Strength of Laminated Safety Glass

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Keywords

Abstract

The strength of laminated safety glass continues to be treated in an overly conservative fashion by façade engineers, consultants and architects in general. The origin of this conservatism is a belief that the compliant nature of a polymer interlayer, relative to glass, results in poor transfer of shear stresses between the glass components of the laminate hence leading to greater glass stress for a given loading/support condition. In this presentation we re-examine the issue of stress development in laminated glass and present an objective protocol for designing laminates for required strength performance. The approach is based upon finite element stress analysis, with a constitutive model for the polymer interlayer, coupled with a statistical glass fracture model and a description of glass stress corrosion cracking. The approach has allowed us to develop a series of design charts for laminated glass that allows selection of interlayer thickness and glass thickness for specified loading/support scenario, temperature and loading rate. An important conclusion of our work is that four-sided simply-supported laminated glass plates under uniform pressure demonstrate comparable strength to equivalent monoliths. Indeed, in certain cases laminates may outperform equivalent monoliths. This finding is understandable since transfer of shear stresses between glass plies plays only a minimal role in stress development during large deformation of plates. Our design charts and the approach are being considered by various standards bodies around the world and should lead to an objective treatment of laminated glass that will allow its true structural benefits to be realized.

Introduction

It has been nearly thirty years since Hooper published his seminal work on the load bearing capacity, or “strength” of laminated glass [1]. In this study Hooper looked at stress development in PVB-based laminated glass beams both from a theoretical and experimental approach. He concluded that the load bearing capability of laminated glass should fall between two limits: 1) the monolithic limit, in which the laminate behaves essentially in an equivalent manner to monolithic glass and 2) the layered limit in which the two glass plies slide over one another and the laminate displays one half the strength of the equivalent monolith. The limit is determined by the effectiveness of shear stress transfer across the interlayer and is strongly affected by loading rate and temperature due to the viscoelastic nature of plasticized PVB. Hooper stated clearly in this paper that the results only strictly apply to beams and should only be taken as a guide in the absence of design information for the specific loading/support case of interest.

Much work has been published since looking into stress development of laminated glass, particularly for 4-side support, uniform pressure loading of plates, which is the most common loading/support scenario for glazing [2-7]. The conclusion from this body of work is that for laminate plates, glass stress development is essentially determined by membrane stretching and that the interlayer shear properties now take on a diminished role in the plate strength properties. As such, laminated glass often displays equivalent strength properties to monoliths. Despite this extensive body of work there has been little change in the way laminated glass is treated in design and a suspicion remains regarding the strength of laminated glass. Laminated glass remains severely over-designed in the world of architecture.

This suspicion is understandable since designers are not likely to treat laminates as...
equivalent to monoliths if there is belief that bending stresses may contribute in some way to stress development in a plate application of interest. Also, there is a belief that laminate strength properties are strongly affected by temperature and loading duration. Designers in general would prefer to have a comprehensive design approach to laminates that give an objective evaluation of performance for the case of interest. We have been developing such a comprehensive design approach for laminated glass over the past several years [8,9]. The approach is based upon finite element stress analysis, with a constitutive model for the polymer interlayer, coupled with a statistical glass fracture model and a description of glass stress corrosion cracking. In this contribution we present some key findings from our approach to strength design for laminated glass.

Layered Experiment-The “Oil” Laminate

As an example of how the overall stress state influences glass stress development and strength performance we present results of a simple experiment. In this experiment we have studied glass stress development in two specimens: 1) a 6 mm monolithic glass plate and 2) a laminate comprising of two plates of 3 mm glass with a thin film of mineral oil separating the plates. We refer to this as our “oil” laminate. Note that the two 3 mm plates were chosen in thickness to match closely the total 6 mm thick monolith. Fifteen rosette strain gages were attached to each specimen and each plate was loaded with uniform pressure on 4-side supports. Figure 1 plots the maximum principal stress development in each plate as a function of applied pressure. The key point to note is that glass stress development is essentially equivalent in the two specimens. Looking in detail, at low applied pressures, the monolith is slightly stronger than the “oil” laminate since bending stresses dominate at small deflections, but at higher applied pressures, the “oil” laminate is actually slightly stronger than the monolith! This result is counter-intuitive. However, the “oil” laminate has transitioned to the membrane dominated stress state more quickly than the monolith and the additional stiffening from membrane stretching leads to a slight benefit. Note this effect has been predicted from stress analyses performed by Vallabhan and co-workers over the years [4,5,7]. For the range of glass design stresses treated in most standards the monolith and “oil” laminate are equivalent. If we consider a laminate made from an interlayer with finite shear stiffness that contributes to the overall thickness we may expect further strength benefits over the equivalent monolith. In support of this point, Figure 1 also plots the measured glass stress development in a 3 mm glass / 2.29 mm PVB / 3mm laminate. As can be seen from these data, the PVB-based laminate requires significantly greater applied pressure to generate the specified design glass stress, and therefore, displays greater strength behavior than the monolith. These observations and the body of published literature cited supports our argument that laminated glass is severely over-designed in most current glazing design practice for 4-side support, uniform pressure (wind) loading. This issue is discussed further in the companion paper in these proceedings.

Design Approach

As a guide to strength design with PVB-based laminates we have constructed charts that aid the selection of polymer type and thickness, glass thickness, for specified loading/support and rate/temperature conditions. These charts have been computed using a procedure described in detail elsewhere [9]. Briefly, the procedure consists of: 1) establishing a constitutive model for the PVB (Butacite™) interlayer by dynamic mechanical analysis [10,11]; 2) carrying out finite element analyses of glass stress development [11]; 3) validating selected analyses against controlled loading experiments [9]; 4) combining stress analyses with a statistical (Weibull) glass breakage model [12-14] that incorporates a time-dependence for glass strength [15,16]. Design charts may then be constructed for specified glass breakage probability and laminate build of interest. Note that the approach of coupling large-deflection stress analysis with a Weibull breakage model and time
dependent strength effects is the basis for the current ASTM design charts for monolithic glass [14].

An immediate question arises to the accuracy of finite element calculations in such complex laminate systems. Accuracy depends upon many factors, both physical, related to the accuracy of materials models developed and experimental boundary conditions imposed in a validation test, and numerical, related to details of the mesh size and element choice. We have performed many validation tests of our approach and have looked at a range of shapes, sizes, support conditions and temperatures. One example of a validation experiment is shown in Figure 2. In this experiment stress development was monitored directly at three locations on a laminate plate. The plate was loaded under uniform pressure and supported on four sides. Predictions from our finite element model of glass stress development are shown in Figure 2 along with measurements of maximum principal stress from strain gages. Agreement between model and experiment is below the measurement uncertainty of 5 %. We have seen a similar level of accuracy in all other validation tests carried out.

An example of such a design chart computed for a 6 mm laminate is shown in Figure 3. This chart has been constructed in ASTM E1300 [17] format using the glass strength parameters specified in that standard [18]. In the USA 6 mm laminated glass is defined as 2.7 mm glass / 0.76 mm PVB / 2.7 mm glass. The chart plots allowable pressure loading contours as a function of plate dimensions for a glass breakage probability of 0.008. Note that the chart is constructed for a 3 s wind loading at 25°C. The chart contains all the common features of the established monolithic counterpart. For monolithic glass a series of such charts for common glass thickness is used in an iterative fashion to select the required glazing thickness. We have developed a set of charts that allows selection of laminate build for specified loading/support conditions, loading rate and temperature. Glass thickness, glass type, PVB thickness are variables in the laminate design and provide more options for construction of a laminate build to meet specified strength performance. These charts are currently being examined by the ASTM committee addressing glass strength.

It is interesting to compare the strength design levels for a laminate with equivalent monolithic

![Figure 2. Glass stress development in a laminated plate at three locations, the plate was subjected to uniform pressure and supported on four sides. The curves are predictions of maximum principal stress from a finite element model.](image1)

![Figure 3. Proposed strength design chart for a 6 mm laminate. In the USA this is defined as: 2.7 mm glass / 0.76 mm PVB / 2.7 mm glass. Contours of allowable uniform pressure are plotted as function of plate size and shape. Note the probability of breakage (0.008), load duration (3s), temperature (25°C).](image2)

![Figure 4. Comparison of strength behavior for 8 mm laminated glass to that of 8 mm monolithic glass. The design strength values computed for the laminate at 50°C have been divided by the strength values from an 8 mm monolithic chart. The figure plots these ratios for the same plate size/shape range in the design charts. Note that there is equivalence in strength between laminate and monolith over a wide range of plate sizes.](image3)
glass. Figure 4 plots the strength ratio: (8 mm laminate strength/8 mm monolithic strength) for the range of plates sizes and shapes graphed in the standard ASTM chart. Note that this comparison has been made for strength properties at 50_C, which represents the upper use temperature deemed reasonable in high wind areas in desert climates in the USA. It can be seen that for a large range of plate sizes that the laminate and monolith are equivalent. Indeed under some conditions the laminate affords better strength performance and is probably due to a slight thickness benefit over the monolith and the fact that the laminate moves more rapidly to the membrane state. Slight reductions in strength are noted for the laminate at high aspect ratios where bending stresses are expected to play a larger role in overall stress development. Such charts should encourage the engineer to take a more objective approach to laminated-glass design and not to use overly conservative penalty factors against laminated glass that are couched in the worst possible loading scenario.

**Conclusion**

We have argued that the design of laminated glass for strength performance is generally over-conservative for large plates subjected to uniform loading and 4-side support. Both experimental and fracture analysis presented support this conclusion and is consistent with much previous work addressing this topic. We have proposed a method to generate design information for laminated glass that incorporates all the necessary features to treat laminate glass breakage. This design information is available in chart form and is being considered by various standards bodies.

**References**

Its use fosters new technical solutions thanks to the ability for users to deploy thinner and lighter laminated safety glass panes. The high post-breakage strength of panels laminated with SentryGlas® permits their use in structural glazing applications. Pvb Interlayer. Ionoplast Interlayer. What is laminated safety glass? PVB Interlayer. Ionoplast Interlayer. Cookies Information. Our website uses cookies in order to recognize the preferences of our users and to optimize the design of this website. By clicking on "Accept" you agree to the use of all cookies. You can withdraw your consent at any time or adjust your settings under "Settings". Further information can be found in our privacy policy. Keywords. Abstract. The strength of laminated safety glass continues to be treated in an overly conservative fashion by facade engineers, consultants and architects in general. The origin of this conservatism is a belief that the compliant nature of a polymer interlayer, relative to glass, results in poor transfer of shear stresses between the glass components of the laminate hence leading to greater glass stress for a given loading/support condition. In this presentation we re-examine the issue of stress development in laminated glass and present an objective protocol for designing laminates. Laminated glass, as used in building applications (protection for shops and commercial building, guarding and balustrading...), is essentially designed for the protection against accidental shocks, against the risk of injury and against intruders and vandalism. Shock and penetration resistance, residual strength, reduction of fragments projection and laceration risk are evaluated by standard tests. This work is a contribution to the experimental investigation of the impact behaviour until perforation of laminated glass. From an experimental study of the hard body impact, the chronology and physical characteristics of the impact are determined. Safety glass is defined as glass which must have passed an impact test (currently BS 6206: 1981 -Specification for impact performance requirements for flat safety glass and safety plastics for use in buildings) and either must not break or must break safely. There are two types of laminated glass: PVB laminated and cast resin laminated glass. PVB laminated is the more commonly used variety. PVB laminated safety glass. Two or more sheets of glass are bonded together with one or more layers of polyvinyl butyral (PVB), a plastic interlayer in sheet form. The principal benefit of laminated glasses is their performance under impact. The glass may fracture but any broken fragments will remain firmly bonded to the interlayer.