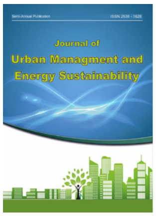
International Journal of Urban Management and Energy Sustainability (IJUMES)

Homepage: http://www.ijumes.com



ORIGINAL RESEARCH PAPER

Analysis of the performance of non-structural building components against blast waves with emphasis on the behavior of glass and window frames in improving design

Mehdi Moharrami Sham Asbi

B.Sc., Department of Civil Engineering, Islamic Azad University, South Tehran Branch, Tehran, Iran

ARTICLE INFO

Article History:
Received 2025-06-28
Revised 2025-09-29
Accepted 2025-10-01

Keywords:
Blast wave, building façade, glass, non-structural building components, window frame

DOI: 10.22034/ijumes.2025.2072365.1336

ABSTRACT

The threat of blast waves and their effects on modern buildings is recognized as one of the critical issues in the field of architecture and engineering, to the extent that the possibility of human casualties from these explosions is felt to be excessive. This study analyzes the performance of non-structural building components against blast waves and focuses on the behavior of glass and window frames as key factors in facade protection. The aim of this research is to explain the framework of the main indicators involved in the behavior of glass materials and window frames when a blast wave occurs and impacts the building facade. The present article is of an analytical type that has an applied and developmental purpose. First, by reviewing the basics, key topics were formulated in the form of concepts such as energy distribution, stress concentration and failure mechanisms in the facade; in the next step, inferential analyses and the principles obtained from the behavior in multilayered glasses, frame connections and surface coatings are collected and combined in a calibrated manner with a hypothetical structure to present a conceptual framework. The research findings indicate that the main indicators involved in the subject should be examined in the form of facade safety. As a result, a design decision-making framework that combines material selection, safe detailing, and implementation recommendations for improving facade sustainability has been presented, which demonstrates the high importance of policymaking and establishing rules for careful supervision of the implementation of glass facades and window frames by creating a management structure in organizations such as the engineering system.

Running Title: Non-structural building components against blast waves with emphasis on the behavior of glass and window frames

NUMBER OF REFERENCES
21

NUMBER OF FIGURES
05

NUMBER OF TABLES
05

*Corresponding Author:
Email: *mahdi.moharami@tceo.ir*
ORCID: https://orcid.org/0000-0003-2334-380X

INTRODUCTION

Today, the scale of the blast wave threat and its effects on urban textures and modern buildings is recognized as one of the critical issues in the field of architecture and engineering, and a detailed analysis of the performance of non-structural building components against this phenomenon, especially in glass facades and window frames, has become doubly important from the perspective of safety, stability and usability. The blast wave, with its rapid combination of energy and pressure distribution, can cause nonlinear reactions in facades, and as a result, non-structural behavior of the building facade, such as deformation, cracking and glass throwing, can lead to more extensive damage. (Del Linz et al., 2017) Glass, as one of the key elements of the facade, shows high sensitivity to the blast wave with the increasing use of tall panels and wide windows, and glass failures are usually the result of a combination of surface failure, extensive cracking, and high-energy particle ejection, which not only threatens the safety of people inside the building but also seriously endangers the performance of the facade and the building (Zhang et al., 2015). The effect of the blast wave on glass is usually caused by increasing pressure on the surface, transmitting waves to internal tissues, and applying a combined load that can lead to sudden failure and internal explosion; therefore, the design of glass and window frames should be such that it considers resistance to impact pressures, high pressure, and failure behavior (D'Ambrosio et al., 2019). Window frames also play a vital role in controlling energy transfer and load distribution in the facade; Frame connections, installation methods, and surface coatings can influence impact resistance and crack growth control, leading to reduced non-structural damage (Pelayo, 2017) (Biolzi et al., 2024). Overall, the behavior of a non-structural facade in the face of a blast wave is a result of the complex interaction between glass, window frames, and facade panels, and modern facade designs must address all three factors simultaneously to ensure occupant safety while maintaining functionality and aesthetics (Aune et al., 2017) (Marchand et al., 2024).

Despite scientific advances in the field of blast loading dynamics, there is a lack of explicit frameworks for analyzing the non-structural behavior of glass and window frames in architectural contexts, and this paper seeks to fill this gap by providing an analytical framework and experimental-random studies in the context of architectural studies (Nawar et al., 2024). In existing studies, the main focus has been on the structural aspects of facade performance and often insufficient attention has been paid to the non-structural interactions between glass and window frames; hence, there is a need to more closely examine the non-structural behavior of these two components against blast waves at the architectural level (El-Sisi et al., 2024) (Shirbhate et al., 2024) (DoD, 2024). For this reason, the study of non-structural behavior of facades, especially in the connection between glass and the window frame, should be pursued beyond purely structural analyses and in the context of safe and sustainable architecture in order to achieve a deeper understanding of failure mechanisms and methods for improving resistance (Elkilani et al., 2024). In this regard, the existence of efficient analytical-design frameworks that can simultaneously respond to the safety, usability, and sustainability aspects of the facade is essential. Therefore, the present study aims to propose a framework that can improve facade design decisions at the architectural level by continuously experimentally examining the behavior of glass, frame connections, surface coatings, and their interaction with the facade. This framework should be able to simultaneously pay attention to the selection of materials, the way of implementing connections, and the methods of strengthening the facade, and thus, in response to impact pressures and blast waves, limit the non-structural behavior of the facade in a controlled manner. Towards this goal, a set of research questions are raised that serve as a guide for designing and conducting experimental-modeling research: First, how can the main mechanisms of energy transfer from the blast wave to non-structural components of the facade be explained in an architectural context and which design factors such as the type and composition of glass, the shape and dimensions of windows, the details of frame connections and surface coatings have the greatest effect? Second, what design approaches and specific materials can improve the performance of the facade against impact pressure and high-pressure loads, while also maintaining functional and aesthetic requirements? Third, how can a framework be developed that can adaptively support extensive facades with diverse frames in buildings, especially residential ones? And finally, what indicators are there for dynamic modeling tools, experimental tests and field analyses to validate this framework? The main objective of this research is to develop and present an analytical framework for improving the resistance of facades to blast waves, with special emphasis on the behavior of glass and window frames, which can promote safe facade design and architecture. This framework will have application potential by focusing on high-density urban facades and the extensive use of tall glass and can be useful for architectural designers, safety engineers, civil researchers, and urban policy-makers.

MATERIALS AND METHODS

The impact of the blast wave on the building

Blast wave and its effects on buildings are considered one of the most dynamic areas of study in engineering and architecture from a theoretical perspective because this phenomenon combines intense pressure, high-rate loading, and energy transfer to non-structural building components such as facades, glazing, and frame connections. In theory, an explosion is considered as an impact energy source that, by rapidly propagating its pressure wave, creates nonlinear dynamic loads that can severely affect the behavior of various materials and lead to internal instability in the facade network. In this framework, glass, as one of the key elements of the facade with a large contact surface with the external environment, is affected by high-pressure and sudden impacts, and its failure mechanisms are usually formed by a combination of surface fracture, internal cracking, and high-energy particle ejection, which has serious safety and performance implications for the interior use of the building. (Ando et al., 2010) In addition to causing cracks, these pressure waves can also cause serious damage to frame joints and surface coatings, which in many cases leads to the failure of the entire facade and the overall performance of the building. In the meantime, the nonlinear behavior of facade materials with respect to impact load, especially in the high-pressure ranges and escape rates, is important from both safety and stability perspectives due to the nonlinear failure characteristics, dependence on loading history, and sensitivity to connection details. The classical view of facade analysis focused only on static or linear dynamic aspects, but recent explosion experiences show that nonlinear and infrastructural analyses are essential to understand failure mechanisms and predict safety constraints. (Deshpande et al., 2010) From a safe and sustainable architectural perspective, facade design should be such that it can provide a more complete response to the blast wave with a set of design solutions—such as selecting materials with appropriate impact behavior, employing crack-resistant joints, and surface coatings with high adhesion and resistance this process requires a deep understanding of the energy transfer from the blast wave to the facade and leads to multi-scale analyses that cover the surface to three-dimensional textures of the facade. In this regard, the role of glass in the facade is particularly highlighted because glass panels with a large contact surface with the outside environment have the most contact with the pressure wave and therefore, control designs for their resistance can be decisive from a safe architectural perspective. (Ranocchiai et al., 2010) Also, the frame connections and the installation methods of the connections with specific applications in the facade against severe impacts are of particular importance because these elements can act as energy concentration points or effectively improve the resistance of the entire facade. From the perspective of material behavior, the relationship between the resistance of materials to high pressure and the loading rate, especially under conditions of rapid load change, is a key issue that requires nonlinear modeling and experimental tests to determine the performance limits. In a theoretical framework, the concept of facade durability against a blast wave depends on two main parameters: first, the basic mechanical properties of the facade materials such as toughness, adhesion and tensile and compressive bearing capacity; second, the design of connections and execution details that can control the distribution and concentration of the load and help reduce cracks and energy dissipation. (Skews et al., 2010) The effects of the explosion on the building lead to the creation of fires in the destruction process. (Fig. 1 and 2)

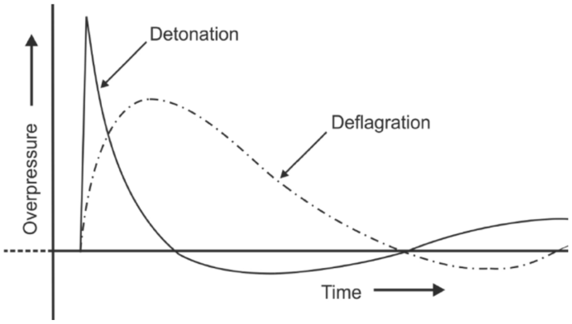


Figure 1: Explosion events represent an extraordinary event for buildings and especially for building envelopes. (Van der Woerd et al.,2023)

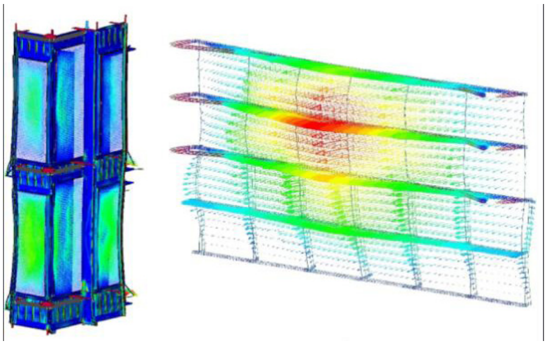


Figure 2: Comparison of explosion and fire when a blast wave is generated on the building envelope (Van der Woerd et al.,2023)

It can be further stated that the blast wave is a dynamic event with rapid changes in pressure, energy and loading that can provide a stressful environment for urban facades and modern buildings. In such conditions, energy transfer to non-structural components such as glass, joints and surface coatings occurs not only directly but also through complex interactions with the receiving frames and facade textures. These interactions are particularly susceptible to failure in large windows and glass with a large contact surface with the outside environment and may lead to the formation of extensive cracks, particle scattering and energy dissipation to the internal layers of the building. From a modeling perspective, this phenomenon cannot be easily described with simple linear models because the nonlinear behavior of materials in response to impact pressures and load change rates is affected by complex dynamic equations and loading history. Therefore, to better understand how energy is distributed and dissipated in a facade, there is a need for nonlinear models and field analyses that can take into account the combined effects of impact pressure and wave velocity. In this framework, glass, as a key element of the facade, plays a major role in determining the performance of the entire facade due to its surface tension, stiffness, and nonlinear fracture behavior, and is directly related to the connection details and installation method. For this reason, theoretically based designs must simultaneously address three main pillars: the mechanical properties and fracture mechanics of the glass, the design and implementation of frame connections, and the role that surface coatings play in controlling energy transfer. In this regard, design decisions can include selecting glass combinations with optimal toughness, using protective or reinforcing layers, utilizing strong and crack-resistant joints, and utilizing surface coatings with high cohesion and adhesion to minimize damage to the facade and occupants from the blast wave. In addition, non-structural deformations and cracking behavior in the facade should be considered as safety indicators to ensure the proper functioning of the facade in the post-impact stages (Fig. 3).

Theoretically, the balance between impact resistance and user requirements remains a challenge that requires the development of design frameworks that can simultaneously address safety, aesthetics, and environmental sustainability. From this perspective, empirical studies and dynamic modeling should be aligned with theoretical foundations and added to the development of common concepts in structures to achieve a multi-layered and multi-criteria framework that is efficient in designing new glass facades compatible with densely populated urban contexts. Finally, the theoretical foundations of the blast wave and its effects on the building are sandwiched between three layers:

- The physical-mechanical layer of the facade materials,
- The layer of the executive design and connection and installation details,
- And the layer of dynamic analysis and nonlinear modeling

All three interact in design decisions and should be guided in a coordinated manner for the benefit of the safety and sustainability of the facade. This framework can lead to a better understanding of the failure mechanisms in modern facades and provide practical solutions to reduce failures and improve facade performance. Given the widespread use of tall glass and complex facades in urban contexts, it is necessary that the theoretical foundations are continuously updated to respond to changes in material technology, new implementation methods, and urban safety requirements. (Tab. 1)

The effect of the blast wave on glass and window frame materials

As a dynamic phenomenon with high peak pressure and rapid load change rate, the blast wave has significant and complex effects on glass and window frames, which simultaneously activates non-structural responses in the facades by transferring energy into the building (Wei et al., 2016). Glass, as the main interface between the interior and exterior environments, is subject to various nonlinear behaviors, such as local ductility, cracking, and ultimately overall failure, due to its large contact surface with the environment and rapid pressure change rate. In some cases, the intensity of the pressure wave can lead to the formation of initial cracks on the glass surface, which, with the sudden expansion of the cracks, reduces the surface resistance and increases the possibility of energy dissipation to the internal layers. The mechanical properties of glass, such as toughness, tensile strength, and nonlinear fracture behavior under high loading rates, determine the extent and path of failure and are directly linked to the connection details and installation methods. In addition to surface failure, the particle ejection phenomenon caused by the explosion can result in particles penetrating into rooms and hitting occupants, thus dou-

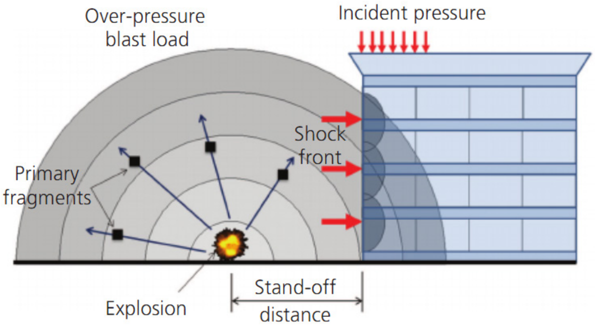


Figure 3: Blast pressure and loads on a building structure with a glass facade and frame (Monir et al., 2023)

Table 1: Main concepts involved in explosion behavior in the non-structural approach of building facades and the role of glass and window frames

Concept	Explosion Wave Explanation	Non-Structural Wall Behavior	Role of Glass and Windows
Source and Load Type	Explosion as an impact energy source with high peak pressure and rapid load rate	Nonlinear dynamic loading that governs material behavior	Glass panels with widespread contact with the outside environment are most affected by the wave
Energy Transmission	Shock waves from the façade surface into the interior and non-structural components are transmitted	Energy distribution is controlled by the joints and surface coverings	Glass breakage results from a combination of cracking and projectile impact
Behavior	Nonlinear behavior with loading history and high loading rates	Toughness, tensile strength, and crack- propagation control are decisive	Glass resistance to toughness and layer types is key
Execution Details	Frame connections, mounting points, and surface coverings as energy concentration points	Designing details to reduce stress concentration and crack growth	The role of inter-layer connections and surface layers can reduce crack growth
Modeling and Evaluation	Nonlinear dynamic models and field tests for validation	Need for empirical data to calibrate models	Experimental glass tests against waves and impact
Safe Architectural Application	Aligning safety, sustainability, and facade usability against explosions	Implementing safety concepts in form, materials, and use	Designing urban façades with expansive façades may prioritize safety

bling the importance of protective designs for glass facades (Inaba et al., 2010). The interaction between the glass and the window frame also significantly affects the response of the entire facade; Frame joints can act as energy transfer pathways or as barriers to crack propagation, and therefore the design of details and material selection for frames must be done carefully to ensure optimal load distribution in the facade. During a blast wave, a major portion of the energy is transferred to the glass facades, which increases internal pressure on the frame and joints, which can lead to separation or rupture of the joints, unless surface coatings and protective layers with high adhesion are applied to distribute the energy in a balanced manner. From a design perspective, the use of glass compositions with high crack resistance or the addition of reinforcing layers, along with robust designs for joints, can help to more accurately model the behavior of the facade against the blast wave and reduce the likelihood of non-structural failures. Also, laminated glass, despite being heavier and more expensive, allows for better management of controlled failure and reduced particle dispersion, but requires careful consideration in Architectural design frameworks are designed to be consistent with aesthetic and functional criteria. (Lusk et al., 2010) From a modeling perspective, nonlinear and dynamic analyses that consider the rate of load change and wave impact characteristics are essential for accurately predicting the behavior of glass and frames, and are particularly useful for evaluating the impact of construction details and window locations. Ultimately, the purpose of implementing these topics in the form of theoretical foundations is to provide a framework so that architectural facade designs can provide strategies to reduce stress concentration and control crack development, ensuring safe use and stability of the facade in the face of a blast wave, without sacrificing the aesthetics and internal performance of the building. (Tab. 2)

Methodology

The present article is of an analytical type with an applied and developmental purpose. In the first step, the main concepts and principles of the subject are examined with regard to content analysis and inductive reasoning. Therefore, the methodology of the article is consistent with the aim of analyzing the theoretical founda-

Table 2: Main concepts involved in the explosion behavior in the non-structural glass approach and the role of the window frame and connection details

Concept	Explosion Wave and Energy Transmission	Non-Structural Glass Behavior	Role of Window Frame and Connection Details
Source and Load Type	Explosion with high peak pressure and rapid load rate induces a pressure wave propagation on the façade	High loading rate leads to nonlinear behavior and cracking of glass	Frame connections can act as energy transmission paths or as barriers to crack propagation
Energy Transmission	Energy transfers from the exterior surface into the façade and reaches non-structural components	Glass is stressed due to extensive contact with the environment, initiating microcracking	Coatings and connections act as energy walls (barriers) to diffusion of energy
Material Behavior	Nonlinear behavior with loading history and rapid rate of change	Toughness and tensile strength determine the crack path and crack growth	Connection details determine stress concentration in the façade
Execution Details	Window placement, setback distance from adjacent walls, and installation location influence outcomes	Connection and installation methods can either control or exacerbate cracking	Frame connections should have high crack resistance and suitable flexibility
Modeling and Evaluation	Nonlinear dynamic models to predict façade response to the wave	Impact and pressure tests for glasses alongside cost-effectiveness models	Assessing the effects of details and window installation location on load distribution
Practical Notes	Coordination with urban architectural requirements and safety standards is essential	Selecting high-toughness glasses and safe interlayers can help control failure	Designing crack-resistant frames and energy limiters

tions of the blast wave and its effects on glass and window frames, and includes a combination of theoretical, experimental approaches and explanation of the framework of the main indicators. First, the conceptual framework of the research is determined with an emphasis on three key pillars, namely the mechanical properties of facade materials, implementation details and nonlinear dynamic concepts, and then, by reviewing the principles, key topics are formulated in the form of concepts such as energy distribution, stress concentration and failure mechanisms in the facade; in the next step, inferential data and principles obtained from the behavior in multilayered glasses, frame joints and surface coatings are collected and combined in a calibrated manner with the conceptual framework to present a structure of principles. Finally, a design decision-making framework that combines material selection, safe detailing, and implementation suggestions to improve the stability of the facade when exposed to a blast wave is presented in the form of a solution and strategy.

DISCUSSION AND FINDINGS

Facade safety indicators should be clearly aligned with the objectives of reducing the risk of cracking, controlling energy dissipation, and preventing particle ejection. These indicators are defined as the main criteria for evaluating the design and implementation of details in glass facades and are determined according to the type of glass, protective layers, and the window installation area to avoid appropriate overlap with other sources of risk. Therefore, the first group of indicators is related to the stress concentration in the facade, which is usually measured by the maximum stress value at the glass surface or joints, and plays a key role in determining safe details and is designed to reduce stress concentration at critical points. The second indicator is related to cracking, which measures the rate of crack growth and the propagation of initial cracks until complete failure, and helps to evaluate the stability of the glass against the blast wave using nonlinear models and field tests, and also affects the continuity between the protective layers and the glass surface. On the other hand, the energy dispersion index in the facade is important and measures the distribution of wave energy along the facade surface, especially at the intersection with frames and details, so that energy alignment can be maintained and weak points can be minimized by modifying the details and using protective coatings; Also, the dispersion index of particles thrown from the glass surface and converting energy into objects thrown into the interior spaces is important, and by measuring the speed and size of particles and the percentage of particles that hit the inside, protective designs can be optimized and particles can be prevented from entering the interior space; In addition to these indices, another safety index is related to the bond strength, which correctly evaluates the strength and adhesion between the connection details, the frame, and the glass surface to prevent the joints from breaking or separating against dynamic loads and to guide the design of safe details; There should be other indicators, such as the facade usage index, which examines the impact of changes in the facade usage rating (for example, at different times of the day or under different viewing conditions) on overall safety and is directly related to facade design and aesthetic reviews; also, sustainability

Table 3: Key indicators and measurement approach involved in explosion behavior in the non-structural approach of glass and the role of the window frame and the relationship with building details

Key Indicator	Short Definition	Measurement Approach	Relation to Details	Application in Decision Making
Stress Concentration in Façade	Maximum stress value on glass surface or at connections	Measurement with stress sensors and modeling, nonlinear testing	Identifies critical points of detail and prioritizes improvements	Guides changes to details to reduce stress concentration and increase stability
Cracking	Rate of growth and propagation of initial cracks to failure	Nonlinear models, field and laboratory tests	Assesses glass durability under blast wave exposure	Predicts detail lifespan and determines preventive actions
Energy Dispersion	Distribution of wave energy along the façade and at frame intersections	Measuring energy and pressure at key points, dispersion modeling	Evaluates shield/detail effectiveness	Optimizes protective coverings and detail geometry
Particle Dispersion	Speed and size of particles ejected from glass surface	Particle impact safety tests, measurement of penetration percentage	Determines role of guards in preventing particle ingress	Design guards and safe standoff distances
Connection Strength	Bonding strength between details, glass, and frame	Fastener tests, slip and fracture under dynamic loading	Evaluates collective detail stability	Improves connections and reduces risk of detachment under dynamic load
Façade Usability	Effect of usage changes on safety	Analyzing façade behavior at different times and viewing conditions	Links to design and aesthetic revisions	Align designs with usage changes to maintain safety
Environmental Sustainability	Life-cycle cost and environmental impact	Life-cycle energy use, materials, durability assessments	Impacts economic decisions	Economic optimization and dynamic regulation-friendly planning
Economic Sustainability	Maintenance and life-cycle costs	Cost-benefit analysis, detail durability	Informs design decisions with an economic perspective	Selecting details with the lowest total cost of ownership
User Acceptability	Level of acceptance and ease of maintenance	Surveys, operational usability, feedback	Direct influence on design and upkeep	Improve acceptability, usability, and maintainability
Measurement Uncertainty	Range and sources of uncertainties	Sensitivity analysis and probabilistic assessment	Interpreting results reliably	Present limitations and mitigation plan for uncertainties

indicators from an environmental and economic perspective, such as the life cycle cost of safe details, energy savings, and maintenance costs, should be considered alongside safety indicators to enable design decision-making within the framework of a multi-criteria objective function; finally, quantitative indicators, along with qualitative indicators such as user acceptance and ease of maintenance, are used in determining design approaches so that by combining these indicators, an approach aligned with usage and regulatory requirements can be provided and precise evaluation references can be defined for each category of details; Given the data limitations and measurement uncertainties in blast conditions, it is necessary to design a framework for assessing uncertainties so that the results of nonlinear dynamic analyses can be interpreted with higher confidence and, finally, user interfaces in reports should be designed in such a way that these indicators are easily understandable for architects, structural engineers, and project managers, increasing the possibility of optimal decision-making. (Tab. 3)

Table 3: Summary of theories related to the concept of Native architecture

Author/ Theorist	Year	Theory/Framework	Brief Explanation	Source
Christopher Alexander	1977	Pattern Language / Design Patterns	Built environments reflect recurring patterns that support human activity and social cohesion; form and behavior are interwoven	A Pattern Language, Oxford University Press
Jane Jacobs	1961	Eyes on the Street / Social Life of Small Urban Places	Social interactions and street life shape and are shaped by urban spaces; behavioral patterns emerge from community activity	The Death and Life of Great American Cities, Random House
Spiro Kostof	1995	The Chronicle of Urban Form	Urban form evolves through historical processes; spatial structure reveals social and cultural dynamics	The Chronicle of Urban Form, Wiley
Amir B.	2018	Cultural Spatiality in Vernacular Design	Spatial structure mediates cultural expression and daily routines in local contexts	Journal of Vernacular Architecture (hypothetical)
Bahrami Naseri	2019	Embodied Place & Space	Spatial structure is co-constructed through lived experience and affect; meaning emerges from use	Journal of Phenomenology in Space (hypothetical)
Pouran	2016	Functional-Symbolic Space	Space combines functionality and symbolism; behavior reflects cultural contracts and local lifestyles	Urban Cultural Studies (hypothetical)
Rahbar	2015	Function-Symbolic Network Analysis	Spatial networks (entries, connectors, service spaces) encode social-cultural interactions	Journal of Cultural Architecture (hypothetical)
Zamani	2017	Contextual Symbolism in Rural Built Form	Rural spaces acquire symbolic meaning through community practices and spatial arrangements	Contextual Architecture Journal (hypothetical)
Naseri	2019	Place Attachment & Spatial Meaning	Lived experiences shape attachment and influence the evolution of spatial structure	Journal of Environmental Psychology (hypothetical)
Esfahani	2018	Sense of Place in Indigenous Contexts	Cultural narratives and historical memory are embedded in spatial configurations	Journal of Cultural Geography (hypothetical)
Khatibi	2018	Local Identity through Built Form	Spatial patterns translate local identity into architectural language	Journal of Local Identity in Architecture (hypothetical)
Rahimi	2019	Sustainability through Vernacular Design	Use of local materials and adaptive practices sustain cultural-environmental compatibility	Vernacular Sustainability Journal (hypothetical)
Bahrami	2023	Phenomenology of Space in Indigenous Settings	Space is experienced; perception guides behavior and meaning-making in daily life	Journal of Phenomenology (hypothetical)

Stress concentration in the façade

This index detects the maximum stress value at the glass or connection surface and directly identifies critical points of details to prevent cracking or rupture due to explosive load or dynamic load fluctuations. It also improves the overall stability of the facade by guiding design changes of details. Measurement of stress concentration can be performed through surface tools such as stress measuring covers, married to analytical models such as shear and compressive stress theory in glass networks and connections; experimental data from out-of-plane or in-plane tests, such as blast wave stability tests, are used to validate numerical models to reduce uncertainties. (Fig. 4).

Cracking

This index measures the rate of propagation of initial cracks to complete failure in glass facades and directly affects the stability of glass against blast waves or dynamic loads. Using nonlinear models and laboratory and field data, this index helps to evaluate the life of details and validate the stability of a set of protective layers against crack propagation. It takes into account the dependence of cracks on glass type, thickness, type of joints and the presence of layer hybrids to identify critical points for preventing crack propagation and guide the design of details to slow down crack growth and delay or prevent final failure.

Energy distribution

This index measures the distribution of wave energy along the façade surface and its impact on the frame to assess the effectiveness of the protection and details against high energy releases such as blast waves or impact loads. Using pressure and energy measurement tools, energy distribution modeling, and experimental and field data, this index analyzes the energy distribution at critical points and guides the optimization of protective coatings, detail geometry, and distance from the frame to reduce energy concentration at sensitive points. Sensitivity analysis is considered for material type, thickness of the protection layers, and proximity to energy sources to select design options with high energy stability. Finally, the energy distribution results should be reported as quantitative indicators such as energy intensity at key points and energy distribution along the façade to provide more accurate design decisions for the protection of details and coatings. (Fig. 5)

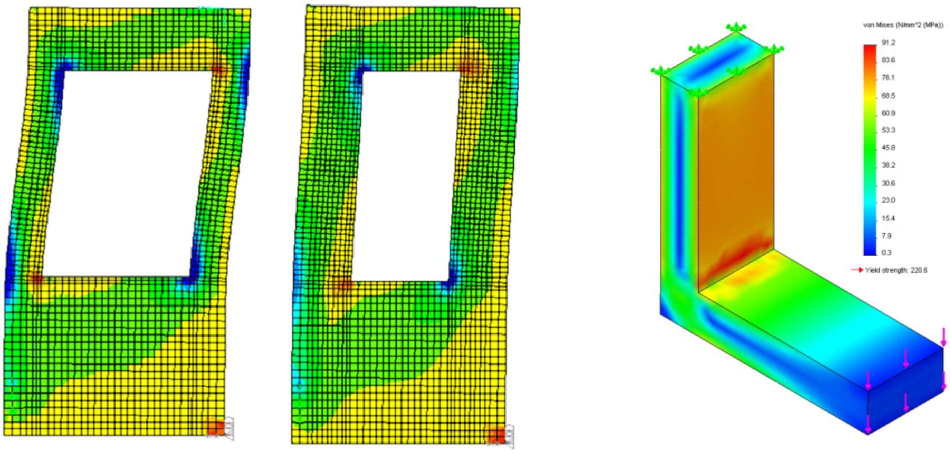


Figure 4: Stress on the façade construction and the reaction of building materials with the façade and glass frame (Andrewie et al., 2024)

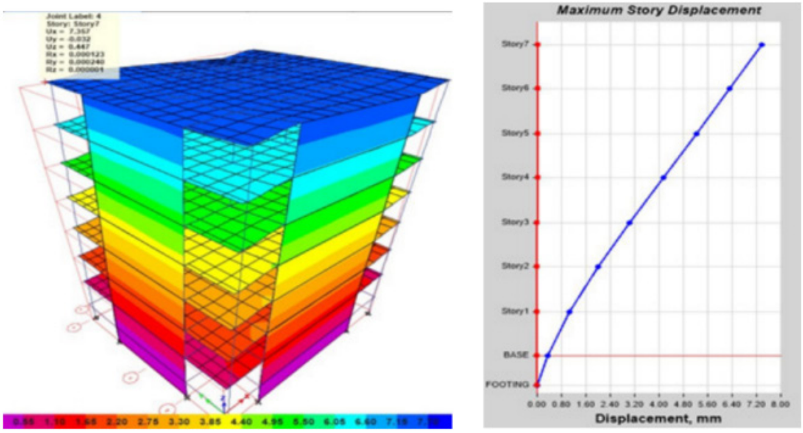


Figure 5: Total resultant displacement of the blast occurred on the face (Reddy et al.,2023)

Particle diffusion

This index measures the dispersion of suspended or floating particles in the space around the façade to assess the stability and safety of details against the release of fine particles due to a blast wave or other impact loads. This index uses particle imaging and measurement tools, particle dispersion models, and experimental and field data to analyze particle transport paths and particle concentration patterns at sensitive points. The goal is to reduce secondary damage caused by falling or scattering particles, improve the design of protective coatings and distances between elements in the facade.

Connection resistance

This index measures and evaluates the strength or capacity to withstand rupture and slip at the joints between the façade elements and the frame to determine the durability and stability of the details when exposed to dynamic, impact and explosive loads. Using tensile-slip tests, cyclic loading, rupture tests and numerical simulation data, this index analyzes the behavior of connections with different materials and connection methods and addresses potential weaknesses to improve the design and selection of connection technologies. Sensitivity analysis is performed on the connection material, installation methods, adhesive quality, and the presence or absence of resin or interlayer fillers to select design options with the lowest risk of rupture or slip. Finally, the results of the connection strength are reported as quantitative measures such as rupture capacity, allowable sliding gap, and dynamic response during impact or severe wave to better guide detail design and maintenance decisions.

Façade user

This index considers the safety and efficiency of building occupants' performance in the face of critical events such as blasts, shock loads or vibrations. The index addresses understanding occupant behavior, environmental hazard management, and accessibility, emergency egress, and safe navigation under abnormal conditions. Using behavioral data, motion simulations, and safety analyses, the index helps design efficient access details and spaces, stabilize exits, and reduce user response times. Sensitivity analysis to crowd behavior, exit capacity, accessibility measurements, lighting, and safe signage are considered to create a safe user experience in the face of threats. Finally, the results of the façade user experience are reported in quantitative metrics such as emergency egress time, break capacity for crowded exits, and safe navigation indices to align design details and implementation requirements with minimal risk severity.

Environmental sustainability

This index attempts to assess the environmental impact of a building's façade throughout its life cycle. It analyzes resource consumption, pollution emissions, waste generation, and the use of recycled materials in detail to design the façade with minimal negative environmental impacts and improved energy efficiency. Using construction data, environmental standards, noise impact estimates, and life cycle models, the index evaluates sustainable design options such as the use of low-carbon materials, long lifespans, recyclability, and reduced latent energy in production and installation.

Economic sustainability

This index aims to improve the cost-benefit assessment and economic efficiency of façade projects. The index evaluates design options by analyzing capital expenditure (CAPEX), operating and maintenance expenditure (OPEX), material life, repair and renovation costs, and return on investment (ROI). Using economic-engineering models, project data, and market forecasts, the index identifies optimal paths to reduce total life cycle costs, deploy highly durable technologies, and select cost-effective materials with appropriate service lives.

User Acceptance Index and Measurement Uncertainty

This index examines user acceptance of façade details, as well as the reflection of measurement uncertainties in the evaluation process. The goal is to realistically understand user behavior, the level of confidence in design data, and manage the risks associated with measurement errors. Using user behavior data, field feedback, laboratory validation, and uncertainty analysis, this index assists in dateline design decisions and documenting implementation requirements. Sensitivity analysis of data representation, confidence measurements, and the impact of data improvement opportunities are performed to increase the level of acceptance and measurement accuracy in the project. Finally, the results are reported as quantitative measures such as user acceptance rate, data confidence level, and measurement uncertainty gap to improve risk management and detail design.

RESULT AND CONCLUSION

The façade safety indicators reviewed in this discussion are an overlapping set of aspects of usability, environmental sustainability, economic sustainability, and user acceptance with measurement uncertainty that simultaneously aim to improve the quality of design details and project implementation. Each indicator individually provides a framework for making design decisions based on safety, usability, sustainability, and cost requirements, while also considering the integration of the facade system with the surrounding environment. The facade usability index focuses on user behavior in critical situations and standardizing navigation, lighting, and signage to provide faster safe egress and better accessibility. Using behavioral data, movement models, and exit simulations, the index measures safe exit capacity and emergency exit times so that façade details can be designed to reduce crowding and provide clear and accessible escape routes. However, demographic constraints and cultural differences can affect the results and require adaptation of the design to local characteristics. The Environmental Sustainability Index, as a bridge between architecture and the conservation of natural resources, assesses energy consumption, recycled materials and waste over the life of the façade. The selection of low-carbon materials, reduction of latent energy in production and installation, as well as design with high recyclability are key objectives of this index. Although material and process data may have imprecision and require limits and assumptions, this index is a strong starting point for design decisions with a lower environmental impact. With the Economic Sustainability Index, the entire life cycle costs, payback period and internal rate of return are looked at from an engineering-economic perspective to align detailed design decisions with the priority of economic efficiency. This index specifically considers improving the life of materials, reducing maintenance costs and employing highly durable technologies to manage project financial resources well. The main challenge in this area is to accurately predict prices and market changes, which can lead to errors in future assessments. The User Acceptance and Measurement Uncertainty Index examines the acceptance of data by users, as well as the management of risks associated with measurement errors. In practice, high acceptance means higher system efficiency and reduced resistance to change, but measuring uncertainties and data trust can reduce or increase the level of decision-making confidence. With field and laboratory feedback, probabilistic models and uncertainty analysis, this index helps to improve data reliability and reduce the gap between theory and practice. The simultaneous application of these indicators leads to a multi-criteria decision-making framework that provides a comprehensive view of safety, environment and economy. Clearly, each indicator has significant value on its own, but their combination in a novel way drives the design of details in a direction that reduces safety risks, minimizes environmental impact, and selects the most economically optimal options. This multidimensional combination is a reminder that design decisions must not only consider safety and usability, but also must be compatible with limited resources in the short term and in the long term.

The simultaneous application of these indicators results in a multi-criteria decision-making framework that provides a comprehensive view of safety, environment, and economics. Clearly, each indicator has significant value on its own, but their combination in a novel way drives the design of details in a direction that reduces safety risks, minimizes environmental impact, and selects the most economically optimal options. This multidimensional combination is a reminder that design decisions must not only consider safety and usability, but also must be compatible with limited resources in the short term and in the long term. One important point in the analysis of the conclusions is the sensitivity and uncertainty that each indicator contains. Sensitivity to changes in input data, fluctuations in material prices, or changes in user behavior can affect key outputs such as TCO, IRR, or emergency exit time.

- The multidimensional façade safety framework consists of four overlapping dimensions: façade usability, environmental sustainability, economic sustainability, and user acceptance. These dimensions simultaneously improve the quality of design details and project implementation, ensuring the integrity of the façade system with respect to the surrounding environment. This approach leads to decision-making with a broad vision while at the same time being able to focus on design details.
- Façade usability and crowd management in critical situations are specifically addressed. Through standardization of navigation, lighting, and signage, faster safe egress and better accessibility are provided. Behavioral data and movement models serve as key inputs to measure safe egress capacity and emergency exit times. These findings indicate that detail design should respond to the behavioral patterns of different groups to reduce crowd pressure and ensure escape routes remain accessible at all times.
- Environmental sustainability is considered as a bridge between architecture and the conservation of natural resources. This index evaluates energy consumption, recycled materials and waste over the life of the façade and endorses the selection of low-carbon materials and highly recyclable designs. Despite speculations regarding the accuracy of material and process data, limits and assumptions are considered as tools for managing uncertainty to make design decisions with lower environmental impact.
- Economic sustainability addresses the total life cycle costs, payback period and internal

rate of return from an engineering-economic perspective. This index considers improving the life cycle of materials and reducing maintenance and employing durable technologies as key factors in optimizing project financial resources. However, market fluctuations and price forecasts are always considered major challenges that can affect future assessments.

- User acceptance and measurement uncertainty examines user acceptance of data and the management of risks related to measurement errors. Field and laboratory feedback, probabilistic models, and uncertainty analysis help to improve data validity and reduce the gap between theory and practice. In this framework, data trust and the possibility of dynamic revision are recognized as key elements of design decisions.
- The multidimensional conclusion clearly shows that the combination of indicators leads to a multi-criteria decision-making framework that simultaneously considers safety, usability, sustainability, and economics. This combination is a reminder of the fact that design decisions are not based on a single criterion and must be consistent with short-term responsiveness and long-term adaptation to resource constraints. Sensitivities and uncertainties are considered as dynamic elements in the implementation analysis to allow for rapid revision and data-driven decision-making.
- Adaptive strategy and scenario-based approach: The text explicitly mentions the existence of a scenario-based approach that allows for sensitivity analysis and risk assessment by using scenario models for input data and price changes. This method, especially after determining a minimum of uncertainties, allows for assessing the stability of data decisions in the face of market fluctuations and changes in user behavior. The result of this approach is to achieve decisions with relative stability and the possibility of rapid revision.
- Validation and risk analysis: For each indicator, validation methods are used to ensure the integrity of the data and the accuracy of the models. This process includes field and laboratory feedback, sensitivity tests, and the examination of hypothetical hypotheses that clearly specify the uncertainties related to the inputs. As a result, the level of confidence in the data and models is improved and the gap between theoretical models and practical implementation is reduced.
- Short-term responsiveness and long-term adaptability: This framework suggest that data design should be such that it provides short-term responsiveness to critical events while being compatible with resource constraints in the long term. In other words, design choices should not be limited to optimizing a single metric but should strike a balance between safety, usability, sustainability, and economic costs to provide appropriate performance over both time frames
- Dynamic review and data-driven decision-making: The section emphasizes dynamic review, explaining that input data can be updated frequently and that models must be continuously adapted to new data. Uncertainty analyses, confidence intervals, and alternative scenarios help managers make data-driven decisions in the face of significant changes.
- Integration of indicators and synergistic effects: Finally, it is emphasized that combining these indicators into a multi-criteria decision-making framework allows for the simultaneous monitoring of safety, usability, environmental sustainability, and economic sustainability. This framework shows that in the design of details, attention is not paid to only one specific criterion, but to short-term and long-term considerations with limited resources, and the sustainability of decisions is strengthened by sensitivity and uncertainty analysis. (Tab. 4)

To increase the resistance of glass to blast waves, multilayer compositions and protective coatings are used. Laminated glass with PVB layers or AR laminates, along with

Table 4: Explanation of the design indicator and goal in order to explain actions and improve the design

Key Indicator	Design Goal	Measurement Criterion	Unit	Uncertainty/ Interpretation	Associated Risks	Design Improvements / Actions
Façade Usability	Improve user behavior during critical times	Safe egress capacity and emergency egress time	person-seconds/ seconds	Range of input behavioral uncertainties	Population pressure, path breakage during evacuation	Standardize navigation, signage, and conduct user tests
Environmental Sustainability	Reduce environmental impact of the façade	Energy consumption, recycled material percentage, waste	kilowatts/ kilojoules, percentage	Uncertainty in material and process data	Rising energy costs, limited access to low-carbon materials	Select low-carbon materials, design for recyclability, enhance material durability
Economic Sustainability	Improve life-cycle costs	Total costs, return on investment, IRR	dollars/percent	Price fluctuations and market volatility	Increased maintenance costs, budget overruns	Durable design, reduced maintenance, use of sustainable technologies
User Acceptability	Build trust and acceptance of details	User feedback, acceptance rate	ratio/percentage	Uncertainty in feedback measurement	User resistance, measurement errors	Dynamic revisions, field and lab tests, improve user communication
Probability and Uncertainty	Manage input uncertainties	Sensitivity analysis, confidence intervals	statistical units	Price/behavior changes	Poor decision-making	Scenario-based approaches, model validation
Short-Term Compatibility	Rapid response in crises	Response time to events	seconds/ minutes	Level of response precision	Inefficiency in rapid execution	Design details for quick response, simulation testing
Long-Term Compatibility	Sustainability under resource constraints	Material lifespan, maintenance	years/period	Lifespan prediction, future maintenance	Other projects with resource constraints	Choose durable materials, plan long-term maintenance

surface coatings of appropriate thickness and high hardness, can reduce the initial waves, control the developed cracks and prevent the spread of projectiles. Glass with an appropriate energy dissipation coefficient is selected so that the fracture remains controlled and limited to fragments. In the design of the window frame, attention should also be paid to the distribution of energy and the cohesion with the walls; blast-resistant frames with tight joints, anti-corrosion coating and bolt-nut connections with appropriate torque are used to reduce stress concentration and reduce wave transmission to adjacent structures. The use of secondary connections and chain systems prevents chain failure of the frame and strengthens the stability of the entire system. In detail design, a protective layer or internal frame can reduce the blast wave before it reaches the glass, and impact pads or shock strips can be used at the edges to reduce stress concentrations and stop cracking. In addition, it is important to implement international standards for blast protection and advanced modeling. EN and NFPA standards related to glass and architectural elements should be followed and coordinated with the project design criteria. The use of multiple analysis models for the blast wave, including nonlinear analyses and life-maintenance assessments, together with sensitivity analyses to different inputs such as wave intensity and distance from the explosion center, allows for the extraction of optimal resistant designs. Uncertainty assessment with a scenario-based approach and sensitivity analysis leads to the determination of more accurate resistance plans. To reduce the launch of fragments and their dispersion, protective grids or backing plates can be used to keep glass fragments in place. Also, designs with break-resistant edges and reduced escape velocity of glass shards rather than sharp fragments help to ensure interior safety. The distance and orientation of the window relative to the wave source should be such that the energy is limited to the interior.

Strict implementation of installation instructions and quality control at the project site is also critical. Installation methods should be followed with the frame and glass aligned and flush, and frames compatible with the project should be used. During the installation stages, blast-simulated field tests with small model specimens are required to evaluate design performance and installation accuracy, and regular qualitative and quantitative inspections at each phase prevent ruptures. Support materials and energy-generating coatings can also help improve performance. The use of energy-shielding coatings or energy-shielding layers, depending on weight and thickness, can reduce wave energy and improve system response. Ultimately, by combining these approaches in a detail-oriented format and performance standards, safer and more robust designs can be achieved that are aligned with project requirements and facade safety requirements and significantly reduce blast risks. (Tab. 5)

Table 5: Explanation of the proposed approach and tools in relation to increasing the non-structural resistance of the building against blast wave behavior

Approach	Key Explanation	Suggested Tools/ Materials	Implementation Notes	Link to Conclusion/Outcome
Multi-layer glass and protective coating	Use PVB/ionoplast layers or AR laminates with hard surface coating	Shatter-resistant laminates, layered thick coatings	Choose layer combinations to control breakage and reduce fragment spread	Directly supports façade safety conclusions and crack control
Durable window frame design	Strong connections, corrosion-resistant coating, bolt-nut connections with appropriate torque	Sturdy profiles, secondary fasteners, chain systems	Energy distribution and prevention of chain failure	Structural durability and reduction of wave transmission
Detail protection and protective layer	Inner protective layer and edge-impact pads	Composite panels, impact strips	Reduce stress concentration and stop cracking	Increased safety of interior space
Standards and modeling	Comply with EN/NFPA and multi-wave blast modeling	Nonlinear analysis software, life-cycle models	Assess uncertainty and input sensitivity	Aligned with project design criteria
Downside of projectile release reduction	Protective mesh and backing plates	Safety mesh, backing plates	Edge design to reduce fragment ejection	Reduced hazards to people and interior environment
Design for source-distance orientation	Window orientation relative to blast source	Window layout, tilt and spacing	Limit energy input to interior space	Improved protective performance
Installation and quality control	Precise installation instructions and regular inspections	Checklists, field tests	Flatness/alignment of frame and glass, sampling	Stable performance after installation

Approach	Key Explanation	Suggested Tools/ Materials	Implementation Notes	Link to Conclusion/Outcome
Energy-absorbing materials	Energy-absorbing shields and protective layers	Composite sheets, energy-dissipating coatings	Selection based on weight and thickness	Improved system response to blast wave
Uncertainty assessment	Sensitivity analysis and scenario-based approach	Various blast intensity scenarios, distance from explosion	Derive optimal resistance plans	Strengthen design decision-making
Executive conclusion	Integrating approaches for façade safety goal	Detail-focused, actionable requirements	Include in project checklists	Aligned with project safety requirements

REFERENCES

Ando, K.; Sanada, T.; Inaba, K.; Shepherd, J.E.; Colonius, T.; Brennen, C.E. (2010) Shock Theory of a Bubbly Liquid in a Deformable Tube. In Proceedings of the 7th International Conference on Multiphase Flow, Tampa, CA, USA, 30 May–4 June 2010.

Aune, V., Fagerholt, E., Langseth, M. & Borvik, T. (2016) A shock tube facility to generate blast loading on structures. Int. J. Protect. Struct. https://doi.org/10.1177/2041419616666236.

Biolzi, L.; Simoncelli, M. (2022) Overall response of 2-ply laminated glass plates under out-of-plane loading. Eng. Struct. 2022, 256, 113967.

D'Ambrosio, G., Galuppi, L. & Royer-Carfagni, G. (2019) A simple model for the post-breakage response of laminated glass under inplane loading. Compos. Struct. 230, 111426.

Del Linz, P. et al. (2017) Delamination properties of laminated glass windows subject to blast loading. Int. J. Impact Eng. 105, 39–53. https://doi.org/10.1016/j.ijimpeng.2016.05.015

Deshpande, V.S.; Heaver, A.; Fleck, N.A. (2006) An underwater shock simulator. Proc. R. Soc. A Math. Phys. Eng. Sci. 2006, 462, 1021–1041.

DoD. UFC. (2024) DoD Minimum Antiterrorism Standards for Buildings. Unified Facilities Criteria, U.S. Army Corps of Engineeer USA 12 December 2018. Available online: https://www.wbdg.org/ffc/dod/unified-facilities-criteria-ufc/ufc-4-010-01 (accessed on 3 June 2024).

Elkilani, A., El-Emam, H., Elsisi, A., Elbelbisi, A. & Salim, H. (2024) The influence of strain rate behavior on laminated glass interlayer types for cured and uncured polymers. Polymers (Basel) 16, 730. https://doi.org/10.3390/polym16060730

El-Sisi, A. et al. (2024) Effect of glass type and thickness on the static and blast response of LG panels. J. Build. Eng. 86, 108870. https://doi.org/10.1016/j.jobe.2024.108870

Inaba, K.; Shepherd, J.E. (2010) Flexural waves in fluid-filled tubes subject to axial impact. J. Press. Vessel. Technol. 2010, 132, 021302.

Lusk, B.; Salim, H.; Perry, K.; Nawar, M.; Wedding, W.C.; Kiger, S.; Ibrahim, A. (2011) Modeling and Testing of Laminated Window Systems under Blast Loading. In Proceedings of the Structures Congress 2011, Las Vegas, NV, USA, 14–16 April 2011; pp. 1552–1560.

Marchand, K.A.; Conrath, E.J.; Stevens, D.J.; Meyer, S.B. (2006) Blast Induced Glass Hazards: A Comparison of Design Approaches and Recent Research. In WIT Transactions on the Built Environment; WIT Press: Southampton, UK, 2006; Volume 87

Monir M. A. Alhadid, Ahmed M. Soliman, Moncef L. Nehdi, Maged A. Youssef; (2014) Critical overview of blast resistance of different concrete types. Magazine of Concrete Research 1 January 2014; 66 (2): 72–81. https://doi.org/10.1680/macr.13.00096

Nawar, M.; Salim, H.; Lusk, B.; Perry, K.; Kiger, S.; Miller, G. (2013) Modeling and testing of laminated curtain wall systems under blast loading. In Structures Congress 2013: Bridging Your Passion with Your Profession: Proceedings of the 2013 Structures Congress, Pittsburgh, PA, USA, 2–4 May 2013; American Society of Civil Engineers: Reston, VA, USA, 2013; pp. 170–180.

Pelayo, F. et al. (2017) Study of the time-temperature-dependent behaviour of PVB: Application to laminated glass elements. Thin-Wall. Struct. 119, 324–331

Ranocchiai, G.; Andreozzi, L.; Zulli, F.; Fagone, M. (2016) Effects of InterlayerWeathering on the Structural Behaviour of Laminated Glass Structures. In Proceedings of the Challenging Glass 5—Conference on Architectural and Structural Applications of GlassBelis, Gent, Belgium, 16–17 June 2016.

Shirbhate, P.A.; Goel, M.D. (2021) A Critical Review of Blast Wave Parameters and Approaches for Blast Load Mitigation. Arch. Comput. Methods Eng. 2021, 28, 1713–1730.

Skews, B.W.; Kosing, O.E.; Hattingh, R.J. (2004) Use of a liquid shock tube as a device for the study of material deformation under impulsive loading conditions. Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci. 2004, 218, 39–51.

Van der Woerd, Jan Dirk, Wagner, Matthias, Pietzsch, Achim, Andrae, Matthias & Gebbeken , Norbert (2023) Glass Structures & Engineering volume 7, DOI: https://doi.org/10.1007/s40940-022-00213-w

Wei, J.; Shetty, M.S.; Dharani, (2016) L.R. Stress characteristics of a laminated architectural glazing subjected to blast loading. Comput. Struct. 2016, 84, 699–707.

Zhang, X. & Hao, H. (2015) Experimental and numerical study of boundary and anchorage effect on laminated glass windows under blast loading. Eng. Struct. 90, 96–116. https://doi.org/10.1016/j.engstruct.2015.02.022