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Investigation of Laminated Glass Failures Due to Thermal Contraction in Thick Interlayers

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Abstract

This paper presents behavior of thick interlayers under extreme cold temperatures, stemming from a review of failures of laminated glass panels for a public project in America's Midwest. The glass included 4.57mm SentryGlas (SG) interlayer to achieve tornado resistance, which is three times the total thickness of typical SG interlayer. Failures, primarily in insulated spandrel areas, were initially attributed to high thermal stresses due to extreme cold winters (-36°C recorded) at the site location. Further study revealed that the contraction of the interlayer, exacerbated by its increased stiffness at low temperatures, was the major contributing cause. Finite element analysis (FEA) and freezer testing replicated the failures, showing Mode II substrate fractures where adhesion exceeded glass strength, leaving a thin glass skin on the interlayer. An additional failure mode was observed where the same contraction stresses exceed the adhesion strength of the interlayer, leading to delamination. Adhesion testing on site samples yielded "High" pummel values, indicating that glass and interlayer failure can occur at very cold temperatures with high interlayer adhesion. This study highlights risks of thick interlayers in cold climates and informs standards for structural glazing.

Keywords

Laminated glass, SentryGlas, thermal contraction, Mode II substrate failure, cold climate

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1. Introduction

SentryGlas (SG) has revolutionized architectural glazing, offering excellent strength for structural applications and, more recently, impact resistance with a thick interlayer for hurricane-prone regions. However, its material properties— including a coefficient of thermal expansion (CTE) 15 times that of glass (1.25×10^{-4} /°C vs. 8.28×10^{-6} /°C) and stiffness increasing 65-fold from 50°C to -30°C—potentially poses challenges in extreme cold climates. 16 of approximately 3500 panels failed in this manner.

Thermal analysis of glass panels typically considers tensile stresses generated at a cold edge when the center or majority of the panel is relatively warm. However, there is limited information in the literature of the behavior of glass laminates under uniform cooling. This should not be ignored as the thermal contraction induced in a 2.1m × 0.9m [6mm glass – 4.57 mm interlayer – 6 mm glass] laminate will result in 42.3kN force stretching the interlayer at -30°C, storing 455 J energy (comparable to .357 Magnum bullet). Interlayers are typically viscoelastic, SG included, and become particularly stiff and strong at cold temperatures.

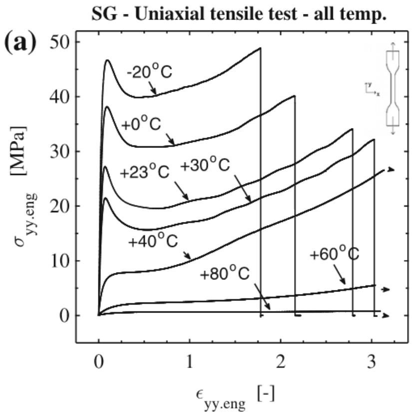

Fig. 1: SG stress-strain curves across a range of temperatures (Santarsiero).

This paper examines the behavior of SG when subject to a uniform cold temperature. The analysis was borne from the review of a significant percentage (0.5%) of failures of insulated glass units utilizing triple-thickness SG (4.57mm) for a project in America's Midwest. These failures occurred during the cold winter months over a 9-year period. Failures were concentrated in spandrel panels – these locations are insulated from building warmth and experience colder temperatures.

2. Background

2.1. Project Overview

Approximately 3500 laminated glass panels were installed for the project from 2014–2016. Typical curtainwall construction was employed, including fritted and insulated spandrel panels. Low e was included against the airspace of all IGU's. The design requirement was for EF2 tornado resistance, which led to the specification of 4.57mm thick SentryGlass 5000 interlayer.

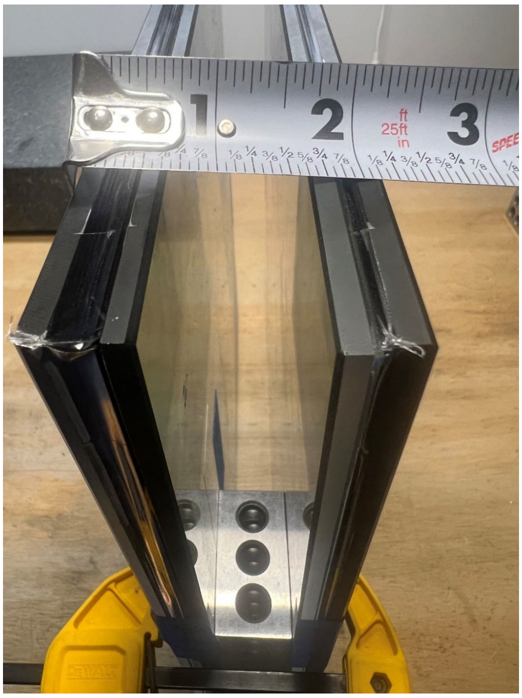

Fig. 2: Comparison of project interlayer thickness (left, 4.57mm) vs typical (right, 1.52mm).

All glass specific to the makeup in question was heat-strengthened. A portion of the project included a banded black frit on the #2 surface, which reduces glass strength by ~50% (as confirmed by testing). The weakened glass due to the frit is irrelevant for wind loads due its location within the laminate. Glass surface temperatures were measured during the investigation period to have reached -28°C for spandrel panels and -17°C for vision panels (these occurring when outside temperatures dropped to -36°C).

2.2. Observed Failures

Over 80% of the failed panels were at spandrel locations and all factures occurred in one or both of the outer two plies. Failures coincided with cold snaps at the project location, where temperatures were below -20°C, often with high winds (>60km/h gusts; Weather data taken from National Weather Service; No accounting of wind speed was taken in surface temperature determinations).

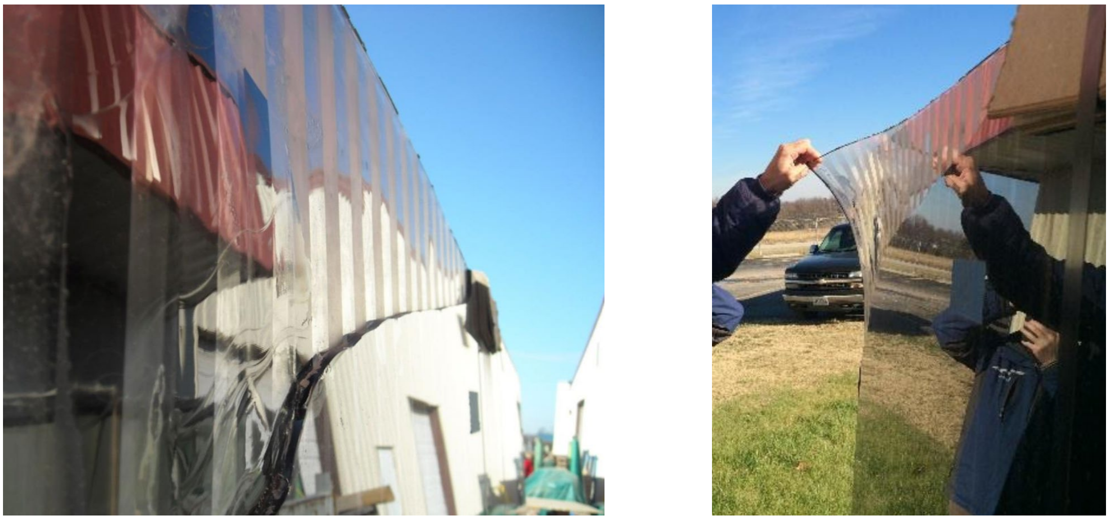

Fig. 3: Failed glass from site. Left: Thin layer of glass stuck to interlayer as evidenced by wavy reflection; Right: Fully detached flexible interlayer at one corner.

Fig. 4: Left: Salvaged site panel with fully detached interlayer and Ply 1 fragment suffering adhesive failure; Right: Failed site panel where a portion of the outer ply has detached from the interlayer, leaving a thin adhered layer of glass across a portion of the detached zone.

The following were considered as potential root causes: low glass strength (lower than HS levels of precompression), poor interlayer adhesion, wind load stresses, conventional thermal stresses, isochore stresses.

3. Methods

3.1. Structural Analysis

Nonlinear FEA (Strand7 FEA software) was used to model the laminate in both 2D and 3D with the interlayer based on viscoelastic material data from Kuraray (SG) & Santarsiero (2016).

Interlayer test results from DIBt Z-70.3-253 (which correlates pummel values with bond strength) were used to validate FE models and correlate tension load acting on the laminate with stresses at the glass/interlayer interface at bond strength.

FE models were then used to simulate the effect of uniform cooling on the laminate with focus on interaction between interlayer and glass. Stresses due to thermal contraction under cooling were compared with stresses at the glass/interlayer interface to determine likelihood of glass or bond failure.

3.2. Freezer Testing

Eighteen 300mm x 300mm specimens, mimicking the project makeup, were exposed to -60°C air temperature for 140 days or until failure in a laboratory freezer. 3 interlayer thicknesses were tested in order to determine a correlation between interlayer thickness and failure: 1.52mm (standard), 4.57mm, 7.62mm. Freezer testing was completed at -60^{o}C so as to achieve a higher rate of failure than the -30^{o}C observed on site.

3.3. Adhesion Testing

Both specimens recovered from the project site and new 300mm x 300mm specimens underwent pummel testing (ASTM C1908) to validate adhesion quality and bond strength. Pummel testing was conducted at room temperature (cold tests excluded as invalid for SG per the Kuraray guidelines).

3.4. Other Tests and Analyses

Other tests and analyses that were conducted include the following and were determined to not being a significant contributing factor and are not considered further in this paper.

- Stresses due to wind load were calculated using FEA. The glass is supported on 4 sides and no stress of significance occurs at the edges where the majority of failures appear to originate.
- Stresses due to conventional thermal stress (cold edge stress) were calculated using FEA, ASTM E2431 and French NF DTU 39 Part 3. Edge stresses were determined to be 9.6 MPa, which is considerably lower than the allowable for HS glass.
- Stresses due to isochore loads were calculated for expected extreme conditions (cold + high barometric pressure and hot + low barometric pressure). The glass is effectively supported on 4 sides for this analysis and no stress of significance occurs at the edges where the majority of failures appear to originate. The maximum net pressure for isochore in winter conditions was calculated as being 19.2 kPa. Isochore only results in stresses at the center of the panel and peak at less than 7.5 MPa.
- SG CTE used for analysis: 12.5e-5 /degC. Glass CTE used for analysis: 8.3e-6 /degC

4. Results

4.1. Finite Element Analysis

Behavior of glass laminates were calculated for cold conditions with the temperature differential considering difference between simulated ambient condition and original autoclaved temperature.

Glass principal stresses peaked at 71MPa for 4.57mm thick interlayer, and are approximately proportional to SG thickness. Shear transfer occurred over a short distance around the perimeter (~2mm), with tension normal to glass surface and shear in parallel to the surface of glass.

A 4 node quadrilateral plate element plane strain model was used after comparisons with a solid model. Minimum element size was 9.77e-4 mm.

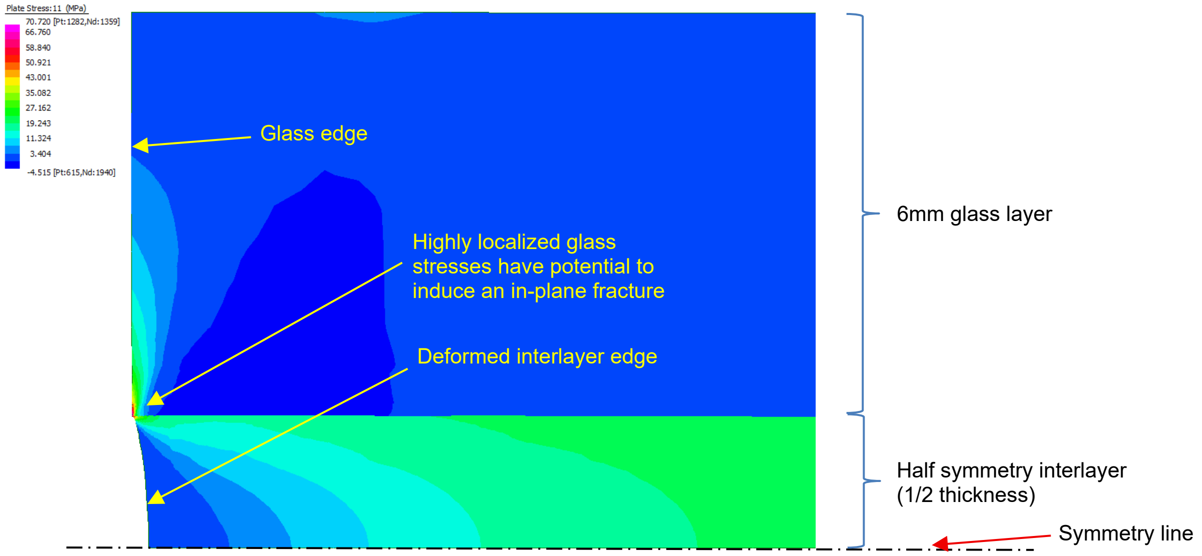

Fig. 5: Symmetric cross section of 4.57mm SG laminate edge, including principal stress contours based on thermal contraction analysis at -30°C. Stresses are localized and have potential of initiating a Mode II (in-plane) fracture to “skin off” the glass from the interlayer.

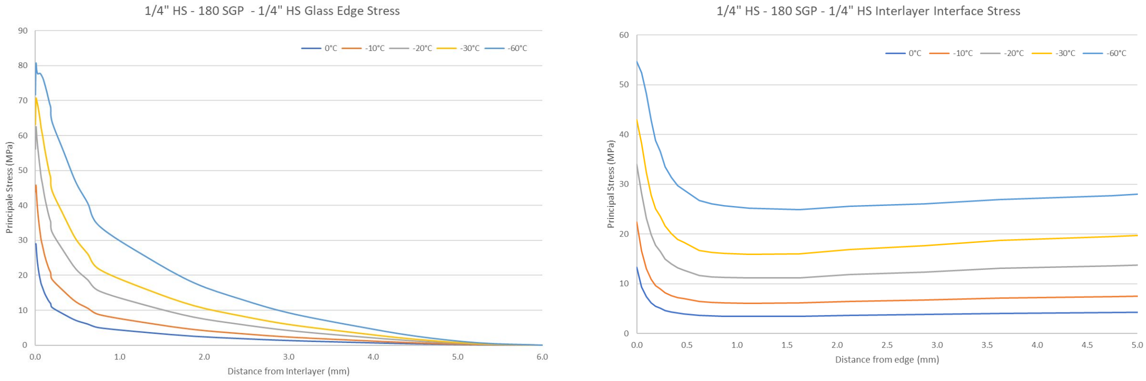

Fig. 6: Calculated stress (glass stress on left, interlayer stress on right) showing localized concentration of stress at edge.

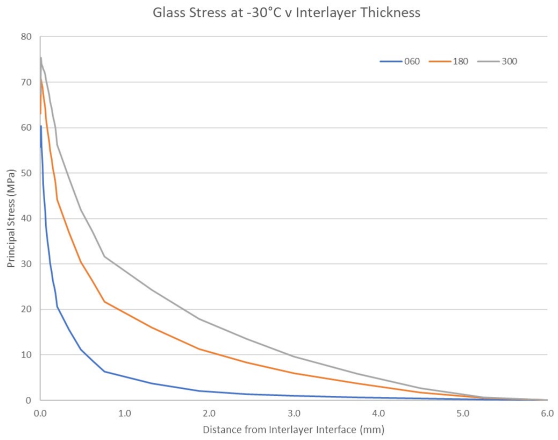

Fig. 7: Correlation of glass stress at -30degC with interlayer thickness, showing increased area under high stress with thicker interlayers.

The FEA results show clear correlation of and increase in both interlayer and glass stresses with increased interlayer thickness. Utilizing the ASTM E1300 RCSS method of determining probability of failure based on applied stress and area of applied stress the effect of increased interlayer thickness on probability of failure is particularly pronounced when comparing 4.57mm interlayer with 1.52 interlayer.

4.2. Freezer Testing

Freezer testing resulted in failures that were approximately linear with interlayer thickness. All failures occurred between 27 and 75 days of cold temperature exposure and testing indicated no relationship between specimen type and time to failure, however, testing indicated very strong correlation between interlayer thickness and probability of failure. All failures resulted in Mode II (in plane) substrate fractures, thin glass skin on interlayer and some adhesive delamination. Failures typically resulted in damage to both sides of an interlayer indicating the weakness on one side of the interlayer results in higher stresses on the opposing side, resulting in failure on both sides.

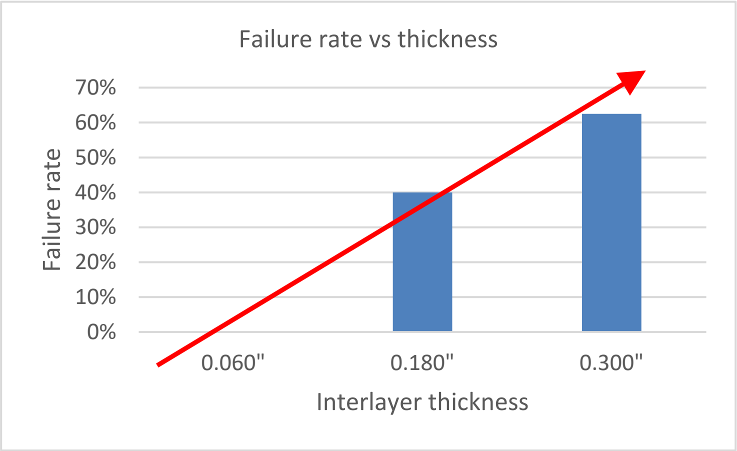

Fig. 8: Correlation between interlayer thickness and failure at cold temperatures.

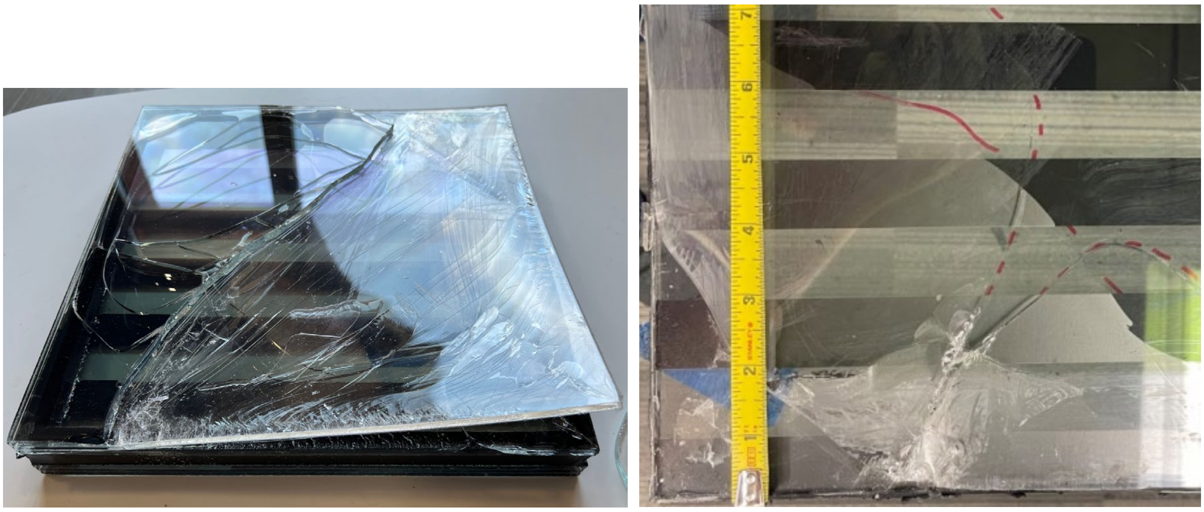

Fig. 9: Freezer tests compared with site glass. Left: freezer test thin layer of glass adhered to on surface (Mode II failure) and adhesive delamination bottom on #3 surface. Right, site sample

4.3. Pummel Testing

Pummel testing conducted on specimens drawing from both site and test specimens at room-temperature all demonstrated "High" adhesion (pummel 6–7).

4.4. Literature Correlation

Similar results have been documented by other practitioners due to the fracture of a fully tempered middle ply in a triple laminate with SG interlayer by both Moreau and Coult. In both cases a Mode II facture (in-plane "skinning" of the glass) would occur subsequent to a typical Mode I fracture (normal to glass plane). Additionally, glue-chipping is a means of intentionally inducing a Mode II failure in glass for decorative purposes. This shear Mode II failure is a relatively under-studied academic field.

5. Discussion

5.1. Failure Mechanism

Failures result from SG contraction in cold, stiffening interlayer pulling against glass. High CTE mismatch creates through-thickness tension/shear, bypassing surface compression from tempering. A combination of highly localized tension stresses and more broad-based shear stress leads to Mode II fractures that occur when adhesion is greater than glass strength, peeling off thin layers (0.5mm) which remain stuck to the interlayer. This behavior is most dominant at spandrel because the heavy insulation sees these reach colder glass temperatures. Additionally, a delamination mode exists where the bond is failed in shear.

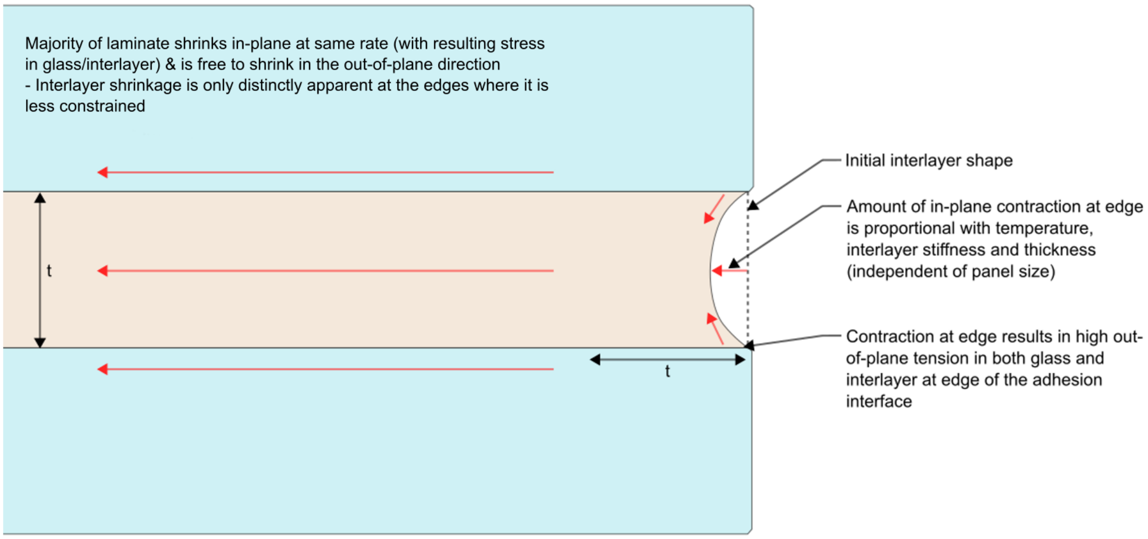

Fig. 10: Mechanism of generating glass stresses from interlayer contraction at cold temperatures.

5.2. Conventional thermal stress

Conventional thermal stresses (hot center, cold edge) was determined not be a cause of failure which is characterized by through thickness cracks starting from a shaded or otherwise cold edge. This was determined both through finite element analysis and site measurement using thermocouples throughout a full year.

6. Conclusions

Increased likelihood in glass and lamination failure can stem from thermal contraction in thick SG interlayers under cold wintertime condition. FEA and testing confirm stresses proportional to thickness, leading to Mode II shear fractures in the body of the glass, and increased likelihood of adhesive type delamination. The SG adhesion frequently proved to be stronger than glass, even after 10 years of service.

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