BLAST PERFORMANCE OF NON-CAPTURED STRUCTURALLY GLAZED INSULATED GLASS UNITS

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A captured glazing system relies on a pressure cap or cover to mechanically transfer forces applied to the glazing panels into the curtainwall framing. Conventional blast resistant curtainwall is designed as captured systems, using the compression gaskets or primary sealant to transfer the blast loads into the pressure cap or blast cover. However, captured systems, with their exposed framing, limit the designs available to architects. Inversely, structural glazing, a popular method for securing building facade materials by means of structural sealant, allows for a smooth, fluid surface without the interruption of a captured system.

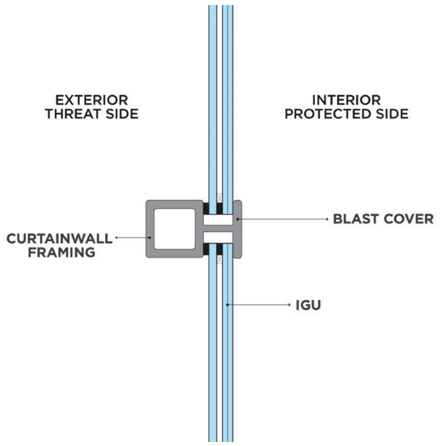
Conventional wall systems place the framing to the interior of the building. During a blast event the primary sealant or gaskets are compressed against the curtainwall framing. In custom configurations, curtainwall framing is often specified to the exterior of the wall system, and the glass is glazed to the interior side of the framing, as seen in Figure 1. Traditionally, blast covers would accompany the interior of the wall system to mechanically transfer direct blast loads into the curtainwall framing.

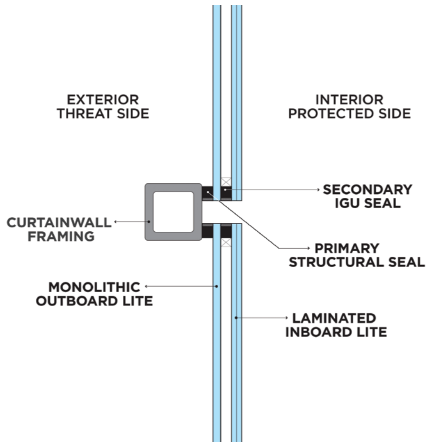
In the interest of architectural progression, Enclos engineers developed a non-captured structurally glazed wall system that will provide building occupants a level of protection when subjected to a typical U.S. General Services Administration blast pressure and impulse. A non-captured, structurally glazed system would provide architects and owners with an additional design option, and provide cost savings due to eliminated design time and material required for blast covers. The purpose of this test program was to develop a methodology for analyzing the secondary seal of an insulated glass unit (IGU) as well as validating the performance through testing.

SCOPE AND OBJECTIVE

The first objective of the test program was to validate the secondary seal's contact bite calculations. The secondary seal of an IGU is typically not subjected to tensile loading from direct blast loads. Curtainwall engineers needed a methodology to calculate the required sealant bite for this glazing configuration.

The second objective was to design a full-scale specimen to an ASTM F 1642 Low Hazard Rating[1] (FEMA 427 Condition 2[2]) subjected to UFC 4-010-01 Applicable Explosive Weights I and II at conventional standoff distances.[3] This test program was conducted to meet the evaluation standards of glazing systems subjected to airblast loading in ASTM F 1642, with results validating the load





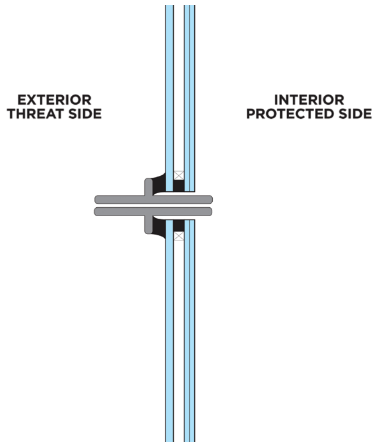


FIGURE 1
A blast-resistant curtainwall design utilizing a blast cover to resist direct blast loads and provide a mechanical connection between insulated glass units (IGU) and curtainwall framing.

FIGURE 2
A plan detail of a non-captured, structurally glazed curtainwall resisting direct blast loads through tension in the primary and secondary seals.

FIGURE 3
An example of a non-captured structurally glazed system with complex mullion.

path and sealant calculations. Three specimens were tested at design pressure in accordance to ASTM F 1642, and a fourth test was run at a 15% overpressure to determine sealant reserve capacity and controlling failure modes.

The scope of the project was to design, fabricate and test specimens. The performance and post-test condition of the secondary seal was evaluated on pass/fail criteria.

DESCRIPTION OF CURTAINWALL SYSTEM

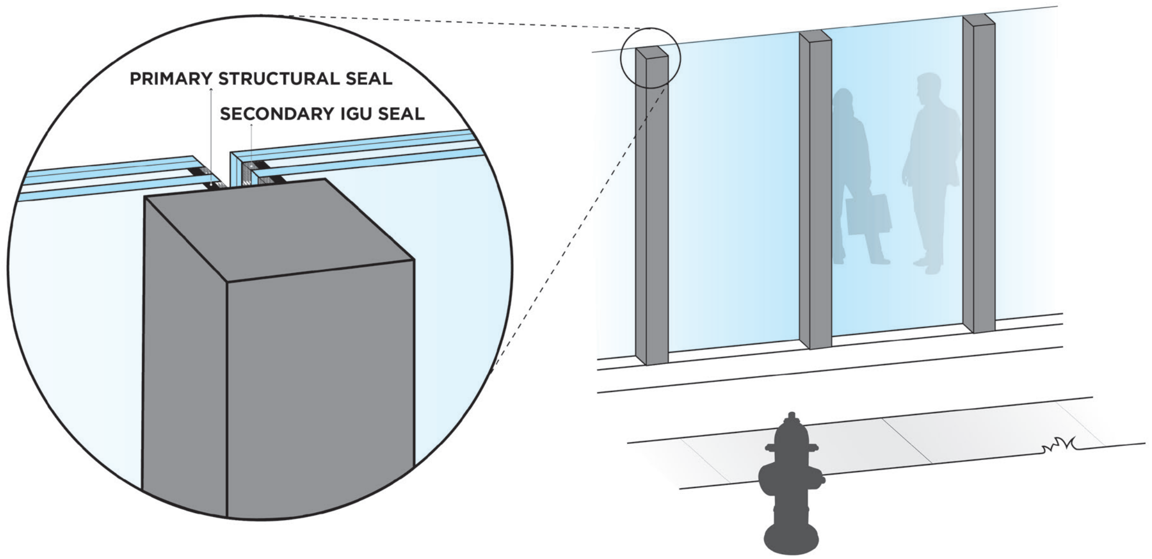
In order to isolate the loading to the secondary seal, the IGU was glazed to the interior of facility. No pressure cap or blast cover was present to capture the IGU to the framing. The IGU was loaded by the airblast pressure and loads were transferred through the primary and secondary seal into the curtainwall framing. Figures 2 and 3 show examples of glazing systems that were tested.

To further illustrate the orientation of the system, Figure 4 shows an elevation of the tested curtainwall system from the perspective of an observer located on the exterior of the wall system.

Test specimens were sized to meet the dimensional limitations of the test facility, with no chamber modifications. The aspect ratio of the IGU was chosen to match typical project specifications. The test specimens had a daylight opening width of 45.25 inch x 106.25 inch (1149 mm by 2699 mm) tall. The dimensions of the IGU glazed to the interior of the framing measured 51.25 inch x 112.25 inch (1302 mm x 2851 mm).

Specimen framing members consisted of 3 inch x 3 inch x 0.25 inch (76.2 mm x 76.2 mm x 6.4 mm) 6061-T6 aluminum tube framing and robust shear block corner connections. Anchorage to the test chamber was achieved by 0.25 inch (6.4 mm) steel tabs spaced 18 inches (457 mm) on center. Closely spaced anchor tabs and robust curtainwall framing was intended to concentrate response to the structurally glazed IGU.

With consideration to the size of the IGU, the makeup was designed to meet the ASTM F 1642 Low Hazard[1] and FEMA 427 Window Performance Condition 2[2] rating for UFC 4-010-01 with Applicable Explosive Weights I and II at conventional standoff distances.[3] Condition 2 allows for small dusting and a few fragments to be present on the sill or floor.[2] The design IGU makeup was specified as a 1/4 inch (6 mm) heat strengthened



monolithic outboard lite with 9/16 inch (14 mm) air gap, 3/16 inch (5 mm) standard annealed, 0.030 inch (0.76 mm) PVB interlayer, and 3/16 inch (5 mm) annealed laminate.

The IGU and components were sourced from typical Enclos vendors and assembled at an Enclos facility using conventional unitized curtainwall means, methods and quality control.

SECONDARY SEAL DESIGN

The design loads were specified by the U.S. General Services Administration, meeting UFC 4-010-01 Applicable Explosive Weights I and II at conventional standoff distances and Performance Condition 2 of the IGU.[4] US government provided glass analysis software was used to calculate the edge shear created at the perimeter of the IGU subjected to the specified blast loads. This edge shear was used to specify the sealant bite according the sealant manufacturer's ultimate sealant shear stress. The sealant bite design was verified by using pressure tributary loading in accordance with ASTM C1401 reproduced in Figure 5.[5]

The sealant stress calculations were performed using the following equation.

$$\sigma_t = \frac{q_{BLAST}}{t_{bite}}$$

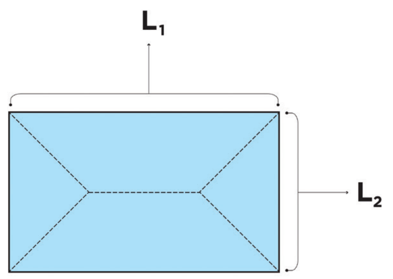
Where:
σ_t: tensile stress in sealant
q_{BLAST}: tributary blast load on secondary seal
t_{bite}: sealant contact between inboard and outboard lite

In an effort to focus all response to the secondary seal, the primary seal between the curtainwall framing and the monolithic lite of the IGU was overdesigned by a factor of three. No safety factors were applied to the secondary seal bite in effort to accurately determine a design methodology and adequacy of the load path.

EXPERIMENTAL METHODS

Specimens were tested using a shock tube supplied by an independent test facility, shown in Figure 6. The shock tube loaded the specimens using a volume of compressed air matching the design pressure and duration as specified by the

FIGURE 4
The unique orientation of the tested system specifies the glazing of the insulated glass unit infills are glazed to the interior of the framing. The absence of blast covers to mechanically secure the IGU to the curtainwall framing creates a non-captured system. During a blast event, the inbound blast wave subjects the primary structural seal (located between the framing and monolithic outboard lite) and the secondary seal (located between the outboard monolithic lite and the laminated inboard lite) in direct tension. The primary and secondary structural seals must be adequate in resisting the blast load in order to protect the occupants to the criteria specified in the project specifications.



test procedure.[4] A shock tube is operated based on theoretical volume of pressurized air instantaneously released. The shock tube is calibrated by test runs prior to the specimen testing. Baffles on the test chamber were used to minimize the effects of reloading by reflections inside the chamber.[4]

The test chamber was a welded assembly of deep steel channels and structural tubes. The chamber provided sufficient stiffness to ensure the response was focused on the test specimens. Test load data was measured using three dynamic pressure transducers, with one transducer located on each wall and one on the floor. The reported test load was averaged from the three gauges.[4]

Test specimens were mounted into the chamber so that loading would be applied to the monolithic exterior lite. Following failure of the exterior monolithic lite, the interior laminate lite would be loaded, creating a tensile reaction in the primary and secondary seals.

High speed cameras documented the response of the specimens. Both cameras were located on the protected side of the IGU – one camera located directly behind the specimen, the other at the side to give a perspective view.

A scratch tube gauge was used to measure the deflection of the sealant for Tests 3 and 4. This device consisted of a tube loosely clamped to the test chamber frame, with one end of the tube pushed to the surface of the glass. The clamp remains stationary on the rigid chamber frame while the tube moves with the glass deflection. Because the scratch gauge was placed directly over the secondary seal, the displacement of the structural sealant could be recorded as it responded to the inboard blast load. Figures 7 and 8 show the pre-tested specimen secured to the chamber and ready for testing.

RESULTS

The tests were run in accordance to ASTM F 1642. A summary of test pressures and observed performance is shown in Table 1. Pressure 1 refers to the design level pressure prescribed by UFC 4-010-01 Applicable Explosive Weights I and II at conventional standoff distances.

FIGURE 5
Diagram of rectangular shape trapezoidal load distribution per ASTM C 1401.

FIGURE 6
The shock tube used for testing consisted of a cylindrical driver, expansion chamber and framing for the specimen.

FIGURE 7
View of pre-test specimen from the protected side of the IGU.

FIGURE 8
View of pre-test specimen from the threat side of IGU. This image was taken from the interior of the shock tube expansion chamber.

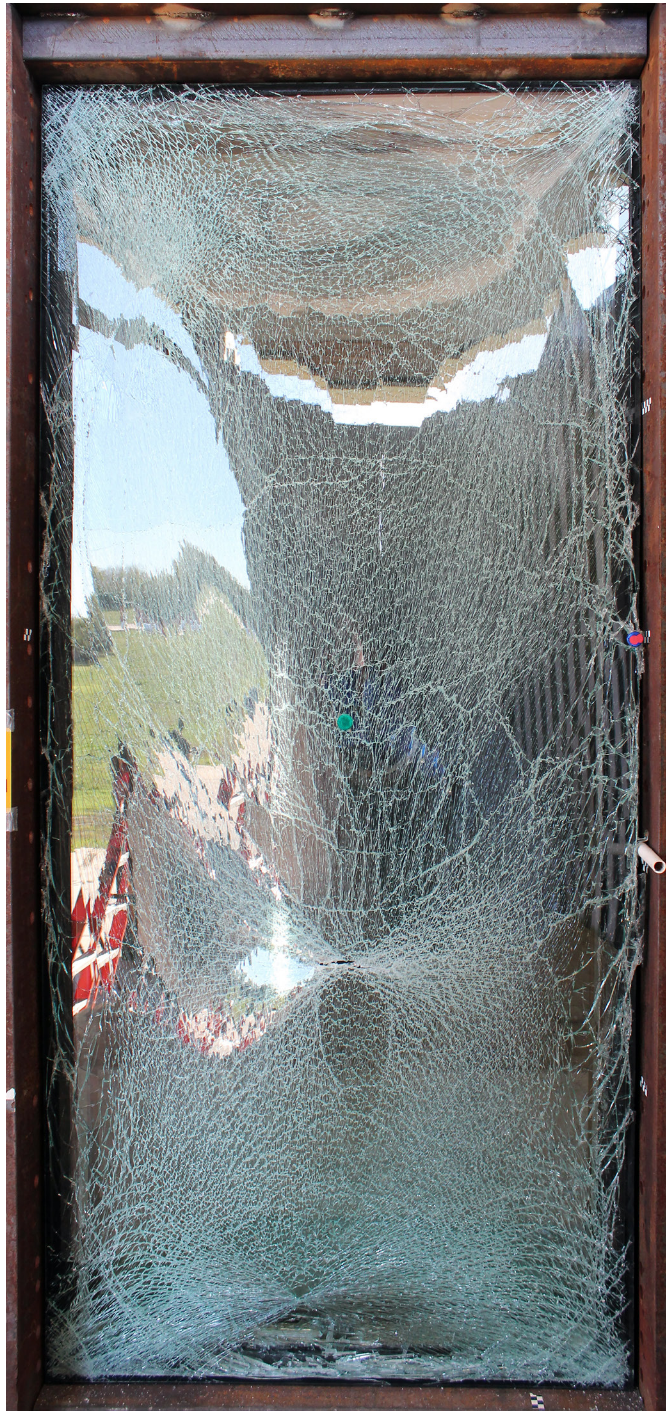


FIGURE 9
Post-test condition of specimen. View is from the protected side of the IGU. Note the fracture patterns in the laminate lite, which are consistent with pressure tributary loading per ASTM C1401, Figure 4.

FIGURE 10
Post-test condition of overload specimen in Test 4. View is from protected side of the IGU. Although blast pressure was increased 15%, fracture patterns in laminated lite remain consistent with pressure tributary loading per ASTM C1401, Figure 4.

TABLE 1
Test Results

TABLE 2
Peak Displacement

TABLE 3
Sealant Displacements

TEST	PRESSURE	ASTM HAZARD LEVEL	RESPONSE DESCRIPTION
1	Pressure 1	Minimal	No damage of secondary sealant of IGU. Glass dusting on floor of witness area.
2	Pressure 1	Very Low	No damage of secondary sealant of IGU. Glass dusting and one fragment on floor of witness area.
3	Pressure 1	Minimal	No damage of secondary sealant of IGU. Glass dusting on floor of witness area.
4	115% x Pressure 1	Low	No damage of secondary sealant of IGU. Limited failure of secondary seal of IGU. Glass fragment debris generated, but less than 10 perforations of witness panel.

TEST	PEAK DISPLACEMENT INCH (MM)	TIME (MS)
1	NA	NA
2	7 (178)	38
3	5 (127)	32
4	9 (229)	45

TEST	SEALANT DISPLACEMENT INCH (MM)
1	NA
2	NA
3	1/16 (1.5)
4	1/8 (3.2)

Post-test inspection of specimens yielded expected failure patterns of the laminated lite, as shown in Figure 9. No failure was observed in the anchor plates, aluminum framing or the primary seal. No failure was observed in the secondary seal or in the laminate lite of the IGU for Tests 1, 2 and 3.

Test 4 experienced a partial failure in a portion of the PVB interlayer along the mid-span of the specimen (as shown in Figure 10), but glass remained attached to the frame.

Reported max displacements at center of glass are found in Table 2. The sealant deflections as measured by the scratch gauge are reported in Table 3.

CONCLUSIONS

Structurally glazing an IGU to the interior of curtainwall framing is adequate to resist direct and rebound blast loads. Test specimens 1, 2 and 3 demonstrate that the secondary seal in an IGU is capable of providing results equal to or greater than ASTM Low Hazard protection when subjected to a pressure and impulse meeting UFC 4-010-01 Applicable Explosive Weights I and II at conventional standoff distances.[4] Additionally, the successful performance of the three specimens met the requirements of ASTM F 1642.

Test 4 demonstrated reserve capacity in the secondary seal and maintained an ASTM Low

FIGURE 11
View of post-test laminate lite at location of sealant and PVB laminate failure. Failure occurred approximately mid-span at point of maximum panel deflection.

Hazard performance for a 15% pressure increase over the UFC 4-010-01 Applicable Explosive Weights I and II at conventional standoff distances.[4] Tearing of the PVB interlayer and failure in the secondary seal (shown in Figure 11) was observed during the overpressure test, indicating that capacities of the two components were closely matched to the peak maximum reaction load.

Structurally glazing an IGU to the interior of curtainwall framing and then loading the specimen without the presence of blast covers did not affect the performance of the IGU and failure patterns in the laminated lite were deemed normal.[4] The success of this test program provides curtainwall engineers a methodology to appropriately size the primary and secondary sealant bite when IGU's are specified to be structurally glazed to the interior of curtainwall framing. Conventional stress calculations and loading diagrams were validated, and demonstrated reserve sealant capacity through testing of the specified blast load, impulse and glass dimensions. Ultimately, these results allow architects and owners to design wall systems with non-captured, blast-resistant curtainwall.