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Broken tempered laminated glass: Non-linear discrete element modeling

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A B S T R A C T

The research presented herein aimed to simulate the structural behavior of laminated glass with all the glass layers broken, by means of the discrete element modeling. This paper focuses on laminated glass composed of two layers made of tempered glass and an interlayer made of either a totally compliant or a relatively stiff material.

The paper demonstrates that discrete element modeling is a viable tool to predict the load–deflection curve from the cracking up to the collapse of laminated glass members, and, hence, to assess the collapse limit states of structural glass. In fact, discrete element modeling may simulate the non-linear composite behavior that the polymeric interlayer and the glass fragments provide a member with, considering the crack patterns of the broken glass, the visco-elasticity of the interlayer, and the structural conditions of the member. The validity of the method is also confirmed through comparisons with other sources — namely, some experiments performed by the authors and an empirical model.

The paper presents the method and the results from its application to typical laminated glass members used for structural glass. Those results provide insight into the effects of the design choices on the post-breakage behavior; emphasis is placed on the role played by the type of interlayer.

1. Introduction to structural glass

This research deals with glass used in buildings for bearing members or for members that, although nonbearing, are characterized by substantial spans; the former carry a fraction of the design loads, the latter carry only their own weight and the live loads that are directly applied to. These members are referred to herein as structural glass [1–3]. Research is devoted to analyzing the post-cracked behavior and to investigating structural glass that is completely broken [4].

Structural glass is made of laminated glass (LG), which has essential structural advantages over monolithic glass when the member is cracked. LG is a sandwich structure manufactured by bonding two or more plies of glass (layers) together with one or more transparent thermoplastic interlayers between the layers [5–7]. The thicknesses and types of glass layers may be equal to or different than each other. In the latter case, LG is referred to as hybrid [8,9]. The most common material used for the interlayer is the PolyVinylButyral (PVB) [2,5,7,10], but newer developments have increased the thermoplastic family for the lamination of glass (EthylVinylAcetate, Thermoplastic PolyUrethane, and, above all, IonoPlastic – IP) [2,4,11].

The lamination prevents the crack from propagating to the other layers and the interlayer minimizes the crack growth in the broken layer, which enables the cracked member to bear a significant fraction of the design loads. Moreover, the interlayer avoids scattering of harmful shards.

It is well-known that glass has a completely linear-elastic behavior in tension and compression [2–4,12,13]. However, its main attribute is that it does not tolerate any settlements, which cause the glass to crack and cracking starts the post-peak behavior. Thus, glass behavior is governed by linear fracture mechanics. Accordingly, the structural capacity derives from glass tenacity, whose value is slight (i.e., $0.75\ \text{MPa m}^{-0.5}$), while the demand is dictated by the square root of the crack length multiplied by the tensile stress at the crack tip (and also multiplied by a coefficient that takes into account crack's shape and position). Such combination is called stress intensity factor. The cracks that cause the stress intensity factor to reach the maximum values are on the surface, i.e. glass flaws [14,15]; in glass structural analysis, thus, the length of a crack is represented by its depth [2,4].

The load-carrying capacity and stiffness of a LG system are considerably lower than the load-carrying capacity and stiffness of the monolithic system with the same thickness [8,16]. As mentioned previously, the growing demand for LG with a structural behavior as close as possible to the monolithic behavior drove the development of new transparent thermoplastic materials that extend the

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physical performance of LG. The greatest enhancements in mechanical properties of interlayers were provided by IP materials, which currently hold an appreciable fraction of the world market share. The key mechanical property difference between an IP interlayer and a PVB interlayer is the viscoelastic behavior for high temperatures or long-term load durations, which makes the shear elasticity modulus of IP be more than two orders of magnitude larger than that of PVB [2,5,17]. Those recent developments in technology have split the thermoplastic family for lamination of glass into two classes, which are referred to herein as totally compliant interlayers (e.g., PVB), and relatively stiff interlayers (e.g., IPs).

Glass ensures transparency only if its thickness is lower than 50–60 mm [1,3]. LG with total thickness lower than 50–60 mm and with layers made of plain (regular) glass may not guarantee adequate load-carrying capacity; more specifically, this is normal with PVB interlayers [18–20] but it is also quite common with IP interlayers [8,16,19]. Thus, LG has to be made of glass with enhanced tensile strength in lieu of plain glass.

Since glass tenacity is a material property, the only way to obtain LG with enhanced tensile strength is to induce initial permanent compressive stresses to the cracked zones of glass. Since the cracks are on the surface (flaws), the tensile strength can be increased only by inducing surface compressive stresses, together with compensating tensile stresses in the glass interior zone. Those coactive stresses are generated with special treatments during the manufacturing process of the glass plies; glass after the strengthening treatment is called prestressed (while glass with no strengthening treatment is called annealed). The treatments to prestress glass are either a tempering process or an ion-exchange process [2,4]. The tempering process produces either tempered glass or heat-strengthened glass, according to whether the cooling phase consists in a thermal shock or a temperature gradient, respectively [2,17]. The ion-exchange process produces chemically-strengthened glass [2].

Owing to the coactive stresses, the tensile strength of heat-strengthened, tempered, and chemically-strengthened glass are greater than the tensile strength of annealed glass at least 1.5, 2.6, 3.3 times, respectively [2]. Furthermore, the failure mode of tempered glass is different than that of the other glass types [2]. The latter consists in large and sharp shards [21], while the former consists in small and blunt pieces of glass [22]. Under every code, tempered (i.e., fully tempered) glass is defined as having a certain edge compression in excess, as well as a breakage pattern that is an ensemble of several quasi-cubical shaped pieces or fragments (called ‘dices’).

The failure mode of tempered glass allows structural glass to satisfy one of the essential fail-safe requirements. In fact, the polymeric interlayer holds in place almost all the fragments of the broken glass, but some pieces can fall down anyway. Therefore, the external layers of LG that can give rise to flying, shattering or falling glass which can injure people or pets and damage things have to break into fragments that are small and not sharp (i.e., small dice shapes, instead of dangerous shards). This requirement can only be fulfilled by tempered glass [2,21,22]. Ultimately, the layers of LG that have to tolerate high stresses and/or to shatter into small, dull pieces must be made of tempered glass.

This paper considers LG composed of two layers made of tempered glass which is a common solution for structural glass, in particular for floors, roofs, façades, and parapets. The interlayer may be either totally compliant (PVB) or relatively stiff (IP). Activity was directed at analyzing LG when all the glass layers are broken. That condition is hereinafter called ‘broken LG’. The paper provides a modeling method that predicts the load-carrying capacity and stiffness of broken LG and provides the results from its application to typical LG members used for structural glass.

2. Post-cracked behavior of laminated glass: broken laminated glass

As any engineering structure, structural glass must be designed to sustain safely all loads and deformations liable to occur during construction and in use, and to have adequate durability. Accordingly, structural glass must satisfy strength limit states, in which each member is proportioned in order to resist the design load combinations for ultimate limit states without cracking [2,14–19] or buckling [2,20,23,24]. Moreover, structural glass must satisfy serviceability limit states, in which each member is proportioned in order to guarantee adequate functional performance (including such items as deflections and vibrations) under the design load combinations for serviceability limit states [8,16,18]. The former (Ultimate Limit States – ULSs) control the safety of structural glass; the latter (Serviceability Limit States – SLSs) define a level of quality of the member and involve the perceptions and expectations of the owner and users.

Engineering structures are subjected to actions such as impacts, impulses, grindings, gratings or abrasions, engravings or piercings, thermal shocks, concentrated forces, which are referred to herein as ‘localized loads’. In the case of tempered glass, the localized loads have to account for the nickel sulfide inclusions as well. Although the localized loads are lower than the design ULS load combinations, the maximum stress (peak of stresses) induced by localized loads in some zones of a member may be higher than the maximum stress induced by the design ULS load combinations. In structures made of reinforced concrete, steel, masonry or timber, those peaks of stresses are redistributed from the small volumes where they are induced by the localized loads, to greater volumes. Consequently, those peaks of stresses may cause the material to exceed the elastic field or to crack, but they influence neither the development of a kinematic mechanism nor the ultimate load. Briefly: the load-carrying capacity of those structures derives from the global structural behavior, while localized loads do not influence the global structural behavior because of inelasticity; thus, their load-carrying capacity is not affected by the effects of localized loads, which result hence in a local behavior only.

Conversely, glass neither displays any plasticity nor tolerates any settlement, i.e. it lacks any inelasticity. The total lack of inelasticity implies that structural glass cannot redistribute those peaks of stresses, which hence crack the glass. The maximum initial crack depth is approximatively the same for any glass that has been subjected to regular processes and treatments. Thus, glass cracking strength is governed by the stress that, together with the maximum initial crack, makes the stress intensity factor reach glass tenacity. That is, glass structural demand is dictated by the peak of stresses, which localizes it, and is resisted by the mode I critical value, which is a local mechanical property, whereas inelasticity does not exist and the global structural behavior does not boost the load-carrying capacity (contrary to the above-mentioned structural types). Thus, the load-carrying capacity of structural glass consists in the load combination for the ULS that cracks the glass, whose level has to be lower than the design ULS load combination. As a result, the localized loads, on one hand, do not represent the load-carrying capacity of structural glass, since a localized load is lower than the design ULS load combination, as above-mentioned; on the other hand, however, the localized loads dictate the maximum load that can be carried by structural glass, since their occurrence starts the post-peak behavior.

Ultimately, the localized loads cannot be included into the design loads, the ultimate load cannot be expressed as a localized load, and glass cannot be warranted against the effects caused by localized loads. Thus, localized loads and the consequent effects cannot be