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Structural analysis of failure behavior of laminated glass

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A R T I C L E I N F O

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A B S T R A C T

The use of laminated glass is increasing since it is able to guarantee robustness requirements so by improving the post-breaking characteristics of the glass. Due to the brittle nature of glass the reason for employing such composite materials are related to their ability to avoid cracks propagation, retain the glass fragments and present a post-cracking phase. Since the behavior of laminated glass depends on the constituent materials and especially on the type of interlayer, this research deals with the structural behavior of laminated glass plates made with different types of interlayer materials: PVB, SGP, EVA and XLAB. Twenty-four specimens were constructed with two annealed glass plies and transparent interlayer and were subjected to four point bending tests with the aim to study their structural behavior in both elastic and post-breaking phases. Laboratory outcomes highlight the enhanced initial-breakage strength of the XLAB plates, as well as the influence of the laminate type on the post-failure safety, since the use of thicker (double or triple ply) and/or stiffer (such as SGP and XLAB) interlayers seemed not to improve the residual load-carrying capacity. Finally, a 3-dimensional FE model is also presented for reproducing the structural behavior of the glass plates. The ability of the numerical model to reproduce experimental results for the load–deflection curves is validated promoting a deeper understanding and knowledge of the capabilities of the different types of interlayers in the context of the laminated glass design.

1. Introduction

Structural robustness is an essential requirement in glass structures design, since glass breaks suddenly (even if stresses are low) due to inclusions within glass, to the presence of micro-defects or to scratches caused by the finishing and cutting process as investigated by Speranzini et al. in Ref. [1]. Robustness is a property that makes constructions not suffer disproportionate failure, including progressive collapse [2]. It can be obtained by eliminating or reducing risks to which structures can be subjected, or by designing structural solutions with low sensitivity to risks [3,4]. Thus structural glass design is based on the new “fail-safe” design philosophy, which is aimed at ensuring safe breakage and avoiding collapse [5]. These objectives can be achieved by structural robustness concepts using structural redundancy, which is the structure's capacity to distribute internal stresses [4,6], so that the failure of its parts does not cause the collapse of the entire structure. Redundancy can be introduced in different ways, which are: section redundancy, structural element redundancy and structural system redundancy. Section redundancy is a feature of laminated glass that avoids cracks propagation and, for this reason, provides structural advantages over a monolithic section especially in the post-breaking phase. Indeed laminated glass is a multilayer made of two or more glass sheets bonded together by a transparent or colored interlayer. The glass sheets can be of the same or different types, or of different thicknesses, and, in these cases, they are called hybrid [7,8]. The function of the interlayer is to distribute impact forces across a greater area of the glass sheets (so that the impact strength of the glass increases), retain the glass fragments, limit the size of cracks, offer residual resistance and reduce the risk of cutting or deep injuries, in the case of breakage [9,10]. Moreover, the interlayer is capable of undergoing plastic deformation during impact [11] and under static loads after impact [12], decreasing the impact energy and absorbing energy as well as reducing the penetration effect by impacting objects [13,14].

Scientific community researchers have made many efforts to acquire new knowledges and develop glass lamination technology. Some studies were aimed at the experimental investigation of: the bending behavior of the laminated glass with different interlayers [15], the mechanical behavior of progressively damaged laminated glass [16], the temperature effect on the structural response of glass/SGP laminates [17], the influence of weathering on the

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mechanical and physical properties of the PVB interlayer [18] as well as the long term response of laminated glass [19,20,21]. Other studies were aimed at: the analysis of curved laminated glass [22,23], the creation of mathematical model for laminated plates with a viscoelastic interlayer [24,25] and the use of discrete element modeling to simulate their nonlinear behavior after the cracking [26,27]. Due to its ability to retain fragments, laminated glass is also used in hybrid glass beams coupled with tensile resistant materials to provide a residual load-bearing capacity [28,29]. Furthermore, adhesion phenomena were studied [4] and more specifically the coupling that the interlayer is able to establish between the glass plies was evaluated [19].

This study deals with the structural behavior of glass plates laminated with different types of interlayer: PVB, polyvinyl butyral; SGP, SentryGlas plus; EVA, ethylene vinyl acetate; XLAB, a plastic film between two plies of ethylene vinyl acetate. The glass plates were constructed with two glass sheets having dimensions of 1100 × 360 × 4 mm, and were laminated with different numbers of interlayer plies. Then, they were tested with a four point bending test using the same load rate with an electronic hydraulic testing machine, in displacement control conditions. The main goal of this experimental campaign was to study the bending behavior of these different types of laminates, analyzing both the elastic and the post-critical phase. Furthermore, a finite element analysis able to model the behavior of the laminated glass plates in the post-breaking phase (considering the cracked section) was performed, at the aim to supply a numerical model useful to the structural design.

2. Laminated glass

Two distinct phases can be discerned in laminated glass behavior: the elastic phase and the post-breaking phase [29–31]. In the former, the glass sheets are not cracked and the stress distribution of each sheet depends on the mechanical characteristics of the interlayer and its ability to transfer the tangential stresses from one layer to another [4]. The elastic phase ends when the glass tensile strength limit is reached or high tensile stresses coincide with randomly distributed surface flaws [1]. In the post-breaking phase, the load can be carried by the uncracked glass plies while the interlayer retains the fragments. When glass sheets are overloaded and are not able to transfer the tensile stress, the interlayer is essential to equilibrium permitting the formation of a resistant couple together with the compression force generated by the direct contact between the pieces [4,27,29]. Furthermore, the high load and the increasing of the load duration can result the loss of the fragments in compression, so that the bending stiffness decreases and the laminate deflection can reach high values depending on the interlayer viscoplastic behavior. The collapse of the laminate occurs due to the reaching of the interlayer tensile strength limit or to the cuts caused by the glass fragments.

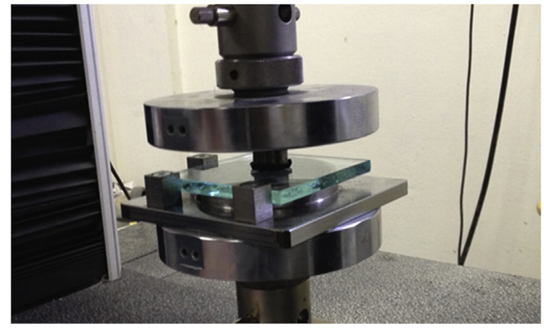

Fig. 1. Method of test by coaxial double rings (CDR).

3. Materials characterization

3.1. Glass

All glass plates were built using soda-lime-silicate float glass, conforming to the European standard as well as to [32]. All glass was provided by the same commercial supplier and was treated during manufacture to reduce the residual stress in the specimens (annealing). Furthermore, since in float glass the air side and the tin side present a different-in-type defectiveness and, consequently, have different strengths, in order to rule out any source of uncertainty, each plate was laid so that the surface that had been in contact with the air during the float process dictated the tensile strength (air surface downward, since it showed higher strength but a greater dispersion of results as compared to the surface in contact with the tin).

To characterize the mechanical properties of the glass plates [33], ruling out any possible source of uncertainty, coaxial double ring tests were performed in accordance with EN 1288–5 (Fig. 1). Accordingly, the mean bending strength of fifteen 100 mm square specimens (4 mm thick) was found to be equal to 162 N/mm^2, while the coefficients of variation was 0.10.

3.2. Interlayer

As concerns the interlayer, four different chemical components were used to assemble the specimens (Table 1):

1. Polyvinyl Butyral (PVB) = Made of polyvinyl alcohol by reaction with butyraldehyde, PVB thermoplastic sheet are tough, resilient safety interlayers used in laminated architectural and automotive glass;
2. SentryGlas Plus (SGP) = It is a semi crystalline thermoplastic interlayer;

Table 1
Characteristics of the interlayer materials.

Interlayer material	Features
PVB	The most important properties are the high transparency, tensile strength, elongation at break, post- breaking strength, good adhesion to glass and high stability against ultraviolet radiation and temperature.
SGP	Because of its high strength, clarity, durability, and easy application, it is widely used in civil applications. It gives good ballistic protection, thinner constructions than are now possible with more conventional laminated glass, energy efficiency and safety.
EVA	It plays an important role in laminated glass - due to the high impact strength, penetration resistance and high transparency. It is also used in decorative art glass, because the manufacture of colored films are possible, and in the production of photovoltaic modules as an encapsulation material for silicon cells, because it ensures better stability against temperature.
XLAB	This new interlayer is significantly stiffer, tougher and chemically more robust than traditional PVBs and provides enhanced structural performance in many applications.