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# Static and dynamic response of progressively damaged ionoplast laminated glass beams

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## ABSTRACT

This paper investigates the mechanical behaviour of progressively damaged laminated glass (LG) beams made with ionoplast interlayers. After the failure of one or more glass plies, the load-bearing capacity of LG beams depends on the capacity of the interlayer to provide coupling effect between broken and undamaged glass plies via adhesion and its own mechanical properties. Dynamic and static tests have been carried out on undamaged and progressively damaged LG beams. The comparison of experimental data with theoretical values obtained neglecting broken plies highlight that ionoplast interlayers assure the transmission of significant shear stresses between broken and unbroken plies, and glass fragments provide a "tension stiffening" effect to the interlayer. Further tests have been carried out on fully damaged LG beams to evaluate their residual load bearing capacity at the time of glass failure and after a five-month interval to assess effects of aging on the bond between ionoplast interlayers and glass fragments.

## 1. Introduction

Over the past decades, a substantial increase in demand of structural load bearing glass elements has occurred. Following the use of glass as the "skin" of a building, transparent structural elements such as beams, columns, and floors are now often created. Glass being a brittle material, one that can be broken even by an insignificant random blow, design of glass structures needs to propose options and requirements in the event of glass failure. Safe design in building structures asks for reliable structures without the risk of catastrophic collapses. It is therefore required to meet serviceability conditions, granting that the failure of any glass element does not turn out into an unexpected collapse of the structure and allows for the required load bearing capacity until substitution or evacuation (fail-safe response). The pre-stressing effect in tempered glass [1,2], resulting in increased tensile strength, might not be beneficial from a structural point of view, as the brittle failure of glass now induces fragmentation into smaller elements. To improve the post breakage behaviour of glass, a traditional technique is to produce laminated glass (LG) by bonding together several plies with a polymeric interlayer. As a strong chemical bond develops between the materials, the adhesion to the interlayer prevents glass fragments from scattering in the event of glass failure.

The most widely used polymeric films for glass lamination are: Polyvinyl Butyral (PVB) [3,4], Ethylene Vinyl Acetate (EVA) [5], and SentryGlas (SG) [6]. Pure PVB requires the addition of softeners that gives plasticity and toughness. The properties of EVA fluctuate from partial crystalline and thermoplastic to amorphous and rubber-like, but an amplified amount of vinyl acetate increases strength and ultimate elongation. SG is an ionoplast polymer primarily composed of ethylene/methacrylic acid copolymers with small amounts of metal salts. Compared with PVB, SG exhibits both higher stiffness and strength.

All of the aforementioned interlayer polymers have temperature dependent rheological properties. In LG, the layered arrangement of stiff glass plies and softer interlayers causes the composite to behave in a peculiar manner [7]. The type of interlayer is knowingly of crucial importance in the undamaged glass phase [8], but even more in the post-breakage phase [9]. When glass plies fail and are unable to bear tensile stresses, both the interlayer's tensile strength and stiffness are needed to provide

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significant residual load carrying capacity. Post-failure analysis is crucial to assess the time interval for a partially or wholly damaged glass element to fail irreversibly under design loads. The performance of damaged LG elements is affected by the size and shape of glass fragments (i.e. glass heat treatment), the strength of the adhesion bond and the stiffness of the interlayer. As a general rule, the bigger size of fragments produced by failure of annealed and toughened glass plies guarantees a greater adhesion to the interlayer and a better post-failure performance compared to tempered glass failure. Regardless the size of the fragments, the performance is ultimately linked to the strength of the adhesion bond and mechanical properties of the interlayer.

A number of relevant studies on the structural performance of architectural laminated glass elements [8–11], including lamination combined with embedded reinforcement [12], have been experimentally and numerically performed. Interesting studies on the behaviour of glass and glass-reinforced beams are also available [13–16].

The paper deals with experimental tests conducted on SG laminated glass beams, made with three fully tempered glass plies, to assess their post-failure behaviour. Both static and dynamic tests were performed and compared.

The interlayer has not any significant influence on the flexural response of LG beams under in plane loading in the pre-failure phase, but the use of an ionoplast interlayer significantly enhances the post-failure response. The authors investigate the tension-stiffening mechanism which arises once one or more glass plies break, and the decay of bond adhesion between glass and interlayers around each glass fragment, which can induce a drastic reduction of tension-stiffening over time.

## 2. Experimental setup

The experimental setup was designed to perform both static and dynamic tests with only minor tweaks and adjustments (Fig. 1).

Specimens were simply supported at both ends on two steel rollers, fixed on a 3560 mm long HE300B steel beam. Steel beam ends were clamped at midspan to testing machine and additionally supported at both ends by vertical struts. Lateral torsional restraints were inserted near the ends of the specimen to prevent injuries and instruments damage in the event of sudden lateral buckling (in any case, restraints were not required as contact with the beams was never observed during any test).

To compensate small misalignments of glass plies and reduce friction between the LG specimen and supports, small aluminium pads were positioned between the specimen and rollers. In addition, a thick aluminium element was inserted between the top of the specimen and the hydraulic actuator to evenly spread the load among all of the glass plies.

For three-point bending static tests, vertical displacements were determined at midspan and at both ends (F1–F3 in Fig. 2). In addition, all specimens were equipped with eight strain-gages, glue to the external plies along the beam height, in the section at a distance of 100 mm from the midspan. The instrumented section was chosen to be as close as possible to the midspan, without being significantly influenced by local effects induced by the load application. In Fig. 2 positions S1 to S4 refer to strain-gages on the frontal ply, while S5 to S8 refer to the strain-gauges placed on the rear one.

Four piezoelectric accelerometers (A1–A4 in Fig. 3) were used in dynamic tests to detect the impulse-induced vibrations. A1 to A3 were placed on the bottom of the specimen, while A4 was fixed to the steel beam at the left support roller to check that the test apparatus was not influencing the dynamic response of the LG specimen by creating a beat interference pattern.

## 3. Specimens

Beam specimens consisted in two LG beams composed by three 12 mm tempered glass plies and two 1.52 mm thick ionoplast interlayers. To investigate the behaviour of the fully damaged composite material, small fractured glass specimens were obtained by cutting fully damaged beams, having all glass plies broken, into smaller specimens (cf. § 4.3). The context will always make clear if the text is referring to “beam specimens” or “material specimens”.

### 3.1. Interlayer

The interlayer used in the lamination process was an ionoplast polymer, stiffer than the majority of conventional laminating materials used in LG manufacturing. At room temperature and for high to medium strain rates (1 s–1 h tests), SG shows an elasto-plastic behaviour with a noteworthy initial modulus: literature values range from 480 to 580 MPa at 24 °C [6,17,18].

From a thermo-mechanical point of view, this polymer maintains significant advantages over PVB for a large range of temperatures, from room temperature to 80 °C [6].

### 3.2. Laminated beams

With the materials described in previous sections, two 180 mm high and 2510 mm long three-ply laminated glass beams were assembled. Resulting specimens had a total thickness of 39.04 mm (12 + 1.52 + 12 + 1.52 + 12 mm).

## 4. Experimental results and data analysis

The breakdown of the recorded data is now presented, and compared with previous available information about the materials. Models are used to try and understand the structural response of LG specimens for progressively increasing damage states.

The experimental program for the beam specimens includes eight tests in four different damage states (Table 1). All tests were carried out at room temperature (≈24 °C). For each state, dynamic tests were repeated two or more times to assess that recorded data were consistent.

Static tests on “beam specimens” were conducted to evaluate the contribution of broken glass plies to the stiffness of Partially Damaged Laminated Glass (PDLG) beams compared to Undamaged Laminated Glass (ULG) beams. Tests were also performed on Fully Damaged Laminated Glass (FDLG) beams, where all three glass plies were broken and hold together by SG interlayers only.

Tests on “material specimens” were performed to investigate the tensile and compressive strengths of the fractured-glass-interlayer composite. Some of the tensile tests were carried out with a photographic follow-up, to investigate the progression of the delamination between glass fragments and the interlayer.

The experimental evidence shows that the residual stiffness of FDLG beams is not negligible thanks to the high short-term stiffness of ionoplast interlayers, differently from the negligible stiffness of beams laminated with PVB interlayers.

Tests were performed under displacement control. In ULG and PDLG specimens with only one damaged ply, the maximum displacement was selected to induce a maximum load of 5.0 kN. In PDLG tests with two damaged plies, the maximum displacement was set to have a lower maximum load (2.5 kN), in order to prevent both beam failure and lateral torsional buckling.