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EDGE CAPACITY OF THROUGH-BOLTED LAMINATED GLASS

PREPRINT

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80th Shock & Vibration Symposium

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ABSTRACT

This paper presents the results of testing and analytical developments sponsored by the U.S. Department of State to investigate the capacity of through-bolted laminated glass edge supports. Design equations and supporting test data are presented that capture the capacity of the through-bolted laminate material in reaction to in-plane membrane induced loading. A simple analytical treatment of edge clamping forces is presented. Preliminary test data supports the validity of the clamping force calculation. The feasibility of designing through-bolted connections that are capable of reaching capacity for the full post-crack in-plane membrane tension of laminate materials is demonstrated. Laminate coupon testing and laminated glass drop hammer testing was executed by the Force Protection Branch of the Air Force Research Laboratory (AFRL) at Tyndall Air Force Base, Florida. Laminate component testing and analytical developments were conducted by Southern Research Institute in Birmingham, Alabama.

INTRODUCTION

The U.S. Department of State, Bureau of Diplomatic Security, Research and Development Group is executing a research program aimed at developing new and innovative ways to retrofit facilities for improved safety against physical threats resulting from blast, ballistic and forced entry attacks. A specific area of focus involves various methods for connection of laminated glass to framing members in window and curtain wall retrofit systems. The primary objective of the current investigation is to develop guidelines for design of through-bolted laminated glass that will support utilization of the full strength and ductility of laminates in the post-cracked-glass phase of blast shock wave resistance. The current research involves static, high strain rate, and high load rate testing that supports development of design equations and guidelines.

BACKGROUND

The current investigation is focused on window retrofit systems wherein laminated glass is connected to framing systems using through-bolted edge connections. The left side of Figure 1 shows an example of a through-bolted edge supported laminated glass connection. The right side of the figure shows the cross-section of the connection. A typical connection is made up of gasket material with pressure bars that serve to press the gasket material against the glass. The bolts are lightly preloaded against the pressure bar causing gasket compression. While the primary goal of the development is to provide required protection against various blast, ballistic, and forced entry threats; a secondary goal is to develop the full capacity of the laminated glass with a minimum of edge distance and number of bolts.

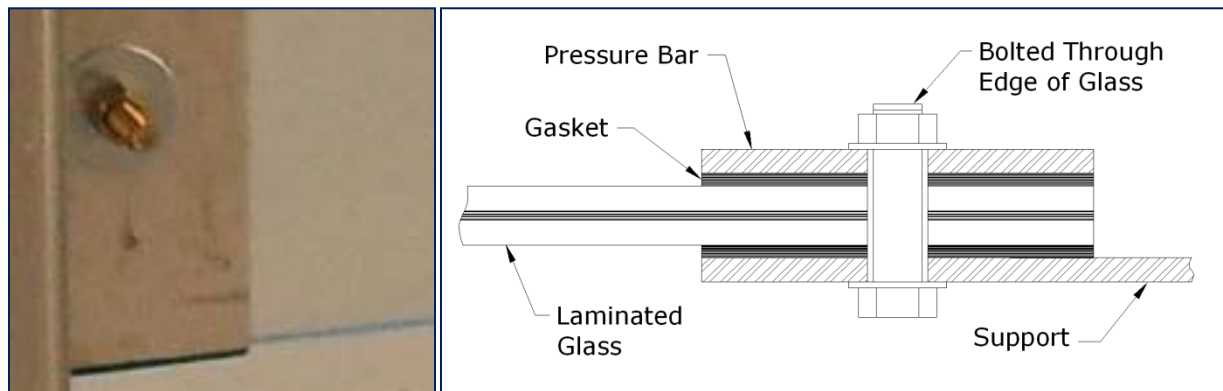


Figure 1. Typical through-bolted edge connection.

The presence of holes in the laminated glass at the through-bolted connection causes concern over the notion of developing the full capacity of the laminated glass. Basic approaches to design result in prediction that severely limit the design capacity of this class of connection. In-plane forces resulting from large deflection lead to tension forces at the edge. Holes in the laminated glass tend to reduce capacity in tension. However, anecdotal evidence primarily obtained from Department of State testing indicates that in many cases through-bolted connections do provide substantial and in many cases adequate support for the glass edge.

Windows subjected to high energy blast loading typically exhibit large deflections resulting in cracking throughout the glass layers of the laminated assembly. It is often the case in blast events that the glass cracks early in the event. The post-crack response of the laminated glass is primarily characterized by the laminate material with glass fragments remaining attached. A common assumption is that the post-crack behavior is dominated by laminate material acting as a membrane with the glass providing mass only. The membrane assumption matches with the current effort to understand the capacity of the edge support relative to in-plane membrane loading. Thus, the current research is focused on characterizing the in-plane capacity of through-bolted edge supported laminated glass.

TECHNICAL APPROACH

Given the basic assumption that the post-crack behavior of laminated glass is primarily controlled by membrane action of the laminate material, a basic technical goal is to document connection guidelines that assure development of the full membrane capacity of the laminate without failure at the connection. It is assumed for the current development that the global capacity of the laminated glass is evaluated under a separate investigation. The issue at hand is local to the connection and is concerned with avoiding failure at or between the bolts that results in edge pull-out.

The edge pull-out resistance of the laminated glass is assumed to be provided primarily by the in-plane strength and ductility performance of the laminate material plus the clamping and friction developed at the gaskets. A series of tests were executed to characterize both contributions to the edge pull-out capacity. Equations based on classical mechanics were developed to predict the capacity. The subsequent discussion documents various aspects of the testing effort and the reliability of the classical predictions. Note that the current discussion documents an approach for treatment of in-plane edge loading near the mid-length of supported edges.

LAMINATE MATERIAL PROPERTIES

While the current effort is not explicitly focused on characterizing the basic material properties of the laminate material, a series of tests were conducted as a reference for subsequent component level testing. The current report documents characteristics obtained using SentryGlas® by DuPont as the laminate material. Laminate materials are often elastic-plastic with relatively high strains to failure. Strain rate effects have a very large impact on mechanical properties including effective yield and tensile strengths plus total strain to failure. Coupon level tests were executed to obtain reference data for material properties. Figure 2 shows the data obtained for two different strain rates.

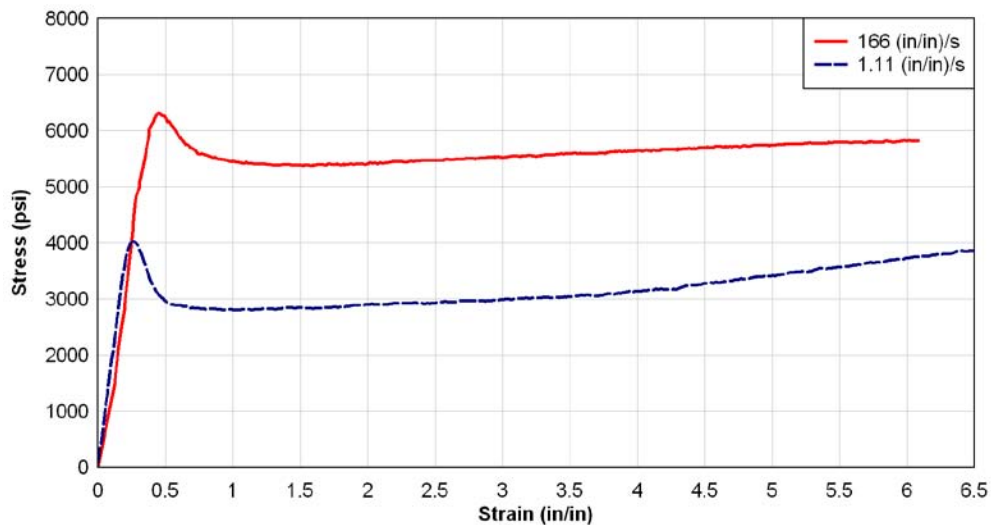


Figure 2. Strain rate sensitive material properties.

Results similar to those in Figure 2 were used to compare with reported values from various sources including manufacturer data. In general terms, the data obtained fell within the range of values reported from other sources. The gist of the material property investigation is that the mechanical properties are very sensitive to strain rate. Other issues that have an impact on material properties include pre and post laminated properties and temperature effects. A noteworthy characteristic of SentryGlas® observed during some of the laminated glass testing discussed below is the highly effective post-crack bond of the glass to the laminate. With the exception of material properties that are specific to SentryGlas®, most of the developments and conclusions in the current report may be applied for other laminate materials that exhibit similar elastic-plastic behavior, very high plastic strains to failure, and highly effective post-crack bond of glass to laminate.

LAMINATE CAPACITY – TEST RESULTS

A series of static component level tests were performed to characterize the capacity of through-bolted laminate material in tension. Figure 3 shows a fixture that was designed and fabricated to perform the component level tests. The fixture is designed to receive multiple bolt spacing and edge distances. Given the basic assumption that the post-crack behavior of laminated glass is primarily controlled by membrane action of the laminate material, a relatively simple technical goal was to provide connection guidelines that assure development of the full membrane capacity of the laminate without failure at the connection. It is assumed for the current development that the global capacity of the laminated glass is evaluated under a separate investigation. The issue at hand is local to the connection and is concerned with avoiding failure at or between the bolts that results in edge pull-out.

Edge pull-out resistance of the laminate material was evaluated using the fixture in Figure 3. The overall width of the fixture shown in Figure 3 is 24in. The bolt spacings were set at integer multiples of 3in. The clear distance from the top fixture to the bottom fixture was set at 12in. The laminate was installed with bolts set at finger tight. The intention was that the laminate tests should characterize the laminate capacity without added resistance from clamping induced friction forces. The right side of Figure 3 shows a typical post-test condition.

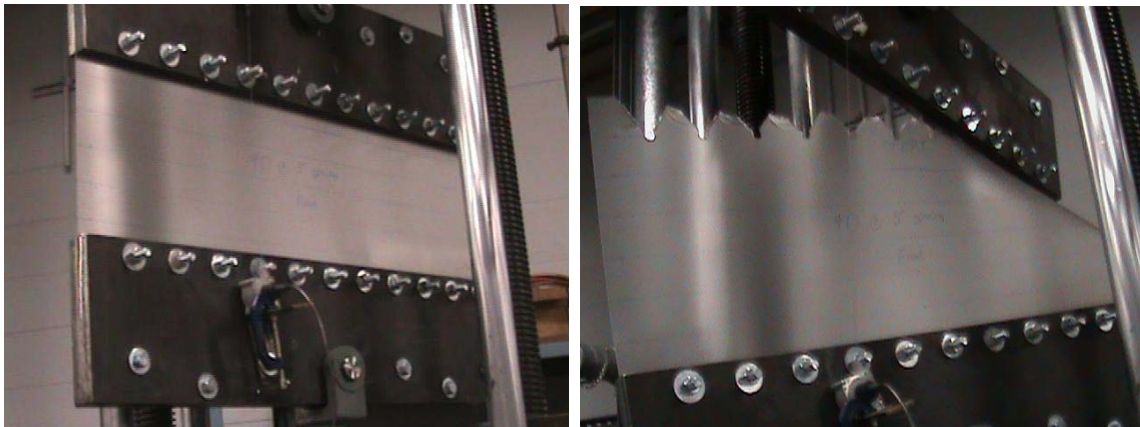


Figure 3. Static component level testing of laminate.

Figure 4 shows the failure mechanisms observed in the laminate edge failures. Shown from left to right are classic V-notch failure, pure shear/pull-out, and hole-to-hole net area tension failure. Figure 5 shows the recorded component edge capacity with variations in bolts spacing and edge distance ratios (e/D). e/D is calculated for the physical edge distance from the center of the hole, e , divided by bolt diameter, D . Note that the tests were all performed using 1/2in diameter bolts with 9/16in diameter holes. The sloped portion of the lines corresponds to V-notch and tear-out failures. The horizontal portion of the 3in spacing line corresponds to hole-to-hole net area failure. Focusing on the upper curve for 3in spacing, as the edge distance increases the capacity increases up to a point where the failure transitions from V-notch and tear-out to net area failure. This observation is consistent with connection failures seen in other structural applications, e.g., classical treatment of bolted connections in structural steel design. It is reasonable to claim that with increased edge distance the lower two curves in Figure 5 would exhibit similar horizontal lines that reflect hole-to-hole net area failure.



Figure 4. Laminate edge failure mechanisms.

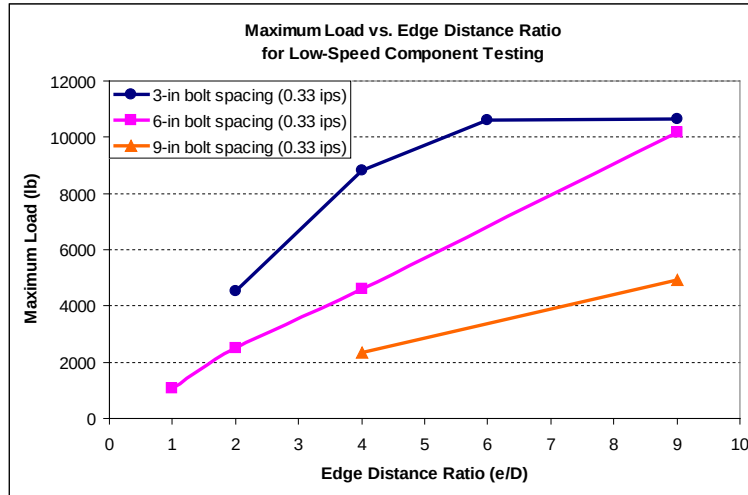


Figure 5. Laminate edge capacity.

LAMINATE CAPACITY – CLASSICAL SOLUTION

A simple equation based on classical mechanics was developed to predict the edge capacity of the laminate material. Figure 6 shows the key geometric parameters used to evaluate the edge capacity. As seen above, failure is either V-notch / tear-out at the bolts or net area tension failure between the bolts. The V-notch failure is captured analytically by simply resolving the tension capacity of the laminate across the sloped lines shown in Figure 6. The net area along the sloped line is obtained using the dimension L_e . The length of the sloped line, L_e , is based on the effective edge dimension h_e where h_e represents an effective perpendicular distance from the edge of the laminate to the failure surface at the inside of the hole. Based on observations and measurements made from the post test specimens, h_e is reasonably approximated by

$$h_e = e - \left(\frac{d}{4} \right) \quad \text{Eq. 1}$$

where d is the hole diameter. The hole diameter d is assumed to be no larger than the bolt diameter plus 1/16in for bolt diameters in the range of 3/8in to 5/8in. The angle θ represents the orientation of the failure plane as recorded

from the laminate testing described above. The measured value of θ ranged from 25 to 45 degrees. The lower value of $\theta=25^\circ$ was chosen for subsequent calculations since it corresponds to a lower effective area prediction and thus a

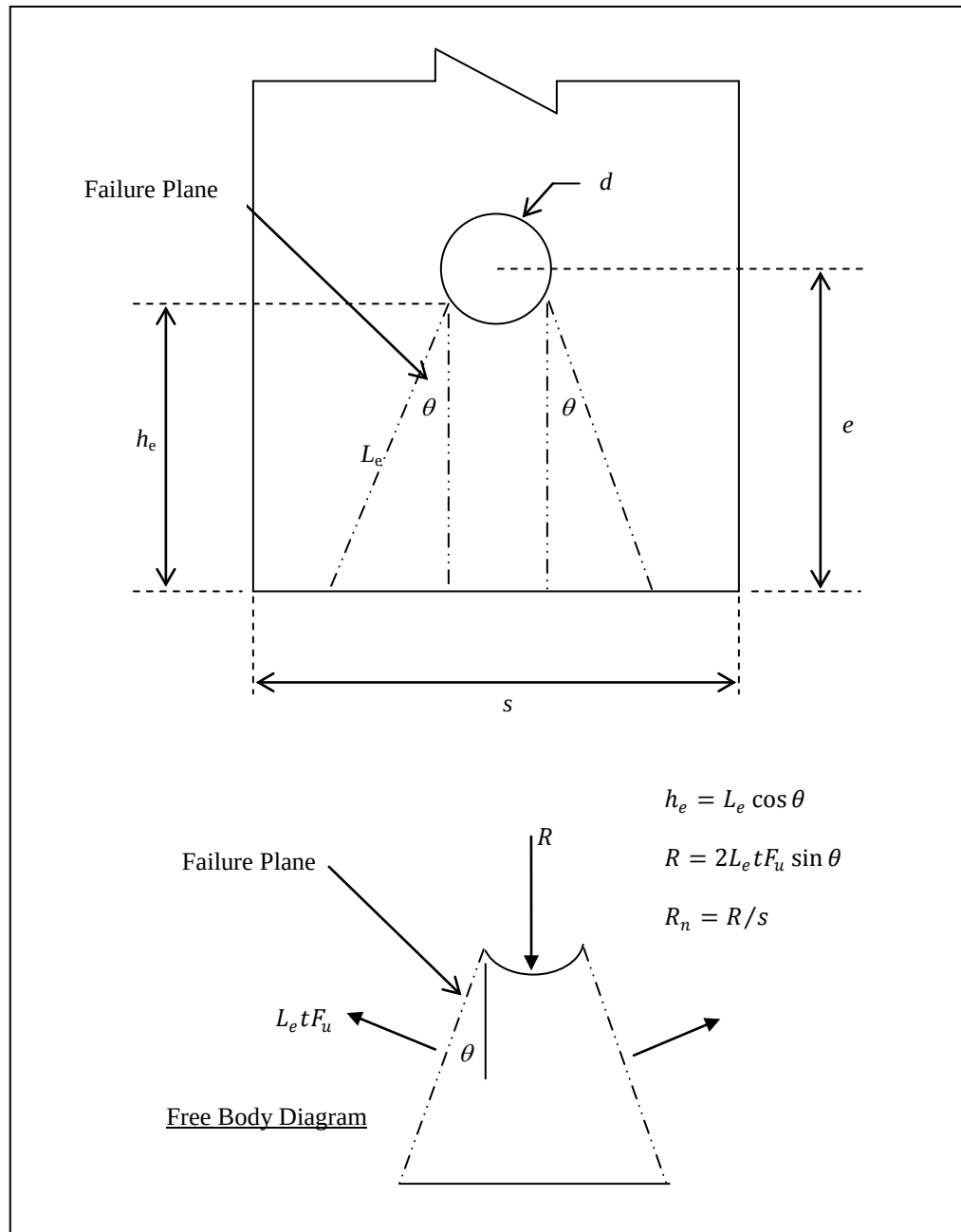


Figure 6. Classical solution parameters.

conservative prediction for the V-notch capacity. Equation 2 below captures the predicted V-notch / pull-out capacity R_n as

$$R_n = \frac{2\left(e - \frac{d}{4}\right)tF_u \tan \theta}{s} \quad \text{Eq. 2}$$

In the equation above, R_n has units of force per unit length, t is the laminate thickness, F_u is the ultimate tensile strength of the laminate, and s is the center-to-center bolt spacing dimension.

The second failure mechanism to be captured for the through-bolted laminate capacity prediction is bolt-to-bolt net area tension failure. The net area capacity is simply calculated from

$$R_n = \frac{(s - d)tF_u}{s} \quad \text{Eq. 3}$$

The $(s-d)$ term in Equation 3 is the net distance between the bolt holes. The predicted capacity is taken as the minimum of the values obtained from Equations 2 and 3.

Test results and analytical predictions are shown for comparison in Figures 7, 8, and 9. The three figures correspond to bolt spacings of 3in, 6in, and 9in respectively. The dashed lines represent the predicted edge capacities as calculated from Equations 2 and 3 above. The values used for the predictions include laminate thickness ($t=0.09$ in), and ultimate tensile strength of the laminate ($F_u=4000$ psi). The solid lines represent the test data shown in Figure 5 above except that the data has been normalized to force per unit length to match the format of the analytical predictions.

Review of Figures 7, 8, and 9 shows good correlation in the shape of predicted capacity curve versus the plotted test data. The predictions underestimate the in-plane edge capacity of the through-bolted laminate. Some of the values used in the analytical prediction may be adjusted to yield better correlation; however, the values used in the current presentation yield consistent and conservative results. The absence of the horizontal line in the 6in and 9in spacing plots is discussed above. In summary, as e/D increases, the predicted capacity is limited by Equation 3 which is characterized by horizontal lines on the charts. Given extension of the e/D scale range, the dashed lines will exhibit horizontal segments.

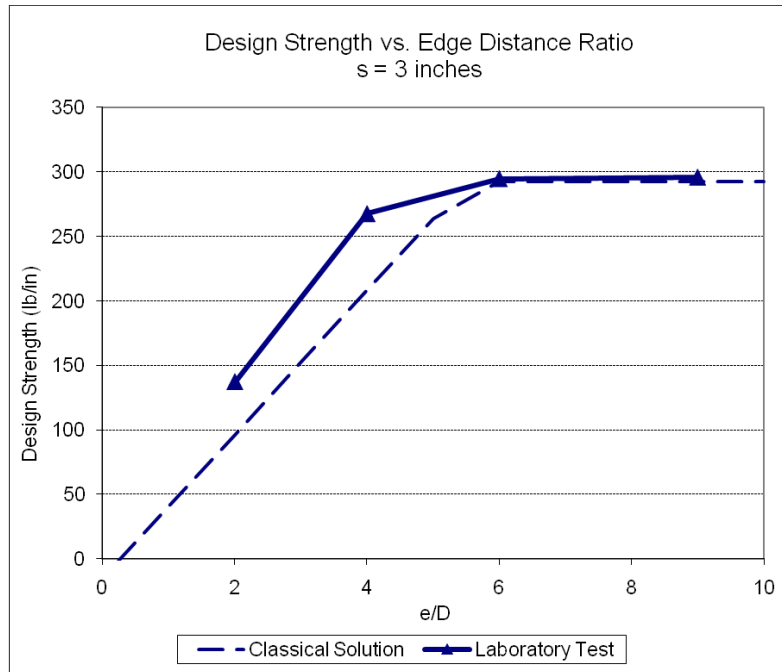


Figure 7. Laminate edge capacity, 3in spacing.

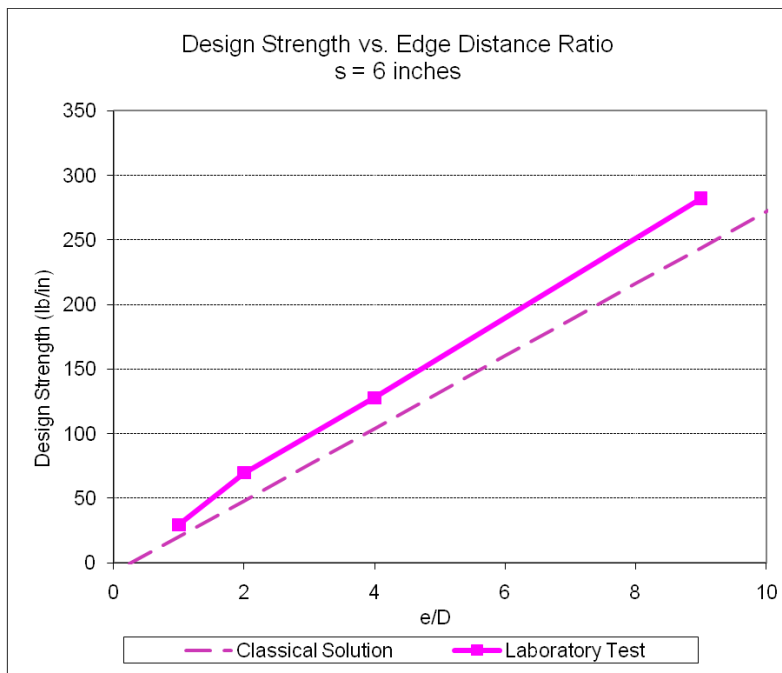


Figure 8. Laminate edge capacity, 6in spacing.

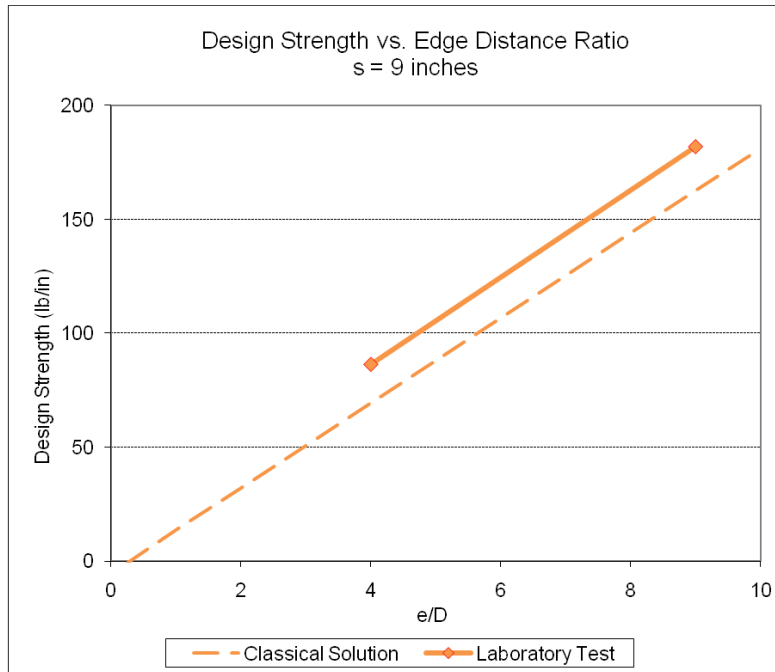


Figure 9. Laminate edge capacity, 9in spacing.

EDGE CLAMPING AND FRICTION – IN PROGRESS

The basic goal of the current effort is to develop bolt spacing and edge distance guidelines for through-bolted laminated glass. One goal of the current investigation is to assure development of edge connection capacity that meets or exceeds the gross capacity of the laminate in a post-crack configuration. The chart below shows an example wherein the gross laminate capacity is plotted as a horizontal line. That gross capacity is seen as the minimum capacity or goal capacity for the connection design. The lower sloped line represents the capacity of the through-bolted laminate alone as is presented in discussions above. A simple friction calculation based on bolt pre-load and corresponding gasket compression is represented by the upper sloped line. As shown in the chart, the combination of laminate edge capacity and clamping induced friction offers great promise for total connection capacity that exceeds the gross laminate capacity.

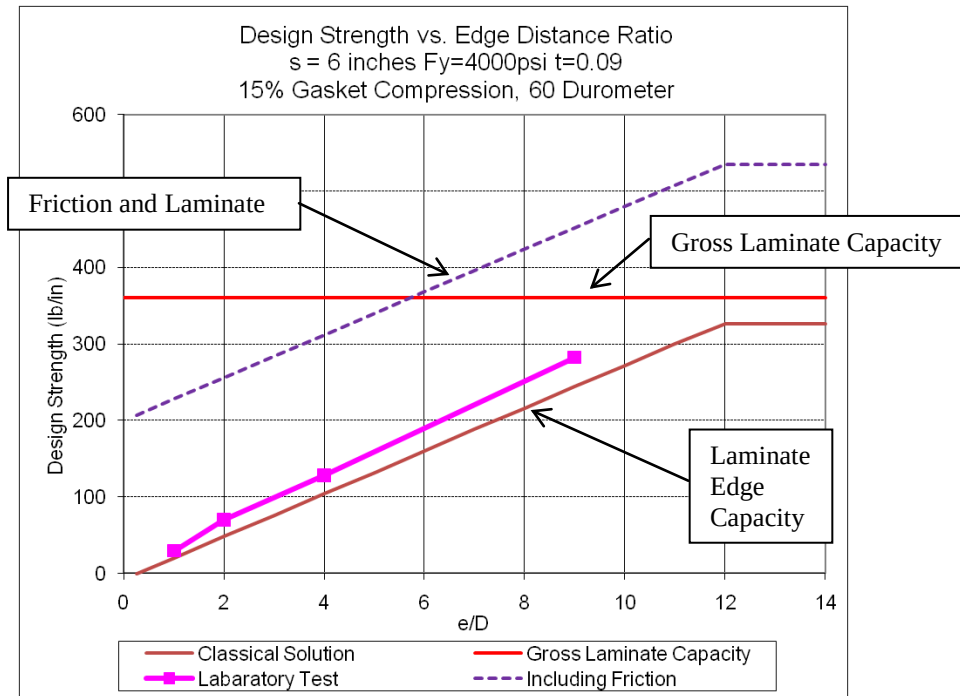


Figure 10. Predicted connection capacity with friction.

A series of tests have been executed at AFRL to capture the effects of clamping friction on the edge capacity of through-bolted laminated glass. A test fixture was designed and installed to use with a drop hammer system. The test setup provides high energy loading resulting in high strain rates in the laminate material. The test was designed to capture the effects of the clamping force with allowance for variations in bolt spacing, edge distance, bolt pre-load, glass type, laminate thickness, input energy, and edge support restraints. A rendering of the test setup is shown in Figure 11.

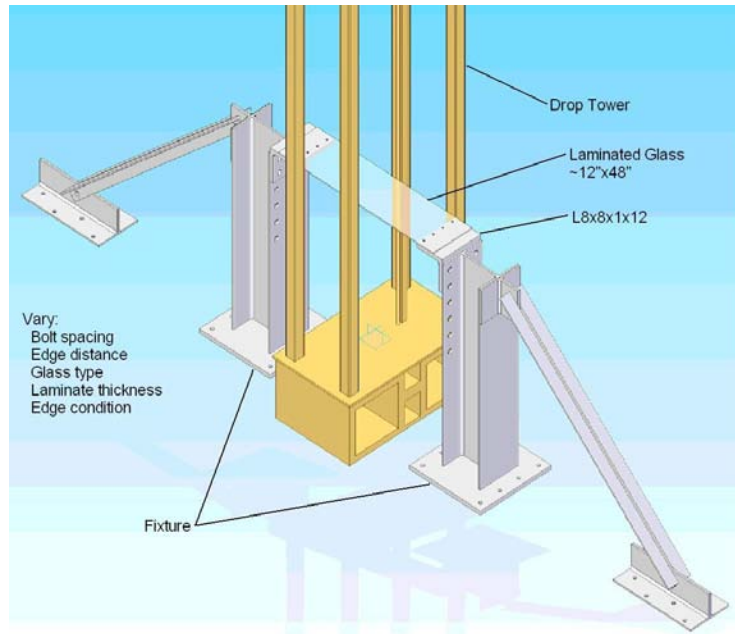


Figure 11. Drop hammer test setup.

Data captured during the drop hammer test included load cell, strain gage, and accelerometer data that supports calculation of edge reactions of the through-bolted connections. The data obtained to date generally supports the validity of an approach similar to that represented by Figure 10.

Observations from the drop hammer testing to date include the fact that the clamping action at the edge is not only sensitive to pre-load but also racking of the glass between the gaskets, cracked glass “digging” into gaskets, and rotational restraint of the glass edge.

A second observation regards the assumption that the post-crack behavior of the glass layup is dominated by the laminate material acting as a membrane with the glass providing mass only. This assumption appears to be questionable. The piecewise continuous attachment of the glass fragments and highly effective post-crack bond between the glass and the laminate yields a post-crack behavior that is globally stiffer than often assumed. There is also observed to be a greater propensity for laminate failure at lower global strains than assumed. While this general observation may have more potential impact on global glass response calculations, it does have a potentially significant impact on the post-crack laminate performance near the through-bolted connections.

As the clamping aspects of through-bolted edge capacity requires further investigation, more testing is currently planned to fill voids in the data set with greater focus on quantifying the effects of bolt pre-load, racking of the glass between the gaskets, cracked glass “digging” into gaskets, and local rotational restraint of the glass edge.

SUMMARY AND CONCLUSIONS

Through-bolted laminated glass edge support capacities have been investigated. Design equations and supporting test data has been presented that capture the capacity of the through-bolted laminate material in reaction to in-plane membrane induced loading. A simple analytical treatment of the clamping force is presented. Preliminary test data supports the validity of the clamping force calculation. The feasibility of designing through-bolted connections that are capable of reaching capacity for the full post-crack in-plane membrane tension of the laminate material is demonstrated. Further testing is required to more thoroughly characterize the key aspects of the clamping effect.

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