered : what kind of solicitation, how applied during an experiment, specific evaluation's criteria (procedure). Eventually, it would be possible for some applications to present a critical (worse) post-breakage performance both at a "low" and at a "high" temperature, associated with different failure patterns or modes : typically, at the "low" temperature the critical failure would be caused by a brittle breakage or tearing of the interlayer at some point; and at the "high" temperature the failure mode would correspond to an interlayer material becoming too soft, in other words with a low viscosity, the failure being then caused by too large deformations, eventually but not necessary also with a tearing of the interlayer.

Considering simple examples, one could be easily convinced that it's not possible to determine absolute critical "low" and/or "high" temperatures of general post-breakage performances only in function of the interlayer material used, nor for a composition of laminated glass product (number, type, and thickness of the glass sheets, interlayer material and thickness, number of layers…).

According to these general statements, it appears necessary to specify a temperature range of use, namely [$T_{E,min}$; $T_{E,max}$], in assessing the performances of a specific application for a particular construction project.

## 2. Orientation tests in climatic chamber on pre-cracked laminated glass beams

### *2.1. Introduction*

The choice of the test configuration was done in order to distinguish the contribution of the two mechanisms (interlayer elongation and delamination) ruling the bridging behaviour at different temperatures, and thus to avoid random cracking patterns in the glass sheets during the tests. For this reason, an initial regular cracking pattern was applied to the glass sheets prior to the tests.

### *2.2. Description of the tests*

The test configuration is a four-point bending test on pre-cracked laminated glass beams loaded about their strong axis (Figure 2). Vertical cracks were made in the two glass sheets, in the middle transversal section of the beam, prior to the test (Figure 1) at ambient temperature (~20 … 25 °C).

Two series of beams with different heights (150 and 360 mm, other characteristic dimensions are shown on Figure 2) were tested within a climatic chamber at three different temperatures (23, 45 and 60°C). At least three tests were done for each height and temperature. The laminated glass samples are composed of two 8 mm thick float glass sheets bonded round a 1,52 mm thick "ionoplast interlayer" of DuPont, with the commercial denomination SentryGlas®, or SG (this is the second generation of the previously released SentryGlas® Plus, or SGP). In a previous contribution [1], the mechanical properties and behaviour of SGP have been compared to these of PVB (polyvinyl butyral), the currently most often used interlayer material in laminated safety glass. We assume that the eventual differences in the mechanical behaviour of the polymer material between SGP and SG are not significative for the kind of research reported here. Some indicative values of mechanical properties of both materials are reminded in Table 1.

Table 1: Mechanical properties of interlayer polymer: indicative values [1].

| Property | unit | PVB | SGP |
|---|---|---|---|
| Volumetric weight (density) | kg/m³ | 1070 | 950 |
| Elastic modulus | N/mm² | 18 | 300 |
| Tensile strength | N/mm² | > 20 | 34,5 |
| Deformation at breakage | % | > 250 | 400 |
| Glass transition temperature $T_g$ | °C | ~10-15°C | ~55-60°C |

Lateral buckling of the beam is avoided by mean of 8 lateral supports covered with a low-friction plastic sheet, placed between the support and the loading rolls on each side of the beam.

The load is applied by mean of a small hydraulic jack, operated by a hand pump. As a consequence, the control of the loading rate was too rough to make a relevant analysis of the time-dependency of the behaviour. During the test, the applied force *Q* and the vertical deflection of the upper point of the middle section *w* were measured.

The deformations were also registered as pictures taken by a digital camera placed outside the climatic chamber.

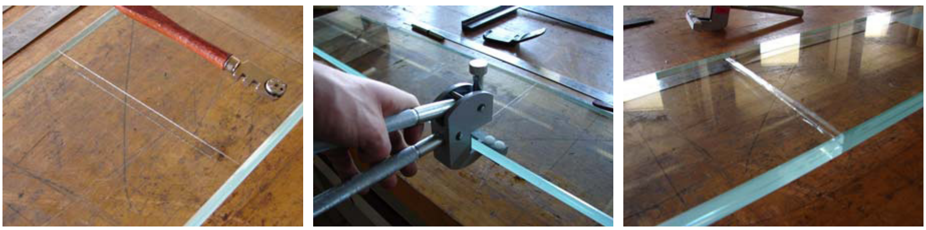


Figure 1: Making initial cracks : scratching the surface / cracking a glass plate / resulting initial cracks .

## *2.3. Test results*

The general deformation pattern of the pre-cracked beams correspond to the expected one, namely that the two parts of the beams behave almost as rigid bodies, with the interlayer bridging the two parts of the beam in the lower zone in tension. At the upper flange, compression efforts appear between the glass pieces round the point of rotation of the opening. These compression efforts are causing some crack propagation in the glass sheets, and under larger load even locally crushing of glass in small pieces round the small zone of contact.

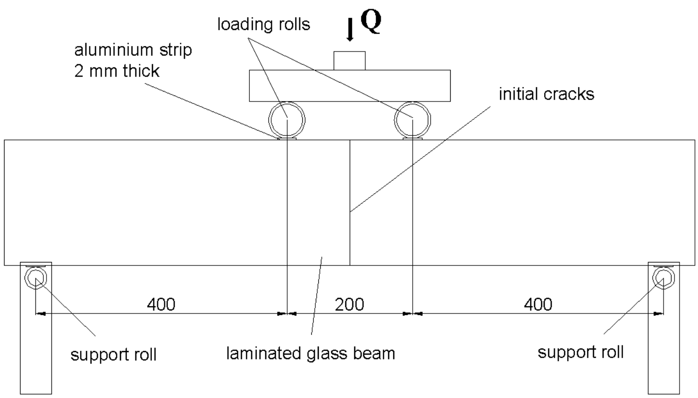



Figure 2: Testing configuration.

Figure 3 compares the average values of the maximum reached load regarding corresponding deflection for each series. The value of the deflection shouldn't be considered as fully representative, since the dispersion of the values on a series was sometimes quite large. Nevertheless, this is already giving an easy to understand order of magnitude of the sensitivity to temperature variation of the post-breakage behaviour of the laminated glass. For instance, for the considered configuration, the maximal value of the carried load is divided by about three between the tests at 23 and 60°C.

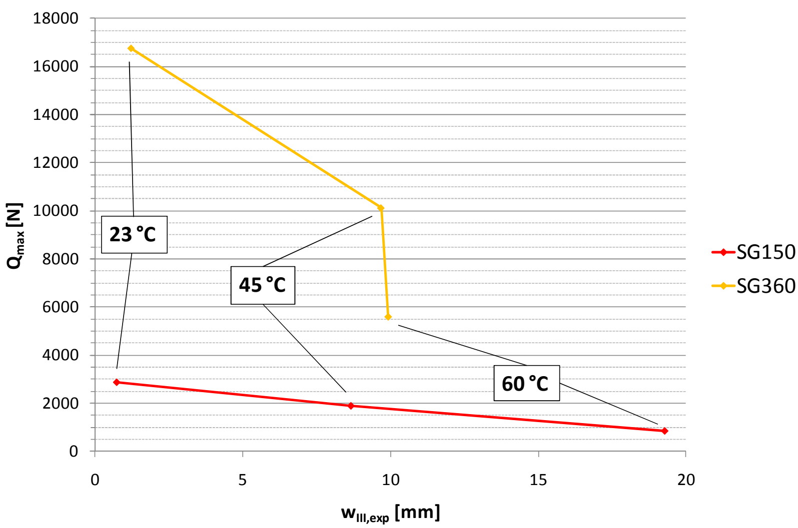



Figure 3: Maximal reached load and corresponding deflection at different temperatures (based on average values by series)

The pictures allow refining the analysis of the deformation patterns. As a trend through all the series, we notice that the bridging behaviour allows larger deformations without apparent local tearing of the interlayer about 45°C; at 23 and 60°C, the deformation and tearing patterns are looking similar, with starting of tearing of the interlayer at smaller value of opening angle, and also with similar delamination length of the interlayer (Figure 4). However, it seems that the maximal value of resistance is corresponding to different deformation levels : the deformation level at 23°C shown on Figure 4 occurred after the moment of the maximum reached load, while the one at 60°C occurred before. The delamination lengths in the test series at 23 and 60 °C are in the order of magnitude or smaller than the thickness of the interlayer; in the series at 45°C, larger delamination lengths are generally occurring.

However, more accurate measurements of the local deformations seem necessary.

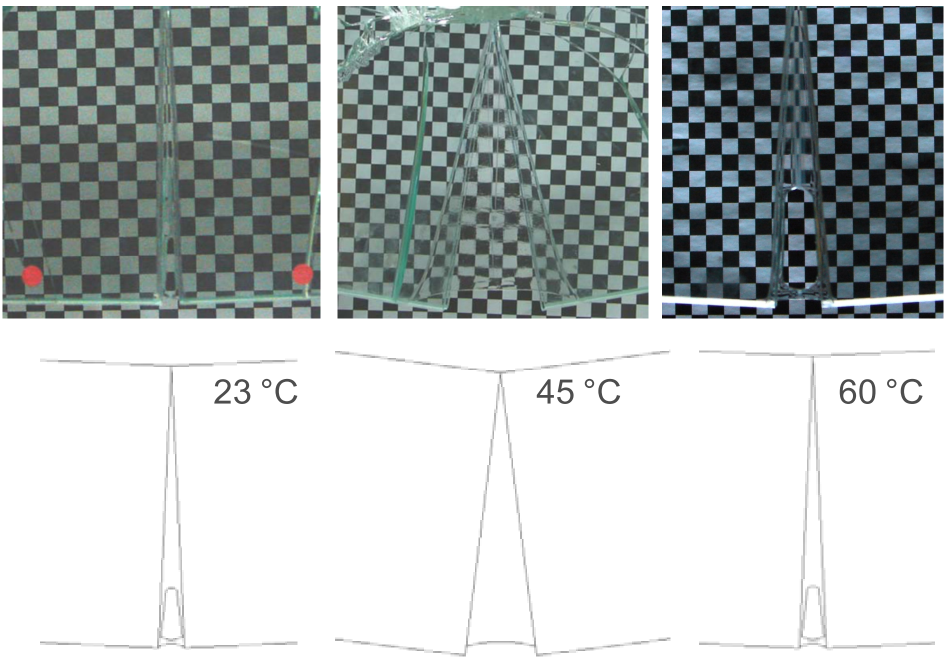



Figure 4: Typical deformation/tearing patterns at the different temperatures (series 150 mm).

Also, the delamination pattern is not often really regular, and even for tests at 45°C we could clearly observe this, as for instance shown on Figure 5.

## 3. Modelling

First attempts were made to compare the deformation pattern with simple analytical and numerical models (finite elements modelling with cohesive elements for the interface between the interlayer and the glass pieces). Figure 6 illustrates a good correspondence between the delamination observed experimentally and obtained with a numerical model using 3D-elements (the figure shows the deformation pattern of the interlayer, the colour gradient represent the stress distribution). Further developments of the model, in particular to describe the behaviour of the interlayer material on the considered temperature range, and further comparisons to validate these are necessary.

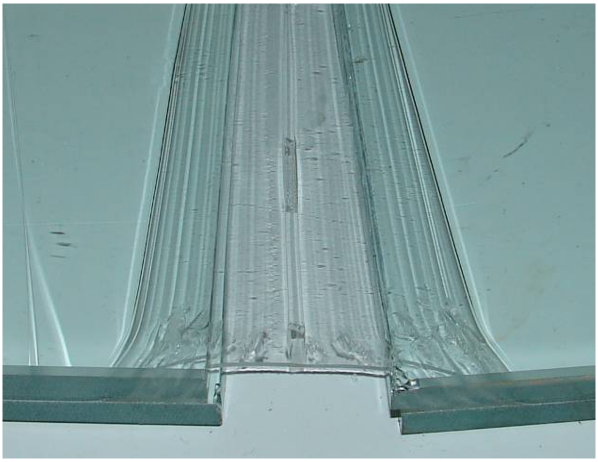
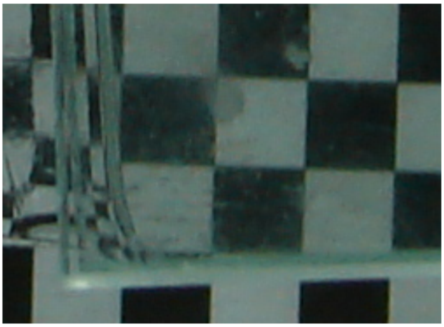


Figure 5: Detail of a particular final delamination pattern of a sample tested at 45°C



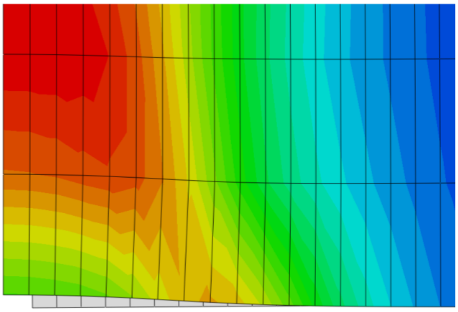


Figure 6: Left: typical delamination pattern at 45°C; Right: model with Finite Elements and cohesive elements

## 4. Comments and perspectives

Results of specific orientation tests about the post-breakage behaviour of pre-cracked laminated glass beams have been presented.

The trend in the experimental results supports the idea developed in the introduction about critical temperatures to consider in assessing the post-breakage performances of laminated glass elements for practical design purposes.

However, more accurate measurements of the local deformations near cracks are necessary to compare the tests with refined numerical models, and the tests have to be achieved at different temperatures in the temperature range of interests. Our focus for further research is the development of experimental testing devices and methods that allow to combine more accurate measurements in combination with a climatic chamber.

## 5. Acknowledgements

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