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Dynamic Modeling of Equivalent Triple Insulated Glazing Units under Blast Loading using WINGARD

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Abstract

Triple-insulated glazing units (TGUs) are an emerging class of architectural glazing systems offering compact configurations, superior energy efficiency, and enhanced thermal performance while exhibiting high blast resistance capabilities. Despite the growing adoption of TGUs in critical infrastructure and high-risk facilities, there remains a lack of widely available modelling tools capable of efficiently predicting their nonlinear dynamic response under blast loading. Although well-established for modeling monolithic and double-insulated glazing unit (DGU) systems to blast loading, WINGARD does not natively support TGU configurations, posing a significant barrier for engineers designing such blast-resistant façades. This study proposes a simplified methodology for representing a TGU as an equivalent DGU system within WINGARD to comply with General Services Administration (GSA) glazing hazard-rating criteria. The methodology preserves the mass, stiffness, and energy-dissipation characteristics of TGUs while remaining compatible with WINGARD's input framework. Comparison made against limited experimental data demonstrates that the methodology captures the dominant blast response characteristics of TGU systems. The findings provide a practical, quick-running methodology for engineers to assess TGU blast performance using WINGARD.

Keywords

Blast loading, triple insulated glazing, dynamic analysis, WINGARD

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1. Introduction

Triple insulated glazing units (TGUs) are increasingly specified in modern façade systems to meet stringent thermal, acoustic, and space-efficiency requirements. A TGU consists of three glass lites separated by two sealed cavities, typically filled with air or inert gas, forming a compact glazing configuration with improved thermal performance relative to conventional double insulated glazing units (DGUs). As the use of TGUs expands into buildings with elevated protection requirements, their structural response under blast loading has become an important consideration in façade design.

The behaviour of glazing systems subjected to blast loading has been studied extensively for monolithic and laminated glass configurations (Hooper et al. 2012; Zhang and Hao 2015; Larcher et al. 2016). For insulated glazing systems, prior research has primarily focused on DGUs, where the presence of a single sealed air gap has been shown to influence load transfer, stiffness, and failure mechanisms under impulsive loading (Guo et al. 2024). These studies emphasize most simplified blast assessment tools and hazard-rating methodologies currently used by practitioners. TGUs differ fundamentally from DGUs due to the presence of two enclosed cavities, which modify the dynamic interaction between glass plies during a blast event. This configuration alters the effective mass, stiffness, and energy-dissipation characteristics of the system through coupled glass–air interaction and sequential load redistribution between plies. As a result, direct application of DGU-based modelling approaches to TGUs is not generally valid. While high-fidelity numerical simulations can capture these mechanisms, such approaches are computationally demanding and impractical for routine design and rapid hazard assessment.

Currently, WINGARD (WINdow Glazing Analysis Response and Design) is one of the leading analytical programs used in the protective design industry for evaluating the blast response of window and glazing systems (ARA 2005). Developed by Applied Research Associates for the General Services Administration (GSA), WINGARD provides a practical engineering framework for defining glazing layups, window geometry, blast loading parameters, and for estimating the resulting dynamic response and fragment hazard. The program is commonly used to assess whether glazing systems satisfy prescribed blast-performance criteria and to compare alternative configurations, including monolithic glass, laminated glass, insulated glazing units, and security-film retrofits. By generating response histories, support reactions, capacity estimates, and pressure–impulse curves, WINGARD serves as an efficient component-level design tool for blast-resistant glazing, bridging simplified hand-calculation methods and more detailed finite element modelling.

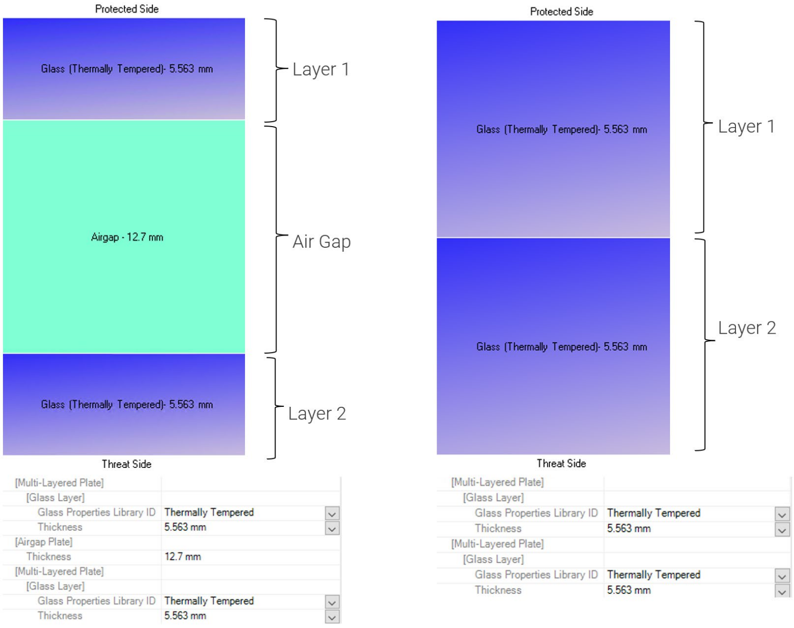
Although WINGARD is widely used for conventional blast-resistant glazing design, its capabilities do not directly extend to triple-glazed units (TGUs). This limitation is significant because TGUs are increasingly used in façade systems for improved thermal and acoustic performance, yet their blast response remains comparatively underdeveloped in the literature. Only a limited number of studies have explicitly examined TGUs under explosive or blast loading, and the available research indicates that the behaviour of the enclosed air cavities can strongly influence the dynamic response of triple-pane systems (Sielicki et al. 2020; Bedon et al. 2022). However, these findings are generally restricted to specific layups, boundary conditions, and modelling assumptions, leaving the broader blast performance of TGUs insufficiently characterized within simplified engineering design methods. To address this gap, the present study develops a practical methodology for evaluating TGUs within the existing WINGARD analysis framework. Since WINGARD is primarily formulated for monolithic, laminated, and double-glazed insulating glass units, the proposed approach represents a TGU as an equivalent double-glazed unit while preserving its effective mass, stiffness, and energy-dissipation characteristics. This allows TGU façade systems to be assessed rapidly at an engineering level using the established WINGARD solver and interpreted in accordance with GSA glazing hazard-rating criteria.

2. Methodology

The current version of WINGARD is limited to modelling DGUs due its limitation of having only a single air gap (air gap here refers to cavity of air or heavy gases and is used to remain consistent with WINGARD modelling limitations) and is not capable of explicitly modelling TGUs with two air gaps. Hence, an equivalent modelling approach on WINGARD has been proposed to indirectly model TGUs with a single air gap. If a TGU unit is made up of [Plate 1–air gap–Plate 2–air gap–Plate 3], then an equivalent TGU can be achieved by treating each plate as a non-composite plate to form a “Stacked Plate Model” where the individual resistance for each plate is computed and combined to form the total system resistance. Further information on the “Stacked Plate Model” is found in the WINGARD theory manual. Based on this approach a TGU unit can be modelled as [Plate 1–air gap–Plate 2–Plate 3] or modelled as [Plate 1–Plate 2–air gap–Plate 3] to produce an equivalent response as the original layup where each plate is defined as its own multi-layered plate. To demonstrate the validity of considering [Plate 1–Plate 2] as equivalent to [Plate 1–air gap–Plate 2] or [Plate 2–Plate 3] as equivalent to [Plate 2–air gap–Plate 3], a series of DGU models with and without an air gap is developed.

3. Validation based on analytical DGU systems

The actual and equivalent DGU models used for validation are presented in Fig. 1 based on a sample layup. The window system was based on a length of 1676.4 mm, width of 1219.2 mm, and height above floor of 609.6 mm. Table 1 demonstrates the structural properties for each model where the equivalent DGU system is treated as a single layer with properties of resistance, mass, and stiffness as the sum of the individual layers of the actual DGU system. Results of displacement, velocity, acceleration, reactions, and fragment flight are compared for each DGU model considering both elastic and plastic ranges of responses to demonstrate that the proposed method is applicable to pre- and post-breakage stages of behaviour.



[Multi-Layered Plate]	
[Glass Layer]	
Glass Properties Library ID	Thermally Tempered
Thickness	5.563 mm
[Airgap Plate]	
Thickness	12.7 mm
[Multi-Layered Plate]	
[Glass Layer]	
Glass Properties Library ID	Thermally Tempered
Thickness	5.563 mm

[Multi-Layered Plate]	
[Glass Layer]	
Glass Properties Library ID	Thermally Tempered
Thickness	5.563 mm
[Multi-Layered Plate]	
[Glass Layer]	
Glass Properties Library ID	Thermally Tempered
Thickness	5.563 mm

Fig. 1: Actual DGU layup (left) and equivalent DGU layup (right).

Table 1: Quantitative comparison of properties between the actual and equivalent DGU models.

Properties/Response	Actual DGU		Equivalent DGU
	Pane 1	Pane 2	Pane 1 and 2
Ultimate Resistance (kPa)	21.08	21.08	42.16
Effective mass (kpa-msec^2)	10.032	10.032	20.065
Max stiffness (kPa/mm)	1.003	1.003	2.007
Average stiffness (kPa/mm)	0.286	0.286	0.572
Natural period (msec)	37.23	37.23	37.23

3.1. Dynamic responses in the elastic range

As shown in Fig. 2, the displacement, velocity, and acceleration responses of the actual DGU model exhibit oscillatory behavior in both the inner and outer panes due to the presence of the air gap. In contrast, the equivalent DGU model records a combined response for the two panes, effectively capturing the average of the oscillating inner and outer pane responses observed in the full model. Figure 3 presents the total and average dynamic edge reactions, along with the fragment flight histories, for both DGU representations. These results demonstrate essentially identical responses between the actual and equivalent models. This agreement is further confirmed by the quantitative comparison in Table 2, which shows that both models produce nearly identical response measures across all evaluated parameters.

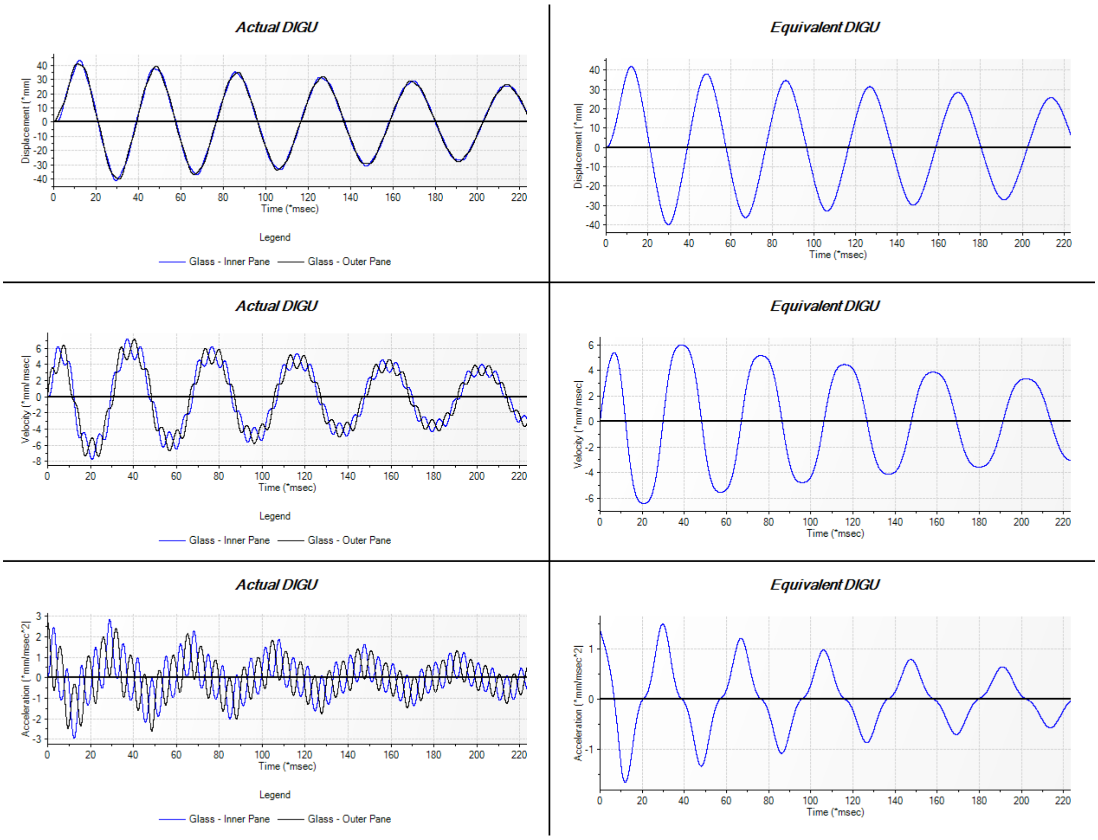
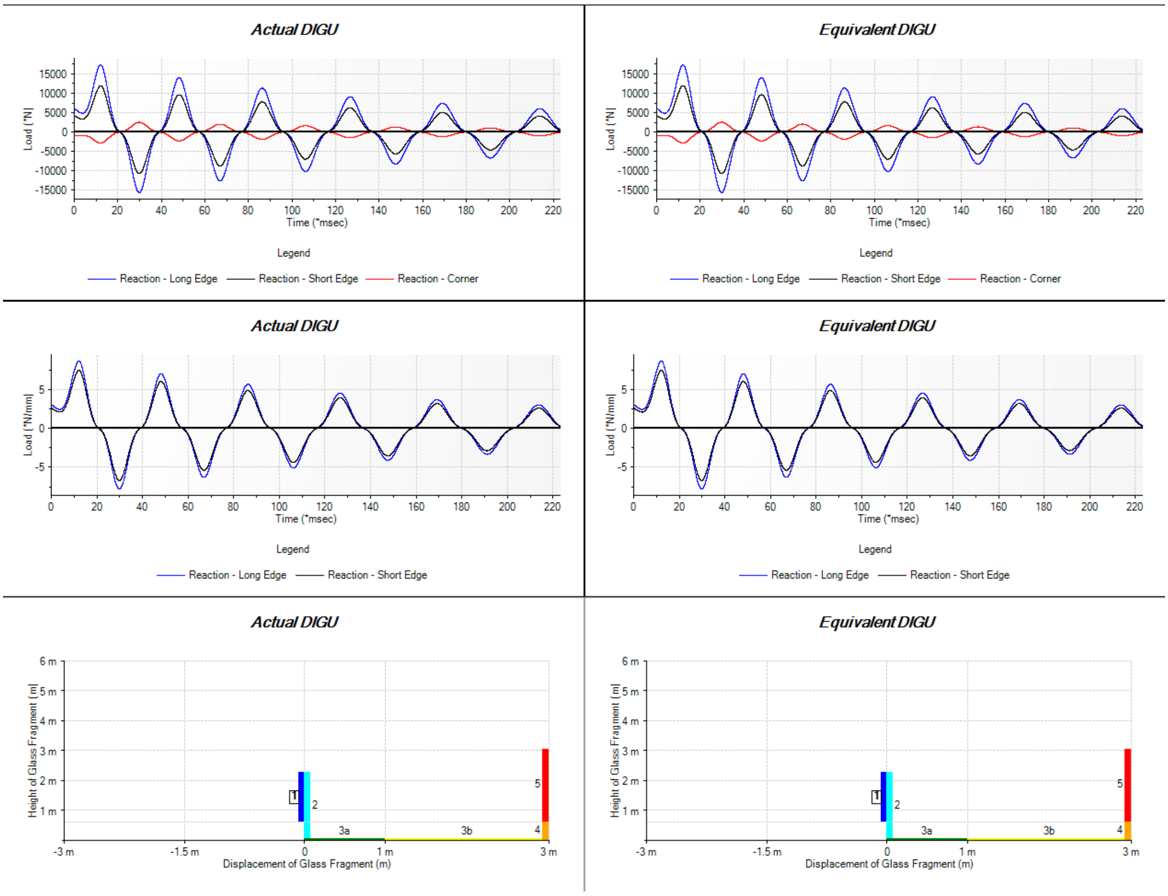


Fig. 2: Comparison of displacement-time, velocity-time, and acceleration-time histories for the actual and equivalent DGU models in the elastic range.


Actual DIGU

Equivalent DIGU

Fig. 3: Comparison of total dynamic reaction, average dynamic reaction, and fragment flight graph for the actual and equivalent DGU models in the elastic range.

Table 2: Quantitative comparison of responses between actual and equivalent DGU models.

Properties/Response	Actual DGU		Equivalent DGU
	Pane 1	Pane 2	Pane 1 and 2
Max displacement (mm)	43.38	40.70	41.95
Time to max disp. (msec)	12.25	11.32	12.08
Peak corner reaction inward (N)	-2834.7		-2835.8
Peak long edge reaction inward (N)	17362		17369
Peak short edge reaction inward (N)	11923		11928
Peak corner reaction outward (N)	2548.1		2551.9
Peak long edge reaction outward (N)	-15607		-15630
Peak short edge reaction outward (N)	-10718		-10734

3.2. Dynamic responses in the plastic range

As shown in Fig. 4, the displacement, velocity, and acceleration responses of the equivalent DGU model closely follow the average response of the oscillating inner and outer panes in the actual DGU model. Similarly, Fig. 5 indicates that the total and average dynamic edge reactions predicted by the two models are in close agreement. The primary difference between the plastic responses of the actual and equivalent DGU models arises from their failure representations. In the actual DGU model, the glass layers are permitted to fail independently and fragment separately. This behavior can produce temporary reductions in edge reaction when the first glass layer fractures, resulting in a drop in the reaction history. In contrast, the equivalent DGU model enforces simultaneous failure of both layers, thereby eliminating intermediate reaction drops and producing slightly higher edge reactions overall. A further difference is observed in fragment kinematics. In the actual DGU model, failure of an individual glass layer occurs at a higher velocity and over a greater projected distance than in the equivalent model, which fails both layers simultaneously with double the mass. As shown in Table 3, the failure velocity predicted by the equivalent model closely corresponds to the average of the failure velocities of the two layers in the actual model [6593.68 mm/s ≈ (8789.63+4254.15)/2 = 6521.89 mm/s]. Likewise, while the maximum final X-direction displacement is identical for both models, the final Y-direction displacement of the equivalent model approximates the average of the two layers in the actual model [368.41 mm ≈ (742.95+0)/2 = 371.48 mm]. It is also noted that the axes of fragment displacement are based on the fragment displacement charts in Fig. 5.

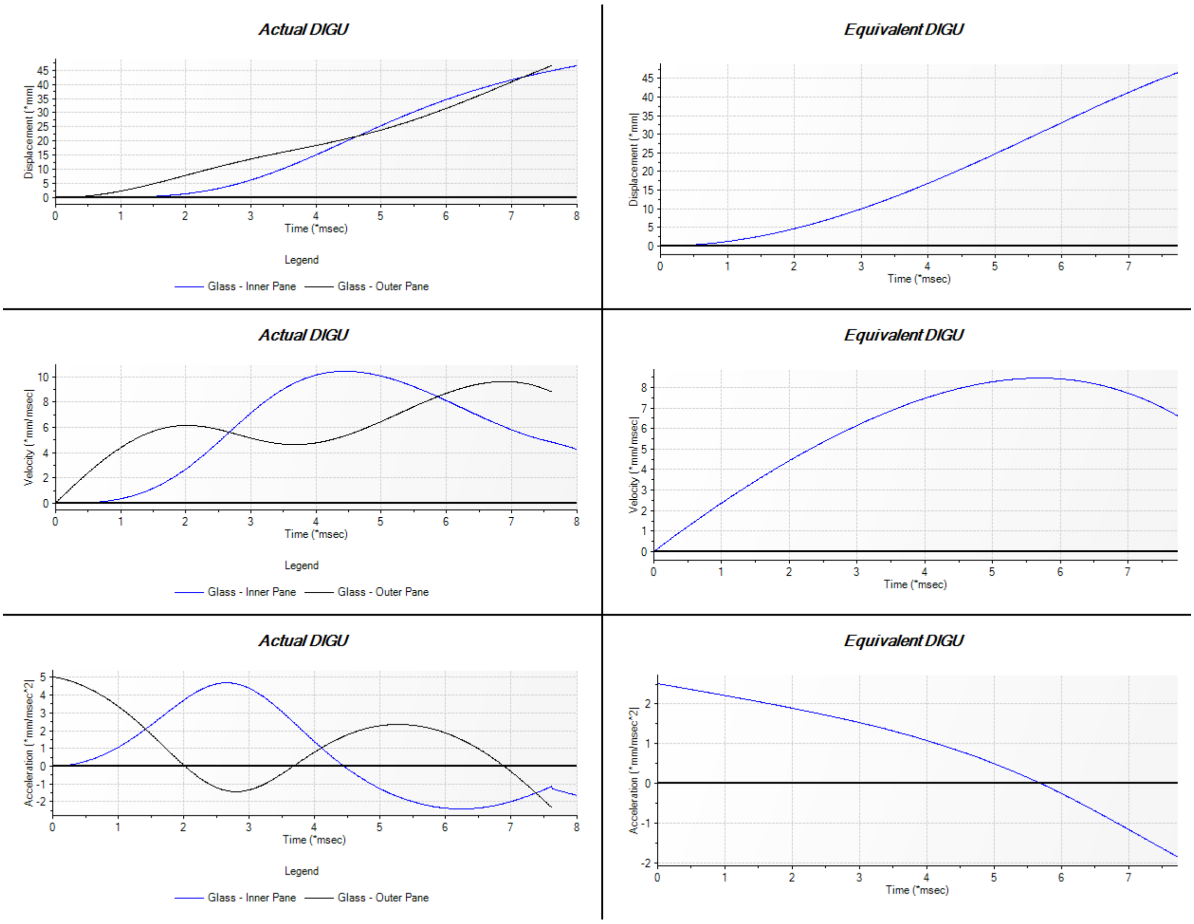


Fig. 4: Comparison of displacement-time, velocity-time, and acceleration-time histories for the actual and equivalent DGU models in the plastic range.

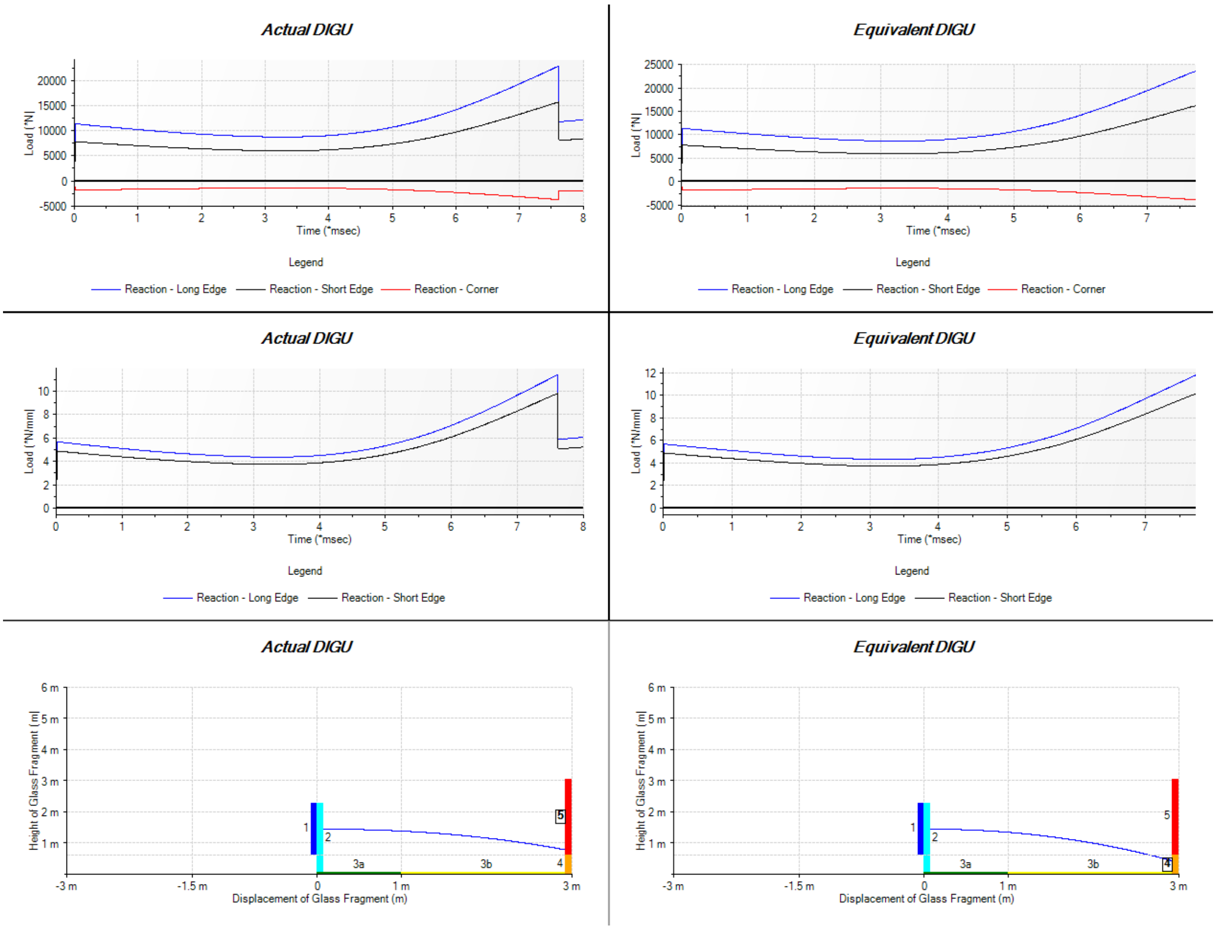


Fig. 5: Comparison of total dynamic reaction, average dynamic reaction, and fragment flight graph for the actual and equivalent DGU models in the plastic range.

Table 3: Quantitative comparison of responses between actual and equivalent DGU models.

Properties/Response	Actual DGU		Equivalent DGU
	Pane 1	Pane 2	Pane 1 and 2
Max displacement (mm)	46.59 (fail)	46.59 (fail)	46.61 (fail)
Time to max disp. (msec)	7.62 (fail)	8.01 (fail)	7.74 (fail)
Velocity at failure (mm/sec)	8789	4254	6593.68
Fragment final x disp. (mm)	3048	2273.55	3048
Fragment final y disp. (mm)	742.95	0	368.41
Peak corner reaction inward (N)	-3729.3		-3860.1
Peak long edge reaction inward (N)	22841		23642
Peak short edge reaction inward (N)	15687		16236

Through these comparisons, it was shown that modeling a DGU in WINGARD using separate multi-layer plate assignments without an explicit air gap produces nearly identical results to those of a fully defined DGU model within the elastic response range. In the plastic range, the equivalent DGU model exhibited slightly more conservative edge reaction forces, while predicting the average failure velocities and projected fragment distances in the Y-direction, and identical fragment distances in the X-direction relative to the actual DGU model. For blast design applications, these results indicate that the equivalent DGU representation provides a highly acceptable basis for predicting maximum displacements, edge reactions, and protection ratings. The demonstrated equivalence of the DGU models forms the basis for representing a TGU configuration in WINGARD. Specifically, a TGU comprising three plates separated by two air gaps [Plate 1-airgap-Plate 2-airgap-Plate 3] may be represented using a single effective air gap. For a given TGU system, it is recommended that two equivalent TGU configurations be evaluated by alternately removing one of the air gaps (e.g., [Plate 1-air gap-Plate 2-Plate 3] and [Plate 1-Plate 2-air gap-Plate 3]), with the governing response taken as the critical design case. Furthermore, the findings of this work generalize to any allowable window size, and a single window size was considered in this work for demonstration purposes.

4. Validation based on experimental TGU response

Experimental blast testing on TGUs remains extremely limited. To date, the only published experimental investigation is that reported by Sielicki, Bedon, and Zhang (2020), who examined the blast response of a full-scale TGU specimen. The tested specimen measured 1.0 m × 1.0 m (0.88 x 0.88 m net dimensions) and consisted of annealed glass plies with PVB interlayers arranged in a 44.4–6 mm air gap–33.1–8 mm air gap–44.1 layup. The glazing was subjected to a blast generated by a 10 kg TNT charge detonated at a standoff distance of 15.1 m, producing the characteristic pressure–time history shown in Fig. 6. The authors reported the measured mid-span deflection response of the TGU and presented a corresponding numerical simulation developed in ABAQUS. The experimentally observed deflection profile and the numerically predicted response were compared directly, providing limited but valuable insight into the global deformation behaviour of TGUs under blast loading.

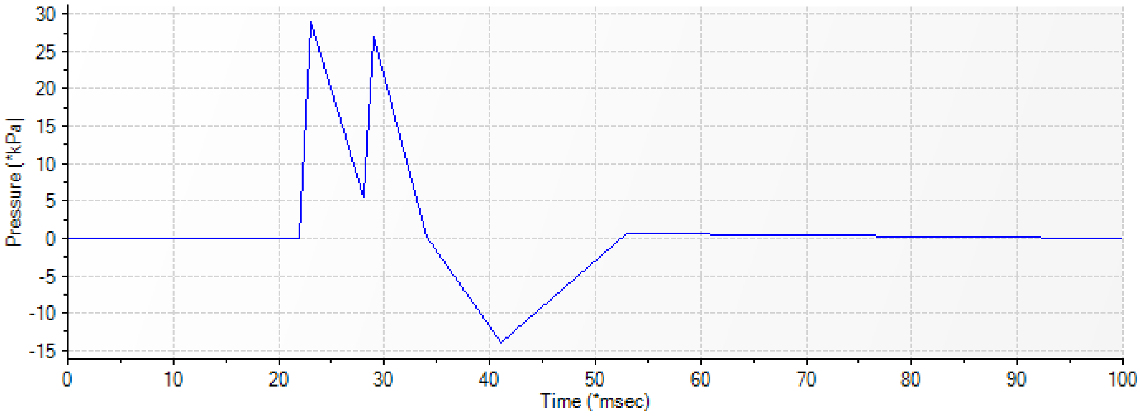


Fig. 6: Pressure-time history applied to TGU from 10 kg TNT (Sielicki, Bedon, and Zhang (2020)).

Table 4: Comparison between experimental and analytical TGU deflection.

	Peak inbound deflection (mm)	Time to deflection (msec)	Support Type
TGU Experiment Sielicki, Bedon, and Zhang (2020)	2.5	2.5	Fixed
Wingard TGU (A)	7.27	6.9	Simple
Wingard TGU (B)	7.35	6.9	Simple

Due to the scarce experimental data on blast-loaded TGU's, we present a high-level qualitative comparison between the experimental outcome of the fixed-supported TGU (Sielicki, Bedon, and Zhang, 2020) and the analytical outputs of the simply supported TGU using the proposed WINGARD modelling scheme. The TGU was simulated using the load curve of Fig. 6 and the resulting peak inbound deflections for the two alternating air-gap removal cases (A and B) are summarized in Table 4. It is emphasized that since WINGARD is limited to simply supported boundary conditions, only a high-level comparison is made with the available experimental TGU results, which employed fixed supports. The WINGARD TGU model predicted an average peak inbound deflection of 7.31 mm occurring at 6.9 ms under simple support conditions, whereas the experimental TGU exhibited a maximum inbound deflection of 2.5 mm at approximately 2.5 ms with fixed boundary conditions. Considering the increased flexibility and delayed peak response associated with simply supported members, the magnitude and temporal trends of the predicted response are consistent with expectations of greater deflection, indicating that the proposed modelling approach provides a reasonable and conservative estimate of TGU blast response.

5. Conclusions

This study addressed a key gap in current blast-resistant glazing analysis by developing a practical and efficient methodology for representing triple-insulated glazing units (TGUs) within the existing WINGARD framework. While TGUs offer clear advantages in terms of thermal efficiency, compactness, and blast resistance, their adoption in protective design has been hindered by the lack of readily available tools capable of capturing their nonlinear dynamic response under blast loading. By reformulating a TGU as an equivalent double-insulated glazing unit (DGU), the proposed approach preserves the governing physical characteristics of the system—namely mass, stiffness, and energy dissipation—while remaining fully compatible with WINGARD's established input structure and GSA hazard-rating requirements. Comparisons with the limited available experimental data indicate that the proposed methodology captures the dominant response features of TGUs subjected to blast loading. Overall, the findings demonstrate that TGU systems can be effectively assessed using WINGARD through the proposed equivalent modelling strategy, enabling rapid, engineering-level evaluations without resorting to computationally intensive high-fidelity simulations.

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