Stress Analysis of a Structural Glazing Assembly Bonded by an Acrylic Foam Structural Glazing Tape under Pressure Loading

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Abstract

In the construction industry, acrylic foam structural glazing tapes are used for attaching glass panels to metal frames in curtain wall, window and door, and skylight/canopy systems. The design of the structural glazing tape bonds for such applications, specifically the bond width or bite required to support the load caused by negative wind pressure (i.e., an air pressure differential resulting in tension on a structural glazing tape bond), follows the industry practice of employing the trapezoidal load distribution equation together with an allowable design bond stress. In the work presented here, a finite element analysis was performed to assess an allowable design stress of 15 psi for a specific structural glazing tape by simulating a third-party wind pressure mock-up performance test.

The simulation of the mock up tests showed that under negative wind pressure in the mock-up test, the structural glazing tape is strained such that it experiences the highest tensile stress along its inside edge at the mid span. Though the highest tensile stress may exceed a stress level of 15 psi (0.10 MPa), it is within the bond strength of the specific tape investigated here for the corresponding strain rates. This indicates that the bond will not fail, which is consistent with the full-scale mock-up test results. Both the experimental and finite element analysis results therefore give support for a 15 psi allowable design stress for the specific structural glazing tape when used in conjunction with the trapezoidal load distribution equation methodology to determine the tape bond width for structural glazing applications.

Introduction

The acrylic foam structural glazing tape(1) investigated in this work is a double-coated pressure sensitive acrylic foam tape for attaching glass or glazing panels to metal frames in curtain wall systems, replacing traditional mechanical fasteners, gaskets, or structural silicone sealants. Its mechanical durability under both sustained and dynamic loads has been demonstrated in numerous structural glazing applications that have been in service since 1990. In the following sections this acrylic foam structural glazing tape(1) will be referred to as 'the structural glazing tape' or 'the tape'.

Footnote:

(1) 3M VHB Structural Glazing Tape B23F (VHB Tape)

Over the years, 3M has conducted various tests and collaborative research with academia in generating the acrylic foam structural glazing tape test data and design guidelines specific for structural glazing and architectural panel bonding applications. Starting in 2007, a series of investigations by the research group led by Prof. David Dillard at Virginia Tech focused on the same acrylic foam structural glazing tape investigated in the work presented here. They developed a statistically significant creep rupture strength database for the tape, and a framework for long term bond strength evaluation for the structural glazing tape that employs the creep rupture strength and a linear cumulative damage model (Townsend, et al. 2010; 2011; 2012). An earlier work by the same authors of this current paper (2013) found that the tape bond can accommodate a certain amount of warpage of the glazing panel due to the combination of the tape's bond strength and its hyperelastic-viscoelastic properties that enable stress relaxation and reduction of spring-back stress of the warped panel.

More recently, in responding to architectural desires for aesthetically slim curtain wall framing as well as design flexibility in attaching glazing panels to frames of varying bonding area or width, 3M commissioned a third party test to assess the feasibility of increasing the bond design allowable stress from 12 psi (0.08 MPa), a value 3M has traditionally recommended for structural glazing applications, to 15 psi (0.10 MPa) for the structural glazing tape bond design against relatively short term wind load pressure. A full-scale mock-up test of a glass curtain wall system bonded by the tape was performed by Construction Consulting Laboratory, International (CCLI) of S-United Inc., an independent consulting laboratory, in accordance with the test method of ASTM E 330-14 "*Standard Test Method for Structural Performance of Exterior Windows, Doors, Skylights and Curtain Walls by Uniform Static Air Pressure Difference*." The tests demonstrated that the structural glazing tape bond on the aluminum frame substrates can support a nominal bond stress at 150% of the 15 psi design allowable stress without debonding. The simulation work presented here was part of the validation work for consideration of the 15 psi design allowable stress. Specifically, the simulation work was aimed at verifying that the tape bonds that passed the ASTM E 330-14 tests can support a bond stress above 15 psi, and therefore substantiate the use of 15 psi as an allowable design stress.

Background information of the full scale curtain wall tests

The detailed information of the full-scale curtain wall mock-up test can be found in the report by CCLI (2015). Some of the key elements of the test and test results are reviewed briefly below to provide background for the simulation work presented here.

<u>Curtain wall structural specimen dimensions</u>

Fig. 1 shows the full-scale mock-up structurally glazed curtain wall system tested by CCLI. The glass panel of the curtain wall system was a double pane sealed insulating glass (SIG) with a 0.25 inch (6.4 mm) tempered glass outboard, a 0.5 inch (12.7 mm) air spacer seal, and a 0.25 inch (6.4

mm) inboard. The overall dimensions of the sealed insulating glass panel were 59 in x 63 in x 1 in (1499 mm x 1600 mm x 25.4 mm). The glass panel was bonded to an aluminum frame by the acrylic foam structural glazing tape along its perimeter as shown in Fig. 1. The tape width was 0.75 inches (19.1 mm) and the thickness was 0.09 inches (2.3 mm). In total, four full scale curtain wall specimens were tested (CCLI, 2015).

Pressure loads

In the CCLI tests, the pressure load was the so-called negative pressure load that, overall, exerted tensile loading on the tape bond in the direction perpendicular to the bond surface.

The 100% design pressure load for this glass panel size and an allowable design stress of 15 psi for the structural glazing tape was 55 lbf/ft^2 or 55 psf (2.63 kPa). This is calculated by using the trapezoidal load distribution equation as described in ASTM C 1401 "*Standard Guide for Structural Sealant Glazing*."

Following the ASTM E 330-14 requirements of testing the structural sealant at 50%, 100%, and 150% of the design pressure loads, the uniform pressure loads applied to the glass in the curtain wall test were 27.5, 55.0, and 82.5 psf (1.32, 2.63, and 3.95 kPa), respectively. The details of the loading rates and loading histories are shown in Fig. 2 and can also be found in CCLI's report (2015).

The tape bond width for the acrylic foam structural glazing tape

The commonly known Trapezoidal Load Distribution method has been generally accepted by the glazing industry as an industry standard. It is a simplified design method to determine a structural sealant (the acrylic foam structural glazing tape) joint bite dimension for a rectangular glass panel. The trapezoidal load distribution theory and the associated design equation can be found in ASTM C 1401 "*Standard Guide for Structural Sealant Glazing*", and more detailed descriptions in work by Haugsby, et al. (1990). Following this guideline and Eq. 2 of ASTM C 1401-14 *"Standard Guide for Structural Sealant Glazing,"* a tape bond that is able to support a design pressure load of 55 psf needs to have a bond width of at least 0.75 inches if the allowable nominal tensile stress on the bond is 15 psi:

$$B = \frac{L_2}{2\,F_t} P_w$$
$$= \frac{59\ in}{2\ (15\ psi)} \frac{55\ psf}{(12in/ft)^2} = 0.75\ in$$

where,

B = tape width or bite

L_2 = the short edge length of the glass panel

F_t = the design allowable stress on the structural sealant or the acrylic foam structural glazing tape

P_w = the design pressure load

The 0.75 inch (19.1 mm) width of the structural glazing tape was selected and used in the ASTM E 330-14 curtain wall tests conducted by CCLI. The tests showed that the tape bond on all four curtain wall glass specimens withstood the pressure loads at 50%, 100%, and 150% of the design pressure of 55 psf (corresponding to the design stress of 15 psi) without any debonding (CCLI, 2015). This included the required 10 second applied negative pressure hold per ASTM E 330-14 requirement, and an additional 60 second applied negative pressure hold at each pressure load, which is beyond the requirement of ASTM E 330-14. Such experimental data in compliance with ASTM C 1401-14 and ASTM E 330-14 standards provide strong evidence that a design allowable stress of 15 psi for the structural glazing tape bond is reasonable and safe. For a more rigorous validation to supplement these experimental results, a detailed stress analysis was performed to understand the bond stress and its distribution. Knowledge of the bond stress distribution coupled with the absence of debonding observed in experimental allows confirmation that the bond supports not only the nominal stress on the tape as predicted by the trapezoidal load distribution equation, but also peak stresses in potential stress concentration areas exceeding 15 psi. This leads to a more comprehensive understanding of the tape bond performance and margin of safety. The results of this study are reported below.

Finite element analysis

The finite element model

Based on the structural glazing assembly specimens used in CCLI's test, the structure was simplified and only essential components were included in the finite element model. The 3D finite element model is shown in Figs. 3 to 5. The model included the double pane glass panel sealed with silicone sealant. This is referred to as an insulating glass unit or IGU. The structural glazing tape was attached to the surface of the inboard glass along its perimeter. The metal frame was assumed to be rigid in this simulation and a fixed displacement boundary condition was applied to the tape-to-metal bond surface in order to simulate bonding to a rigid substrate. Notice that spacers, typically of elastomeric materials, between the inboard glass and metal frame (mullions), are absent from the finite element model here, as well as from the full-scale test specimens of CCLI because the structural glazing tape functions as both the bonding adhesive and the spacer due to its precise thickness dimension and adequate stiffness to support the weight of the glass panel while in a horizontal position without being squeezed out.

The pressure load and the loading time history applied in this analysis were the same as those used in the CCLI's tests. In particular, a uniform pressure load was applied on the surface of the inboard glass panel causing a tensile stress on the tape bond. In the simulation, the pressure was ramped up at the same rates used in the test (Fig. 2). After the pressure reached the designated value, the pressure was held for 10 or 60 seconds and unloaded following the same loading history in the tests. Following the exact loading time history of the tests is necessary in order to model the tape's viscoelastic response to the load.

Besides the pressure load, an internal pressure of 1 atmosphere (14.7 psi) was applied in the cavity between the two panels of glass to simulate the filled insulation air pressure typical of an IGU.

It was assumed that the glass panel is perfectly flat with no pre-assembly warpage. A total of six simulation cases were completed in this analysis. The only differences among these six cases were the maximum pressure load applied, the loading rate, and the pressure dwell time. Four of the cases are related to the design pressure load of 55 psf and corresponding to a design allowable stress of 15 psi, and the other two were related to the design pressure load of 44 psf and corresponding to a design allowable stress of 12 psi, which is the current design allowable stress for the structural glazing tape.

The analysis was performed using the ABAQUS finite element analysis package. The 3D solid continuum element C3D8 was used for the glass and silicone sealant, and C3D8H for the tape.

The material models

The IGU was modeled as a linear elastic body with a modulus of elasticity of 9863 ksi (68 GPa) and Poisson's ratio of 0.3. The modulus of elasticity of the silicone sealant used in this model was 131 psi (0.90 MPa), comparable to those found in Dow Corning Corporation's Silicone Structural Glazing Manual (2011). The Poisson's ratio of the sealant was 0.4.

The structural glazing tape was modeled as a hyperelastic and viscoelastic material to capture its compliant nonlinear stress-strain behavior and viscous characteristics. The hyperelastic material model based on the second order polynomial strain energy density function in conjunction with a viscoelastic model in the form of a Prony series was calibrated in a previous work by the same authors (Salmon, Nie, Austin, and Bystrom, 2013) and was used here. This nonlinear elastic and viscoelastic material model allowed simulation of the rate dependent behavior including stress relaxation of the tape in the actual loading history used in the test by CCLI.

Results and discussion

Deflection and displacement near the edge

In the CCLI test, displacement gauges were placed on 3 of the 4 curtain wall specimens as shown in Fig. 1 to measure the total deflection of the double-pane glass panel plus that of deformation of the tape. The gauges' probes were near the edge on the inboard glass to record the deflection of the panel which can be seen in Fig. 1, while the bases of the gauges were fixed on the metal frame of the curtain wall specimens. The probe locations were:

> Edge locations: at the mid span of the long edge and about 0.2 in (5 mm) away from the inside edge of the tape bond
>
> Corner locations: at the corner of the panel and about 0.4 in (10 mm) away from the inside edge of the tape on either the short edge or the long edge of the glass panel.

The measurements were made at the completion of 10 or 60-second pressure duration tests according to CCLI (2015). It should be pointed out here that the distance from the tape edge was visually estimated during the test; actual location measurements were not available.

Due to the technical difficulties in measuring the stress or strain in the tape in the test, the deflection measurements by these displacement gauges were the only data available for validation of the finite element model. The average value of the deflection measurements from edge locations was used here for comparison with the simulation results, while the average deflections from the corner locations were not used in this analysis due to their relatively low values (less than 0.002 inches), their low signal-to-noise ratios, and the resulting associated uncertainty in these measurements.

Shown in Fig. 6 is the contour plot of the deflection (U3) the glass panel viewed from the outboard side, and in Fig. 7 the deflection of the inboard glass panel across its mid long span at the end of the 10-second loading duration for the pressure load of 27.5, 55.0, and 82.5 psf. From Fig. 7, it can be seen that the experimental measurements and the predicted deflections from this simulation generally agree well.

The analysis predicted that the maximum deflection occurs at the center of the glass panel and remains relatively constant over the pressure duration time of 10 to 60 seconds (Fig. 8), consistent with the test observation. This is to be expected as the tape creep strain predicted in this analysis is less than 3% over the time period investigated here.

<u>Stress on the acrylic foam structural glazing tape bond and the bond design allowable stress</u>

The stress distribution contour plots in Fig. 9 show that the tensile stress on the structural glazing tape bond is not uniform when a uniform pressure is applied to the inboard glass panel. First, along the tape length, the higher tensile stresses are concentrated in the mid-section of the long and short edges of the panel. Second, across the tape width, the tensile stress is only in the inside edge portion of the tape, while in the outside edge portion, the tape is under compression due to the bulging deflection of the glass panel.

This location where the maximum tensile stress on tape occurs is shown in Fig. 5 and is termed as A_{VHB}. For the three pressure loads of 27.5, 55.0, 82.5 psf, the time history of the maximum tensile stress at location A_{VHB} is plotted in Fig. 9. For the pressure loads of 44.0 and 66.0 psf (corresponding to the 12 psi design stress), the stress at A_{VHB} is plotted in Fig. 10. Shown in Fig. 11 are the contour plots of the tensile stress on the tape at the mid-span of the long edge immediately after the pressure load reached its peak value. During the 10 seconds of constant pressure load hold period, the tensile stress on the tape decreased due to relaxation of the tape.

As shown in Fig. 9 (c), and Fig. 10 (c), the predicted maximum tensile stress on the tape bond exceeded the 15 and 12 psi design allowable stress. While this may seem to cause some question about the tape bond strength, it is, for the purpose of this particular study, a valid confirmation that the actual tape bond strength is above 15 psi since no debonding was observed in the actual tests by CCLI.

To further assess the structural glazing tape's ability to withstand the stress above 15 psi experienced in the full-scale mock up tests, the peak stress in the tape under the test pressure is compared with the tape's bond strength measured on aluminum T-block substrates in a 3M internal test. For the pressure loading rates of 0.063, 0.085, and 0.095 psi/s (0.44, 0.59, and 0.65 kPa/s) applied on the glass panels in CCLI's tests, the corresponding maximum strain rates are 0.025, 0.030, and 0.030 /s, respectively, while the corresponding maximum stresses are 27.5, 40.6, and 53.6 psi (0.18, 0.28 and 0.36 MPa), respectively (Fig. 9). As shown in Fig. 12, the peak stresses in the tape under the applied pressures are below the tape's bond strength for the strain rate range concerned here. Once again, these results are consistent with CCLI's test results of nodebonding failure of the acrylic foam structural glazing tape under the applied pressure loads.

Both the experimental results and this analysis suggest that the maximum tensile stress on the structural glazing tape may exceed 15 psi by up to 2 to 3.5 times. However, these peak stresses are below the tape's bond strength and would not cause debonding. Therefore, the simulation results here support the consideration of a new design allowable stress of 15 psi under the circumstance of designing bond width for the acrylic foam structural glazing tape following the guideline of ASTM C 1401-14 using the trapezoidal load distribution equation, especially for the situation of the wind pressure loading rate between 0.06 and 0.10 psi/sec and pressure duration below 60 seconds.

Summary

A finite element analysis was performed to provide additional data to verify the feasibility of a 15 psi design allowable stress for the bond width design of a specific acrylic foam structural glazing tape made by 3M, specifically when following ASTM C 1401-14 *"Standard Guide for Structural Sealant Glazing"* employing the trapezoidal load distribution equation.

This analysis simulated a pressure test of a full scale mock-up curtain wall system bonded by the acrylic foam structural glazing tape with a bond width designed using a design allowable stress of 15 psi.

- Under the monotonic ramp-up loading with a loading rate of 0.063 to 0.95 psi/s, the simulation predicted that the acrylic foam structural glazing tape may experience peak stress exceeding 15 psi in stress concentration areas along its inside edge in the mid-span. However, the tape'sbond strength is sufficiently high to withstand these peak stresses without debonding, which is supported both by the full mock-up test results by CCLI and by the tape's T-block bond strength data. Specifically, the analysis predicted that the tape bond strength is about 65% higher than the peak stress on the tape bond for a pressure load of 55 psf and strain rate of 0.03/s. Therefore, the simulation results support the consideration of a design allowable stress of 15 psi when designing the acrylic foam structural glazing tape bonds using the ASTM C 1401-14 trapezoidal load distribution equation for similar loading conditions to those investigated here.
- The 15 psi design allowable stress for the acrylic foam structural glazing tape is for a relatively short duration of less than 60 seconds of wind load pressure. For a more prolonged loading duration (e.g., static loading), the tape's creep rupture strength, in addition to the ramp-to-fail strength, need to be considered for the design of the bond. More information of this design approach can be found in an earlier work by Townsend, et al. (2010; 2011; 2012).
- The 15 psi design allowable stress value for the specific acrylic foam structural glazing tape investigated here is available for consideration for use in the trapezoidal load distribution equation to determine the tape's bond width. Due to the assumptions and simplifications employed by this design equation, extra caution should be taken when using 15 psi as a design allowable stress in other applications or analyses.

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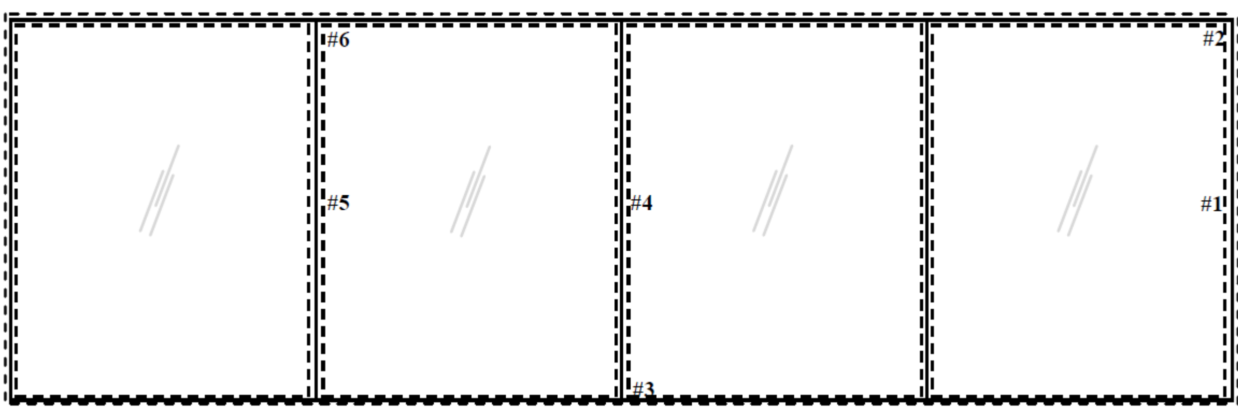
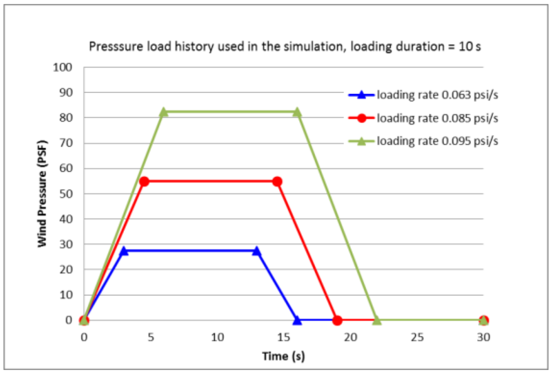
(a)



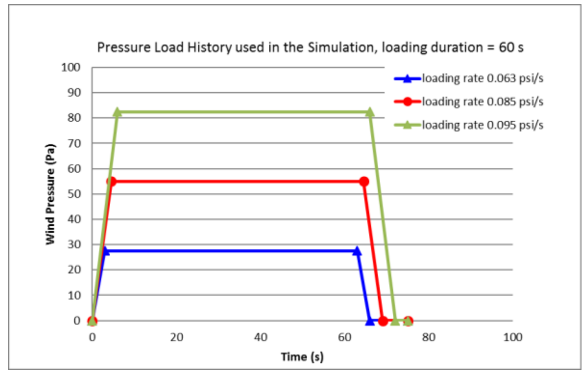
(b)

Fig. 1. The test setup of the full scale curtain wall pressure test by CCLI. (a) Photos of the test set up. The displacement gauges along the edge of the glass panel were used to measure the deflection of the panel under the test pressure. (b) Illustration of the locations of the displacement gauges (courtesy of CCLI).



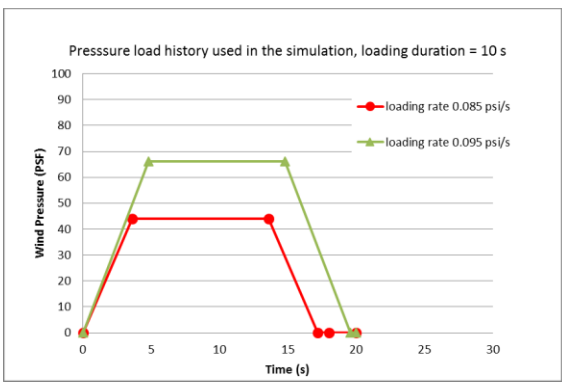
Pressure load history for 10 sec dwell time and 15 psi bond design allowable stress

(a)



Pressure load history for 60 sec dwell time and 15 psi bond design allowable stress

(b)



Pressure load history for 10 sec dwell time and 12 psi bond design allowable stress

(c)

Fig. 2. Pressure loading rates and loading history of the full scale curtain wall tests by CCLI.

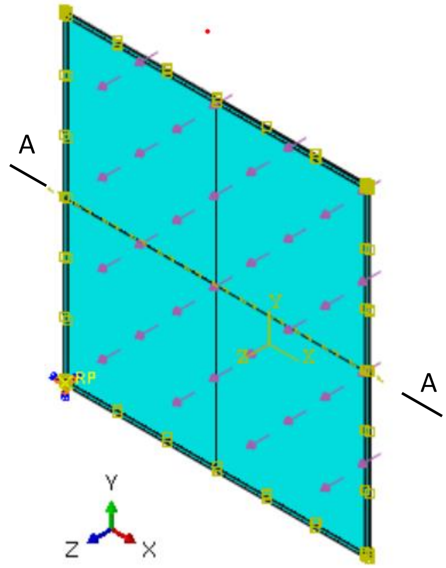


Fig. 3. The finite element model of the curtain wall specimen used in the ASTM E 330 test by CCLI. The double pane glass panel was bonded by the acrylic foam structural glazing tape to a rigid metal frame.

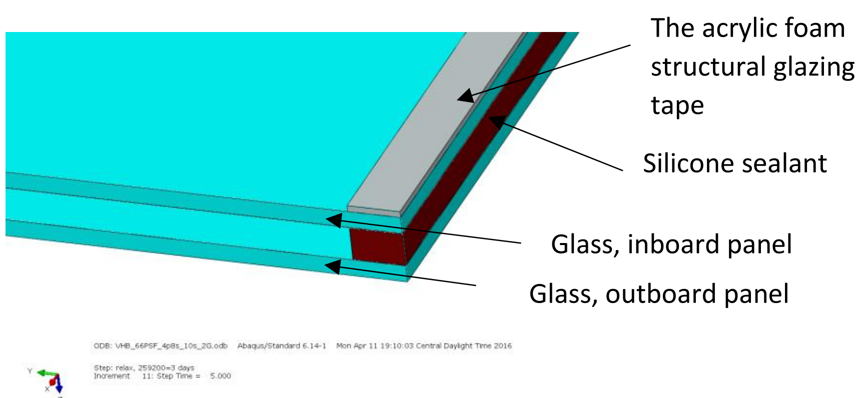


Fig. 4. Cross section (shown here is only the right portion of AA cross section in Fig. 3) of the finite element model of the double pane glass panel. The perimeter of the inboard and outboard glass panels was sealed with silicone sealant

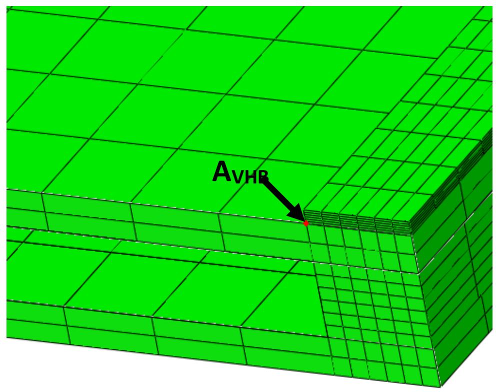


Fig. 5. Finite element mesh in the region of the curtain wall system shown in Fig. 4. A relatively fine mesh was used for the acrylic foam structural glazing tape to better reflect the non-uniform stress distribution. Location A_{VHB} on the structural glazing tape at the mid-span of the long edge of the glass panel is used later for examining the maximum tensile stress on the acrylic foam structural glazing tape.

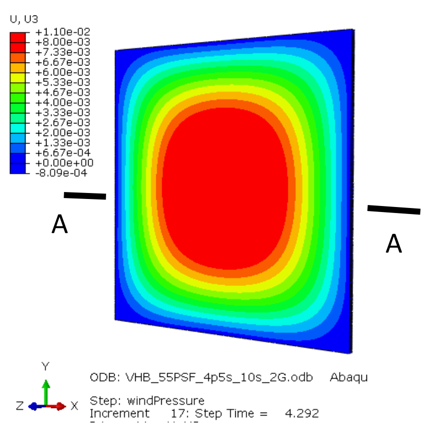


Fig. 6. Contour plot of the deflection of the glass panel immediately after the pressure load is ramped up to 55 psf in the finite element simulation showing the deflected shape.

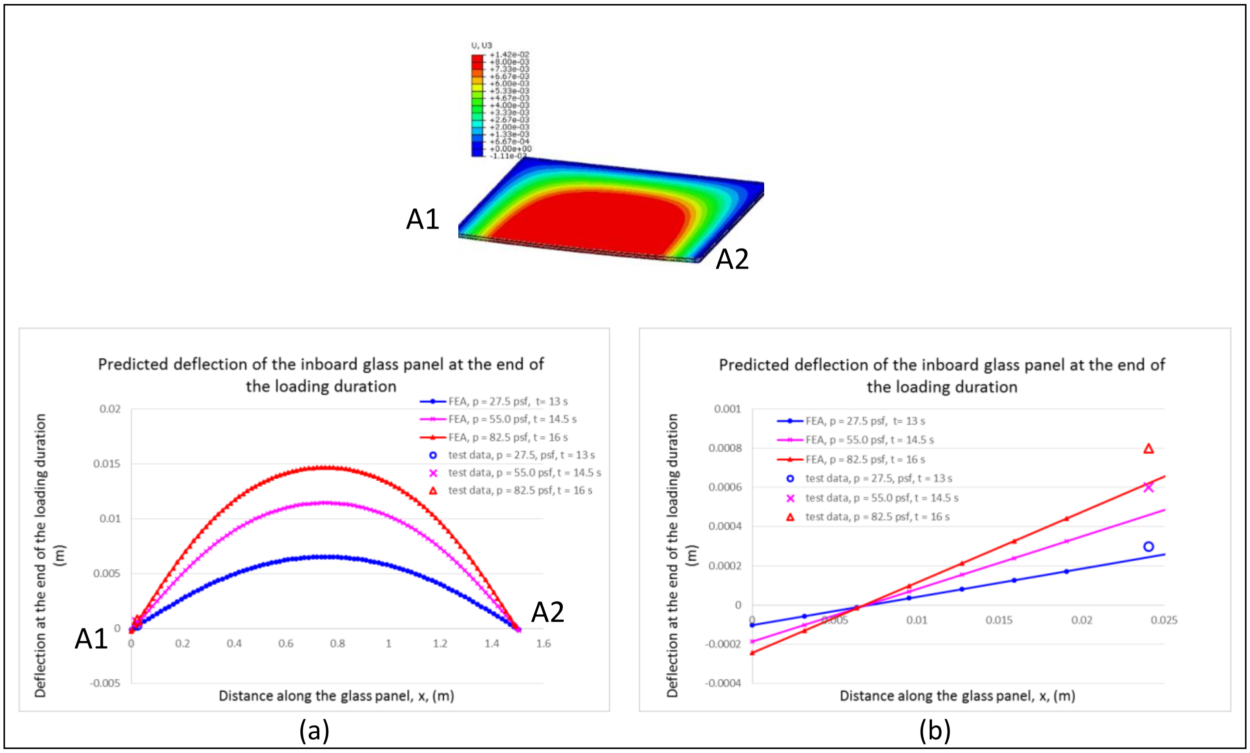


Fig. 7. Deflection of the inboard glass panel across its mid long span, A1-A2, at the end of the loading duration for pressure loading of 27.5, 55.0, and 82.5 psf. The time at the end of the loading duration is 13.0, 14.5, and 16.0 sec for the three loading cases, respectively. (a) across mid long span, A1-A2; (b) detail of (a), near the edge A1.

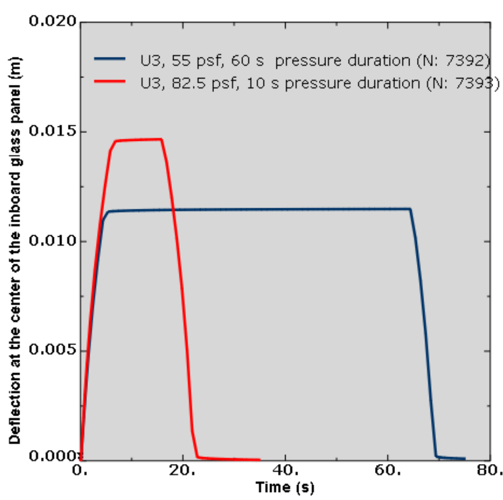


Fig. 8. Time history of the deflection at the center of the inboard glass panel showing relatively constant deflections over the pressure load duration time of 10 to 60 seconds.

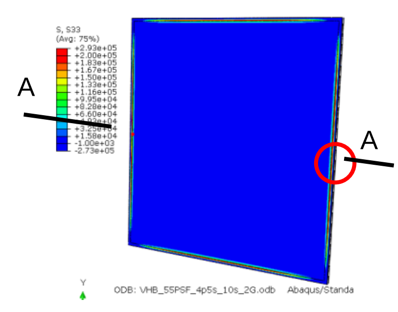
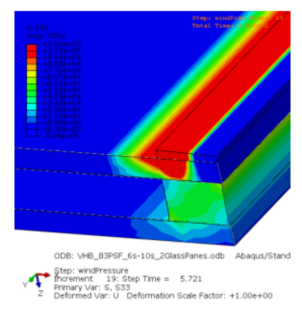
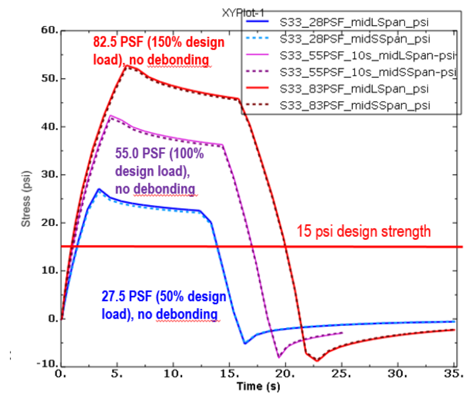
		
The curtain wall system (a)	Tensile stress on the tape bond at cross section A-A (b)	The maximum tensile stress history of the tape at location A_{VHB}. For 15 psi design stress allowable. (c)

Fig. 9. The maximum tensile stress on the acrylic foam structural glazing tape (a) contour plot of the tensile stress, S33, immediately after the pressure load reached its peak value, (b) details of the stress, S33, at the mid-span of the long edge, (c) the maximum tensile stress on the tape at location A_{VHB} (shown in Fig. 5) during the pressure loading history.

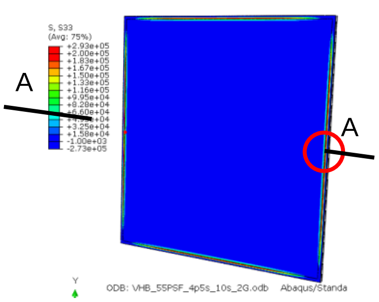
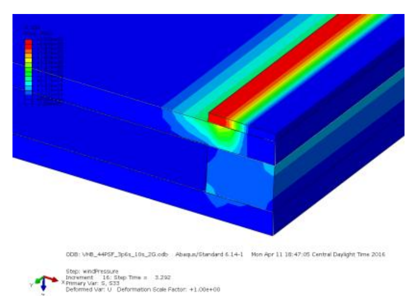
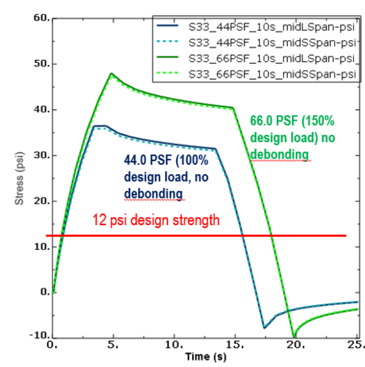
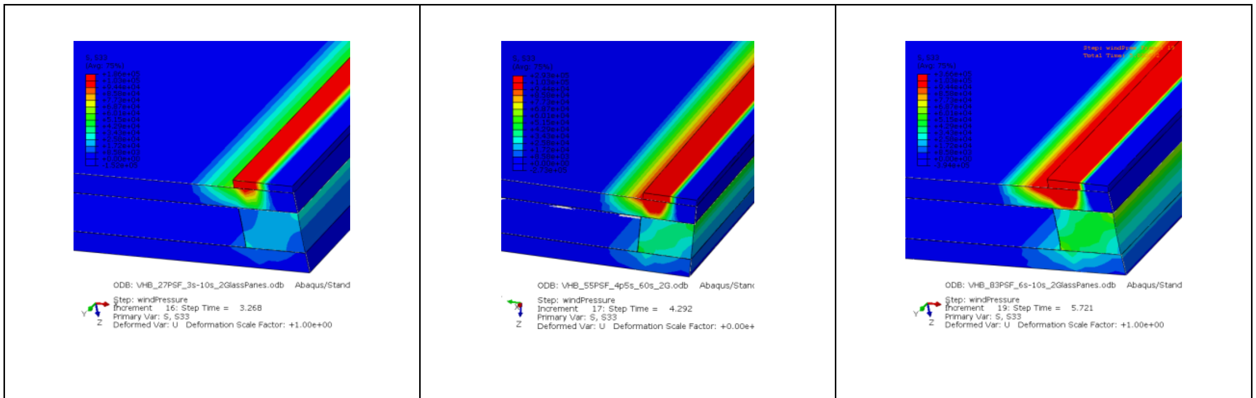
		
The curtain wall system (a)	Tensile stress on the tape bond at cross section A-A (b)	The maximum tensile stress history of the tape at the mid span of the long edge of the glass panel, location A_{VHB}. For 12 psi design stress allowable. (c)

Fig. 10. The maximum tensile stress on the acrylic foam structural glazing tape (a) contour plot of the tensile stress, S33, immediately after the pressure load reached its peak value, (b) details of the stress, S33, at the mid-span of the long edge, (c) the maximum tensile stress on the tape at location A_{VHB} (shown in Fig. 5) during the pressure loading history.



27.5 psf	55.0 psf	82.5 psf

Fig. 11. Contour plots of the tensile stress on the acrylic foam structural glazing tape at the mid-span of the long edge immediately after the pressure load reached its peak value.

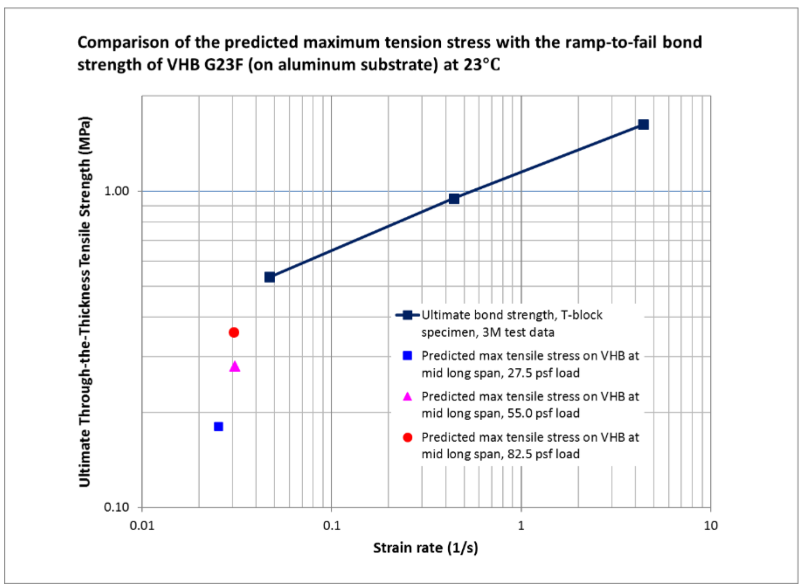


Fig. 12. Log-log plot of the acrylic foam structural glazing tape bond strength vs strain rate and comparison of the predicted maximum tensile stress on tape during the full scale mock-up test by CCLI. The ultimate bond strength of the acrylic foam structural glazing tape bond was measured in an earlier work by 3M (Austin and Bystrom, 2014)