HIGH-PERFORMANCE LAMINATED GLASS FOR STRUCTURALLY EFFICIENT GLAZING

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ABSTRACT

In this contribution we examine the mechanical behavior of laminated glass and show that improvements in performance may be achieved through the use of a stiff, structural, non-PVB, interlayer. Enhancements in mechanical properties, such as strength, creep, post-glass breakage coupled with enhancements in durability and materials compatibility, are provided with an Ionoplast structural interlayer (DuPont™ SentryGlas® Plus) that extends the performance of laminated glass well beyond the established PVB limits. The use of analysis tools based on finite elements and effective thickness methods is also presented. Such tools allow the designer to optimize the performance of laminated glass and take full advantage of the performance attributes of an Ionoplast interlayer. Examples are given of projects where such a structural interlayer provides key enabling technology and the most cost-effective, value-engineered design solution.

KEYWORDS
Laminated Glass, Strength, Design, Finite Elements, Safety, Ionoplast, PVB, Effective Thickness

INTRODUCTION

Architectural laminated safety glass is dominated by the use of PVB interlayers, such as DuPont™ Butacite®. This ascendancy can be attributed to the long (> 70 years), successful history of PVB use in the automotive industry for laminated safety glass windshields. Although many requirements for automotive laminates and architectural laminates are the same, there are notable differences. The main distinction is the need for post-glass breakage compliance in automotive applications to reduce the propensity for head trauma in an accident. Also, the demands of performance longevity for architectural applications generally exceed those needed for automotive applications. If we relax the need for post-glass breakage compliance (softness) and scrutinize the performance needs for architectural applications, we quickly realize that polymers with enhanced structural, temperature and durability performance are attractive for architectural applications. Here we examine the use of one such structural interlayer: DuPont™ SentryGlas® Plus. This interlayer is based on a different chemistry to PVB and has been developed from a class of DuPont™ proprietary polymers. SentryGlas® Plus was introduced commercially some ten years ago to meet the needs for high-performance hurricane resistant glazing in the United States. In recent years, we have seen rapid growth in the use of SentryGlas® Plus in non-hurricane applications, as the structural and durability advantages of this interlayer have been realized. Associated with the growth in applications of a structural interlayer has been
the development of property information and design methodologies that have enabled the most mechanically and cost efficient safety glass designs. The use of finite element methods has played a central role in the implementation of structural interlayers for laminated safety glass and is also discussed.

SOME STRUCTURAL PERFORMANCE LIMITS FOR PVB-BASED LAMINATES

The performance limits for PVB-based laminated glass are generally well known and in many instances defined in national standards and building code regulations. For example in the United States, ASTM E1300-06 (Load Resistance of Glass in Building), uses design charts to map the load resistance of laminated glass under wind load. The charts show that for square panels, under short-duration loading up to 50º C in four-side supports, PVB-laminates show essentially equivalent strength to monolithic glass for common applications. However, when aspect ratio increases and the glazing support is less than four sides (for example in frameless glazing), PVB laminates are always weaker than equivalent monoliths and exhibit greater deflection for a given load. Elevated temperatures and long duration loads further challenge the load transfer of the PVB interlayer due to viscoelastic relaxation of the polymer modulus, resulting in sub-monolithic performance. Invariably, design solutions require the use of thick glass or heat treatments to compensate for the lack of load transfer across the PVB interlayer. Additionally, where long load duration loads or high temperature loading is required, the interlayer contributes little to the mechanical performance of the non-broken laminate, leading to structural design at the so-called “layered” limit - viz: two glass plies sliding in contact (in a manner similar to an insulated glass unit). These limitations have driven buildings codes in some regions, such as Hong Kong, to take a very conservative approach to laminated glass design and ignore any mechanical benefit from the PVB interlayer.

One of the key safety aspects of laminated glass is the post glass breakage structural performance imparted by the interlayer, in case of accidental glass breakage. The compliance and creep characteristics of PVB laminates after breakage require special detail to be placed on glass type selection and attachment methods to properly take advantage of the PVB performance. Elevated temperatures, extended load durations and frameless can be challenging for standard PVB laminates and constrain the designs available to the façade engineer.

IONOPLAST INTERLAYER

The generic definition of an Ionoplast interlayer is “A stiff sheet (Young’s modulus greater than 100 MPa at temperatures up to 50º C) comprised primarily of ethylene / methacrylic acid copolymers containing small amounts of metal salts, that may be permanently bonded to glass.” The key mechanical property difference between an Ionoplast interlayer and a PVB interlayer is the modulus and viscoelastic behavior. Figure 1 shows a Young’s modulus comparison between DuPont™ Butacite® (PVB) and DuPont™ SentryGlas® Plus (Ionoplast) determined from Dynamic Mechanical Analysis measurements (following ASTM D 4065). Several features may be noted from these data: 1) At “low” temperatures (< 0º C), the Young’s modulus for both polymers converge (glassy modulus); 2) The PVB polymer softens rapidly and goes through glass transition at room temperature; 3) The Ionoplast polymer goes through glass transition at ~ 55º C; 4) The Ionoplast polymer maintains a significant stiffness advantage over PVB for a large range of temperature (room temperature to 80º C). Note the modulus axis in
Figure 1 is a logarithmic scale so the stiffness advantage of the SentryGlas® Plus is often in excess of ten times or more.

![Figure 1](image)

Figure 1: Young’s Modulus comparisons for PVB and Ionoplast Interlayers

All polymer interlayers are viscoelastic in nature and so the time scale also affects the stiffness response. Data collected from dynamic mechanical analysis and direct creep measurements have been used to establish elastic property values for a wide range of temperature and load duration. Table 1 and Table 2 show such data for DuPont™ SentryGlas® Plus.

### TABLE 1
**YOUNG’S MODULUS VALUES FOR DUPTONTM SENTRYGLAS® PLUS (IONOPLAST)**

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Load Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 s</td>
</tr>
<tr>
<td>10 °C</td>
<td>692.</td>
</tr>
<tr>
<td>24 °C</td>
<td>581.</td>
</tr>
<tr>
<td>30 °C</td>
<td>442.</td>
</tr>
<tr>
<td>35 °C</td>
<td>353.</td>
</tr>
<tr>
<td>40 °C</td>
<td>113.</td>
</tr>
<tr>
<td>60 °C</td>
<td>4.65</td>
</tr>
</tbody>
</table>
TABLE 2
POISSON RATIO VALUES FOR DuPONT™ SENTRYGLAS® PLUS (IONOPLAST)

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Poisson Ratio, $\nu$</th>
<th>1 s</th>
<th>3 s</th>
<th>1 min</th>
<th>1 hr</th>
<th>1 day</th>
<th>1 mo</th>
<th>10 yrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 °C</td>
<td>0.442</td>
<td>0.443</td>
<td>0.446</td>
<td>0.450</td>
<td>0.454</td>
<td>0.458</td>
<td>0.463</td>
<td></td>
</tr>
<tr>
<td>20 °C</td>
<td>0.448</td>
<td>0.449</td>
<td>0.453</td>
<td>0.459</td>
<td>0.464</td>
<td>0.473</td>
<td>0.479</td>
<td></td>
</tr>
<tr>
<td>24 °C</td>
<td>0.452</td>
<td>0.453</td>
<td>0.458</td>
<td>0.465</td>
<td>0.473</td>
<td>0.482</td>
<td>0.489</td>
<td></td>
</tr>
<tr>
<td>30 °C</td>
<td>0.463</td>
<td>0.466</td>
<td>0.473</td>
<td>0.485</td>
<td>0.488</td>
<td>0.497</td>
<td>0.499</td>
<td></td>
</tr>
<tr>
<td>40 °C</td>
<td>0.481</td>
<td>0.484</td>
<td>0.492</td>
<td>0.498</td>
<td>0.499</td>
<td>0.499</td>
<td>0.499</td>
<td></td>
</tr>
<tr>
<td>50 °C</td>
<td>0.491</td>
<td>0.493</td>
<td>0.497</td>
<td>0.499</td>
<td>0.499</td>
<td>0.500</td>
<td>0.500</td>
<td></td>
</tr>
<tr>
<td>60 °C</td>
<td>0.497</td>
<td>0.498</td>
<td>0.499</td>
<td>0.500</td>
<td>0.500</td>
<td>0.500</td>
<td>0.500</td>
<td></td>
</tr>
<tr>
<td>70 °C</td>
<td>0.499</td>
<td>0.499</td>
<td>0.500</td>
<td>0.500</td>
<td>0.500</td>
<td>0.500</td>
<td>0.500</td>
<td></td>
</tr>
<tr>
<td>80 °C</td>
<td>0.500</td>
<td>0.500</td>
<td>0.500</td>
<td>0.500</td>
<td>0.500</td>
<td>0.500</td>
<td>0.500</td>
<td></td>
</tr>
</tbody>
</table>

These property sets may then be used in various analysis methods for designing structurally efficient laminated safety glass, Bennison et al (2001).

STRUCTURAL PERFORMANCE OF IONOPLAST LAMINATES

In this section we present comparisons of laminate structural behavior using either Butacite® (PVB) or SentryGlas® Plus (Ionoplast) interlayers. A key benefit of a SentryGlas® Plus interlayer is the full structural coupling achieved between glass plies in the laminate. These structural properties are maintained to elevated temperatures and long-term load durations. This provides much enhanced strength behavior and reduced laminate deflection versus a conventional PVB laminate.

Strength Behavior

Figure 2 gives comparative examples of the load resistance (or strength) of laminated glass fabricated with different interlayers and monolithic glass. These tests have been carried using a four-point bend methodology based on ISO 1288-3. Figure 2 plots the maximum principal glass stress (measured with strain gages) as a function of applied load for three beam constructions: a) monolith - nominal 10 mm annealed glass; b) laminate - nominal 5 mm annealed glass / 0.76 mm PVB interlayer / 5 mm annealed glass; c) laminate - nominal 5 mm annealed glass / 0.76 mm Ionoplast interlayer (DuPont SentryGlas® Plus) / 5 mm annealed glass. Note for clarity, this figure shows only the maximum glass stress at the center point of the beam. Several points may be noted from the data presented in Figure 2. First, if we chose a glass design stress (allowable stress) of 17 MPa, we can see that the PVB laminate requires less applied force to generate the design glass stress than for the monolithic glass control, i.e. it is “weaker” or shows less “load resistance” than the monolith. Second, the SentryGlas® Plus laminate actually requires slightly more load than the monolithic glass control to generate the glass design stress, i.e. it is “stronger” than the PVB laminate and the control monolith. Note these data have been collected at a test temperature of 50º C. The observation that the SentryGlas® Plus laminate is stronger than the monolithic glass control is surprising at first glance. However, this interlayer is stiff enough to transfer shear stresses efficiently from one glass ply to the other and the total laminate thickness.
is greater than the monolith. Due to minimum thickness variability, the nominal 10 mm monolith actually is 9.5 mm, whereas the 10.76 mm laminate is 10.1 mm in thickness. The efficient transfer of shear stresses coupled with the larger section modulus of the laminate results in greater strength behavior for the SentryGlas® Plus laminate.

![Graph showing glass stress development as a function of applied load](image)

**Figure 2:** Glass stress development as a function of applied load

**Deflection Behavior**

The deflection behavior of the same beams used in stress measurements has also been collected and is presented as Figure 3. Note for clarity, this figure shows only the maximum deflection at the middle of the beams.

![Graph showing maximum beam deflection as a function of applied load](image)

**Figure 3:** Maximum beam deflection as a function of applied load
Several features can be noted from these data. First, for a given load the PVB laminate deflects more than the monolithic control beam. Second, the SentryGlas® Plus laminate deflects the least at any given load. Again this reflects the relatively poor shear transfer efficiency of PVB and the efficient shear transfer properties of the stiff SentryGlas® Plus interlayer.

Also plotted on this figure is the predicted deflection-load characteristic for a 9.5 mm monolithic glass using ISO 1288-3. Note the predicted response accurately reflects the observations and shows the experimental procedure is accurate. Secondly, we have also plotted the response of a laminate, assuming the interlayer is simply a liquid, i.e. zero shear coupling. This is the so-called “layered” limit used in many standards to treat laminated glass conservatively. It can be seen that the PVB interlayer does contribute some shear transfer under the condition used in this experiment (50º C, “short” duration loading rate).

**Effect of Temperature**

In order to investigate the role of temperature on glass stress development, the ISO 1288-3 bend tests have been carried out at different fixed temperatures from room temperature to approximately 75º C. Care has been taken to compensate properly for temperature effects in the measurement of glass stress using strain gages. Figure 4 plots the applied force needed to generate a glass stress of 17 MPa, which has been chosen as a design (or allowable) stress for this example. These data demonstrate several key points: 1) the load resistance of PVB based laminates decreases monotonically with temperature for the range studied; 2) The load resistance of SentryGlas® Plus laminates is insensitive to temperature until about 55° C, after which some reduction occurs; 3) the control 10 mm glass load resistance remains constant with temperature (i.e. strain gage protocol and temperature corrections are adequate).

![Figure 4: Load-temperature behavior for various beams](http://www.dupont.com/safetyglass/)

Note the SentryGlas® Plus laminate is slightly stronger than the monolithic control, again because it is slightly thicker. This laminate behaves as if is a single monolithic glass sample at temperatures below 60° C.
Post Glass Breakage Behavior

A further advantage of the structural properties of an Ionoplast interlayer is the improved mechanical performance of a laminate in case of accidental glass breakage. The stiffness advantage of the interlayer over PVB, which is maintained to high temperatures (see Figure 1), results in a more robust condition if the laminate is broken accidentally. One such application of this performance feature is in the Planar™ | SentryGlas® Plus system. This frameless glazing system combines the most established engineered brand of Point supported glass with DuPont’s high performance SentryGlas® Plus interlayer. During system evaluation, tests have been performed in which the tempered glass has been broken using a diamond tipped punch. The resistance to impact and pull-out from the bolted fittings has been tested by repeatedly dropping a 136 kg weight from a 1 meter height onto the laminate at temperatures between – 20° C and 55° C. Even though the glass has been broken in the test protocol, the laminate survives the impact and shows minimal tendency to tear free from the fittings under these conditions.

Structural Durability

Key to the performance of laminated glass using a structural interlayer is the retention of mechanical properties over the life of the building. Extensive product testing and surveys of actual SentryGlas® Plus-containing laminates in service for over ten years in Florida have shown that this interlayer maintains its mechanical/structural performance and is less prone to the development of edge features typical of many other type of laminated glass. For example, measurements of bending stiffness for laminates exposed to varying weathering, in Florida (temperature excursions between 0° C to 45° C, and relative humidity up to 90 %) show the bending stiffness is essentially unchanged over time and is direct evidence of the interlayer durability. The interlayer also passes the USA Florida Dade County requirements of 5 years accelerated weathering with less than 10 % change in physical properties. Additional testing such as thermal cycling between -40° C to 82° C, ASTM Xe-arc testing, EMMA testing have also been carried out on SentryGlas® Plus laminates with minimal change in mechanical and optical properties.

STRUCTURAL ANALYSIS

A key contributing factor in the implementation of high performance structural glazing is the development of modeling and design techniques that enable the engineer to take full advantage of the structural performance of Ionoplast interlayers. High quality modeling also places the onus on materials suppliers to provide appropriate property values that are suitable for design calculations (see Section: Ionoplast Interlayer). Here we discuss two important approaches to modeling laminated glass.

Finite Element Method

The finite element method of analyzing laminated glass is described in detail elsewhere, Bennison et al (1999), Van Duser et al (1999). Here we show the accuracy of the method in predicting the behavior of laminated glass plates. The deformation of four-side supported plates has been studies by subjecting a series of plates with varying sizes, aspect ratios and laminate constructions to uniform pressure. The plates have been supported following ASTM E997-01. Plate deflection and glass stress have been measured and recorded at multiple locations using
deflection gages and rosette strain gages respectively. Figure 5 shows an example of results from two independent plates, 1 m x 1 m in size with a construction of 5 mm annealed glass / 0.76 mm Ionoplast interlayer (DuPont SentryGlas® Plus) / 5 mm annealed glass. Note for clarity, this figure shows only the stress at the plate center.

![Diagram](image)

Figure 5: Stress development at the plate center. (Data courtesy of Professor Huang Xiaokun, China Academy of Building Research, Beijing)

Also shown in figure 5 is a prediction of stress development as a function of applied pressure from a finite element simulation of this plate test, ABAQUS™ (2008). This is not a “fit” to the data but a prediction and as can be seen, is accurate. The finite element method allows simulation of laminate deformation under complex loading/support scenarios and varying thermal/load duration histories. It has proved to be the most accurate and flexible method for analysis. Many other validation experiments have shown that this approach is capable of accurately simulating deformation as function of temperature, rate and different geometry, such as pressure loading of a plate simply supported on all four sides (membrane-dominated stress state). Combining this stress analysis method with statistics of glass breakage and static fatigue effects provides the basis for the computation of the strength design charts for laminates contained in ASTM E1300-06. The approach described in this method is capable of simulating changes in thermal and time history of loading plus long-term creep behavior.

**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 (1987). 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:

$$
\Gamma = \frac{1}{1 + 9.6 \frac{EIh_v}{Gh^2a^2}}
$$

With:

$$
I_s = h_1h_{s;2}^2 + h_2h_{s;1}^2
$$

$$
h_{s;1} = \frac{h_1h_1}{h_1 + h_2}
$$

$$
h_{s;2} = \frac{h_2h_2}{h_1 + h_2}
$$

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

Where:

$h_v$ = Interlayer thickness
$h_1$ = Glass ply 1 minimum thickness
$h_2$ = Glass ply 2 minimum thickness
$E$ = Glass Young’s modulus
$a$ = Length scale
$G$ = Interlayer shear modulus

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

Figure 6: Effective thickness for deflection calculations
For calculations of laminate deflection, the laminate effective thickness, $h_{ef;w}$, is given by:

$$h_{ef;w} = \frac{\sqrt[3]{h_1^3 + h_2^3 + 12\Gamma_I}}{2}$$

(6)

Figure 6 shows the effective thickness for deflection calculations as a function of interlayer shear modulus, $G$, for the laminated beams used in the ISO 128803 testing.

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

$$h_{1;ef;\sigma} = \frac{h_{1;w}}{\sqrt{h_1 + 2\Gamma h_{x;2}}}$$

(7)

$$h_{2;ef;\sigma} = \frac{h_{2;w}}{\sqrt{h_2 + 2\Gamma h_{x;1}}}$$

(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 ($\Gamma \rightarrow 1$) and approaches the layered limit (IGU approximation) for compliant interlayers ($\Gamma \rightarrow 0$). 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. 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.

DESIGN SOLUTIONS WITH AN IONOPLAST INTERLAYER

Here we present an example of a real structure in which the use of SentryGlas® Plus has provided an elegant design solution that has extended the laminate performance beyond a PVB limit and reduced the total solution cost. The structural properties of SentryGlas® Plus have been fully utilized by Pilkington engineers in the development of the Planar™ | SentryGlas® Plus System. Frameless laminated glass based on Planar™ | SentryGlas® Plus provides designers with the most structurally efficient glazing systems available, i.e. minimum laminate thickness, larger glass spans and fewer support fittings.
An example of a Planar™ | SentryGlas® Plus System can be seen in Figure 7, which shows the barrel vault roof of the Yorkdale Shopping Mall in Toronto, Canada. The snow load specification for this roof was 65 pounds per square foot (3.1 kPa) applied for 30 days. To meet this specification with a PVB interlayer for the desired panel size and supports, an insulated glass unit (tempered pane plus laminated pane) with a total glass thickness of 35 mm would have been needed. With the Planar™ | SentryGlas® Plus System one pane of 10 mm thick glass and one pane of a 17.5 mm laminate, i.e. 26 mm total glass, has been used. This is a weight saving of over 25 % for the units. Note the structural design utilized the effective thickness concepts described in conjunction with performance testing.

CONCLUSIONS

We have presented performance data and commercial examples that highlight the structural advantage of laminated glass made with an Ionoplast interlayer. The combination of the unique structural properties of this interlayer with modern engineering analysis methods, enables the design of high-performance, cost-effective laminated architectural safety glass.

Acknowledgements

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References


