Mechanical Deformation and Fracture of Glass/PVB Laminates

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Abstract

The design of laminated safety glass for specified mechanical performance is discussed. The use of computational modeling for the design of laminates is demonstrated in a treatment of glass first cracking resistance. The modeling approach has been used to construct objective performance charts for laminated glass that may be used to select glass and polymer thickness for specified geometry, loading, rate and temperature conditions.

Introduction

Glass-polymer laminates are used for glazing where safety and/or security considerations preclude the use of monolithic glass. The most common polymer interlayer used is plasticized polyvinyl butyral, PVB, such as Butacite®. For most applications, glass-polymer laminates must be designed to meet performance specifications for: 1) resistance to glass cracking under uniform loads; 2) safe fragmentation behavior; 3) energy absorption upon projectile impact; and 4) post-glass fracture integrity.

We propose that an objective basis for laminate design may be established using computational methods of fracture and deformation analysis that have been thoroughly validated by model experiments. The use of such methods is demonstrated here in developing a design protocol for specifying glass first cracking performance in response to uniform pressure loading of laminated glass. The protocol is based on finite element stress analyses of laminates that include a constitutive model for the deformation of the plasticized polyvinyl butyral, PVB (Butacite®) interlayer. Stress analysis is coupled with a statistical fracture description of glass cracking with provision for the effects of stress-corrosion cracking. The design approach has been used to construct objective performance charts for laminated glass that may be used to select glass and polymer thickness for specified geometry, loading, rate and temperature conditions.

Design Model

Finite Element Model

Figure 1 shows a laminate plate consisting of two sheets of glass joined by a polymer interlayer. Glass sheets are modeled using 8-node solid elements with incompatible modes and the polymer interlayer is modeled using 8-node solid elements with incompatible modes using a hybrid formulation. The complete model includes the boundary conditions shown in Figure 1 and materials properties specified below.

Figure 1. Finite element mesh for the geometry analyzed. The plate is simply supported and subjected to uniform lateral pressure.

Note that the interlayer thickness is accounted for explicitly. The model has been solved using the finite element program ABAQUS™ [1].
and validated against analytic solutions and experiments on disks and plates [2,3].

**Constitutive Properties**

Plasticized-PVB (Butacite®) shows rate and temperature dependent stiffness behavior and is characterized as a linear viscoelastic solid [4]. The Williams-Landell-Ferry (WLF) relation is used to describe time-temperature superposition, which is how temperature effects enter naturally in the model. The shear relaxation modulus is determined from tensile storage and loss moduli measurements for Butacite®, $E'$ and $E''$ respectively, measured over a range of temperatures under cyclical strain loading at different frequencies. The bulk modulus, $K(t)$, has been determined using hydrostatic volumetric tests in a mercury-containing pressure cell over a range of temperature and is ~ 2.0 GPa. For computational convenience the shear relaxation modulus has been represented by a generalized Maxwell series [1]. The superimposed data and fits for $G(t)$ are shown in Figure 2. Glass is modeled as linear-elastic, Young’s modulus, $E = 72$ GPa and Poisson ratio, $\nu = 0.22$ [5].

$$\sigma_{\text{oi}}$$ is a scaling stress (for unit area), and $m$ is the Weibull modulus for each glass surface $i = 1$ to 4. The Weibull effective stress (WEF), $\sigma_{\text{W1}}, \sigma_{\text{W2}}, \sigma_{\text{W3}}$ and $\sigma_{\text{W4}}$, is:

$$\sigma_{\text{W}} = \frac{2}{\pi} \int_0^{\pi/2} \left( \frac{\sigma_1 \cos^2 \theta + \sigma_2 \sin^2 \theta}{2} \right) \frac{1}{\sigma_{\text{W}}} \, d\theta ; \quad (2) \text{ Eq. 2}$$

The angle $\alpha$ is defined as: $\sigma_2 > 0 \Rightarrow \alpha = \pi/2; \sigma_2 < 0 \Rightarrow \alpha = \tan^{-1}(\sigma_1/\sigma_2); \sigma_1 < 0 \Rightarrow \alpha = 0$. The advantage of using the Weibull effective stress over the maximum principal stress is that the formulation accounts for changes in area and stress distribution as a function of loading, plate geometry and specimen type.

**Sub-Critical Crack Growth**

The computation of probability of failure can be extended to include strength reduction from sub-critical crack growth in glass due to stress-corrosion cracking. Failure prediction models for glass handle this effect by using a time-averaged stress [8]. Stress evolution in laminated glass is dependent on loading history due to polymer viscoelasticity so the effect of sub-critical crack growth is incorporated in the evaluation of the WEF at each loading stage:

$$\sigma'_{\text{eff}}(t') = \left[ \frac{2}{\pi} \int_{\Omega} d\Omega \left( \int_{t'}^{t} \sigma''(t^*) d^* \right)^n \right]^{1/n} ; \quad (3) \text{ Eq. 3}$$

where $n$ is an exponent that characterizes the weakening effect due to sub-critical crack growth. $\sigma''(t')$ is the stress history, up to time $t$, and $t^*$ is a reference duration.

**Stress Development in a Laminate**

Consider the case of a 2.44 m x 1.52 m plate, with 0.76 mm Butacite® and 2.92 mm glass. Figure 3 shows contours of maximum principal stress development in the glass on the supported surface for a pressure load of 1.72 kPa. The main feature of interest is that the computed stress pattern clearly shows the influence of corner and geometry restraints as the maximum principal stresses are concentrated in regions that move in a diagonal trajectory from the plate center towards the corners with increasing applied pressure. This

![Figure 2. Shear relaxation modulus of PVB (Butacite®) as a function of time.](image-url)
concentration of stress into regions of progressively diminishing area strongly influences the resulting Weibull effective stress. Also, the ratio of maximum to minimum principal stress changes as loading increases and results in an influence on the Weibull effective stress.

The example demonstrates glass stress development behavior in laminates that is counter to the current notion that laminates develop significantly greater stress than monolithic glass at a given applied pressure. Indeed this notion has led to a factors based approach to design that discounts the strength of laminates against equivalent monoliths. This common misconception that laminate plates demonstrate diminished load-bearing capacity compared to monolithic glass has its origin in the analysis of beams, [9]. The pioneering study by Hooper [9] established the concept that the load-bearing capacity of laminated glass is bounded by a monolithic limit, equivalent to monolithic glass, for a stiff interlayer and a layered limit, equivalent to two freely sliding glass beams, for a soft interlayer. However, the conclusions are inappropriate for characterizing the behavior of large glass plates for a number of reasons. First, the beam bending conditions considered by Hooper do not probe the membrane-dominated stress state that develops during the large deflection of plates close to glass first cracking. Second, the contribution from the interlayer to overall stiffness depends on beam length. Third, plane stress conditions obtain during the bending of narrow beams whereas, plane strain is the case in large plates. It has been shown that the earlier onset of membrane stresses in laminate plates can cause them to be stronger than equivalent monoliths [10].

The development of Weibull effective stress with applied pressure at a temperature of 25 °C is plotted in Figure 4. Initially, the WEF increases linearly with applied pressure as bending stresses develop. The WEF demonstrates nonlinear behavior as membrane stresses develop at greater loading. We have chosen to limit the range of loading in our calculations to produce stress levels in the glass that encompass the currently accepted ranges and associated failure probabilities for design with annealed monolithic glass (15 – 25 MPa).

Also plotted are the WEF for monolithic glass with: 1) thickness equal to the total glass thickness in the laminate, \(2h_g\) (= 5.84 mm), i.e. the “equivalent” monolith, and 2) thickness equal to the total glass thickness and polymer thickness, \(2h_g + h_p\) (= 6.6 mm). It can be seen that the laminate in this case demonstrates essentially the same load-bearing capacity as the equivalent monolithic glass.

The approach presented may also be used to predict the effect of temperature on laminate first cracking performance. Figure 5 plots the effect of temperature on WEF at an applied pressure of 0.97 kPa (~20.2 psf). It can be seen that...
temperature has a minimal effect on the WEF for this case. A design glass stress of $-15$ MPa is used in this example, which gives a probability of failure of $-0.001$ for the ASTM E1300-97 [11] Weibull parameters.

Design Charts

From a users design perspective, our approach needs to be transparent and design cases need to be evaluated. The rich complexity of laminated glass makes this a challenge. However, we are equipped with a procedure to generate design charts for first glass cracking under uniform load of laminated glass. The best representation of design information is a topic for debate, but for now we follow the glass thickness selection chart format used in ASTM E1300-97 [11]. These charts contour maximum allowable applied pressure as a function of glazing size and aspect ratio for a specified glass thickness and failure probability. Figure 6 is an example of a design chart for the glass first cracking performance of laminated glass under uniform pressure. The chart was computed using the approach described for the following: glass thickness $= 3$ mm, Butacite® thickness $= 1.52$ mm, Weibull modulus, $m = 5$, stress corrosion exponent, $n = 16$, load duration, $t^* = 60$ s, temperature, $T = 20^\circ C$. It has the same overall features of the ASTM E1300-97 [11] charts: contours of maximum allowable pressure for a range of glazing dimensions with a specified glass thickness, Butacite® thickness and Weibull effective stress. A laminated glass designer would use a series of such charts following the same procedure used in E1300-97. In the case of laminates, the designer would also have the option of adjusting the interlayer thickness to achieve a desired performance level. This type of chart would allow an objective design recommendation to be made for laminated safety glass. We have deliberately not made any reference to the associated failure probability in the example chart shown but have specified the maximum Weibull effective stress (WEF) that the glass should be subjected to. The mathematical foundation of our design engine has separated out the normalizing stress, $\sigma_o$ in Equation 3, from the WEF. We did this due to the ongoing debate as to the appropriate values for this scaling stress and Weibull modulus, $m$, for glass to be used in glass performance. The chart shown in Figure 6 was computed for a WEF $= 15$ MPa, which corresponds to a probability of failure $P_f < 0.001$ for the $\sigma_o$ values used in ASTM E1300-97 [11]. For a given value of $m$, debate over the value of $\sigma_o$ will change the failure probability associated with a specified WEF.

The benefit of the design chart is that the glazing engineer is not constrained by an approach that uses monolithic glass charts and penalty factors. Design is therefore objective and optimized for the case of interest allowing use of appropriate glass and interlayer thickness.

Summary

We have argued that design guidelines for laminated glass may be established using modern computational methods of fracture and deformation analysis. An example is presented of objective performance charts for laminated glass that may be used to select glass and polymer thickness for specified applied pressure, geometry, loading, rate and temperature conditions. We see this work as a first step in establishing an objective design methodology for laminated glass. Further components of a comprehensive design method that includes impact and post-glass fracture performance will require developments in modeling and supporting experiments to handle the complexity associated with glass fragmentation and large strain polymer deformation.

References


