The structural behavior of laminated glass is a complex topic. 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 15 years.

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STRUCTURAL PROPERTIES OF LAMINATED SAFETY GLASS

INTRODUCTION

The structural behavior of laminated glass is a complex topic. 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 15 years. This progress is primarily attributable to advances in mechanics and associated computational tools (e.g. FEA software) and the development of appropriate interlayer property information that accurately captures the effects of load duration and temperature on the polymer properties.

The result of this body of work is the capability to now model accurately the structural behavior of laminated glass using modern finite element analysis (FEA) 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 FEA technology. These simplified design approaches are often inaccurate, although usually conservatively so. Such conservative approaches tend to result in an abundance of over-designed laminated glass systems, which in turn leads to unnecessary extra cost. Accordingly, there is a 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.

This chapter outlines the properties and structural advantages of laminated safety glass and how common interlayer types (i.e. PVB and SentryGlas® ionoplast interlayer) perform under various test conditions. This includes tests that enable comparisons to be made between the structural performance of PVB laminates, ionoplast interlayer (SentryGlas®) laminates and monolithic / tempered glass. These tests include bending / deflection tests (four-point bending), as well as tests that enable the effective thickness of laminated glass to be determined accurately.

This chapter also describes the various methods currently available for comparing and calculating the strength of laminated safety glass.
**BENDING TESTS**

In the glazing industry, the Four-Point Bending Test is the industry-standard test for determining the strength and stress properties of laminated glass and monolithic tempered glass. These tests are defined in EN ISO 1288-3 standards.

EN ISO 1288-3 is a useful test for studying laminated glass, including load-bearing capacity (i.e. applied load-glass stress behavior and laminate deflection behavior).

The effective thickness of laminate can be extracted directly from these tests. Temperature and load duration effects can also be analyzed.

The Four-Point Bending test involves measuring the glass stress (using strain gauges) and sample deflection. These are normally short duration tests that also involve simulating sudden gusts of wind. During these tests, the temperature is normally varied from room temperature up to around 70 °C (158 °F).
In tests at Butacite®, the materials compared in the tests were:

- **Monolithic glass:** nominal 10 mm (3/8 in) annealed
- **Butacite® PVB laminated glass:** nominal 5 mm (3/16 in) | 0.76 mm (30 mil) | nominal 5 mm (3/16 in)
- **SentryGlas®:** nominal 5 mm (3/16 in) | 0.76 mm (30 mil) | nominal 5 mm (3/16 in)

**GLASS STRESS DEVELOPMENT**

From the test results it can be seen that laminates with SentryGlas® develop the least glass stress at a specified applied load.
The test results show that laminates with SentryGlas® develop the least deflection at a specified load.
BENDING TESTS - EFFECT OF TEMPERATURE

When the samples were heated in a temperature-controlled chamber, the test results show that laminates with SentryGlas® were insensitive up to around 50 °C (122 °F).

However, the structural performance of PVB laminate is temperature-sensitive. For short duration loads, PVB laminates show reduced strength (compared to the equivalent monolithic glass) above 20 °C (68 °F).
BENDING TESTS ON BALUSTRADES

Kuraray Interlayer Solutions has also collaborated with an independent research institute in the UK to compare the structural performance of glass balustrades made from PVB laminates, SentryGlas® and monolithic glass. The Balustrade Test Program, which was developed by UK consultant John Colvin, compared the pre-glass breakage strength and deflection properties of the glass panels, which were manufactured by UK company Kite Glass.

The panels measured as follows:
- 19 mm (3/4 in) tempered monolithic
- 10 mm (3/8 in) tempered | 1.52 mm (60 mil) PVB | 10 mm (3/8 in) tempered
- 10 mm (3/8 in) tempered | 1.52 mm (60 mil) SentryGlas® | 10 mm (3/8 in) tempered

These tightly controlled tests used common loading and support systems. Cantilever supports or bolted infill panels were used according to BS 6180. Line load and point load testing was carried out in accordance with BS 6399-1. Glass strength and deflection were measured at a temperature of 23 °C (73.4 °F).

FREESTANDING BARRIER (CANTILEVER)

In these tests, a line load of 1.5 kN/m (8.5 lbf/in) was applied to the top edge of the glass panel. In the center and corners of the panel, concentrated load of 1.5 kN (337 lbf) was also applied.
The test results clearly demonstrate that laminates with SentryGlas® interlayer develop the least deflection under the same load conditions.

The test results also show that laminates with SentryGlas® interlayer develop the least glass stress under the same load conditions.
CONCLUSIONS

In both sets of tests, laminates with SentryGlas® interlayer performed in a manner that was similar to the equivalent thickness of monolithic glass, both in terms of the deflections and the stresses induced. However, the PVB laminates developed significantly higher stresses and deflections than the equivalent thickness of monolithic glass. Therefore, laminated glass manufactured with PVB interlayer cannot be considered as having a performance equivalent to monolithic glass of similar thickness when it is used in barrier / balustrade glass panes, subject to concentrated loads and / or fixed loads at discrete points.

4.2.4 EFFECTIVE THICKNESS

The structural performance of laminated glass is commonly considered by defining the effective thickness, i.e. the thickness of a monolithic glass beam with equivalent bending properties in terms of stress and deflection. This method captures many of the important variables that influence performance. General expressions have been proposed on the basis of simplified models, but these are either difficult to apply or inaccurate.

How is it measured?
In 2009, a method for determining the effective thickness for laminated glass for use in numerical analysis was added to ASTM E1300. A similar approach is also proposed in the latest European standard, prEN 13474 (2009), which uses OMEGA numbers for the ‘Coupling Approach’. Previously, glass thickness selection was limited to laminated glass charts presented in the ASTM E1300 Standard with a PVB interlayer. The effective thickness methodology provides an equivalent monolithic thickness based on the interlayer properties and glass geometry. Utilizing the effective thickness with a numerical analysis method, stresses and deflections for laminated glass can be easily modeled.

ASTM E1300-09 effective thickness approach with analytic expression for the bending case is an acceptable approach, but the key here is to have analytic expressions that are close to the problem being investigated.
Other test methods for determining the structural properties of laminated safety glass include the use of 3D finite element analysis methods with full viscoelastic models. This method is accurate and captures the rate and temperature effects and is capable of modeling complex loading/support conditions. Test results can be validated for a range of rates, temperatures and bending states.

2D finite element methods with effective interlayer stiffness is also an acceptable method, although this method is conservative and so does tend to overestimate stress. However, it is useful for evaluating the effect of different interlayer types.

\[
h_{eff} \text{(Deflection)} = \sqrt[3]{h_1^3 + h_2^3 + 2 \frac{\bar{A}}{a}}
\]

\[
\bar{A} = \frac{1}{1 + 9.6 \frac{h_2}{G} \frac{h_1}{a^3}}
\]

\[a\] measure of shear transfer (0 - 1)
CALCULATING AND COMPARING THE STRENGTH OF DIFFERENT LAMINATES

GLASS STRENGTH CALCULATOR

In order to help designers and structural engineers estimate the stress and deflection behavior of glass laminates, Kuraray has developed an online software tool, which can be accessed via the SentryGlas® website. ‘The Strength of Glass Calculator Tool’ enables users to compare different types and thicknesses of laminates made from SentryGlas® or PVB interlayers.

The tool is able to model various support scenarios and loads, including one and two-sided support; line loads or uniform pressure loads; and selectable time and temperature conditions. By varying these factors, users can simulate different wind conditions and snow loads, etc.

The tool can be used to calculate the following:
- Maximum glass stress under load and comparison to design strength specified in various standards such as ASTM E1300
- Laminate deflection
- Effective laminate thickness
- Laminate behavior as a function of time and temperature

It is important to understand that the Kuraray ‘Strength of Glass Calculator Tool’ is only intended as a helpful guidance tool and does not imply any guarantee of true glass laminate behavior in the design or engineering of actual architectural glass structures.

STRUCTURAL BENEFITS OF SENTRYGLAS®

From the various tests outlined, it can be concluded that SentryGlas® interlayer extends the performance of laminated glass. This enhanced structural performance allows laminate designs with:
- Thinner glass systems (Downgauging glass thickness)
- Larger panel sizes
- Extended pressure / temperature performance ranges
- Minimal support in frameless glazing systems
Kuraray Interlayer Solutions:
STRUCTURAL PROPERTIES OF LAMINATED SAFETY GLASS

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