

Maximizing Transparency for Glazing Wall Systems Subjected to Blast Loading

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Abstract

Advances in blast-resistant glazing have shifted critical design demands to supporting frames, where aluminum mullions may govern façade failure under elevated blast-induced reactions. Ensuring compatibility between glazing capacity and framing performance is essential to achieve balanced, capacity-based façade design and prevent disproportionate damage. This study investigates blast load transfer at the glazing–mullion interface by quantifying demand-to-capacity ratios for aluminum mullions, steel-retrofitted aluminum mullions, and structural steel mullions across varying glazing panel sizes. Edge reactions from double- and triple-insulated glazing layouts are obtained through nonlinear dynamic analyses in WINGARD, while mullion response is evaluated using single-degree-of-freedom methods. Results show that high-performance glazing, particularly triple-insulated units, improves glazing survivability but can generate reaction forces exceeding the capacity of conventional aluminum mullions. Discussions on the design, architectural, and fabrication challenges related to each mullion type is provided. The findings highlight the necessity of coordinated glazing-to-framing design, offering practical guidance for achieving code-compliant, blast-resistant façade systems while clarifying trade-offs among compatibility, reinforcement requirements, and architectural constraints.

Keywords

Blast loading, triple insulated glazing, steel mullion, balanced design

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1. Introduction

Blast-resistant curtain wall design has traditionally prioritized glazing survivability. However, the increasing use of high-performance glazing layups with enhanced blast resistance can shift the governing limit state from glass failure to the supporting framing system. This is especially true for large glazing panels and high-performance glazing assemblies, such as laminated and triple-insulated glazing units (TGUs), which can remain intact under severe blast loading while transferring substantially higher edge reactions to the supporting mullions, anchors, and attachments. In such cases, improved glazing capacity does not necessarily improve overall façade performance unless the framing system is proportioned to accommodate the increased dynamic demand.

Previous blast façade research has consistently demonstrated that framing response is a critical determinant of curtain wall performance under blast loading. Through full-scale experimental testing and analytical modeling, Brewer et al. (2015, 2016) showed that blast-resistant façade design must explicitly account for reaction-force transfer through studs/mullions and supporting attachments, with overall system performance strongly influenced by the ability of framing components to sustain both impulsive and rebound demands. At the member scale, Chavan (2021) further showed through shock-tube testing and analytical assessment that commercially used aluminum mullions can become the controlling design factor under blast loading, and that mullion hardening significantly alters displacement demand, damage progression, and pressure–impulse resistance.

Collectively, these studies highlight a critical design implication: as glazing systems become larger and more blast-resistant, mullion and framing capacity increasingly governs façade performance. This underscores the need for blast-resistant curtain wall design to explicitly assess mullion demand-to-capacity and glazing–framing compatibility. However, the existing literature does not provide a clear, systematic comparison of mullion behavior across a broad range of glazing panel sizes and glazing layups, and a gap remains in transparently demonstrating how these variables influence the relative performance of different mullion systems

To address this gap, the present study systematically evaluates how mullion capacity and response vary with glazing type and panel size in blast-resistant curtain wall systems. Specifically, the study evaluates typical aluminum mullions, deep aluminum mullions, aluminum mullions with steel inserts, and structural steel mullions subjected to edge reaction demands from both double-insulated glazing units (DGUs) and TGUs. Six glazing panel dimensions are considered for each glazing type to capture the influence of panel size on reaction demand and framing performance. The objective is to provide a transparent comparison of glazing–framing compatibility across these cases, and to clearly demonstrate how glazing type and panel size shift the governing demand-to-capacity relationship among different mullion systems.

2. Methodology

Four glazing panel sizes (shown in Fig. 1) and two glazing layups were considered in this study. The glazing layups consisted of a DGU with layup 10 mm HS – 12.7 mm air gap – 6.6.4 HS, and a TGU with layup 10 mm HS – 12.7 mm air gap – 10 mm HS – 12.7 mm air gap – 6.6.4 HS. Each glazing configuration was analyzed using WINGARD (Applied Research Associates, 2005), and the average dynamic edge reactions along the vertical mullions were extracted for subsequent framing analysis. For each glazing system, the reaction time history used in the study corresponded to the glazing system capacity at the point of reaching a GSA 3b hazard rating (with a 14 msec positive duration), such that the framing

demand was evaluated at a consistent glazing performance limit state. It is noted that the ability to identify glazing edge loading for a given GSA rating and positive duration is a feature of WINGARD. The extracted mullion edge-reaction time histories were then used as input to the Dynamic Component Modeler Software (DCMS) (Applied Research Associates, 2020), to evaluate mullion response using a single-degree-of-freedom (SDOF) approach. By adopting a balanced design approach, the capacity of the connected members (framing, connections, etc.) should be greater than the capacity of the glazing. As a result, the framing must resist edge reactions for a blast loading scenario that causes a GSA 3b hazard rating for a selected glazing unit. This also means that by selecting a TGU which has a higher blast resistance than a DGU, the edge reactions resulting from a GSA 3b condition would be significantly greater than a DGU unit of the same size.

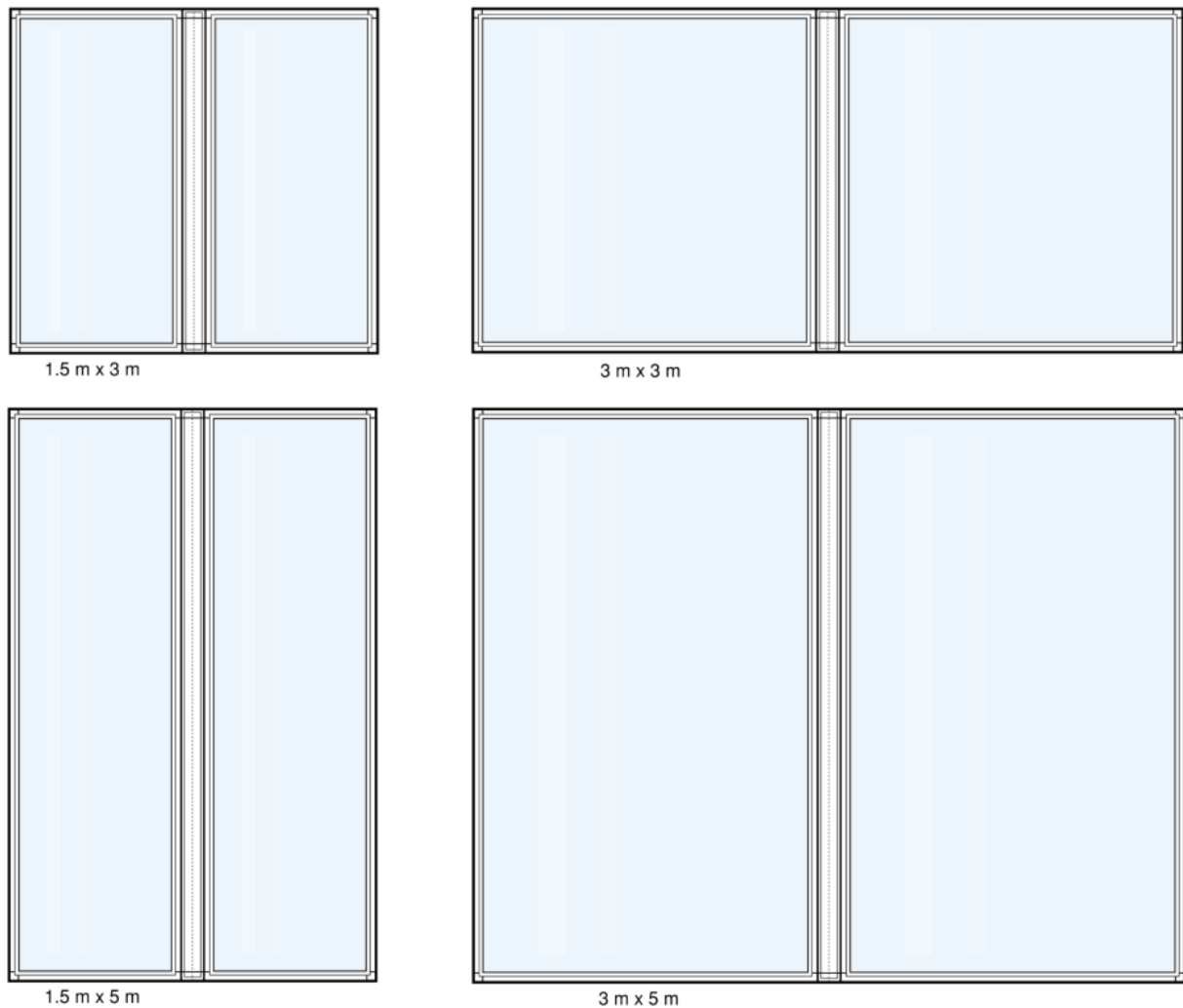


Fig. 1: Representation of the glazing panel sizes used to produce dynamic edge loading on a mullion.

Four mullion cross-sections were considered (depicted in Fig. 2). Section A represents a conventional aluminum mullion and was used as the baseline framing configuration. All baseline dimensions were 6 in depth \times 2.5 in width \times 0.2 in wall thickness. Section B, Section C, and Section D were selected as alternative mullion design schemes intended to improve blast resistance of the framing system relative to the baseline section. Section B is a deeper aluminum mullion with an 8 in depth (all other dimensions unchanged), representing a geometric strengthening approach that increases section stiffness and bending resistance through increased depth. Section C is based on Section A with an internal built-up steel insert profile, representing a hybrid strengthening approach in which additional steel

reinforcement is non-compositely introduced within the aluminum mullion to enhance resistance while retaining the original external envelope. Section D has the same geometry as Section A but uses structural steel in place of aluminum, representing a material substitution approach that increases stiffness and strength while maintaining the same nominal section dimensions. 6063-T6 Aluminum material was used in the analysis as a bilinear material model.

These three alternative sections were included to compare different framing enhancement strategies that may be used in practice to improve blast performance while accommodating architectural and detailing constraints. In particular, the selected schemes allow comparison between (i) increasing member depth, (ii) reinforcing an existing aluminum profile with an internal steel insert, and (iii) replacing the aluminum mullion with a steel section of the same nominal geometry. This provides a transparent basis for evaluating how changes in geometry, reinforcement strategy, and material selection affect mullion response under the same glazing-induced reaction demands.

For each mullion analysis case, loading was defined by considering a mullion supporting one glazing unit on either side (i.e., a tributary configuration of two adjacent lites). In addition to the applied dynamic edge-reaction time history, an added lumped mass was included to account for framing-associated inertia, taken as 20% of the tributary glazing mass supported by the mullion. All frames were considered as simply supported.

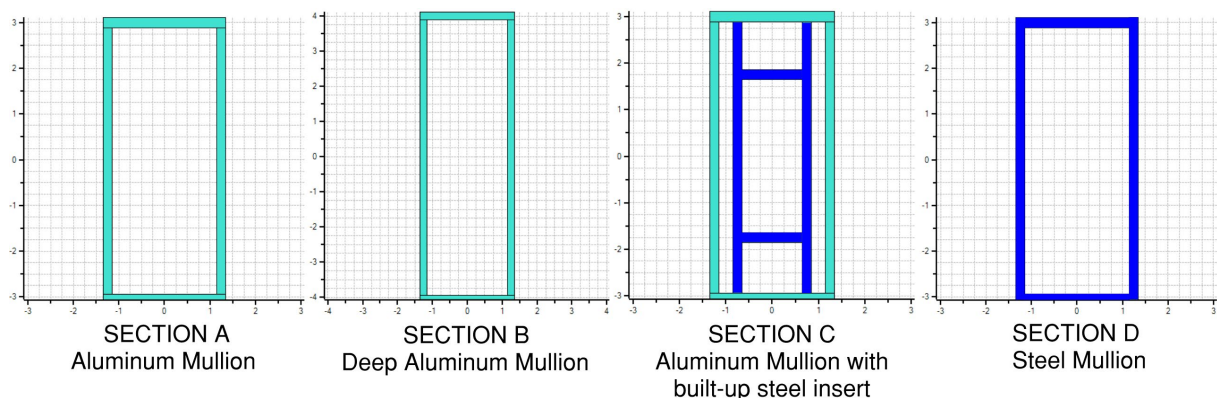


Fig. 2: Representation of the glazing panel sizes used to produce dynamic edge loading on a mullion.

3. Results and Discussion

3.1. Support rotation

Mullion performance was evaluated in terms of support rotation, with a reference rotational limit of 6° adopted to represent a Low (L) level of protection. Protective design standards such as UFC 3-340-02 and CSA S850 use support rotation thresholds to define varying levels of protection. Table 1 summarizes the resulting support rotations for the four mullion sections under edge-reaction demands corresponding to the glazing-system capacity for the considered glazing units. The results show a clear dependence of framing response on both glazing configuration and mullion design, and they confirm that framing demand can become critical as glazing resistance increases.

For the baseline aluminum mullion (Section A), support rotation increases substantially for larger glazing units and for the TGU cases. Under DGU loading, Section A remains below 6° for the 3×1.5 m and 3×3 m units (4.4° and 3.8° , respectively) but exceeds the limit for the larger 5×1.5 m and 5×3

m units (9.0° and 7.2°). Under TGU loading, Section A rotations exceed the limit in all cases, with rotations of 6.4°, 6.9°, 11.5°, and 9.7° for the 3 × 1.5 m, 3 × 3 m, 5 × 1.5 m, and 5 × 3 m units, respectively. This indicates that the baseline aluminum mullion becomes inadequate once glazing capacity and associated edge reactions increase, particularly for larger panel formats.

Section B (deeper aluminum mullion) provides a substantial reduction in rotation relative to Section A across all cases, demonstrating the effectiveness of increasing mullion depth as a geometric strengthening strategy. For DGU cases, Section B remains below 6° for all glazing sizes (2.2°, 1.8°, 5.1°, and 4.2°). For TGU cases, it remains below the limit for the two smaller units (3.2° and 3.5°), exceeds the limit for the 5 × 1.5 m case (6.9°), and is exactly at the reference limit for the 5 × 3 m case (6.0°). These results suggest that increasing depth can produce acceptable framing response for many cases but appear to be insufficient for the most demanding TGU configurations.

Sections C and D consistently produce the lowest support rotations and remain below the 6° threshold in all cases considered. Section C (aluminum mullion with steel insert) produces rotations between 1.3° and 4.1°, while Section D (steel mullion with baseline geometry) produces rotations between 1.2° and 4.3°. Their performance is markedly improved relative to Sections A and B, particularly for the larger TGU cases where framing demand is highest. For example, for the 5 × 1.5 m TGU case, rotation is reduced from 11.5° in Section A to 4.1° and 4.3° in Sections C and D, respectively. Similarly, for the 5 × 3 m TGU case, rotation decreases from 9.7° in Section A to 3.8° and 3.9° in Sections C and D.

A notable trend in Table 1 is that TGU cases generally produce higher mullion rotations than corresponding DGU cases, reflecting the increased reaction demand associated with the more robust glazing layout. In addition, larger glazing dimensions tend to increase framing demand, although the relative influence depends on the panel aspect ratio and the resulting edge-reaction characteristics extracted from WINGARD. Overall, the results demonstrate that as glazing systems become more resistant and panel sizes increase, the governing performance limit can shift to the framing system unless mullion capacity is upgraded accordingly.

Table 1: Support rotation in degrees for different mullion sections based on edge reactions obtained from GSA 3b capacity for varying glazing units. Low safety rotational limit is 6 degrees.

	SECTION A	SECTION B	SECTION C	SECTION D
3 x 1.5 m DGU	4.4	2.2	1.5	1.4
3 x 3 m DGU	3.8	1.8	1.3	1.2
5 x 1.5 m DGU	9	5.1	3.1	3.1
5 x 3 m DGU	7.2	4.2	2.7	2.7
3 x 1.5 m TGU	6.4	3.2	2	2.0
3 x 3 m TGU	6.9	3.5	2.1	2.1
5 x 1.5 m TGU	11.5	6.9	4.1	4.3
5 x 3 m TGU	9.7	6	3.8	3.9

4. Design, architectural, and production challenges

The structural performance based on support rotation indicates that framing design becomes a controlling issue in cases with higher blast demands and in glazing configurations with greater blast resistance, particularly for larger units and TGU layouts. In these cases, the baseline aluminum mullion

(Section A) is frequently insufficient to maintain acceptable rotational response, while the deeper aluminum option (Section B) improves performance but may require mullion depths that are difficult to accommodate within typical façade sightline, envelope, and architectural coordination constraints. As a result, the practical design solution for many demanding cases is likely to shift toward reinforced or hybrid framing schemes, most notably Section C (aluminum mullion with internal steel insert), which provides substantially improved blast resistance while preserving the external aluminum-based framing profile. However, Section C introduces additional shop complexity relative to Sections A and B because it requires a multi-step assembly process: extrusion/forming of the aluminum mullion, fabrication of the built-up steel insert, and individual insertion/fit-up of the steel reinforcement within the aluminum section. This process increases labor and quality-control demands. A further challenge associated with Section C is fabrication tolerance and fit-up between the extruded aluminum profile and the fabricated steel insert. In practice, tolerances in both the aluminum extrusion geometry and the fabricated steel reinforcement can make insertion difficult, particularly over long mullion lengths, and this often requires the steel insert to be reduced in size to ensure constructability and assembly in the shop. This constraint can significantly reduce the efficiency of the steel reinforcement, since the insert may need to be shallower than structurally optimal to fit within the aluminum cavity. Consequently, a reinforced aluminum mullion may require a heavier steel insert than an equivalent all-steel mullion solution to achieve a similar stiffness or rotational response. The fit-up challenge is further amplified as mullion length increases, where maintaining alignment and successfully sleeving the steel insert through the aluminum member becomes more difficult and labor-intensive.

Alternatively, Section D (steel mullion with the same nominal geometry as the baseline aluminum section) offers acceptable structural performance while being able to remain within architectural constraints due to its material strength allowing for smaller section sizes. This promotes substantial gains in stiffness and strength without increasing visible frame depth, making it especially attractive for larger glazing units and higher blast-demand cases. From a fabrication standpoint, it is generally simpler than the hybrid insert option (Section C), since it avoids the additional step of fabricating and individually fitting a snug steel insert inside an aluminum extrusion. Instead, it follows a more direct single-material steel fabrication workflow with conventional cutting, connection detailing, and finishing (Knickerbocker, 2025). Steel also offers an additional structural advantage in blast-resistant mullion design due to its reduced susceptibility to local buckling relative to thin-walled aluminum sections. This is particularly important under blast loading, where achieving reliable dynamic plastic capacity is required for acceptable energy absorption and deformation response. In thin-walled aluminum mullions, local plate buckling can occur before the full plastic capacity of the section is mobilized, thereby limiting ductility and reducing the effective resistance available under impulsive loading. By contrast, steel sections are generally better able to sustain inelastic response with more stable post-yield behavior, making them better suited to applications where dynamic plastic response is expected to contribute to blast resistance. The main limitation of Section D is not technical performance, but industry adoption, as most curtain wall production teams and supply chains are still centered on aluminum extrusion-based systems.

Material usage presented in Table 2 also highlights the trade-offs among the proposed mullion systems and allows a first-order embodied carbon comparison. Section A uses 5.8 kg/m of aluminum, while Section B increases aluminum usage to 7.2 kg/m due to the greater depth. Section C retains the same aluminum usage as Section A (5.8 kg/m) but adds 14.4 kg/m of steel through the internal insert, and Section D uses 16.9 kg/m of steel with no aluminum. Using screening-level embodied carbon factors of 2.0 kgCO₂e/kg for steel (SE 2050 ECOM tool) and 6.83 kgCO₂e/kg (European consumption) or 13.2

kgCO₂e/kg (worldwide average) for aluminum (Reynaers Aluminium Ltd. 2023), the estimated embodied carbon per meter is: Section A = 39.6 kgCO₂e/m (EU Al) or 76.6 kgCO₂e/m (global Al); Section B = 49.2 or 95.0 kgCO₂e/m; Section C = 68.4 or 105.4 kgCO₂e/m; and Section D = 33.8 kgCO₂e/m. Under these assumptions, Section D provides the strongest structural performance while also yielding the lowest embodied carbon per meter among the four options because it eliminates aluminum and relies on a relatively low steel carbon factor. Section C remains an important design option because it preserves the aluminum exterior profile and improves blast resistance substantially, but its hybrid configuration can be more carbon-intensive than Section D in this simplified comparison due to the combined aluminum and steel material demand.

Table 2: Material usage for each mullion system.

	SECTION A	SECTION B	SECTION C	SECTION D
Material quantity	5.8 kg/m Aluminum	7.2 kg/m Aluminum	5.8 kg/m Aluminum	0.0 kg/m Aluminum
	0.0 kg/m Steel	0.0 kg/m Steel	14.4 kg/m Steel	16.9 kg/m Steel
CO ₂ e (European)	39.6	49.2	68.4	33.8
CO ₂ e (Global)	76.6	95	105.4	33.8

5. Conclusions

This study demonstrates that blast-resistant curtain wall design can become framing-governed as glazing panel size and glazing blast resistance increase. By evaluating four glazing sizes and two glazing layouts (DGU and TGU) and applying WINGARD-derived dynamic edge reactions to SDOF mullion models in DCMS, the results showed that the baseline aluminum mullion (Section A) is inadequate for several larger and/or TGU cases based on a 6° support rotation reference limit. While increasing mullion depth (Section B) improved performance and was sufficient in many cases, it remained marginal or inadequate for the most demanding TGU configurations. In contrast, the reinforced aluminum mullion with a steel insert (Section C) and the steel mullion with the same nominal geometry (Section D) consistently provided acceptable rotational response across all cases, indicating that material reinforcement/substitution strategies are more effective than depth increase alone for high-demand glazing systems.

Beyond structural response, the study also highlighted the practical trade-offs that govern mullion selection in blast-resistant façade design. Section C offers a strong balance between blast performance and architectural compatibility by preserving the external aluminum mullion envelope but introduces added fabrication complexity due to the need for precise steel insert fabrication and fit-up. Section D provides excellent structural performance and can satisfy architectural envelope constraints, but its adoption is currently limited by the predominance of aluminum extrusion-based curtain wall production workflows. Overall, the findings reinforce the need for explicit glazing–framing compatibility assessment in blast-resistant curtain wall design and show that framing strategy selection must balance structural performance, architectural constraints, fabrication practicality, and material impacts.

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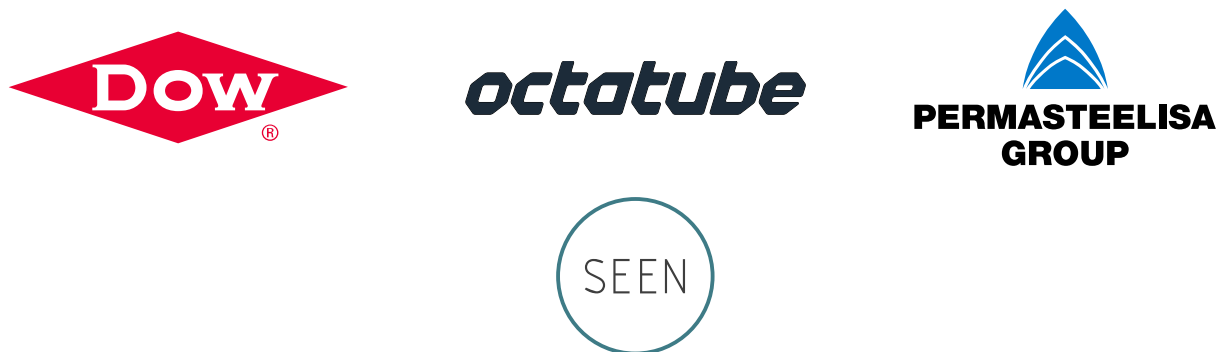
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