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Explanation of effective indexes on the performance of non-structural building components against blast waves with emphasis on the behavior of glass and window frames

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ABSTRACT

Over the past twenty years, threats to buildings from explosions have significantly increased. Non-structural components, particularly glass and window-frames, are especially vulnerable to blast loads, yet there is limited agreement on which factors most strongly affect their performance under such extreme conditions. This study seeks to systematically identify and rank the key factors influencing the blast performance of non-structural glazing systems using a multi-round fuzzy Delphi method. The research is analytical with an applied aim and also has a developmental aspect in the context of qualitative modeling. Data were collected through documentary and library sources, complemented by questionnaires and interviews with 15 experts and specialists within a defined statistical population. Core concepts—including non-structural building performance, façade systems, building frames, non-structural connections, and the impact of explosions on buildings—were initially analyzed through content analysis. Based on inductive reasoning and literature review, a preliminary framework of factors was developed. The fuzzy Delphi method was then applied over multiple rounds in a participatory decision-making process to extract, weight, and evaluate these factors. Results show that, based on mean values, layer bonding quality, 4.53; glass layer thickness, 4.36; blast intensity, 4.35; adherence to recognized design standards, 4.32; temperature effect, 4.21; glazing-frame connection, 4.13; barrier presence, 4.09; blast duration, 4.08; interlayer damage mode, 4.07; and the anchorage system, 4.04, are the influential factors in defining the performance index framework of non-structural building components against blast waves. Quantitatively, these factors consistently received high mean scores in the Delphi process, highlighting their critical role in structural integrity, post-fracture behavior, and overall blast resilience of glass and window-frame systems. These findings provide a validated, expert-driven foundation for prioritizing design considerations and developing performance-focused strategies for blast-resistant glazing systems, bridging the gap between theoretical analysis and practical implementation.

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INTRODUCTION

A significant percentage of economic losses is related to the damage of non-structural components, typically neglected within a Life Safety-focused seismic design approach, despite their inherently high vulnerability and capital investment when compared to the structural cost (Whittaker, 2003). Over the last two decades, threats to buildings caused by explosions have become increasingly important for society (van der Woerd et al., 2022). Explosions consist of rapid and wild release of energy in the form of shock wave, light, heat and sound. These shock waves consist of highly compressed air traveling at supersonic velocity (Zhang & Bedon, 2017). Explosion events, like accidents on an industrial site or a terroristic attack, cause different hazard sources. Besides primary hazards, like the blast wave, secondary hazards like fragments can threaten exposed humans in the surrounding area (Fischer et al., 2021). High-intensity blast overpressures generated by external sources of explosives cause significant damage to windows, potentially producing lethal glass shards or other windows fragments flying into the occupied areas of buildings at supersonic velocities. This kind of damages caused by the blast ranges from reparable to collapse with considerable loss of life depends on the magnitude of peak overpressure generated from the explosion and blast resistance of the structure/building (Anas et al., 2022). From the statistical data of historical explosion events, a significant number of casualties were caused by high-speed shattered glass (Chen, 2023). In most of the cases, blast events are so destructive that glass fragments and shatters are thrown away for hundreds of meters from the detonation source (Zhang & Bedon, 2017). If glass fragments are supposed to fail within 1 m distance from the opening, the threat is rated as “very low”; when the fragments fly longer than 0.6 m at 3 m distance, the hazard level is rated as “high” (Zhang & Bedon, 2017). Under accidental and extreme design actions, it is generally rec-

ognized that glass components represent the most vulnerable element and a possible severe risk for people, due to the intrinsic brittleness of glass and to the possible propagation of shards. In this sense, several research studies have been dedicated, especially in the last few years, to the analysis of glass windows and facades under accidental actions such as Bedon et al. 2017 and Figuli et al. 2021. (Fig. 1)

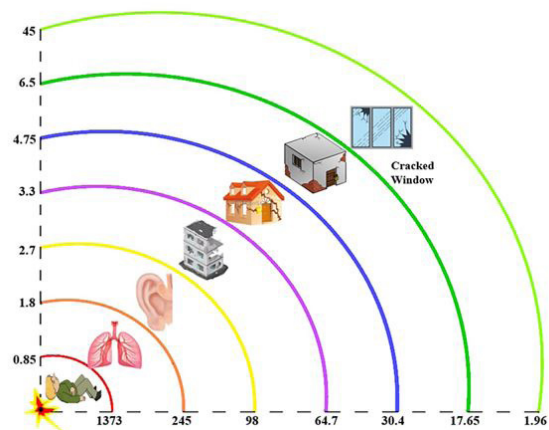


Figure 1: Injuries from blasts associated with specific overpressure levels and their corresponding standoff distances. (Shirbhate & Goel, 2020)

Glass shards, flying and falling from fenestrations present major sources of injuries when explosions occur in urban areas (Norville & Conrath, 2001; Blocker and Blocker 1949; Brismar and Bregenwald, 1982); Glass as an omnipresent material has been popularly used for windows and facades. Because of the relatively weaker strength of glass as material for construction, as compared with other traditional structural materials such as concrete and steel, glass elements and windows in particular are typically fragile components and therefore highly vulnerable to extreme loads such as air blast waves or hazards in general. As a result, specific fail-safe design rules are required for glass systems, even under ordinary loads (Feldmann et al., 2014). In the vast view, Glass is used in modern architecture widely as a part of facades often in combination with a steel substructure. However, glass is in

general also the most fragile part of a structure and its failure results in splinters that could seriously injure persons inside the building. The windows of critical buildings and in general of critical infrastructure can be strengthened (and their protection increased) (Larcher et al., 2016) (Fig. 2).



Figure 2: Failure of windows in Terrorist attack in Oslo, 2011 (Larcher et al., 2016)

Failure of windows under blast loading generally falls into four categories: (1) no glass breakage with glass remaining attached to the frame; (2) cracking while still attached, with a limited number of shards entering the interior; (3) global failure where panes detach and travel into the building, with categories scaling the travel violence (as per GANA, 2010); and (4) window separation and travel away from the building, caused by the interplay of negative-phase timing, dynamic rebound, and weaker outward restraints (Duke et al., 2011). The basic criteria for an optimal design of blast-resistant fenestration is that the glass panels should remain intact and in the frame, broken but not blown out. The frame itself should stay attached to the background building (i.e. the supporting wall). As such, the wall/structural background should finally remain intact to hold the frame in position (Figuli et al., 2017). (Fig. 2 & 3)

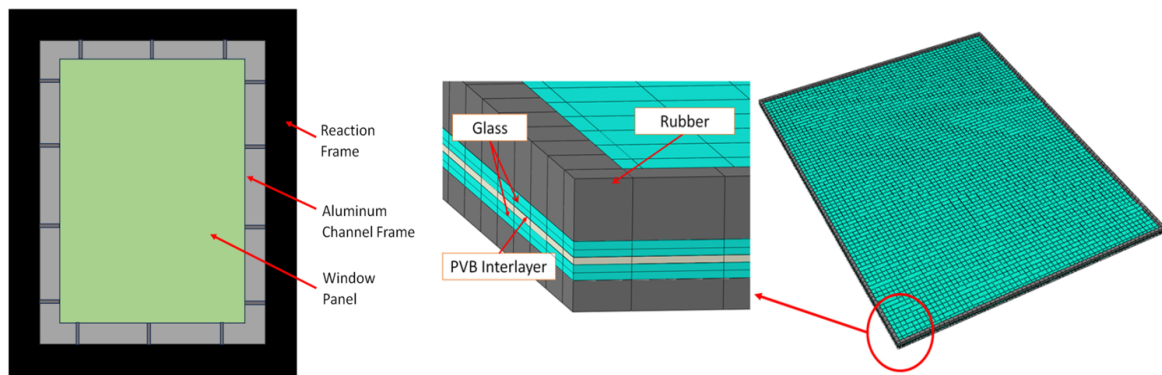


Figure 3: Glass window setup during in the shock tube. (Elbelbisi et al., 2023)

Despite growing research on blast effects in glass and fenestration, understanding of key non-structural performance indexes under blast loading remains limited. Many studies emphasize facade structure or general fragility rather than glass–frame interactions under extreme blasts, offering limited practical guidance for design. Window frames are a critical yet under-explored factor in blast design. They set bound-

ary conditions, influence deformation and fracture patterns, and determine whether shards are retained or expelled. Key factors include frame material and stiffness, geometry, connections, anchorage, and post-breakage interaction with laminated layers. This study systematically analyzes the indexes governing glass and frame performance under blast waves, focusing on material behavior, boundary conditions, an-

chorage, post-fracture capacity, and glass–frame interactions to improve building safety and resilience. Understanding the behavior of glass and window–frame systems under blast loading has therefore become a central focus in recent research. Previous studies have approached this problem through experimental investigations, numerical modeling, and analytical formulations, each offering different insights into damage mechanisms and failure thresholds. These works form the foundation for the following review.

MATERIALS AND METHODS

The Behavior of Glass and Window Frames Under Blast Loads

Over the past two decades, glazing systems under blast loading have been investigated

along three interconnected streams: blast-wave characteristics and load modeling; mechanical response and failure mechanisms of both monolithic and laminated glass; and the role of supporting frames, anchorage, and post-fracture retention. While these strands illuminate the interaction among blast pressures, material behavior, and detailing, the literature remains fragmented and would benefit from an integrated, cross-disciplinary synthesis. Across experimental, numerical, and review studies, key performance indexes such as glass fracture patterns, frame retention, frame deformation, load transfer pathways, and mitigation effectiveness—consistently emerge and should be integrated into a unified framework: (Tab. 1)

Table 1: Literature framework of research

No.	Title	Author	Year	Research type	Aim/Objects	Findings
1	Blast Loads and Testing Methods for the Blast Resistant Design and Performance Verification of Industrial Plant Facilities: A State-of-the-Art Review	Lee, S.-H., Kim, S.-H., Choe, G.-E., & Kim, H.-S	2025	State-of-the-art review	Examine current blast-load models and testing methods for industrial facilities and propose improvements	Existing anti-terrorism guidelines inadequately address VCEs; testing methods vary in capability; recommends extending shock-tube and simulator capabilities and developing performance-based standards for industrial plants
2	Towards blast safety of glass facades: Research advances and prospects	Chen, S., Chen, X., Lu, Y., Guo, X., Yi, S., & Luo, Y	2025	Review article	Summarize recent progress in blast-resistant glass façade design, material behavior and modelling	Highlights limited practical strength of glass (< 100 MPa), gaps in Weibull-type statistical models, and the need for ageing studies and integrated design tools

3	Mitigating Blast Hazards: Experimental Evaluation of Anti-Shatter Films and Catcher-Cable Systems on Conventional Windows	Andrae, M., Van Der Woerd, J., Wagner, M., Pietzsch, A., & Gebbeken, N	2024	Experimental study	Test the effectiveness of anti-shatter films and catcher-cable systems for conventional glazing	Demonstrated enhanced safety by limiting fragment travel and retaining glass pieces; specific performance metrics not detailed in the excerpt
4	Study on the Influence of Window Glass Size on Blast-Resistant Performance	Wang, X., Zhong, B., Tang, J., Gao, C., & Li, M	2023	Numerical parametric study (simplified P-I method)	Quantify how glass aspect-ratio, area and thickness affect blast resistance	Smaller length-to-width ratio, smaller area and greater thickness all increase blast resistance; square panes perform best; empirical P-I predictions validated against test data
5	Experimental and Numerical Investigation of Blast Wave Attenuation by Using Barriers in Different Configurations and Shapes	Eslami, M., Keshavarz MirzaMohammadi, P., Khalilpour, S. H., Parsa, H., & Kodure, V	2023	Combined experimental-numerical study	Reduce blast-wave loading in corridor-like structures by using barrier systems	Up to 50 % peak-pressure reduction with barriers occupying only 23 % of the cross-section; configuration T9 (9 pairs) gave the highest overall reduction ($\approx 41\%$); Y- and V-shaped barriers outperformed circular ones because of added turbulence
6	Blast-Resistant Window Anchors. I: Experimental Investigation	Alameer, A., Jacques, E., Elnabesly, G., & Saatcioglu, M	2023	Experimental investigation	Generate design data for blast-resistant window anchors and assess anchor forces	Anchor shear forces often lower than static predictions; rigid substrates produce higher forces; mechanical glazing outperforms wet glazing at high load.

7	A Study on the Bending of Laminated Glass Under Blast Loading	Samieian, M. A., Cormie, D., Smith, D., Wholley, W., Blackman, B. R. K., Dear, J. P., & Hooper, P. A.	2022	Experimental study (novel testing)	Understand laminated-glass response to high-rate bending representative of blast loading.	Thinner interlayers promote tearing, thicker promote delamination; allowing frame bending absorbs energy and raises load capacity; post-crack flexural rigidity is significant and must be included in design.
8	Numerical Analysis of TGU Windows Under Blast – GLASS-SHARD Outlook	Bedon, C., Larcher, M., Bez, A., & Amadio, C.	2022	Numerical study	Explore blast performance of ordinary triple-glass-unit (TGU) windows.	Load-bearing capacity and residual performance indicators were quantified; damage initiation and evolution in TGU components were captured.
9	Experimental Studies on Blast Performance of Unreinforced Masonry Walls: A state-of-the-art review	Anas, S. M., Alam, M., & Umair, M	2022	Review of experimental studies	Summarize experimental investigations of URM walls under blast and identify research gaps	For peak pressures > 2 MPa, brick/mortar strength effects are negligible; GFRP strips or polyurea coatings improve deflection resistance; high-fidelity FE models are needed for future work.
10	Blast Protection Techniques: A Review	Kangda, M. Z	2022	Review	Compile and categorise blast-load estimation methods and protection strategies	Identifies Kinney-Graham formulation as widely used; stresses importance of negative-phase pressure and effectiveness of steel-fiber concrete, base isolation and viscous dampers

11	Overview of dynamic test methods for examining the glass window resistance	Jankura, R., & Mach, V	2021	Review article	Identify the parameters examined in various dynamic tests (manual burglary, impact, explosion) and compare how they are classified in the relevant standards	Dynamic loading can increase glass strength up to three times because cracks have less time to propagate. / Classification schemes differ markedly between burglary, impact and blast standards, leading to inconsistent parameter sets. / The same glass properties are evaluated with different metrics across standards, complicating comparative assessment
12	Numerical Simulation of Blast Loads of Building with and without Glass Window	Zhou, X., Xie, L., & Yan, J	2021	Numerical simulation study	Assess how a glass window influences blast loading on a typical building	Presence of glass slightly raises peak over-pressure (error grows from ~2.8 % at Z = 0.5 to ~12 % at Z = 2.0) and the barrier effect becomes more pronounced at larger distances
13	Overview of dynamic test methods for examining the glass window resistance	Jankura, R., & Mach, V.	2021	Review	Compare standards for window-glass resistance to burglary, impact, explosion and wind loads	Finds that the same physical properties are often evaluated with differing parameters across standards, leading to inconsistent assessment
14	Comparison of traditional vs low-damage structural and non-structural building systems through a cost/performance-based evaluation	Bianchi, S., Ciurlanti, J., & Pampanin, S	2020	Cost-performance evaluation (numerical) Cost-performance evaluation (numerical)	Assess economic and performance benefits of low-damage structural & non-structural technologies in RC buildings permutation	Low-damage systems cut 50-year Expected Annual Losses by \(\$150-300 /m ² and reduce downtime by 2-7 months; benefits persist even when only a subset of components is upgraded

15	Investigating the Origin of Breakage of Panes Subjected to Blast Loading by Acoustic Emission Testing	Woerd, J., Roller, C., Brenneis, C., & Stolz, A.	2020	Experimental (AET) study	Determine precise location and timing of initial crack in blast-loaded laminated glass panes	AET successfully localized crack origins; average spatial deviation ≈ 7 cm vs. optical method; initial-crack times measured for all tests
16	A Critical Review of Blast Wave Parameters and Approaches for Blast Load Mitigation	Shirbhate, P. A., & Goel, M. D.	2020	Critical review	Summarise blast-wave parameters, scaling laws and mitigation concepts	Highlights that lightweight materials and mitigation strategies can significantly reduce blast response; stresses need for accurate prediction of over-pressure and impulse
17	Vulnerability and Protection of Glass Windows and Facades under Blast: Experiments, Methods and Current Trends	Zhang, X., & Bedon, C	2017	Review/state of the art-	Compile experimental, analytical and numerical studies on glass-window blast response and identify mitigation trends	Glass is highly vulnerable (shatter distances up to 8.5 km); failure modes depend on blast duration (planar vs. spherical); HS/FT glass and interlayer anchors improve performance; existing design codes often underestimate response
18	Blast-Resistant Glazing Design	Norville, H., & Conrath, E	2006	Design-methodology paper presenting prescriptive standards	Provide two practical methods (UFC DoD 2003 and ASTM F 2248-03) for blast-resistant glazing design	Both rely on laminated glass; ASTM F 2248-03 generally yields higher protection because it uses a 3-s equivalent load and a defined explosive threat, while UFC DoD 2003 offers a simplified approach for unknown threats

While the existing literature provides substantial insights into non-structural component performance under blast loading, clear gaps persist regarding which factors most effectively predict the way glass and window frames behave under blast waves. This study addresses these gaps by focusing on the factors listed in (Tab.2), which are grounded in the background shown

in (Tab.1). Through a targeted review, we identify how these indexes influence response characteristics and establish the rationale for their inclusion in the subsequent analysis. The findings from the literature review motivate and justify the table presented below, which connects the reviewed evidence to the specific factors and metrics examined in this work.

Table 2: Literature-Derived Factors Influencing Glass and Window Frame Behavior under Blast

No.	Factor	Description/Notes
1	Layer Thickness	Greater interlayer and glass thickness generally enhance blast resistance by increasing energy absorption and delaying crack propagation.
2	Inter layer Configuration	Laminated interlayers (multiple plies) improve post-crack residual capacity and reduce fragment dispersion compared to monolithic glass.
3	Layer Bonding Quality	Higher bonding quality between layers reduces delamination risk and improves overall integrity under high-rate loading.
4	Interlayer Material Type	The choice of interlayer material (e.g., PVB, SGP) influences damping, adhesion, and crack arrest behavior during blast events.
5	Frame Type	Frame geometry and material determine the frame's bending stiffness and its ability to share and dissipate blast-induced energy with glazing.
6	Glazing Frame Connection	Strong, well-designed connections between glass and frame minimize stress concentrations at interfaces during shock loading.
7	Fastener Spacing	Optimized, closer fastener spacing enhances load transfer and reduces local deformations at glazing edges under blast.
8	Edge Condition	Smooth, well-supported edges reduce stress concentrators and delay crack initiation in glazed panels.
9	Anchorage System	Robust anchorage systems improve transfer of loads from glazing to structural supports and limit glazing movement
10	Catcher Cables	Catcher cables or similar fragment-retention devices reduce fragment travel distance and improve occupant safety after glazing failure.
11	Additional Reinforcement	Supplemental reinforcement (stiffeners, beads, or laminates) increases system stiffness and energy absorption capacity.
12	Retrofit Presence	Retrofit measures can significantly enhance blast performance when designed to address existing glazing weaknesses.
13	Blast Intensity	Higher blast intensity elevates peak loads and accelerates damage progression, necessitating stronger glazing systems.
14	Barrier Presence	Barriers can modify wave transmission to glazing, potentially reducing peak loading or altering impact characteristics.
15	Loading Rate	High loading rates increase dynamic stress and may worsen crack initiation if materials are not rate-sensitive; laminated structures can mitigate this.
16	Blast Duration	Longer blast durations sustain loading and can exacerbate damage through cumulative damage and delayed failure mechanisms.
17	Interlayer Damage Mode	Delamination, interlayer cracking, and debonding dictate post-crack performance and energy dissipation pathways.
18	Energy Absorption	The combined system energy absorption governs how much blast energy is dissipated before glazing failure occurs.
19	Temperature Effect	Elevated or reduced temperatures alter material stiffness and damping, affecting blast response.
20	Ageing State	Ageing reduces material properties like strength and ductility, degrading blast resistance over time.

21	Glass Aging	Age-related changes in glass (microcracking, surface flaws) can lower resistance to blast-induced damage. Age-related changes in glass (microcracking, surface flaws) can lower resistance to blast-induced damage.
22	Interlayer Aging	Aging of interlayers reduces adhesive strength and energy absorption capacity, increasing failure risk.
23	Standards Referenced	Compliance with standards sets minimum performance criteria and guides design choices for blast-resistant glazing.

Methodology

The present study is analytical in nature, with an applied objective, and simultaneously possesses a developmental characteristic concerning qualitative modeling. The research paradigm is interpretive, and the overall design is qualitative. Data collection is conducted through documentary/library sources and complemented by intermediate methods such as questionnaires and interviews with specialists and experts within a clearly defined statistical population. Initially, core concepts of the topic such as non-structural performance of buildings, façade systems and building frames, non-structural connections, explosions and their effects on buildings are examined using content analysis. Through inductive reasoning and by reviewing prior research, the preliminary framework of the study is developed. Subsequently, by leveraging conceptual and ideational emergence in the subject, and employing the fuzzy Delphi method within a participatory decision-making approach across multiple rounds, a specified set of factors is ex-

tracted. These factors are then weighted and tested over several rounds by a panel of experts comprising 15 individuals. Finally, the questionnaire link is digitally distributed via Google Forms, and the collected responses are analyzed using computational software after feedback.

DISCUSSION AND FINDINGS

Findings of the Delphi Method Implementation

In the first round, the panel members identified 18 factors out of the 23 factors extracted from successful previous studies as having high and very high influence on the performance of non-structural building components against blast waves, with particular emphasis on the behavior of glass and window frames. The detailed and comprehensive results of the first-round questionnaire survey are presented in the table below (Tab.3). Factors such as Frame Type, Fastener Spacing, and Edge Condition were excluded from the Delphi process due to having a mean importance value of less than 2.5.

Table 4: Second-Round Fuzzy Delphi Results for Identifying Effective Factors Affecting the Performance of Non-Structural Building Components Under Blast Loading (Glass and Window Frames)

No.	Factor	Mean Value	Variance	Minimum Value	Maximum Value
1	Layer Thickness	3.77	0.35	2	5
2	Interlayer Configuration	a	0.45	2	5
3	Layer Bonding Quality	3.67	0.25	2	5
4	Interlayer Material Type	3.31	0.31	2	5
5	Glazing Frame Connection	3.79	0.41	2	5
6	Anchorage System	3.76	0.31	2	5
7	Catcher Cables	3.42	0.29	2	5
8	Additional Reinforcement	3.67	0.31	2	5
9	Blast Intensity Barrier Presence	3.83	0.39	2	5

10	Barrier Presence	3.79	0.21	2	5
11	Blast Duration	3.55	0.31	2	5
12	Interlayer Damage Mode	3.79	0.27	2	5
13	Energy Absorption	3.34	0.47	2	5
14	Temperature Effect	3.81	0.45	2	5
15	Ageing State	3.45	0.19	2	5
16	Glass Aging	3.22	0.15	2	5
17	Interlayer Aging	3.30	0.17	2	5
18	Standards Referenced	3.84	0.15	2	5

Findings of the Third Research Round

After completing the second research round and evaluating the panel experts' opinions, a revised questionnaire was again distributed to all panel members. In this round, the panel identified 10 out of the 12 presented factors as having high and very high influence (mean value greater than 4) on the proposed framework of blast

performance indexes. The detailed and comprehensive results of the third-round questionnaire survey are presented in the table below (Tab.5). Factors such as Additional Reinforcement and Catcher Cables were excluded from the Delphi process due to having a mean importance value of less than 4.

Table 5: Third -Round Fuzzy Delphi Results for Identifying Effective Factors Affecting the Performance of Non-Structural Building Components Under Blast Loading (Glass and Window Frames)

No.	Factor	Mean Value	Variance	Minimum Value	Maximum Value
1	Layer Thickness	4.32	0.25	3	5
2	Layer Bonding Quality	4.47	0.21	3	5
3	Glazing Frame Connection	4.09	0.37	3	5
4	Anchorage System	4.01	0.29	3	5
5	Catcher Cables	3.85	0.19	3	5
6	Additional Reinforcement	3.85	0.18	3	5
7	Blast Intensity	4.33	0.25	3	5
8	Barrier Presence	4.06	0.17	3	5
9	Blast Duration	4.01	0.16	3	5
10	Interlayer Damage Mode	4.02	0.21	3	5
11	Temperature Effect	4.16	0.32	3	5
12	Standards Referenced	4.25	0.14	3	5

Findings of the Fourth Research Round

In the fourth round of developing the proposed index framework, the influencing indexes on the performance of non-structural building components against blast waves—along with the third-round mean scores and the panelists' previous

responses—were presented to all experts. At this stage, 10 factors remained from the initial set of questionnaire items, and the panel members identified all 10 factors as having high and very high influence (mean value greater than 4) (Tab.6).

Table 6: Fourth -Round Fuzzy Delphi Results for Identifying Effective Factors Affecting the Performance of Non-Structural Building Components Under Blast Loading (Glass and Window Frames)

No.	Factor	Mean Value	Variance	Minimum Value	Maximum Value
1	Layer Thickness	4.35	0.22	4	5
2	Layer Bonding Quality	4.52	0.19	4	5
3	Glazing Frame Connection	4.11	0.32	4	5
4	Anchorage System	4.03	0.27	4	5
5	Blast Intensity	4.34	0.23	4	5
6	Barrier Presence	4.02	0.15	4	5
7	Blast Duration	4.02	0.14	4	5
8	Interlayer Damage Mode	4.03	0.18	4	5
9	Temperature Effect	4.17	0.25	4	5
10	Standards Referenced	4.26	0.13	4	5

Findings of the Fifth Research Round

In the fifth round of developing the proposed index framework, the questionnaire derived from the results of the previous round was redistributed to all panel members in order to reach the final and definitive set of factors. The same 10 factors were once again identified as key indexes influencing the performance of non-structural building components against blast waves.

The detailed and comprehensive results of the fifth-round questionnaire survey are presented in the table below (Tab.7). Kendall's coefficient of concordance was calculated as 0.791 for the panel members' responses regarding the ranking of the 10 factors.

Table 7: Fifth -Round Fuzzy Delphi Results for Identifying Effective Factors Affecting the Performance of Non-Structural Building Components Under Blast Loading (Glass and Window Frames)

No.	Factor	Mean Value	Variance	Minimum Value	Maximum Value
1	Layer Thickness	4.36	0.18	4	5
2	Layer Bonding Quality	4.53	0.21	4	5
3	Glazing Frame Connection	4.13	0.25	4	5
4	Anchorage System	4.04	0.24	4	5
5	Blast Intensity	4.35	0.21	4	5
6	Barrier Presence	4.09	0.14	4	5
7	Blast Duration	4.08	0.12	4	5
8	Interlayer Damage Mode	4.07	0.17	4	5
9	Temperature Effect	4.21	0.24	4	5
10	Standards Referenced	4.32	0.12	4	5

Reasons for stopping the process

The results of the five rounds of implementing the Delphi method in this study indicate that consensus was achieved among the panel members for the following reasons, and therefore the repetition of further rounds can be discontinued:

1. In the second round, more than 50% of the panel members selected 18 influential factors contributing to the development of the proposed index framework affecting the performance of non-structural building components against blast waves, with emphasis on the behavior of glass and window frames, all of which exhibited mean values greater than 2.5. In other words, the identification of 18 key factors by more than half of the panel members reflects a strong form of consensus among experts. This consensus not only enhances the credibility of the study but also supports the formal recognition of influential factors within the design and optimization process. When a group of specialists emphasizes a specific set of factors, it indicates their significance and the need for greater attention to them in future design practices.

2. The standard deviation of the panel members' responses regarding the importance of the factors in the third round decreased significantly compared to previous rounds. This substantial reduction in standard deviation implies that the panel members' viewpoints became more closely aligned. This convergence may be attributed to ongoing discussions and information exchange during earlier rounds, which led to a shared understanding of the key issues. The lower the standard deviation, the stronger the indication that the identified factors have reached a common level of agreement and mutual understanding, which can ultimately contribute to the formation of a unified perspective within the community of designers and architects.

3. Kendall's coefficient of concordance for the panel members' rankings of the factors in the third round was equal to 0.791. Considering that the number of panel members exceeded ten,

this value is regarded as highly significant. A Kendall's W of 0.791, as a quantitative measure of agreement among panel members, provides a clear representation of opinion convergence. This value, particularly in light of the relatively large panel size, demonstrates the scientific reliability of the results. In other words, the observed convergence in outcomes is promising and can lead to more informed decision-making and more effective design strategies.

4. The Kendall's coefficient of concordance for the ranking of the 10 influential factors involved, increased by only 0.026 in the third round compared to the second round. This coefficient, representing the degree of agreement among panel members, does not indicate a substantial increase across successive rounds. In other words, the lack of a meaningful rise in the concordance coefficient between the second and third rounds suggests that the consensus process has reached a stabilization point and that repeating the survey is unlikely to yield additional benefits. This can be considered a positive sign, as it indicates that the group has achieved a shared understanding and can now focus on implementing the results.

5. The final Delphi round identified 10 factors with mean values exceeding 4.0, indicating a high level of expert consensus regarding their influence on the blast performance of non-structural glazing systems. Among these, indexes related to the intrinsic properties of laminated glass—particularly layer bonding quality and layer thickness—achieved the highest mean scores (approximately 4.3–4.5), highlighting their dominant role in governing structural integrity and post-fracture behavior under blast loading. Indexes associated with blast loading characteristics, including blast intensity and blast duration, as well as boundary-condition-related parameters such as glazing–frame connection and anchorage system, were also consistently ranked within the high-influence range, reflecting their critical contribution to load transfer and failure control mechanisms.

The concentration of mean values within a narrow high range confirms the stability of expert judgments and indicates that the Delphi process reached a reliable convergence point. (Fig. 4)

RESULTS AND CONCLUSION

The results obtained from applying the fuzzy Delphi method over five consecutive rounds to identify and analyze the indexes influencing the performance of non-structural building components under blast loading demonstrate that the expert decision-making process gradually moved toward convergence and reduced uncertainty. In the first stage, 23 initial factors were evaluated with mean values predominantly ranging from 3.1 to 3.8 and relatively high variance, indicating considerable dispersion in expert opinions and the absence of a definitive consensus regarding the level of influence of different factors. This condition reflects the exploratory nature of the initial fuzzy Delphi round, in which experts were still assessing the relative importance of factors and judgments had not yet reached sufficient stability.

As the process entered the second and third rounds, a statistically meaningful increase in the mean scores of most factors was observed, accompanied by a simultaneous reduction in variance. These quantitative changes indicate the gradual refinement of expert perspectives and the elimination of less important or ambiguous factors. At this stage, factors directly related to the mechanical behavior of glass and its connection system to the frame—such as layer thickness, interlayer bonding quality, blast intensity, and glass-to-frame connection—experienced a noticeable increase in scores. In contrast, factors of a more secondary or execution-oriented nature, including fastener spacing, edge conditions, or post-installation retrofit presence, were progressively excluded from the analysis cycle due to lower mean values and instability in expert judgments.

In the third round, the set of factors was narrowed down to 12 key factors, with the mean

scores of many approaching or exceeding 4. This level of scoring indicates the formation of a relative consensus among experts. In particular, factors associated with the direct response of laminated glass to blast loading—such as layer thickness, interlayer bonding quality, restraint systems, and glass-to-frame connections—were identified as dominant factors in determining non-structural performance. The reduction of variance to values close to 0.20 at this stage signifies decreased dispersion in judgments and increased confidence in the quantitative outcomes.

During the fourth and fifth rounds, changes in mean values were minimal and generally less than 0.05, indicating that the fuzzy Delphi process had reached a saturation and stability point. In these stages, the final mean values of the factors predominantly ranged between 4.0 and 4.5, while variances decreased to their minimum levels, approximately between 0.12 and 0.25. This condition reflects strong expert consensus and high reliability of the selected final indexes, suggesting that further Delphi iterations would not produce meaningful changes in the final results.

From a quantitative ranking perspective, indexes such as interlayer bonding quality, layer thickness, blast intensity, and reference to design standards achieved the highest mean values in the fifth round and were identified as highly critical factors. This finding indicates that the blast response of glazing systems is primarily governed by the intrinsic properties of laminated glass systems and the degree of compliance with recognized blast-resistant design standards. At the subsequent level, factors such as glass-to-frame connection details, restraint systems, interlayer damage modes, and temperature effects were ranked, reflecting their significant role in force transfer and progressive failure control, albeit with greater dependence on boundary conditions and specific blast scenarios.

Overall, the quantitative analysis of the fuzzy Delphi results shows that out of the initial 23 factors, only a limited subset of indexes with high mean values and low variance succeeded

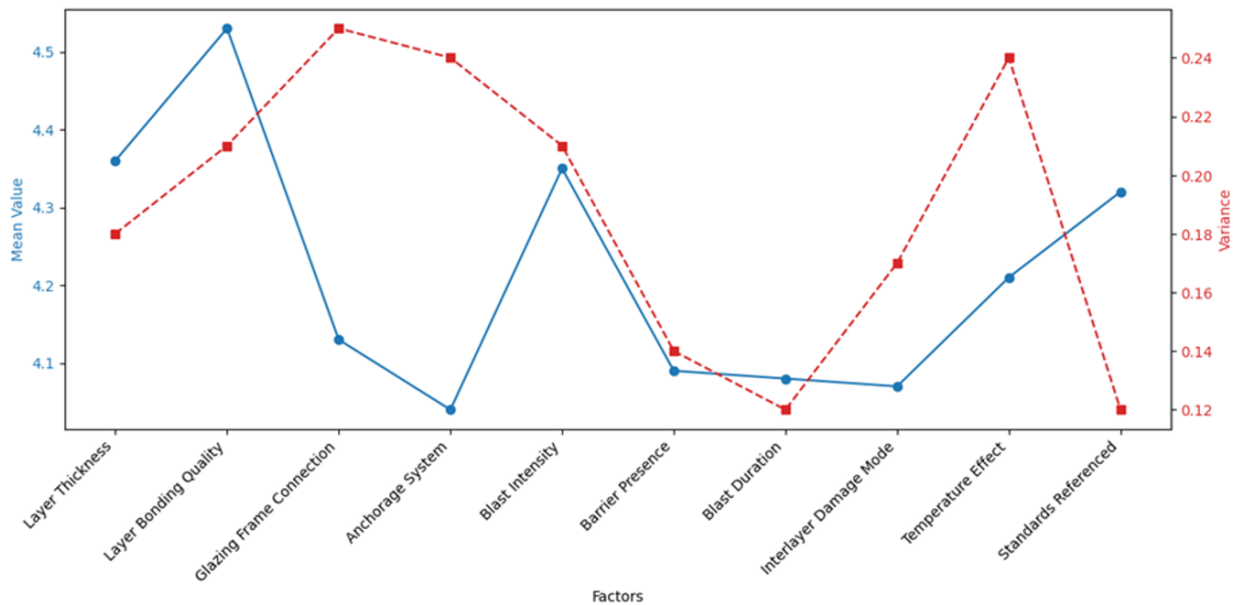


Figure 4: Trend of Mean and Variance for 10 Final Factors

in achieving expert consensus. These indexes are predominantly related to the mechanical and behavioral characteristics of glass and its connection system, playing a decisive role in the performance of non-structural building components under blast loading. Therefore, it can be concluded that blast-resistant design and retrofit strategies should primarily focus on improving glass properties, connection quality, and adherence to validated standards, while secondary and execution-related factors play a subordinate role and exert indirect, context-dependent influence.

In this regard, the ten final factors extracted through the fuzzy Delphi method can be employed as key variables in experimental design, allowing each index to be examined both independently and in interaction with other parameters. Laboratory investigations may include quasi-blast tests, such as high-rate impact loading or blast wave simulators, enabling controlled variation of load intensity and duration. This approach supports the validation of expert consensus outcomes and helps bridge the gap between theoretical analysis and the actual behavior of glazing systems.

In the subsequent phase, it is recommended that experimental programs be designed to si-

multaneously examine material properties and construction details. For instance, variations in glass layer thickness, interlayer type and bonding quality, and glass-to-frame connection configurations can be implemented across different test specimens to evaluate their effects on failure modes, energy absorption, and glass fragment projection. The acquisition of high-resolution data through pressure, displacement, and strain sensors, combined with high-speed imaging, enables the extraction of more precise behavioral patterns, which can serve as a foundation for the development of advanced numerical and analytical models in future stages of the research.

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