Effective Laminate Thickness for the Design of Laminated Glass

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First presented at Glass Processing Days 2009, Tampere, Finland

Abstract

In the design of laminated glass to meet various structural loads, engineers generally make simplifying assumptions or make reference to procedures given in various standards. The current Australian standard, AS1288, which was published in 2006, allows the total glass thickness to be used for short-term load duration but for medium or long-term load durations it gives relationships for load sharing factors for the glass components. However, these methods may not give correct results and the Australian standard alternatively allows a full non-linear analysis, modelling the glass-interlayer sheets behavior, to be undertaken. Since such an analysis is not readily available to all designers, a Working Group was formed in Australia in order to determine if a procedure using the effective thickness of the laminated glass could be adopted for the design of laminated glass. This paper presents the results of the investigation carried out by the authors for the purpose of assisting the Working Group in adopting revised design procedures for use in the Australian Standard. The investigation includes a review of data from test programs in which the laminate effective thickness has been measured directly and compared to simplified calculation methods based on the effective thickness approach. Additionally, finite element methods are compared to an effective thickness approach to calculating laminated glass structural behavior.

Introduction

The structural behavior of laminated glass is a complex topic and many factors influence the response of a laminated plate or beam to an imposed load. Despite this complexity, much progress has been made in understanding laminated glass in the last decade [1-3]. This progress is primarily attributable to advances in mechanics and associated computational tools [4] and the development of appropriate interlayer property information that accurately captures the effects of load duration and temperature on the polymer constitutive properties. The upshot of this body of work is the capability to model accurately the structural behavior of laminated glass using modern finite element methods. However, the glass design industry often takes the approach of
using simplified calculation methods for engineering laminated glass due to the slow adoption of finite element technology. These simplified design approaches are often inaccurate, although usually conservatively so. Such overly-conservative approaches result in much over-design of laminated glass along with an associated, unnecessary cost penalty. Accordingly, there is an industry need to develop calculation methods that capture accurately the mechanical response of laminated glass while being relatively straightforward to implement in standards and existing calculation methodologies. In this contribution we examine the so-called "effective-thickness" method for the design of laminated glass. This method has been proposed for several developing standards in Europe, USA, China and Australia. We will present evidence that the method has the capability of being used in structural calculations for the performance of laminated glass and captures many of the important variables that influence performance.

Effective Thickness Concept

The concept of the "effective" thickness of laminated glass has recently gained traction in the design community and is based on analysis of composite sandwich structures originally developed by Wölfel [5]. The analysis proposes analytic equations that provide a method of calculating the thickness of a monolithic beam with equivalent bending properties to a laminated beam. This thickness then can be used in place of the actual thickness in analytic equations for deformation of beams and simplified finite element analysis. The analytic equations describe the shear coupling between two glass plies through the interlayer. The shear coupling depends primarily on the interlayer shear stiffness, $G$, glass properties, laminate geometry and the length scale in the problem. The shear transfer coefficient, $\Gamma$, which is a measure of the transfer of shear stresses across the interlayer, is given by:

$$\Gamma = \frac{1}{1+9.6 \frac{EI_s h_v}{Gh_s^2 a^2}}$$  (1)

With:

$$I_s = h_1 h_2^2 + h_2 h_1^2$$  (2)

$$h_{s1} = \frac{h_1 h_2}{h_1 + h_2}$$  (3)

$$h_{s2} = \frac{h_1 h_2}{h_1 + h_2}$$  (4)

$$h_s = 0.5(h_1 + h_2) + h_v$$  (5)

Where:

$h_v$ = Interlayer thickness
$h_1$ = Glass ply 1 minimum thickness
$h_2$ = Glass ply 2 minimum thickness
$E$ = Glass Young’s modulus (70 GPa)
$a$ = Length scale (shortest bending direction)
$G$ = Interlayer shear modulus

The shear transfer coefficient, $\Gamma$, varies from 0 to 1.0.

For calculations of laminate deflection, the laminate effective thickness, $h_{ef, w}$, is given by:

$$h_{ef, w} = \frac{1}{3} \left[ h_1^3 + h_2^3 + 12 \Gamma h_v \right]$$  (6)

For calculations of the maximum glass bending stress, the laminate effective thicknesses (one for each glass ply) are given by:

$$h_{1, ef, \sigma} = \frac{h_{ef, w}}{h_1 + 2 \Gamma h_{v2}}$$  (7)

$$h_{2, ef, \sigma} = \frac{h_{ef, w}}{h_2 + 2 \Gamma h_{s1}}$$  (8)

The calculation normally needs only to be performed for the thickest ply, unless there are different types of glass in the laminate that have different allowable stresses. The primary interlayer property that influences the laminate deformation is the shear modulus, $G$. The shear modulus is a measure of the plastic interlayer’s shear resistance. The greater the shear
resistances, the more effectively the two glass plies couple and resist deformation under loading. The effective laminate thickness approaches the total laminate thickness for stiff interlayers ($\Gamma \to 1$) and approaches the layered limit (IGU approximation) for compliant interlayers ($\Gamma \to 0$). Note that the polymer does not need to achieve the glass modulus value to impart efficient structural coupling.

Strictly, the analysis only applies to pure bending of beams and it is important to identify the correct length scale to use in a design calculation (usually the shortest dimension along a bending direction). Despite these restrictions, the approach is a great simplification to the analysis of laminated glass and when properly used, can provide efficient design solutions with minimal computation. Key to the use of this approach is the availability of comprehensive interlayer modulus data and knowledge of the temperature/load duration conditions for the loading actions.

**Experimental Measurements of Laminate Effective Thickness**

Here we propose a method to determine experimentally the effective thickness of a laminated glass ply under well-defined loading and support conditions. These tests have been carried using a four-point bend methodology based on the proposed ISO 1288-3 standard. The method comprises of three steps: 1) measure the maximum glass stress (or deflection) for a range of applied loads (at a specified loading rate and temperature); 2) Fit a straight line to the stress-load characteristic using a linear least squares method and determine the slope, $\Phi$, of the fitted line; 3) Extract the effective thickness, $h_{\text{eff}}$, using:

\[
h_{\text{eff}} = \sqrt{\frac{3(L_s - L_v)}{2B\Phi}}
\] (9)

Where: $L_s$ = support dimension (1,000 mm) $L_v$ = loading dimension (200 mm), and $B$ = specimen width (360 mm).

Figure 1 plots the maximum principal glass stress (measured with strain gages) as a function of applied load for nominal 5 mm annealed glass / 0.76 mm Ionoplast interlayer (DuPont™ SentryGlas®) / 5 mm annealed glass.

![Figure 1](image1.png)

**Figure 1** Maximum principal glass stress in a nominal 5 mm glass / 0.76 mm SentryGlas® / 5 mm glass laminate.

Note tests have been run for a temperature range of 25 ºC to 80 ºC.

![Figure 2](image2.png)

**Figure 2** Effective thickness of a nominal 5 mm glass / 0.76 mm SentryGlas® / 5 mm glass laminate.

The measured laminate effective thickness as a function of temperature extracted using the procedure described above is graphed in Figure 2. Note that the effective thickness is essentially 10 mm for this ionoplast laminate at temperatures of 50 ºC and below. Above
50 °C, some reduction in effective thickness is seen as the interlayer begins to soften.

The proposed methodology has good capability for measuring the effective thickness of laminated glass under a specified deformation state and allows study of the role of load duration and temperature in laminate behavior. More extensive results from these studies will be presented elsewhere.

Comparisons of Effective Thickness Predictions with Experimental Results

We now use the effective thickness methodology described above to calculate the effective thickness of the laminates used in the bending experiments. Firstly, accurate measurements of the glass and interlayer thickness are needed. The measured laminate construction used in the test was: 4.63 mm annealed glass / 0.76 mm DuPont™ SentryGlas® / 4.63 mm annealed glass (total laminate thickness = 10.02 mm). The length scale chosen for calculation purposes was set at 1 m, the support rolls span in the four point bend test. The remaining piece of information needed for calculations is the interlayer shear modulus for the various temperatures at the appropriate time scale (1 minute in this case). Table 1 shows the shear modulus properties of the Ionoplast interlayer (DuPont™ SentryGlas®).

<table>
<thead>
<tr>
<th>Temperature, $T$ ($^\circ$C)</th>
<th>SentryGlas® Shear Modulus, $G$ -- 1-minute load duration (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>225</td>
</tr>
<tr>
<td>20</td>
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</tr>
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<tr>
<td>70</td>
<td>1.88</td>
</tr>
<tr>
<td>80</td>
<td>0.83</td>
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</table>

Table 1 SentryGlas® shear moduli for a range of temperature (1-minute load duration).

The effective laminate thickness for stress behavior calculated using equations 7 and 8 is plotted in Figure 2. As can be seen, the predicted effective thickness behavior is in close agreement with the measured behavior. We have also carried out similar experiments using PVB laminates and have found the calculation method to be accurate in describing the effective thickness of laminates in the four point bend test.

Analysis with the Effective Thickness: Cantilevered Laminated Glass Balustrade

We now examine the use of the effective thickness approach for calculating glass stress and laminate deflection of a cantilevered laminated glass balustrade.

Figure 3 shows the example of interest. The standard analytical formulae can be used to determine the maximum glass stress, $\sigma_{\text{max}}$, and laminate deflection, $\delta_{\text{max}}$:

$$\sigma_{\text{max}} = \frac{6Pa}{h_{1,\text{eff}}^2}$$

(10)

$$\delta_{\text{max}} = \frac{4Pa^3}{Eh_{3,\text{eff}}^3}$$

(11)

For the example of:

- $P = 0.75$ kN/m
- $a = 1$ m
- $h_{\text{glass}} = 6$ mm (use 5.8 mm ISO minimum)
interlayer = 1.52 mm
\( G_{\text{interlayer}} = 59.9 \text{ MPa} \) (SentryGlas®: 60 mins at 30 °C)
\( E_{\text{glass}} = 70 \text{ GPa} \)

The effective thickness values are:

- Laminate Effective thickness (deflection), \( h_{\text{eff,w}} = 12.94 \text{ mm} \)
- Laminate Effective thickness (stress), \( h_{\text{1,eff,c}} = 13.02 \text{ mm} \)

Inserting these effective thickness values into equations 10 and 11, gives the glass stress and laminate deflection values. These values are presented in Table 2.

As can be seen from Table 2, the values predicted using the effective thickness approach with known analytic formulae compare well with those derived from the finite element method.

**Conclusions**

We have demonstrated that the effective thickness method is a useful approach to calculating glass stress and deflection of laminated glass. The approach provides a simplified methodology for design work and adequately incorporates the major variables that influence the behavior of laminated glass. The methodology is currently being reviewed by standards bodies globally.

**References**


<table>
<thead>
<tr>
<th>Glass Stress, ( \sigma_{\text{max}} ) (MPa)</th>
<th>Laminate Deflection, ( \delta_{\text{max}} ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FE Effective Thickness</td>
<td>FE Effective Thickness</td>
</tr>
<tr>
<td>27.8</td>
<td>26.6</td>
</tr>
<tr>
<td>18.5</td>
<td>19.8</td>
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</tbody>
</table>

**Table 2** Computed glass stress and laminate deflection for a cantilevered laminated glass balustrade. Effective thickness predictions and finite element (FE) predictions are compared.