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BLAST-BALLISTIC PROTECTION RESEARCH AND DEVELOPMENT

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14. ABSTRACT The primary emphasis of the research effort was on mitigating the threats associated with blast loading on occupied structures. Within the general area of blast effects research the report addresses two primary areas of concentration. First relates to direct support of blast tests through analytical predictions, test article design refinement, support of test planning, and support of forensic evaluations. The second concentration of effort relates to the development of guidelines for through-edge-bolted glass panels as an option for window and curtain wall retrofit systems. The report documents material testing, component testing plus development of engineering equations and guidelines for practical design.					
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1. SUMMARY

This report summarizes Southern Research Institute's (SRI) support of the Air Force Research Laboratory (AFRL) in execution of the Department of State (DoS) Solutions to Protect Against Terrorism (SPAT) program. The primary emphasis of the research effort was on mitigating the threats associated with physical, blast, ballistic and forced entry attacks on occupied structures. SRI's focus area for this program was primarily blast effects

Within the general area of blast effects research, SRI had two primary areas of concentration. First was in direct support of blast tests through analytical predictions, test article design refinement, support of test planning, and support of forensic evaluations. As discussed below, predicted performance generally captured the key aspect of actual tested response. Considerable effort was expended on correlation of analytical models with test result. Analytical model improvements often resulted.

A second concentration of effort was in the development of guidelines for through-edge-bolted glass panels as an option for DoS window and curtain wall retrofit systems. The effort involved material testing, component testing plus development of engineering equations and guidelines for practical design.

2. INTRODUCTION

The research summarized in this report reflects SRI's efforts aimed at support of AFRL and DoS in physical security developments primarily as part of the SPAT program. The primary focus of the SRI team was in support of mitigating the effects from terrorist bomb attacks on DoS facilities. The SPAT program has a major thrust toward window and curtain wall retrofit systems designed to provide occupant protection at levels far greater than conventional construction used at many existing DoS facilities.

Given the variations in site conditions and threats seen across the spectrum of DoS facilities, conventional physical security methods are limited in application and often yield overly conservative, expensive and impractical designs. The SPAT program seeks development of solutions that have the effect of pushing past conventional limits with new and innovative approaches to retrofit systems.

SRI supported the research effort through two primary areas of concentration. The first involves technical support of retrofit system design, pre-test simulations, testing, and post-test forensic evaluations and correlation for specific retrofit systems. Several different systems were addressed by SRI. Results of the analytical modeling, design support, test support, forensic evaluation, and post-test correlation are reflected in various project specific documents including design drawings and status reports. Accordingly, the purpose of the report is to provide an overview of technical methods with key results highlighted. Excerpts from various cases are provided in the report below. The results should provide the reader with a measure of effectiveness of the methods used to influence the design process with resulting improvements in design efficiencies through fewer test cycles.

The second general area of focus involves development of design and application guidelines for through-edge-bolted laminated glass. The primary focus of the effort is for application of SentryGlas® by DuPont. The material has much higher strength than other laminate interlayer materials and therefore is of particular interest for the DoS retrofit systems. Cost effective and practical solutions emerging from the SPAT program often involve movements and displacements of the glass portion of the retrofits that far exceed conventional approaches. A resulting challenge included the ability to provide connection of the glass to the framing systems that would maintain engagement during high deformations and displacements seen during blast events.

A fundamental goal of the through-bolt edge investigation was to identify an edge design condition that would allow full exercise of the global capacity of the laminated glass. The investigation led to results that serve to optimize the effectiveness of the edge connection. Variation in edge conditions and bolt pre-load were considered in the investigation. A by-product of the investigation relates to observations regarding the global performance of the laminated glass, particularly in regards to post-crack behavior. A fundamental assumption used in many analytical treatments of laminated glass was observed to be incorrect.

In the context of the through-bolted-edge support glass investigation, the current report provides a review of technical approaches, analytical developments, key results, and observations. Specific design and installation recommendations are provided.

3. RETROFIT SYSTEMS

A primary emphasis of the SPAT program is development of retrofit window and curtain wall systems that address the wide range of conditions found at DoS facilities around the globe. Many different concepts have been developed to address the varied conditions. The SPAT program includes concept design and proof testing in a series of open arena blast tests. Each test is typically given a numerical designation with the most current test designated as SPAT XI. SRI supported SPAT VII through XI at various level of involvement. The basis of SRI's role was to help refine concepts in terms of performance during blast events and to support improvement of design constructability and repeatability.

3.1. Methodology

SRI's support of the open arena blast testing of the SPAT window and curtain wall retrofit systems includes: 1) analytical modeling and blast effects simulation, 2) constructability reviews and support of design for practical consideration of fabrication 3) test planning support, 4) support of pre-test observation and installation review, 5) post-test forensic evaluation support, 6) post-test correlation of measured results with analytical predictions, and contribution to various reports, technical presentations, and technical papers. The current report is intended to provide an overview with examples of SRI's contributions to the retrofit system development process.

3.1.1. Analytical Modeling and Blast Effects Simulation

The systems under development in the SPAT program are often far more complicated than those most often addressed by classical methods alone. The complications stem from multiple combinations of component types, component interactions, allowance for very large movements and distortions all driven by the wide variation in site condition found in DoS facilities. The number of variations provides motivation for application of analytical methods that can capture and predict key technical aspects of structural performance during a blast event. The technical complications of the systems warrant application of transient nonlinear finite element method for pre-test simulations and predictions. A commercial finite element program, LS-Dyna [1] was used for high fidelity modeling and simulation.

The finite element models include consideration for high load rate effects of material strengths, large displacements, large strains, and component interaction through friction. Structural steel components are typically modeled with elastic-linearly hardening-plastic material models. Element erosion is most often included where failure strain is a controlling factor. Bolted connections are treated in a similar manner except threaded connections are given reduced capacities to account for the effects of threads. Embedded concrete anchors that provide interfaces between the retrofit systems and floor / roof slabs are modeled with the assumption that the slabs are non-responsive. The anchor tension and shear capacity limits are captured via spot weld constraints that allow release of the anchor bolts at designated load levels.

The systems include a laminate glass component that are most often through-bolted along two edges of the glass. The laminated glass material model in LS-Dyna is used to capture the pre and post cracked behavior of the laminated glass. Assumptions integral to the laminated glass material model formulation are similar to those used in window evaluation programs like

HazL [2] and WINGARD [3]. Fundamental to those assumptions is an allowance for relatively large post-crack strain of laminate interlayers. That assumption was found to be flawed for application of SentryGlas® in retrofit system blast tests and the through-bolted development discussed below. However, the material model does serve to transfer blast loading to the primary structural element. The resulting predictions tend toward overestimation of glass deflections. The glass is assumed to remain engaged with the supports so that the load is transferred to the framing structure for the full duration of the blast load. Implied in this assumption is the requirement to qualify the glass and glass attachment through other methods.

Blast loading is applied using pressure versus time curves. The values for pre-test simulations are obtained from classical blast programs like HazL [2] and ConWep [4]. Selected post-test calculations and correlations were performed using measured pressure from the specific test and location of interest. Note that there is often relatively high variation in actual pressure values depending on the location within a given test. Many of the retrofits are set inside a test cube behind a framed opening that is covered in with typical storefront glass windows and framing. The pressure values used for analysis do not allow for clearing effects and shock wave energy losses associated with passing through wall openings or for energy reductions associated with breaking and transporting the storefront component. Additionally, the full reflective pressure is most often applied to the model without consideration for the effect of pressure reductions associated with structural softening of the pressure boundary and localized clearing effect as the retrofit surfaces deflect (often by large amounts).

Along with the conservatisms associated with the loading assumptions, conservative values are most often assumed for material properties and component capacities. The primary intent of the models as used to support the test program is to reasonably predict performance during a blast event. While the models by design do not have significant safety factors applied there is typically ample capacity beyond the level predicted by the models. Application of the models for actual design situations should be done with careful consideration as to whether additional safety factors should be applied.

3.1.2. Constructability and Practical Design Considerations

The SPAT program involves multiple design concepts and variations. Concept designs are generally communicated via DoS architectural design drawings. The SRI team supported design review, solid model visualization, detail development, constructability and installation consultations. The team's efforts were rooted in decades of experience related to curtain wall applications, steel fabrication and construction support.

3.1.3. Test Support

Test support provided by SRI includes test planning, pre-test observation, and post-test forensics. Test plan support involved issues of instrumentation and item installation. Pre-test observation included general observation of the test setups, photography, and selected measurement of critical dimensions. A critical aspect of many of the SPAT concepts is attachment of glass to the frames. As the project progressed, increasingly greater attention was given to glass bolt details, installation, and preload (torqueing). Post-test forensics included photography, measurement of key deformations and general observations. In selected cases, the SRI team contributed to the AFRL's Quick Look Reports through correlation of predicted results with test results.

3.2. Results

SRI's contributions ranged from formal calculation results to general observations. Communication methods included interim reports, printed calculations, email and verbal communications. Selected aspects of the SRI contributions were included in AFRL's Quick Look Reports. Results presented below represent examples of the contributions made by the SRI to the SPAT series.

3.2.1. Analytical Modeling and Blast Effects Simulation

The systems under development in the SPAT program often exhibit responses that are well outside of conventional blast design methodologies. The results of the high level finite element modeling techniques serve to guide design decisions and highly nonlinear aspects of the design that are very difficult to capture short of full scale testing.

Figure 1 represents the finite element model of a base support “pedestal” retrofit system. The analytical predictions indicated likely disengagement of the primary top and bottom horizontal glass frame members and separation from the pedestal notches. The simple addition of the end stops as shown in Figure 1 was predicted to prevent the disengagement. Post-test observations similar to what is shown in Figure 2 indicated a clear need for the end stops. Absent the end stops the frame members would have disengaged with resulting system failure.

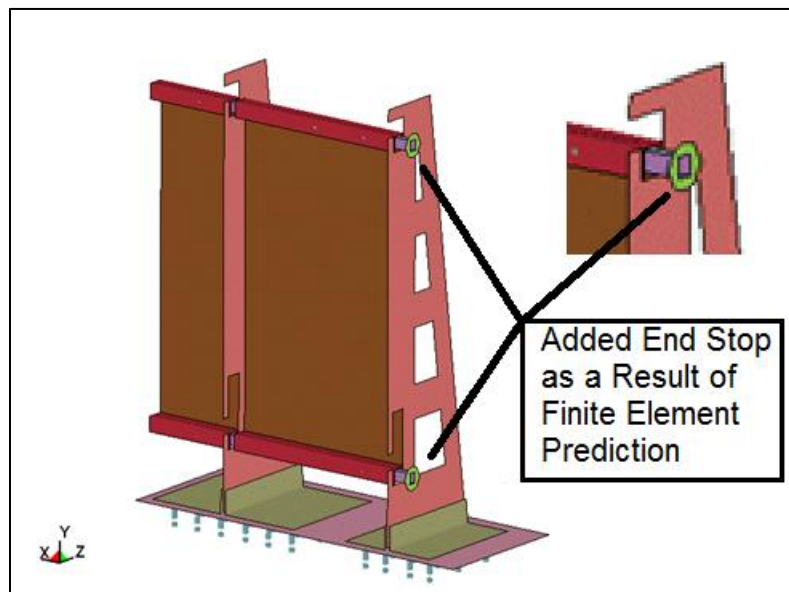


Figure 1. SPAT VIII—Pedestal Finite Element Model

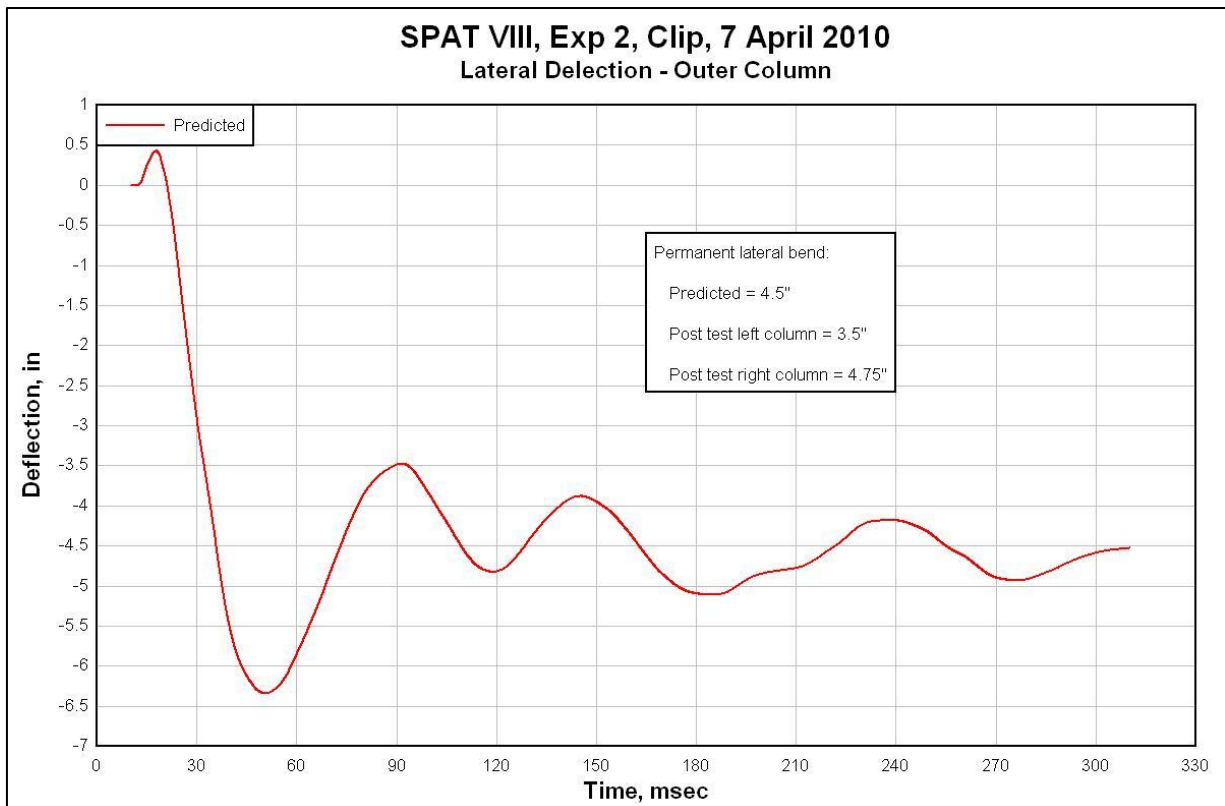


Figure 2. SPAT VIII—Pedestal End Stop Post Test

Multiple other cases exist where finite element predictions helped to guide the design process toward more optimum designs while reducing the number of test cycles. Analytical predictions include displacements, stresses, component forces and reactions. The resulting values influence design details including member dimensions and material; bolt size, number and grade, anchor bolt size, grade, number and placement. Figure 3 shows an exterior view of one of the retrofit concepts. The design includes glass panels with frames having notched “clips” that engage pins on the exterior face of primary structural columns. An example of analytical predictions is in Figure 4 which shows the predicted lateral displacement of the exterior columns.



Figure 3. SPAT VIII—Clip Design



3.2.2. Constructability and Practical Design Considerations

The SRI team used a combination of extensive pertinent experience and tools from solid modeling to offer refinements to design aimed at improving constructability and assuring repeatability and consistency between manufacturing and installation sources. In this context, constructability includes part and component fabrication as well as installation. Figure 5 shows an exploded view of one of the solid models developed by SRI. The solid model may be used to visualize the assembled geometry with consideration of geometric inconsistencies and interferences. The associated set of drawings defines part geometries, materials, component specifications, quantities, welding details, fabrication details and installation details.

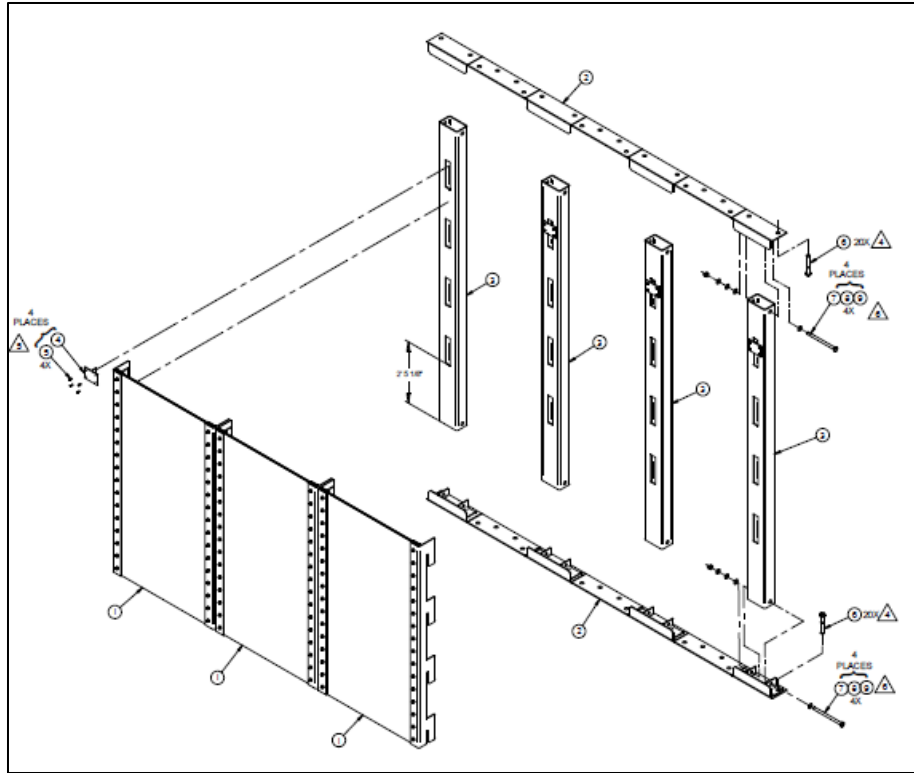


Figure 5. SPAT X Slot Hung—Exploded View from Solid Model

3.2.3. Test Support

Test support provided by SRI includes test planning, pre-test observation, and post-test forensics. Test plan support involved issues of instrumentation and item installation. Most communications were through technical discussions and email exchanges. In all cases, balance is sought between seeking results that are useful for evaluations and post-test correlation versus practical limits of instrumentation capability and data volume management.

Pre-test observation included general observation of the test setups, photography, and selected measurement of critical dimensions. The nature of the test setups and scale of the tests prohibited significant changes leading up to the tests. Therefore, observations in the nature or deviations from design intent or areas where there may be design improvements were noted. A case in point involves the general issue of cracking of glass during installation. Design modifications were made in terms of glass details, connection details and installation procedures to help minimize the occurrence of glass breakage during installation.

Post-test forensics included photography, measurement of key deformations and general observations. In selected cases, the SRI team contributed to the AFRL's Quick Look Reports through correlation of predicted results with test results. Figure 6 shows an example of pre-test predictions compared with post-test data. The various annotations provide information that aids in evaluating the results and explain similarities and differences in the data. Note the wide variations in material properties and loading associated yields a corresponding variation between test results and predictions. The demanding nature of the test conditions including speed and

magnitude of system response often causes loss of gages or inaccurate gage measurement that compound the variation in prediction versus test results. In any case, it has been demonstrated that the predictions are helpful in guiding the design process. The finite element models used for the predictions can be used for actual design with the addition of appropriate safety factors. Figure 7 shows a typical example of how much similarity there is between predicted and tested performance.

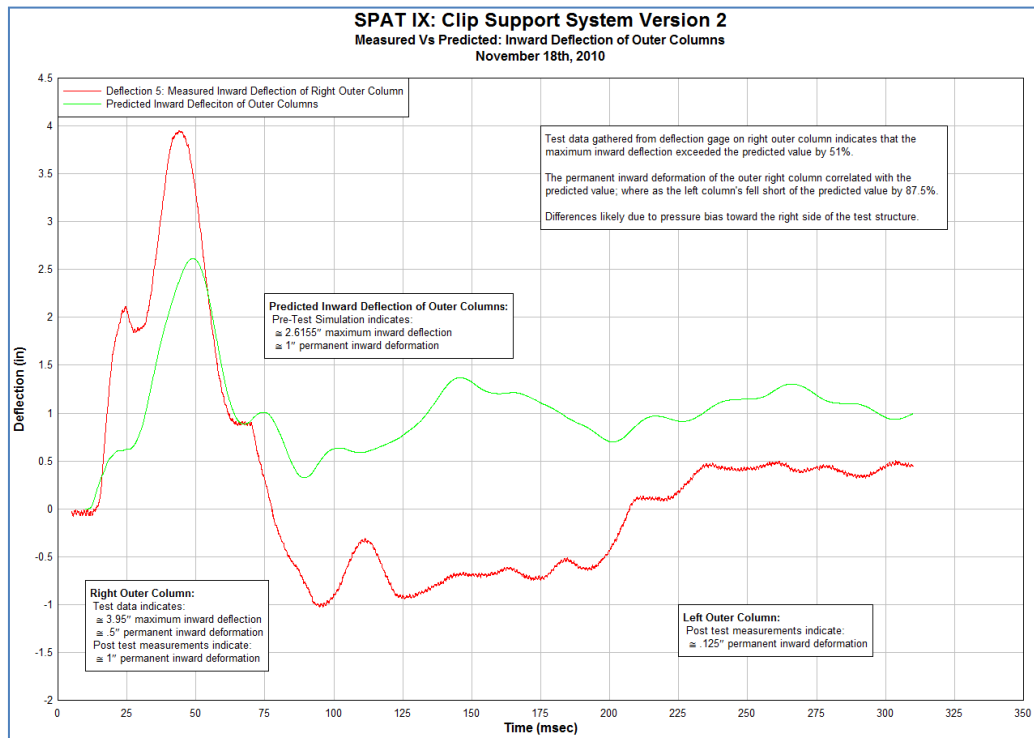


Figure 6. SPAT IX—Clip Post-test Correlation



Figure 7. SPAT X Clip 2—Prediction versus Test

In addition to supporting the specific requirement of the SPAT program, the SRI team participated in efforts to disseminate technical knowledge gained to the broader community of blast engineering. References 5–7, represent papers, presentations or reports that were directly or indirectly influenced by lessons learned through the support of retrofit development efforts at AFRL.

3.3. Conclusion

SRI's support of AFRL in the retrofit development program (SPAT) served to facilitate system improvements in terms of practical fabrication and installation issues while satisfying DoS design requirements. Information gained in the process not only supported the specific program requirements but yielded information of value to the blast engineering community at large.

4. THROUGH-EDGE-BOLTED LAMINATED GLASS

As discussed above many of the retrofit systems developed through the SPAT program exhibit deflections, distortions, and global system responses that are well outside most classical approaches to blast effect mitigation. A critical aspect of suitable response to window retrofit systems is that the glass remains attached to the frame after a blast event. A fundamental goal of the current investigation was to develop guidelines that provide for glass edge support capacities supporting full exercise of the capacity of the laminated glass panels. While all of the testing and calculations are based on DuPont's SentryGlas® laminate interlayer material, the general results may be adapted to other laminate materials.

4.1. Background ¹

The current investigation focuses on window retrofit systems wherein laminated glass is connected to framing systems by using through-bolted edge connections. The left side of Figure 8 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 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.

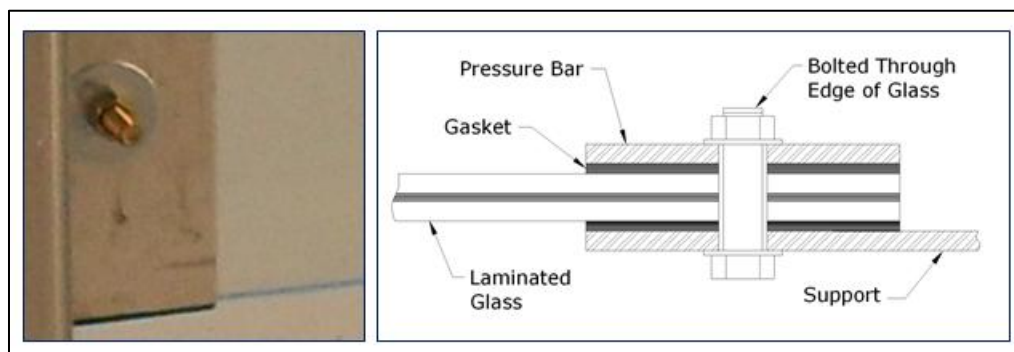


Figure 8. Typical Through-bolted-edge Connection

The presence of holes in the laminated glass at the through-bolted connection causes concern over the possibility of developing the full capacity of the laminated glass. Classical approaches to design result in predictions 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 tension capacity. However, anecdotal evidence primarily obtained from DoS testing indicates that, in many cases, through-bolted connections do provide substantial—and adequate—support for the glass edge.

¹ Section adapted from Reference 9.

Windows subjected to high energy blast loading typically exhibit large deflections, resulting in cracking throughout the glass layers of the laminated assembly. Most often, 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 the current effort to understand the capacity of the edge support relative to in-plane membrane loading. Thus, the current through-bolted-edge investigation focuses on characterizing the in-plane capacity of through-bolted-edge supported laminated glass.

4.2. Methodology

Analytical models based on simple equations from engineering mechanics were used to develop equations aimed at qualitatively capturing the edge capacity of through-edge-bolted laminated glass. However, most of the effort of the investigation was focused on testing to provide confirmation and tuning of the analytical models. Part of the investigation included evaluating options other than through-bolting. Results of that investigation are included below. Considerable attention was placed on practical issues associated with installation of the through-edge-bolted laminated glass. Practical issues addressed include avoidance of glass cracking during installation and developing proper bolt pre-load. Specific recommendations are summarized in the results below.

The current report provides an overview of the investigations with key results and recommendations below. The testing included coupon testing, component level testing, edge pull out testing and drop hammer testing. SRI [8], Duke (2009) et al [9], and Duke (2011) et al [10] provide extensive discussions of the various tests, test plans, fixture designs, and typical test results. A summary of key results is provided in the discussion below.

4.3. Results

The key results of the through-edge-bolted investigation include basic material characterization through coupon testing, component edge capacity as related to edge pull out resistance including the effect of clamping force along with various other edge conditions. While dynamic component level effects are addressed through drop hammer tests, most of the testing was performed using quasi-static load rates. In consideration of the high load rate associated with the application, high strain and high load rate tests were performed.

4.3.1. Coupon Testing

Coupon level testing on the interlayer material was conducted for two primary purposes. First was to seek clarity regarding basic material properties that were previously reported from various sources. Tensile tests were conducted at AFRL using various strain rates. Figure 9 shows an example of the resulting data where engineering stress versus engineering strain is plotted for various strain rates. Table 1 summarizes a comparison between test results, manufacturer data, and data from various sources in industry. As seen in the table, the recommended manufacturer's data fall within the range of the tested and common values for tensile strength and percent elongation. The modulus of elasticity value obtained from test is considerably lower than the manufacturer's data. The tested value falls at the lower end of the common value range while the

manufacturer's data falls at the upper end of the common value range. The causes for the large differences are unknown. While the value for modulus of elasticity may have a significant impact on the global response of the glass panels, it has little effect on the edge capacity, which is the issue under investigation.

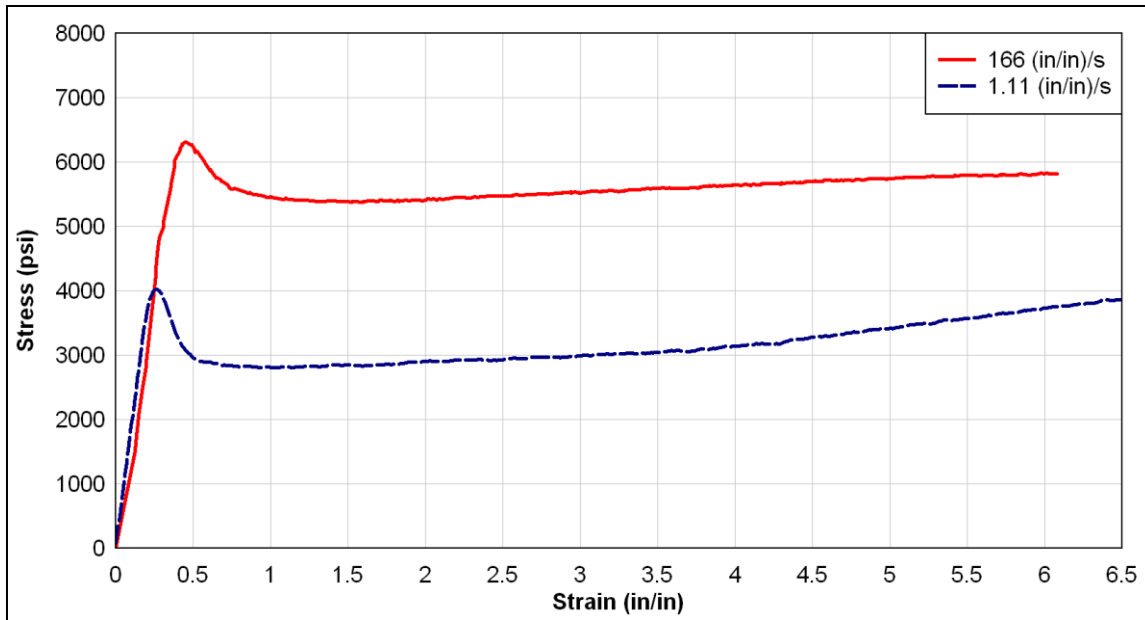


Figure 9. Stress versus Strain for Various Strain Rates

Table 1. Material Property Comparison

	Current Investigation	Manufacturer Data	Common Values
Tensile Strength (psi)	4000-6500	5000	3600-6500
Elongation (%)	500-1000	400	400
Modulus of Elasticity (psi)	30000	43500	30000-43500

A second motivation for coupon testing relates to the “uncooked” versus “cooked” condition of the interlayer material for various tests. The uncooked condition refers to the material as supplied by the manufacturer. The term cooked refers to the exposure of the material to heat during the lamination process. It had been reported that there is some variation between the cooked and uncooked properties. Thus, the intention was to determine what level of error may be involved in using results from uncooked tests in applications where the material is actually cooked.

Figure 10 shows the variation in yield stress with strain rate for both uncooked and cooked interlayer material. The trend of increasing yield stress with strain rate confirms other measured and reported data. There is evidence of differences between cooked and uncooked material, particularly at the highest strain rate. For the current application, strain rates are typically closer

to the mid-range of those plotted. As such, there is less than a 5% variation in the results. The small variation along with the fact the cooked material has slightly higher strengths add credence to using results from uncooked component testing.

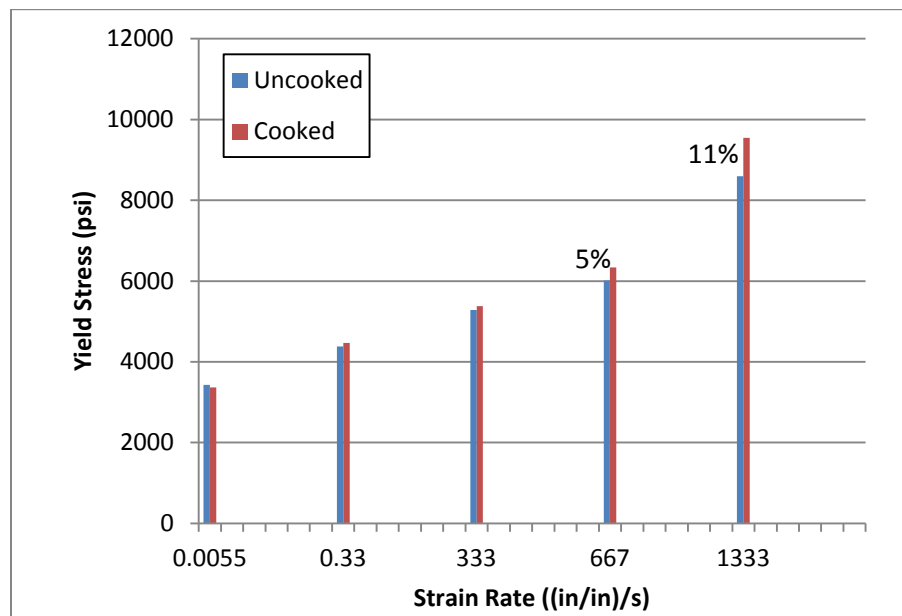


Figure 10. Yield Stress versus Strain Rate for Uncooked and Cooked

4.3.2. Interlayer Pull-out Resistance²

Duke et al [9] presented test results aimed at characterizing the in-plane pull-out capacity of a common uncooked laminate material. The test setup is shown in Figure 11. Tests were conducted with variations in bolt spacing and edge distances. Failures at or between the bolts were observed that match classical bolted connection results for in-plane tensile loading. Shown in Figure 12 from left to right are classic V-notch failure, pure shear/pull-out, and hole-to-hole net area tension failure.

² Section adapted from Reference 9.

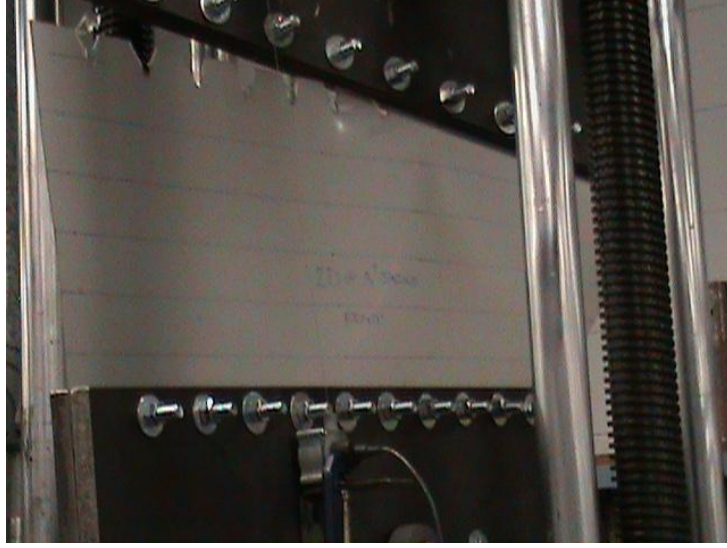


Figure 11. Static Component Level Testing of Laminate

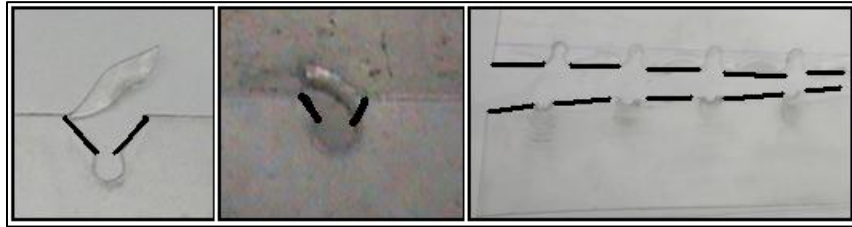


Figure 12. Laminate Edge Failure Mechanisms

Simple equations based on classical mechanics were developed to predict the edge capacity of the laminate material. Figure 4 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 / tear-out resistance is predicted by Equation 1

$$R_n = \frac{2\left(e - \frac{d}{4}\right)tF_u \tan\theta}{s} \quad (1)$$

where 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 bolt-to-bolt net area tension failure capacity is calculated from

$$R_n = \frac{(s - d)tF_u}{s} \quad (2)$$

The $(s - d)$ term in Equation 2 is the net distance between the bolt holes. The minimum value from Equations 1 and 2 is taken as the capacity of the laminate.

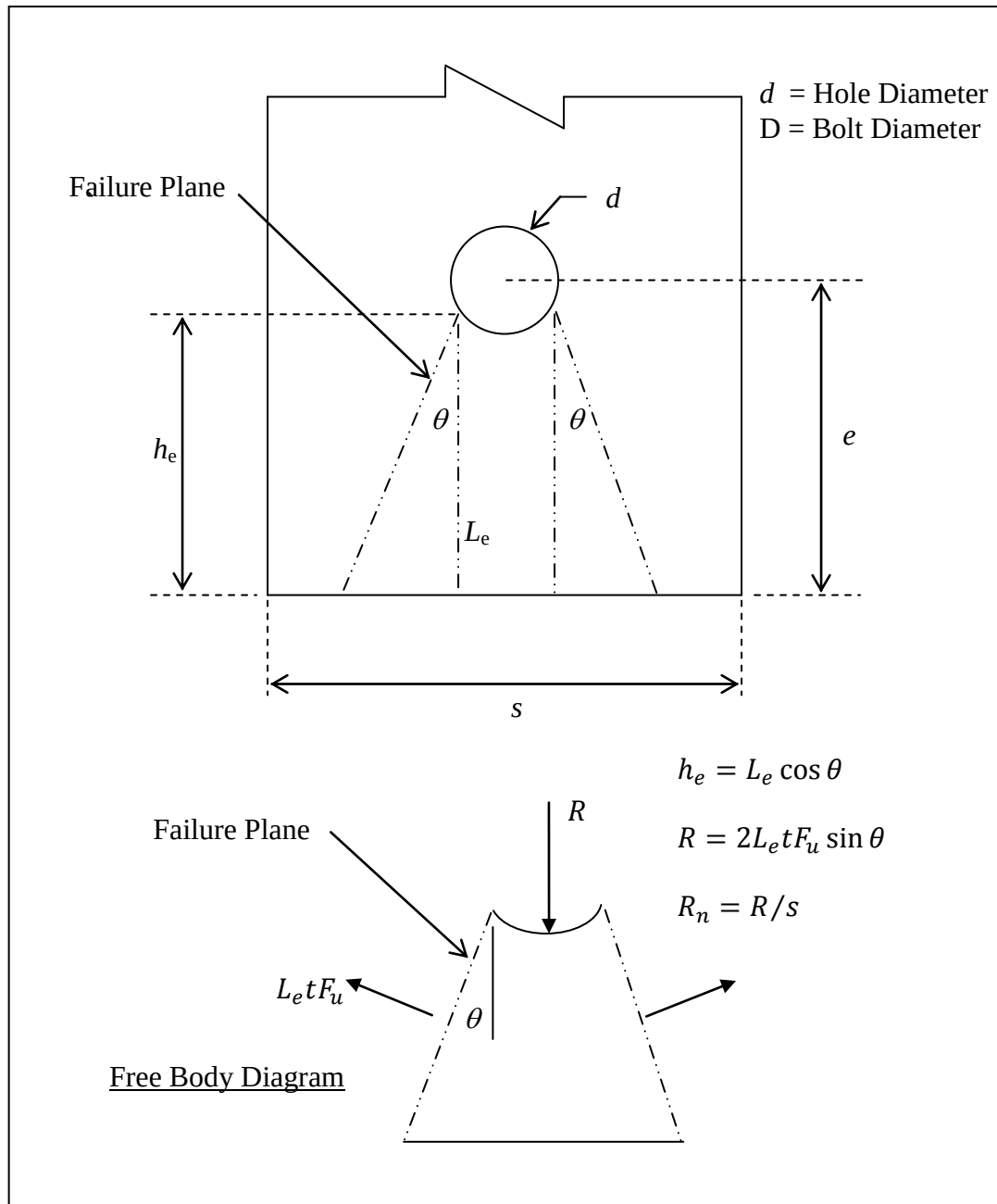


Figure 13. Classical Solution Parameters

Test results confirm that the capacity prediction shown above provides reasonable and conservative values for the edge capacity of the interlayer material. Additional tests have been performed that were aimed at capturing other key aspects of through-edge bolted connections. Specifically, a series of drop hammer tests was conducted where various make-ups of laminated glass panels were supported by a rigid frame and subjected to impact loading. The results supported the predictions represented by Equations 1 and 2 above. There were also clear

indications that a more fundamental understanding of the connection characteristics would serve to clarify interpretation of the drop hammer results. Thus, additional static tests were conducted to characterize additional aspects of the edge capacity.

4.3.3. Edge Capacity—No Clamping

In furtherance of the process of quantifying the pull-out resistance of the through-edge-bolted laminated glass, tests were conducted that demonstrate the edge capacity for laminated glass and cooked interlayer material versus uncooked material. This comparison provides an extension of the basic capacity of the uncooked interlayer shown in the previous section. A test setup similar to that shown in Figure 11 was used. The specimens were 36-in wide. Bolt edge distances were set at 3D, 4.5D, and 6D along with bolt spacing of 3, 6, and 9 inches. The interlayer material for the uncooked, cooked, and laminated glass samples were all from the same manufacturer's lot and therefore should have had consistent material properties. In all cases, the interlayer material was 0.09-in SentryGlas®. The laminated specimens had the interlayer laminated between two panes of 0.25-in fully tempered glass.

Figure 14 shows the pull-out force for the case of 3-in bolt spacing. The value of "1.40" shown above the 6D group is the ratio of the laminated pull out force to the uncooked pull-out force. The uncooked value is use as the reference since many of the results to date were based on uncooked interlayer material. Note that the pull-out resistance for the cooked material is generally less than that of the corresponding uncooked. This point runs counter to the high load rate data shown in Figure 10. The primary difference is likely due to the surface roughness of the materials. The surface of the cooked material was much smoother than the uncooked material. The pull-test set up had the material sandwiched between steel plates with through bolts installed finger tight. While the initial clamping force was small, the pull-out process caused the material to be "bunched up" near the bolt hole thus causing the material to press against the inside of the fixture plates. As this occurred it is very likely that the resulting friction was larger for the rougher uncooked material. While this point is duly noted, it has no significant effect on the final application of the results since the actual configuration is laminated material.

The primary value of this part of the investigation relates to the increase in pull-out resistance for laminated glass versus uncooked interlayer material. Table 2 shows the ratio of pull-out force for laminated glass versus uncooked material for various bolt spacing and edge distances. As shown in the table, the laminated components had considerably higher pull-out resistance. The glass typically cracked early in the loading cycle. However, most of the cracked glass remained bonded to the interlayer. The resulting structure was basically the continuous interlayer with piecewise continuous stiffening from the cracked but still attached glass. Note that this piecewise continuous stiffening effect as it relates to deficiencies of conventional blast design of windows is discussed in Duke et al [7].

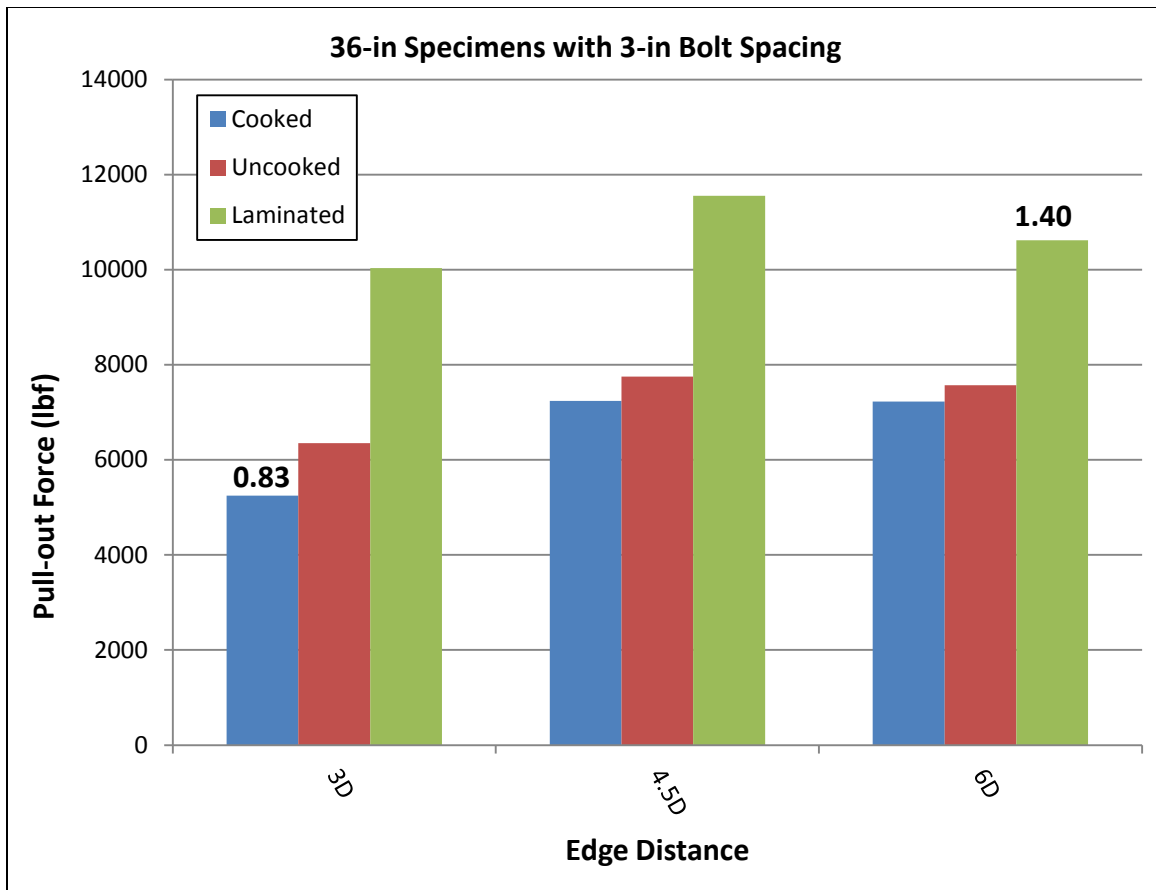


Figure 14. Pull-out Force for Various Conditions, 3-in Spacing

Table 2. Laminated Pull-out Capacity Factor

Bolt Spacing (in)	Edge Distance	Factor
3	3D	1.58
3	4.5D	1.49
3	6D	1.40
6	3D	1.21
6	4.5D	2.22
6	6D	2.03
9	3D	1.83
9	4.5D	2.24
9	6D	1.94

A second point that explains the higher pull-out resistance with the laminated glass relates to the cracked glass “digging into” the gasket material. In the case of the laminated glass pull-out test, gasket material as used in the actual application was used to protect the glass from pre-mature

cracking. As with the interlayer above, the bolts at the lower edge were finger tight so the initial clamping force was small. Note that in all of the pull-out tests, the upper edge was fully bolted with the bolts pre-loaded to prevent slippage so that the lower edge was consistently the “tested edge”. Figure 15 shows an example of the cracked glass engaging the gasket and pulling it out of the fixture. Images similar to Figure 16 showed clear evidence of interaction between the cracked glass and the gasket material. It is suggested that the same bunching effect discussed above causes the cracked glass pieces to press against and engage the gasket material. This effect will be shown to be highly pronounced in the subsequent discussion related to clamping effects.



Figure 15. Pull-out Test, Laminated, No Clamping



Figure 16. Pull-out Test, Laminated, No Clamping, Glass-Gasket Engagement

4.3.4. Effects of Clamping³

A series of tests were conducted to quantify the effect that clamping force due to bolt pre-load has on pull-out resistance. Figure 17 shows the test setup wherein laminated glass specimens had slotted holes at the bolted edge. The purpose of the slots was to quantify the pull-out resistance absent the bunching effect at the inside edge of the bolt hole. Effectively the bolts were free to pass through the edge unimpeded. As expected and as discussed below, the clamping associated with bolt pre-load tension proved to be a critical component of the pull-out resistance.

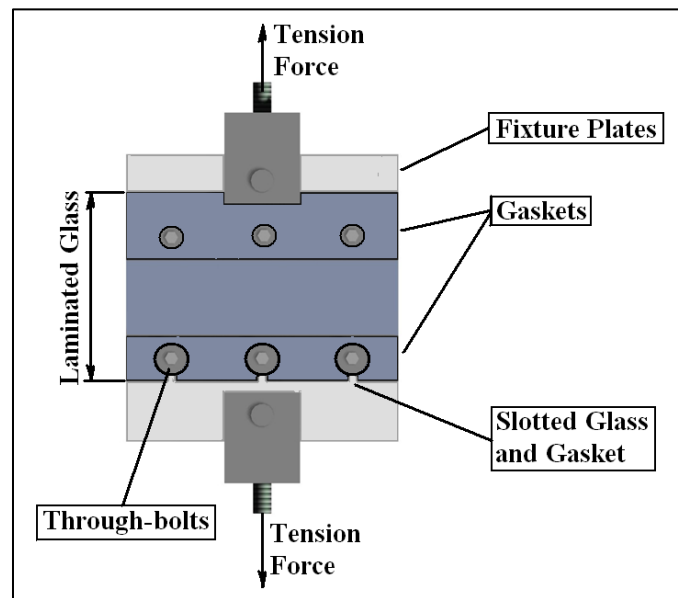


Figure 17. Slotted Glass Setup

4.3.4.1. Bolt Pre-load versus Torque

A practical issue associated with bolted connections where tension preload is important is how to assure that the bolts are installed with the proper range of preload. In classical structural applications, various methods are available to control preload including the turn-of-the nut method and load indicator washers. In the window and glass curtain wall industry, bolt torque measurement is often the preferred method. All of the methods have advantages and disadvantages under the best of conditions. In the current research where gasket material and laminated glass are in the stack of bolted layers, there are additional concerns over proper bolt preload. In an effort to quantify bolt preloads in this context, bolt tension forces were measured using load cells. Corresponding bolt torques were also measured. Figure 18 shows a plot of preload versus torque. A semi-empirical formula that is widely used to estimate bolt torque versus preload is $T=0.2FD$ where T (in-lb) is torque, F (lbf) is preload bolt tension and D (in) is the bolt diameter. The data in Figure 18 provides reasonable correlation with the classical formula and thereby supports the notion of using the formula to estimate compressive forces in the gasket.

³ Section adapted from Reference 10

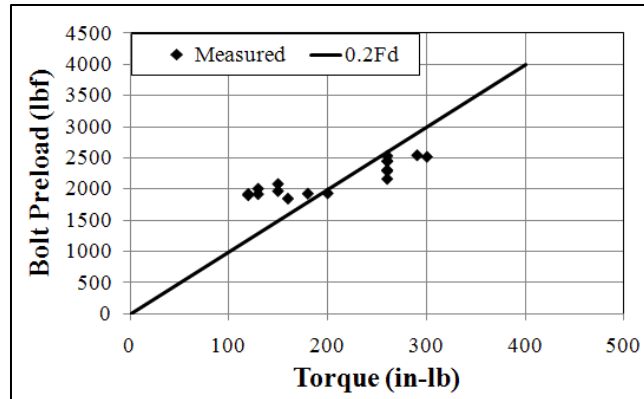


Figure 18. Bolt Preload versus Torque

4.3.4.2. Slotted Holes at Edge

As indicated above, several test specimens were used that have slotted holes at the edge. The goal for this portion of the test was to quantify the effective friction versus clamping force (bolt preload) for smooth and cracked glass. The slots allow pullout without engagement between the bolts and the inside edge of the bolt holes. That is, the goal is to obtain friction only with the understanding that the structural capacity of the laminate interlayer is quantified using Equations 1 and 2 above.

Pull-out tests were conducted using the setup shown in Figure 17. Table 3 lists the geometrical characteristics of the specimens. The bolts at the bottom (slotted) edge were pre-loaded using torque values (or in some cases load-cell measurements in conjunction with torque values as in Figure 18). The pull-out tension force was measured for each specimen. Table 4 summarizes those results for the slotted specimens. Note that in all but one case the glass layers cracked early in the loading. This is likely due to the bolts bearing on the inside edge of the holes near the top edge of the glass. In the one case where the glass did not crack, the effective friction force corresponds to the case of smooth glass on gasket material. Using the classical preload estimate from $0.2FD$ the effective preload force is calculated to be 4200 lbf. Given two surfaces of contact, the effective coulomb friction value is 0.3. While one data point should not be considered statistically defensible, it is worth noting that 0.3 is considerably lower than values in the literature for similar materials.

Figure 19 provides a plot of the pull-out force versus the average bolt torque. A plot of effective friction versus gasket compression force (bolt pre-load) would yield a plot with a similar shape. An immediate point to take from the shape of the curve is the fact that the linear curve fit does not pass through zero force at zero torque. The fact that at least some preload is present and the glass is cracked combine to yield a gasket to cracked glass interface that is far different than that of simple coulomb friction. The digging in effect clearly contributes to the complexity of the problem of predicting edge capacity. Observations made during the test indicate that the cracked glass does not simply slide on the gasket. There is actually surface shaving and cutting of the gasket by the glass at the crack locations. It is suggested that in the presence of gasket compression forces, the cracked glass edges function much like teeth that dig into the gasket. Evidence of this effect is even seen in the case of no pre-load as shown above in Figure 16.

Table 3. Slotted Specimen Characteristics

Laminated glass make-up	0.25 in. Heat Strengthened 0.18 in DuPont SentryGlas® 0.25 in. Heat Strengthened
Overall dimensions	18 in. wide, ~12 in. high
Bolt size	0.5 in.
Bolt spacing	6.0 in.
Edge distance	1.5 in. (3d)
Gasket material	EPDM, Durometer 60, Shore A
Gasket width	3.0 in.

A second point to take from Figure 19 is that while an increase in torque correlates to an increase in pull-out force, there is not a one-to-one relationship. Approximately 80% of the maximum pullout resistance was developed with 500 in-lb torque as compared with 1500 in-lb. In addition, there is concern over the sensitivity of laminated glass to cracking during the installation and bolt pre-loading process. These points suggest that there is a practical limit to value of increasing torque to increase pullout resistance.

Table 4. Pull-out Force versus Torque

Bolt Torque1 (in-lb)	Bolt Torque2 (in-lb)	Bolt Torque3 (in-lb)	Average Torque (in-lb)	Pull-out (lbf)	Glass not cracked
180	120	120	140	2572	X
130	130	200	153	5542	
160	150	150	153	6202	
260	260	260	260	8777	
260	260	260	260	7399	
300	290	260	283	7944	
192	192	312	232	8143	
240	348	360	316	6203	
240	396	432	356	5332	
600	600	600	600	8784	
830	830	830	830	9991	
750	800	750	767	9472	
1390	1494	1330	1405	10580	
1440	1480	1546	1489	9970	
1480	1480	1480	1480	8755	

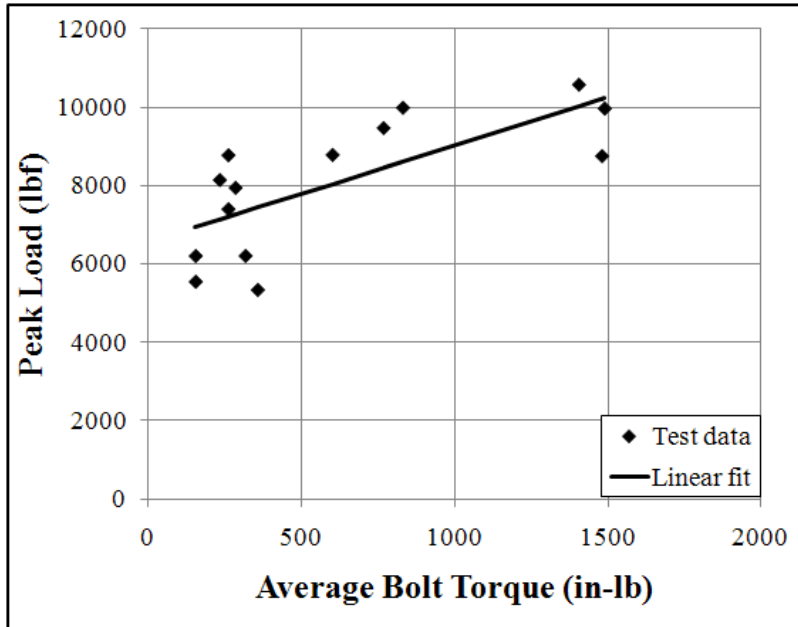


Figure 19. Pull-out Force versus Torque—Slotted Edge

4.3.4.3. Gasket Relaxation

Given that clamping force is an important variable in developing the desired level of pull-out resistance, the effects of time on gasket pressure is of concern. A series of tests were performed using the gasket material listed in Table 3 where the material was preloaded via bolt torque. The torque was checked over a period of about three weeks. The data indicates that gasket relaxation does occur with most of the relaxation occurring in the first few hours. After three weeks, most of the torque values stabilized at levels above two-thirds the initial torque values. Thus, it is suggested that the installation torque be set at 1.5 times the goal preload torque. The resulting torque should stabilize at or above the goal value.

4.3.5. Various Edge Conditions

The current investigation was focused on edge pull-out resistance for through edge laminated glass. Additional consideration was given to other edge held arrangements and the respective resistances to edge pull-out.

Table 5 provides a list of various edge conditions that were tested for pull-out resistance. The various conditions included some that were intuitively promising and others that were primarily for reference value only. The glass specimens used to develop Table 5 were 18 inches wide. The glass laminate makeup included 0.18 inch SentryGlas® sandwiched between two layers of 0.25 inch tempered glass. Where bolts were included, there were three bolts at 6 inch spacing. With the exception of Conditions 4, 5 and 6 gaskets were included at the bolted interfaces.

Table 5. List of Edge Conditions

Condition Number	Description
1	Bolted - 6D Edge (Baseline)
2	Bolted - No Preload - 3D
3	Bolted - No Preload - 6D
4	Structural Silicone, Three Strips
5	Structural Silicone, Two Strips
6	Structural Silicone, Two Strips - 3D
7	Contact Cement no Bolts
8	Contact Cement - 3D
9	Point Supported - 3D
10	Point Supported - 4.5D
11	Point Supported - 6D
12	Bolted - 3D Edge
13	Strip at Outer Edge - 3D
14	Perforated and Scalloped Edge - 3D
15	Full Perforated Inner Sheet - 3D

4.3.5.1. Bolted

Conditions 1, 2, 3 and 12 are similar to Figure 16 except with varying levels of preload, as documented below.

4.3.5.2. Structural Silicone

Figure 20 shows Condition 5 (two strips of structural silicone). The edge support consisted of two strips of 0.75-in wide Dow 995 structural silicone separated by a 0.25-in air gap. The air gap was effected using 0.25-in open cell glazing tape. The purpose of the air gap was to facilitate curing within each strip of silicone noting that curing time is very sensitive to distance from air-exposed-surfaces. Conditions 4 and 6 are similar except for the addition of a silicone strip in Condition 4 and the addition of pre-loaded bolts in Condition 6. Note that the silicone edge conditions having multiple strips with air gaps provide special challenges in terms of the actual glazing process. Figure 21 shows an as-tested example of the three silicone strip configuration.

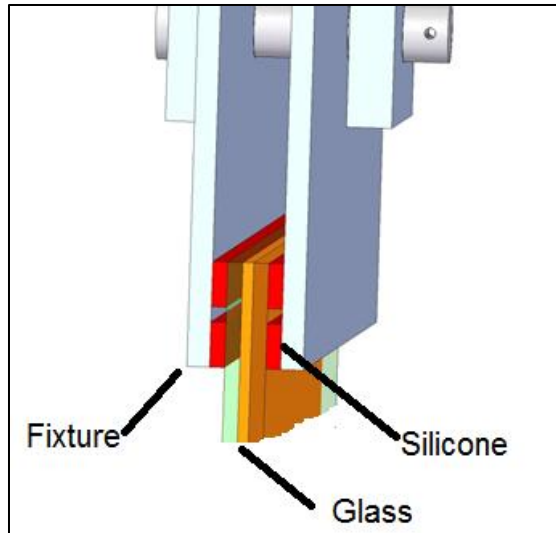


Figure 20. Structural Silicone

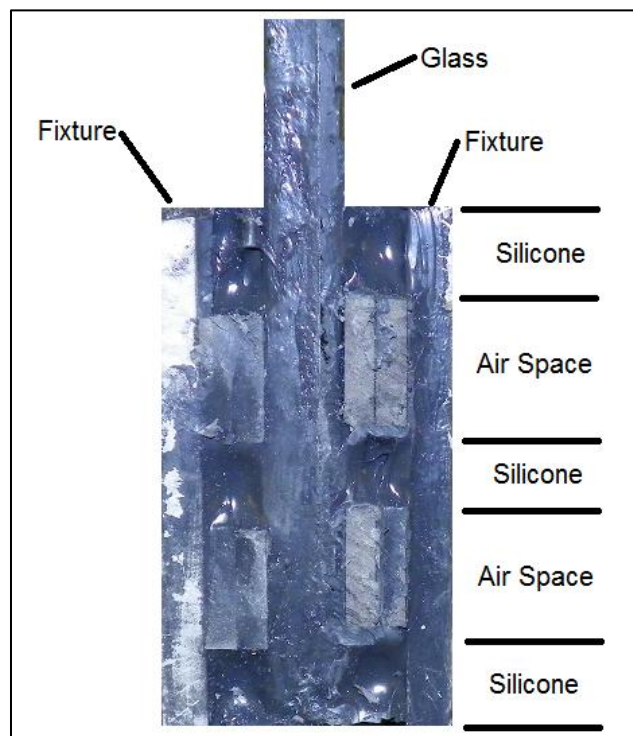


Figure 21. Three Strips of Silicone – As Tested

4.3.5.3. Contact Cement

Conditions 7 and 8 included application of 3M 1357 Contact Cement between the gaskets and the mating surfaces. The intention was to minimize slippage at the gasket to glass and gasket to steel plate fixture surfaces. Condition 7 had cemented gaskets while Condition 8 had cemented gaskets along with preloaded bolts.

4.3.5.4. Point Supported

Figure 22 shows an example of point supported glass. The glass edge is supported at discrete points corresponding to the through-bolts. All of the other conditions considered in this investigation had continuous support along the tested edges. Conditions 9, 10 and 11 had various edge distances as indicated in Table 5. The bolt pre-load were all comparable to the other bolted conditions (900 in-lb nominal pre-load). The point supported condition was effected for the test using 3-in diameter gaskets at the bolts. Note that the current investigation focused on pull-out resistance. The point supported condition as compared with continuous edge support is much more sensitive to punching and tearing associated with out-of-plane loading of glass. The punching effect should be considered in application of the point supported concept.



Figure 22. Point Supported Glass

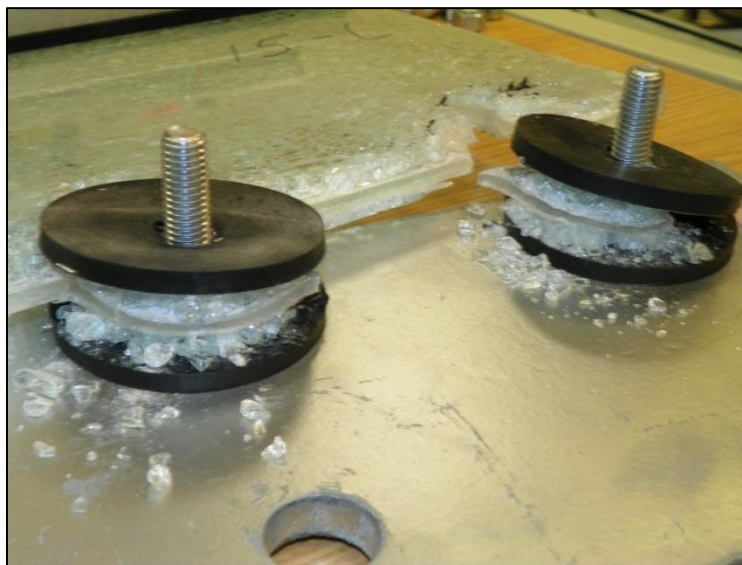


Figure 23. Point Supported Condition, Post-test

4.3.5.5. Metal Strip at Outer Edge

Conditions 13 had a 0.060-in thick stainless steel strip embedded along the outer edge of the interlayer. The interlayer was made up of three layers of 0.060-in thick SentryGlas® with the edge of the middle layer replaced by the metal strip (Figure 24). The notion behind this concept was to reinforce the edge against V-notch edge tear-out as seen in Figure 12.

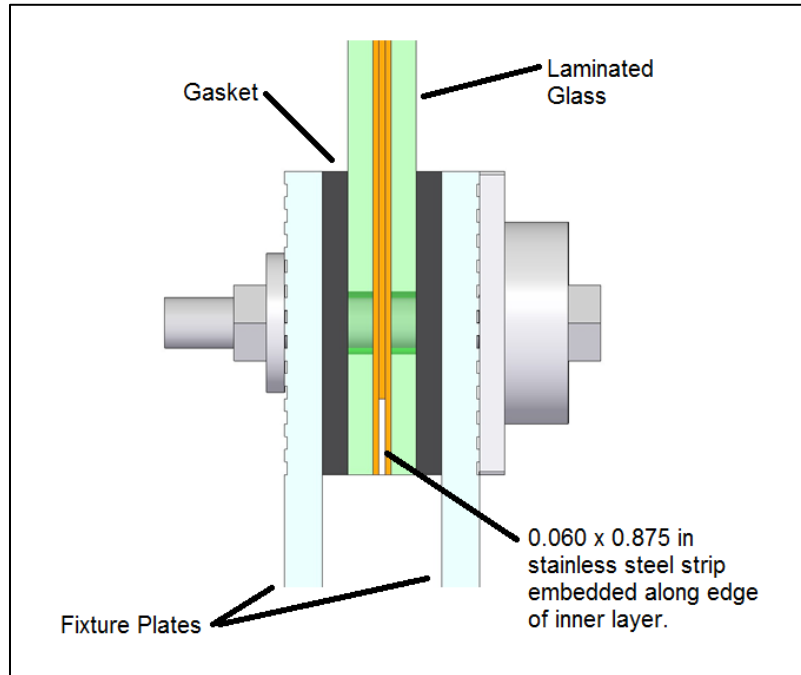


Figure 24. Metal Strip at Outer Edge

4.3.5.6. Perforated and Scalloped Edge

One concept of internal edge reinforcement of the interlayer is shown in Figure 25 (Condition 14). The primary goal in this case was to provide reinforcement around and between the bolt holes. The perforations and scalloped shape provided enhanced integration of the reinforcement into the interlayer. The scalloped edge was intended to reduce the tendency for net tension failure at the edge of the reinforcement. In this case, the perforated reinforcement was 0.036-in thick stainless steel with 0.25-in holes and 58% open area.



Figure 25. Perforated and Scalloped Edge Reinforcement

4.3.5.7. Full Perforated Inner Sheet

Condition 15 was included as a point of reference for the possible effects of including a full sheet of perforated reinforcement. The full perforated sheet as shown in Figure 26 is the same material as in Condition 14.



Figure 26. Full Perforated Sheet

4.3.5.8. Earlier Test Series

Additional conditions were included in one series of pull tests. The glass type in that case was heat strengthened, as opposed to tempered, as were all conditions in Table 5. Gaskets were reused during the tests and therefore the gasket condition was not as carefully controlled as with Conditions 1 through 15 described above. A third key deviation is in the bolt torque and pre-load sequence. In the earlier, tests the bolts were repeatedly checked for several minutes and the corresponding final torques recorded. In an effort to simulate more practical field conditions, the bolt torques for the conditions in Table 5 were set at 900 in-lb. The torques were recorded after 10 minutes. On average, the bolt torque was reduced by 20% on average due to gasket relaxation within 10 minutes of the initial application of torque. With these notions in mind, results for the additional conditions have limited correlation value relative to 1 through 15. However, they are included for reference purposes.

Two edge conditions included application of 3M VHB® (very high bond) glazing tape between the gaskets and the mating surfaces. The intention was to minimize slippage at the gasket to glass and gasket to steel plate fixture surfaces. One case had only taped gaskets while the second case had taped gaskets along with preloaded bolts.

A second set of conditions included inner and outer stainless steel strip reinforcement at the bolted edges. In both cases, the 0.06-in thick strips were centered on the bolts. The inner reinforcement strip replaced one-third of the interlayer thickness along the bolted edge for the first case. In the second case, the outer reinforcement strips were bonded to the glass with 3M VHB® glazing tape.

4.3.5.9. Summary of Results

Based on the results of the bolt torque investigation discussed above, a standard nominal torque of 900 in-lb was set as the goal torque for the preloaded conditions. The measured pull-out forces were adjusted to account for the variations in the applied torque using the results shown in Figure 13. Condition 1 was used as the baseline for the values reported in Table 6. Note the adjusted pull-out force for Condition 1 was 10861 lb. Thus, Table 6 lists the ratio of pull-out force for the various conditions relative to Condition 1. In a similar manner, Figure 27 shows pull-out force ratio versus edge condition number.

Table 6. Pull-out Force Ratio for Various Edge Conditions

Condition Number	Description	Pull-out Force Ratio
1	Bolted - 6D Edge (Baseline)	1.00
2	Bolted - No Preload - 3D	0.32
3	Bolted - No Preload - 6D	0.53
4	Structural Silicone, Three Strips	0.71
5	Structural Silicone, Two Strips	0.60
6	Structural Silicone, Two Strips - 3D	0.93
7	Contact Cement no Bolts	0.07
8	Contact Cement - 3D	0.81
9	Point Supported - 3D	0.63
10	Point Supported - 4.5D	0.78
11	Point Supported - 6D	0.98
12	Bolted - 3D Edge	0.65
13	Strip at Outer Edge - 3D	0.79
14	Perforated and Scalloped Edge - 3D	0.80
15	Full Perforated Inner Sheet - 3D	0.91

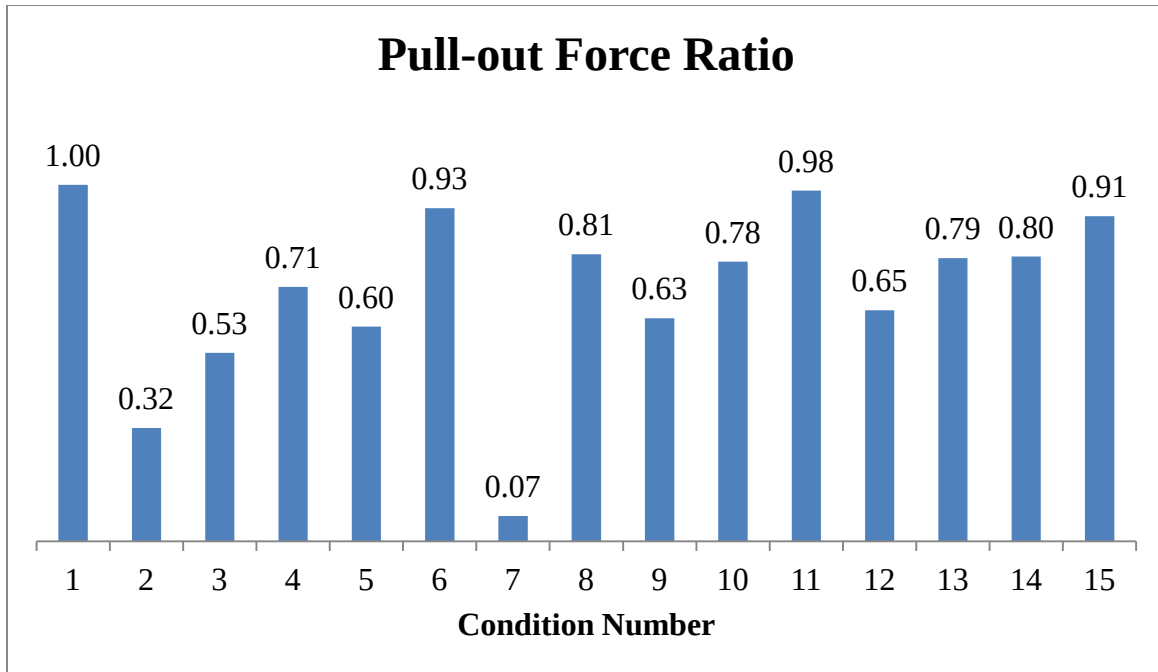


Figure 27. Pull-out Force Ratio versus Edge Condition Number

4.3.5.10. Discussion of Results

The bolted Conditions 1, 2, 3 and 12 were primarily provided as reference values. However, comparison of Condition 2 with Condition 3 and Condition 12 with Condition 1 highlights the effect of increased edge distance. Comparison of 2 with 12 and 3 with 1 highlights the effect of the bolt preload.

Structural silicone is a very common edge support mechanism in the window and curtain wall industry. The three cases represented by Conditions 4, 5 and 6 were tested to demonstrate the potential of structural silicone. Note that the strength of the silicone bond is not developed until the structural silicone is cured. Typically curing time is sensitive to nearest distance from air-exposed surfaces to the interior of silicone volume. Once the bead width exceeds about 1.0 in (0.5 in distance from air-exposed surface to interior of silicone), the curing time becomes a limiting factor in terms of practicality. For example, data from DOW indicates that the curing time for a 1-in wide bead of DOW 995 is 31 days at 70° F and 50% relative humidity. Increasing the bead width to 2.0 in increases the cure time to 124 days. Thus, the tested configurations included multiple beads separated by open cell glazing. The goal was to gain strength by increasing the total width of the silicone bond while obtaining full cure at a reasonable time. It is clear from the data that the structural silicone provides significant pull-out resistance but falls short of the baseline values. The bolted and silicone combination was tested for reference. Capacity similar to the baseline value was demonstrated.

In the case of contact cement with no bolts (Condition 7), the pull-out resistance was too small to be considered further. However, Condition 8 compared to Condition 12 shows a marked increase in pull-out resistance when the contact cement was used along with preloaded bolts.

Conditions 9, 10 and 11 represent the pull-out resistance for the point supported condition. The results are comparable to the values for continuous gasket support. As seen in Figure 28, there was considerable evidence of glass “digging into” the gasket surfaces. This effect was evidenced in most of the bolted with gasket conditions where there was not an explicit bond between the glass and the gasket. Indications were that most of this effect was concentrated near the bolts and the digging patterns generally mirror the pattern of the V-notch edge failure mechanism.

Repeating the caution regarding the point supported results, the current investigation focused on pull-out resistance. The point supported condition as compared with continuous edge support is much more sensitive to punching and tearing associated with out-of-plane loading of glass. The punching effect should be considered in application of the point supported concept.



Figure 28. Point Supported Gasket and Glass, Post Test

Not shown in Table 6 and Figure 27 are the results from the earlier pull tests. Although well below SPAT requirements, the VHB tape alone was demonstrated to provide significant resistance to pull-out. In that case, the tape was approximately 3.0-in wide. It provided a pull-out resistance that compares to a 0.625-in wide bead of silicone. Unlike the contact cement, combining VHB tape with pre-loaded bolts yielded a significant decrease in the edge pull-out resistance. Replacing the middle 0.06-in thickness of interlayer with a steel strip yielded a pull-out force of about half the baseline value. Adding strips to the outside of the glass yielded results very close to the baseline.

4.3.5.11. Conclusions

The results of the pull-out tests for various end conditions provide practical results useful in evaluating the merits of various end conditions. However, in no case did changes to end condition improve pull out resistance beyond the preloaded 6D edge condition. Thus, the practical merits of simply using generous edge distances with preloaded bolts have been demonstrated. In balance to this conclusion is the fact that 6D edge distances translate to relatively large obstructions to the window sight lines. The two conflicting concerns must be balanced for a practical application.

4.3.6. Dynamic Effects

Dynamic effects were experimentally addressed using drop hammer testing as described in references 8 and 9. In general terms, the results obtained from the drop hammer tests plus results from multiple SPAT tests reinforce conclusions and recommendations discussed above. One additional point that should be highlighted is the tendency of the interlayer of the laminated glass to “snap off” due to bending near the supports. This effect can be greatly amplified if the bolts holes are too close to the inner edge of the support. Figure 29 shows an example of bolts (bolt hole) very close to the supported edge. The stresses due to bending at the edge of glass amplify the tendency for failure at the bolt line.



Figure 29. Bolts Very Close to Inner Edge of Support

A second point that was demonstrated during the drop hammer testing is the notion of allowing edge rotation and the resulting tendency to reduce the snap off effect at the edge of the glass. Figure 30 was a modification executed during the drop hammer testing that demonstrates the possible benefits of allowing the support edge to rotate thus minimizing the glass edge bending induce snap off. However, the arrangement in Figure 30 did not facilitate maintaining constant pre-load. Note that many of the SPAT concepts exhibit very large translation and rotation of the edge supports and are designed to maintain pre-load during a load event.

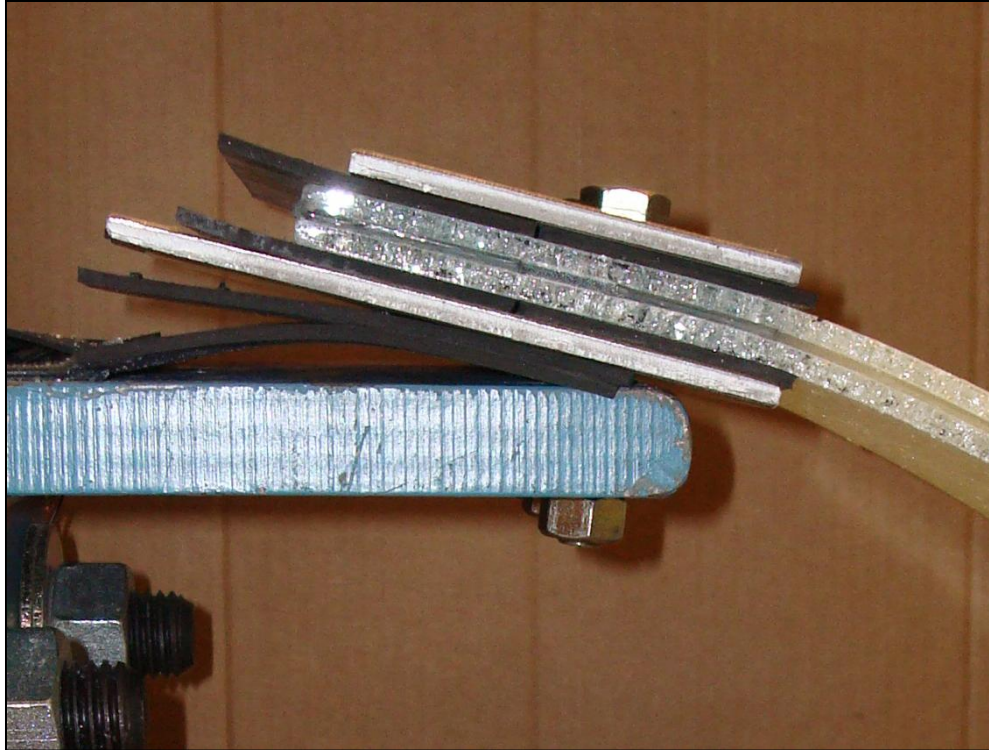


Figure 30. Allowance for Edge Rotation

4.3.7. Practical Guidelines

A considerable volume of technically significant information has come out of the investigation to date. Much of the information is of value to the general knowledge of the engineering community. However, the primary goal of this investigation remains to support efforts to provide suitable design guidelines for through-bolted-edge support glass. The following recommendations may not be ideal in every case but should be considered applicable to current applications with the SPAT program. Clearly, the data presented above can be adapted to SPAT as well as other applications.

4.3.7.1. Bolt Spacing and Edge Distance

The recommended edge distance is approximately $4.5D$ (assuming 0.5-in diameter bolts). Under no circumstance should the edge distance be less than $3D$. While $6D$ provide added reserve capacity, the interference in sight line due to the wider support is often a concern. $4.5D$ offers a good balance between connection capacity and limiting sight line interruption.

The bolts should be centered on the contact edge. Specifically, $4.5D$ from the bolts to the outer edge of the glass should be mirrored as $4.5D$ from the bolts to the inner edge of the support.

Given edge distances of $4.5D$, the bolts should be spaced at approximately 6 in. Note that for larger spaces the bolt strength can become a limiting factor (assuming 0.5-in Grade 8 bolts and 0.18-in SentryGlas® interlayer).

4.3.7.2. Bolt Pre-load

Based on test results specific to the through-bolted-edge investigation and general results from SPAT tests, it is essential that the bolts be preloaded to a suitable level. The recommended preload sequence is currently included in standard aspects of SPAT designs. In summary, for 6 inch bolt spacing, the recommended initial pre-load torque is 900 in-lb which translates into an effective torque for calculation purposes of 600 in-lb.

4.3.7.3. Crack Mediation

In general terms there is a high sensitivity to cracking the glass associated with through-bolted glass. During installation, contact between the bolts and the inside edge of the glass at the holes would often result in crack initiation. One remedy to this issue is shown in Figure 31. The inside edge of the interlayer is at a smaller diameter than the holes in the glass. The interlayer serves to center the bolt while maintaining separation between the bolt and the inside edge of the glass. Note that this could be facilitated through inserts or grommets. However the concept in Figure 31 was found to readily integrate into the lamination sequence and it provided the added benefit of providing some room for misalignment between the holes in the glass layers.

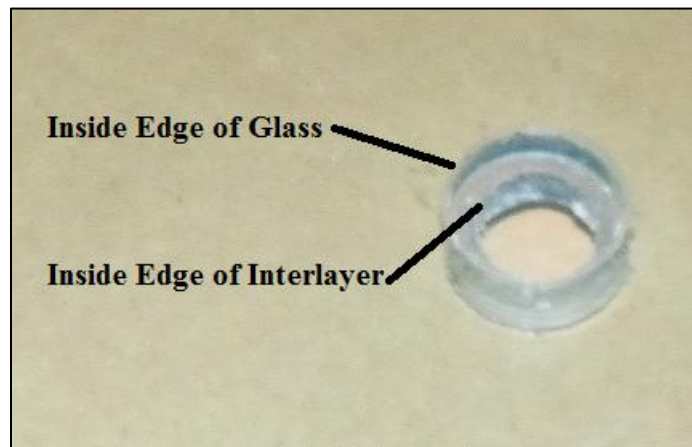


Figure 31. Inner Edge of Hole in Laminated Glass

4.3.7.4. Connection Rotation

Many of the SPAT designs allow glass support translations and rotations that far exceed that allowed by conventional approaches. Results from through-bolted-edge investigations as well as the broader SPAT retrofit tests indicate that allowance for edge movements can significantly improve the performance of laminated glass in a load event. Clearly, it is important that the clamping force be maintained during the load event so that the glass is not pulled from the support.

4.3.7.5. Global Capacity of the Glass

It is important to note that in all of the pull-out testing the failure was at the connection. Even with 6D edges and relatively high pre-load, global failure between the connections was not witnessed. As such, the results of the current investigation should be taken as a path to evaluation of pull-out capacity which is a critical aspect of the connection performance. However, the

global performance of the glass is not included in the current investigation and should be executed as a separate evaluation on a case by case basis.

4.4. Conclusion

Practical guidelines have been developed for evaluation and design of through-edge-bolted laminated glass. Specific guidelines include bolt edge distances, bolt spacing, bolt preload, crack mediation during installation and application of the through-edge-bolted concept to highly reactive support conditions as present in many of the SPAT retrofits. Various edge conditions were investigated and evaluated in terms of respective pull-out capacities. It is noteworthy that in all of the tests conducted the post-crack behavior of the laminated glass did not exhibit large global strains.

5. CONCLUSIONS

SRI's support of AFRL through the SPAT program and the through-bolted-edge investigation provided a wide range of benefits to the research, including theoretical developments, test planning, test support, test execution, practical design support and constructability support. Several practical guidelines, as outlined in Section 4.3.7, were developed that support the actual development of retrofit concepts. Specific guidance to retrofit development was provided through high level analytical modeling.

6. RECOMMENDATIONS

It is suggested that a research program be developed that focuses on the global performance of laminated glass with consideration for large support translations and rotations. In addition, in no case has there been evidence of large post-cracked global strains in the interlayer material. This is fundamentally contrary to the assumptions integral to many of the classical window programs and existing finite element material models. This issue should be included as one aspect of the recommended program focused on global behavior of laminated glass.

A key aspect developing pull-out resistance in the through-bolted-edge support is the bolt pre-load induced pressure at the gasket to glass and frame interface surfaces. The research described above included gasket relaxation test with durations of about three weeks. Consideration should be given to investigating the long-term effects of time and environment on maintaining the contact pressure.

While the results presented above for point supported glass indicate impressive pull-out resistance, the capacity is likely very sensitive to the through thickness tearing at the bolts. It is recommended that the global performance of point supported glass be evaluated accordingly.

7. REFERENCES

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LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

°F	degrees Fahrenheit
AFRL	Air Force Research Laboratory, Tyndall, Air Force Base, Florida
D	bolt hole diameter (length)
<i>d</i>	bolt diameter (length)
DoS	Department of State
<i>e</i>	edge distance (length)
ft	foot; feet
F_u	ultimate tensile strength (force per area)
in	inch(es)
in-lb	inch pound (torque unit)
lbf	pounds force (force unit)
psi	pounds per square-inch (stress unit)
<i>R</i>	resistance per bolt (force)
R_n	resistance per unit length (force / length)
SPAT	Solutions to Protect Against Terrorism
SRI	Southern Research Institute
<i>s</i>	bolt spacing (length)
<i>t</i>	thickness (length)
θ	failure angle (degrees)