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Numerical Approaches for the Analysis of Glass Facades Under Seismic Loads

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ABSTRACT

In the last two–three decades, glass facades have gained more popularity due to their highly impactful esthetic and sustainable applications. However, their constitutive glass components are rather vulnerable and require proper analysis strategies to design them efficiently in structural terms, especially against extreme loads, such as earthquakes. To save time and costs, numerical approaches and simulations represent a powerful and versatile technique that can be used to predict the seismic behavior of glass facades under several loading and boundary conditions. Besides that, the lack of specific guidelines to support the model assembly and calibration for these analyses makes these steps uncertain and rather challenging. Among other open issues, this study collects and revises a selection of literature studies that emphasized the use of numerical simulations for glass facades subjected to earthquakes. Attention is focused both on framed glass facades and frameless (point-fixed) solutions. From the literature analysis, several modeling strategies emerge. Most importantly, difficulties and uncertainties in modeling complex glass facades are pointed out, especially with regard to the geometrical and mechanical optimization and the introduction of robust simplification approaches. It is observed that secondary components, such as setting blocks or gaskets, are often disregarded, which can have major consequences for the structural analysis and detailing of seismic effects in glass components.

1 | Introduction

In the modern world, when societies are grappling with environmental pollution, the construction industry is working to enhance the sustainability of building components. This is why glass facades have become more popular in the last two–three decades, not only due to esthetic purposes, but also for many other multiperformance benefits, which include also structural features. Glass facades, which are more common in tall buildings and skyscrapers, are usually associated with concepts of lightweight and transparency, modern architecture with modularity and easy installation, illumination, energy-saving features, and so forth. Despite all these features, glass facades are complicated systems due to their fragility, vulnerability to cracks, and needing careful handling and installation [1]. Therefore, even more complex tasks can be expected from the structural design and analysis of glass facades subjected to earthquakes [2, 3].

Several surveys and studies have disclosed that glass curtain walls suffer major damage due to interstory drifts caused by seismic events, even if the main structure experiences minimal damage.

Figure 1 shows some historic examples of glass facades that experienced severe damage during the Northbridge earthquake (1994), the Chile earthquake (2010), and the Christchurch earthquake (2011), whilst the main building was still safe. Such damages can usually be associated with the incompatibility between the deformation in the main structure and facade components [1], which is further emphasized by the brittle behavior of glass.

Specifically, talking about the structural performance of glass facades implicitly recalls several solutions for its constituent components, first of all, the glass panels. Their behavior depends, in fact, upon many basic and interconnected features, such as the type of glass (annealed, heat-strengthened, and fully tempered), the system adopted for the glass panel (monolithic, Laminated

FIGURE 1 | Examples of structural damage observed in real glass facades after earthquakes. Figures reproduced from [4] with permission from Elsevier©, license number 6110680457389 (September 2025).

Glass [LG], Insulated Glass Unit [IGU], and Laminated-Insulating Glass Unit [L-IGU]), the type of connection between the glass panel and the supporting members (i.e., framed systems based on transoms and mullions, or point-fixed glass facades [PFGFs], etc.). Additionally, at the material level, connectors and secondary components play a critical role, given that glass is rather weak in tension, and must therefore be protected against premature stress peaks. Annealed glass has the lowest tensile strength (45 MPa in terms of characteristic nominal value), heat-strengthened glass offers a nominal tensile strength equal to 70 MPa, and fully tempered glass is the strongest, with 120 MPa strength against tensile forces [2].

At the system level, LG and IGU solutions behave rather differently under typical mechanical loading and boundary conditions. LG elements, in which two (or more) glass panels are packed together by using an interlayer (see Figure 2), do not shatter into pieces after breakage and behave as a single sandwich unit. On the other side, IGUs can be composed of two (or more) glass panels (either monolithic or LG) that are separated by a cavity between them, which represents a further influencing parameter for their mechanical analysis. Finally, the seismic response is strongly sensitive to different connection systems. In a point-fixed system, large stresses are developed near the fixings and the glass holes [3], while framed connection systems are typically associated with maximum stresses at two opposite corners of the glass panel [1, 4].

Combining all the above parameters can generate hundreds of different solutions for glass facades, which indeed should be possibly analyzed and verified by following generalized modeling steps. Moreover, since glass facades are different in shape, size, connection, restraining systems, and so forth, it is always important to understand their structural behavior when subjected to seismic loads, and efficiently take advantage of numerical modeling strategies to optimize the simulation cost, but at the same time preserving the robustness of simulations, in reproducing and predicting the real mechanisms and effects. Major risks from improper seismic analysis and design of glass facades are associated with the consequences of drift between storeys, which can cause the breakage of glass panels and their fall apart from the building [5]. Such a situation is a priority because it has a great impact on the economy, but especially on the safety of the population.

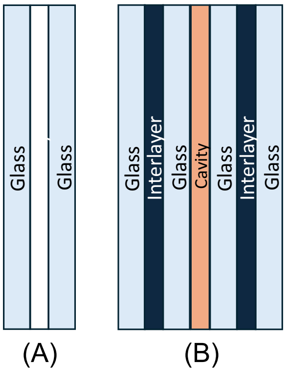

FIGURE 2 | Schematic representation of constituent layers in (A) Laminated Glass, and (B) Laminated-Insulated Glass Unit. The authors own the copyright.

Researchers have also suggested that even when glass facades are accurately designed at the component level, their analysis as a part of more complex buildings cannot be omitted or roughly simplified, particularly from the seismic design of high-rise buildings. Such a simplified assumption may, in fact, cause a crucial underestimation in the dissipation capacity of the building, as well as in many other local effects.

According to [6] around 82% and 92% of total building costs are utilized in nonstructural elements for office buildings and hospitals, respectively. This is largely covered by facades, which indeed can be properly optimized by using reliable simulation techniques and design assumptions.

To assess the real structural response of a glass facade, designers can take advantage of complex experimental setups and mock-ups that must resemble the actual boundary conditions and should provide accurate results. However, modern techniques such as numerical simulation tools have gained increasing popularity and have proved their potential for the seismic analysis of such complex facade systems. These techniques not only extend and validate the available experimental results, but also allow for saving time and cost of analysis, and further optimize the design detailing.

Indeed, the numerical modeling of glass facades is still uncertain and hardly generalizable. The application of numerical techniques and finite element analysis (FEA) for seismic considerations depends upon the complexity of the model and computational cost. Although there are numerous numerical approaches that have been utilized by different researchers, the question is whether such approaches are robust and can be extended for their general application to glass facades. Hence, this paper will provide a systematic review of all such studies that have used numerical approaches and also identify the most important challenges faced by researchers while analyzing different glass systems.

2 | Literature Selection Methodology

A systematic literature review was conducted to identify relevant research studies available on the seismic behavior of glass façade systems. The research articles were collected from databases, such as Scopus (ScienceDirect), Web of Science, ResearchGate, Academia, Google Scholar, and others using the combinations of keywords, such as "Seismic analysis of Glass facade," "Curtain Wall," "Finite analysis of Glass Façade," "framed glass façade," "Point-Fixed glass Façade," "laminated glass," "Numerical Analysis of Glass Façade," and so forth. Research papers were published only in the English language in various peer-reviewed journals and conferences were included. Only the articles focusing on the structural performance of glass facades, particularly against the seismic forces, were included, while articles dealing with architectural design without considering structural analysis were excluded. The collected research articles were further screened based on their relevance to modeling approaches, practical applications, boundary conditions, current trends, and material assumptions, and various studies were then analyzed and compared. A scheme of the adopted review strategy is shown in Figure 3.

3 | Numerical Tools and Techniques for the Seismic Analysis of Glass Façades

3.1 | Software Packages for the Seismic Analysis of Glass Façades

For decades, the FEA has been known to represent an efficient strategy to find approximate solutions to even complex mathematical problems, including those typical of the building engineering field. Similar to various technical applications, the structural (and other) performance of glass facades can be efficiently assessed by using different numerical tools and approaches. For instance, the study presented in [7] and others used ABAQUS computer software for the thermal analysis of building envelopes, while [8] and others utilized COMSOL Multiphysics for similar purposes. Accordingly, for the seismic analysis of glass facades, many software packages are generally adopted to capture the most important local and global mechanisms, especially for research-oriented applications, as well as to derive robust, simple modeling strategies of practical use for design activities.

The ANSYS software was used by [9, 10] and others for analyzing the seismic responses of glass facades, while the ABAQUS software was employed by [1, 11, 12] and many others. The SAP software has also been utilized by many researchers for the seismic analysis of facades, such as [13, 14]. However, these studies implicitly remark how the obtained numerical results can be strongly dependent on the adopted modeling and calibration strategies.

For instance, the seismic response of a single-story building with a glass and aluminum front was evaluated by [15], and two software packages were employed (ABAQUS and SAP90). The selected system was an example of framed connection (see also Figure 6), but it was roughly described as a simple glass panel without considering mullions, transoms, and other frame accessories, which are indeed important for obtaining more realistic results. Additionally, the analysis was conducted in two ways: in the first case, gravity load was excluded, while in the second case, gravity load was included. Afterwards, the ground motion was applied in two directions (perpendicular and parallel to the glass surface). However, by adopting the same strategies in different software packages, some discrepancy in results was recorded. It was found, for example, that the in-plane drift calculated by ABAQUS and SAP90 differed considerably when ground motions were applied perpendicular to the plane of the glass panel. Better agreement was observed with ground motions applied parallel to the plane of the glass panel. The maximum displacement

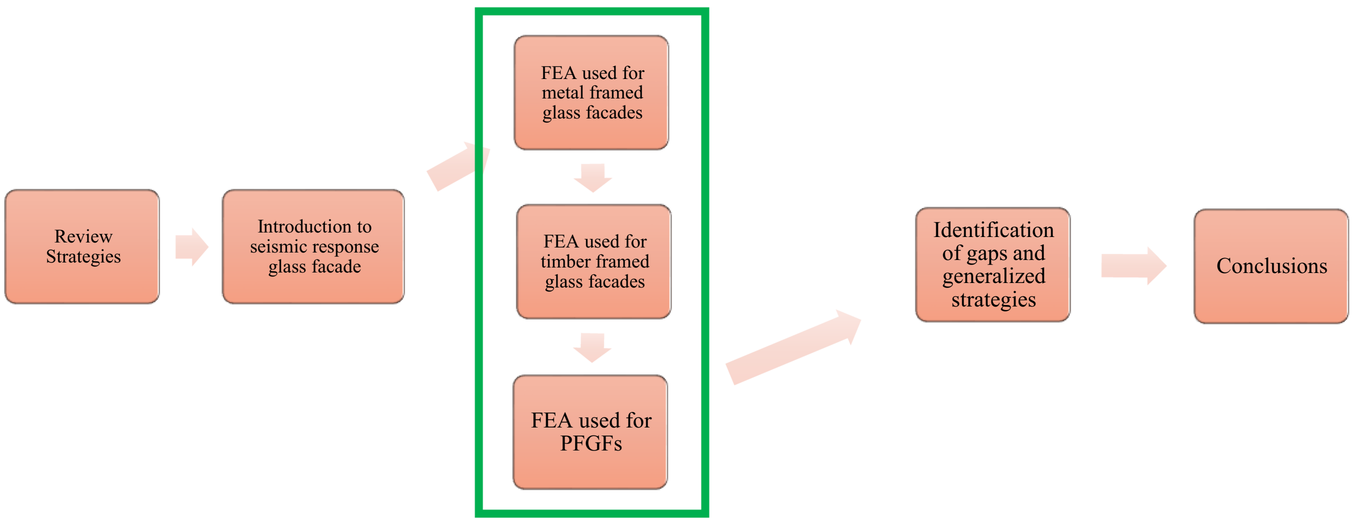

FIGURE 3 | Adopted review strategy. The authors own the copyright. FEA, finite element analysis; PFGFs, point-fixed glass facades.

obtained from the ABAQUS model, taking the gravity load into account, was 36% lower than the maximum displacement obtained from SAP90. Similarly, the maximum drift in the glass panel obtained from ABAQUS software, taking gravity load into account, was 61% lower than the maximum drift obtained from SAP90 software. This huge difference in results was possibly justified by different features: the element type (such as shell elements for SAP90 and three-dimensional [3D] solid elements for ABAQUS), the meshing size (which was not explicitly mentioned for the glass panel), and even possible interpolation functions. It is hence evident that many factors influence the numerical results, first of all, the model assembly and physical/kinematic description of glass facade components. Although numerical results save time, cost, and manpower, the numerical techniques must be properly implemented and refined to get exact results [16].

3.2 | Numerical Approaches to Analyze Facades

The seismic analysis of glass facades by numerical approaches can take advantage of a robust framework for predicting their response, both in-plane and out-of-plane. However, a key role is assigned to the detailed modeling and calibration of its components, so that such a kind of simulations could allow a detailed assessment of local and global behaviors [17].

Among the most used fixing systems for glass facades (i.e., the framed, Figure 4A) and the PFGF system (Figure 4B), there are major differences and expected mechanical contributions from the basic components.

Each connection solution has, in fact, specific applications and is characterized by different types of complexities and technical challenges that should be properly taken into account for modeling purposes.

In the point-fixed connection system, the glass panels are usually supported by bolts at corners, and sometimes even at the midspan section of long-span edges. The hole inside the panel can be cylindrical or have tapering inner and outer diameters, such as in the study presented by [18]. Other typical accessories include the spider arms, the supporting shafts, and so forth.

At the same time, the framed solution (which is also called the stick system) consists of several elements, such as aluminum-type transoms (horizontal supporting members) and mullions, silicon-type gaskets, rubber setting blocks, and so forth. In both cases, the seismic performance of glass facades mainly depends upon the interaction between glass panels and the supporting components.

Moreover, literature studies, have also revealed that the friction between the glass panels and gaskets, and the stiffness of the connection system, can strongly influence the overall facade's behavior when subjected to seismic forces [19]. Accordingly, a roughly simplified numerical description of these small components can have major consequences on the numerical estimates.

3.3 | Seismic Analysis of Metal Framed Glass Facades

In the last few decades, the seismic performance of framed glass facades has been investigated using both experimental and analytical approaches. The fundamental "limit states" for analyzing their typical seismic response were established by crescendo tests introduced in 1996. This approach highly influenced testing standards, such as [20] for framed systems, and had a great influence on industry standards, such as AAMA 501.6 and ASCE 7–16. In parallel, the FEMA 461 remained a fundamental seismic testing protocol for similar systems. However, the modern world needs nondestructive and efficient numerical approaches to predict the behavior of glass facades. Such approaches are not only replacing and minimizing the role of experimental methods, but also extending higher levels of accuracy and reducing the complexity of conventional experimental and analytical methods. To get accurate results through numerical approaches, researchers must take into consideration the real behavior of framed glass against seismic forces. Figure 5 shows how the framed glass facade behaves when it is subjected to in-plane lateral forces. This section, in particular, focuses on the literature research contributions summarized in Table 1.

One of the first published studies on the seismic response of glass facades was conducted at the University of California in

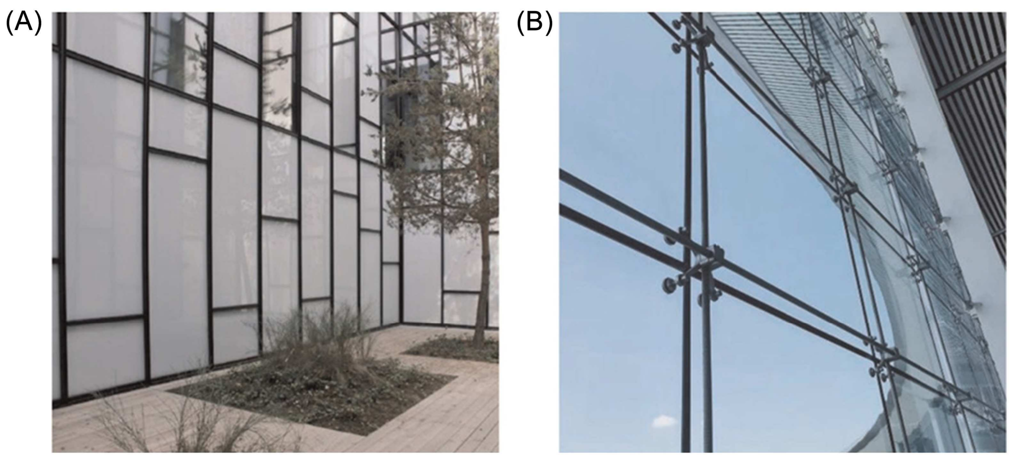

FIGURE 4 | Examples of (A) framed glass facade, and (B) frameless/PFGF. Figures reproduced from [17] under terms of the CC BY 3.0 license. PFGFs, point-fixed glass facades.

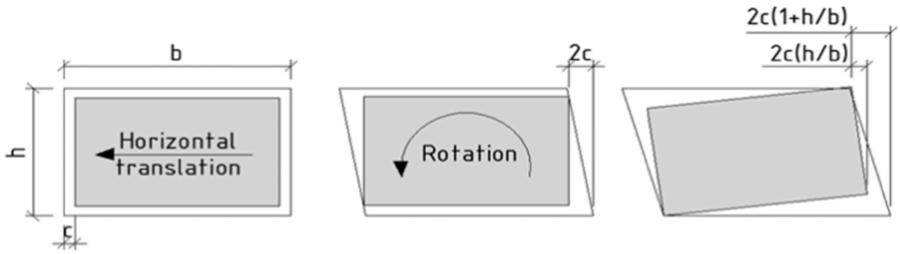

FIGURE 5 | Schematic representation of the response of a framed glass panel subjected to in-plane lateral forces. Figure reproduced from [21] under the terms of the CC BY-NC-ND 4.0 license.

1960 [31], revealed that the frame used to support the glass panels has a strong influence on the seismic response of curtain walls. Consequently, the researchers have concluded that framed glass panels have large movement potential, and the relative interstory drift depends not only on the size of the glass panel but also on the clearance between the frame and the glass panel. A new experimental work conducted in 2011 at the University of California revealed that the way of application of load on the panel, as well as the panel geometry, also has a strong influence on the maximum relative drift of curtain walls [32].

It is important to note that in similar systems (see, e.g., Figure 6), the metal frame components and especially the secondary components, such as the setting blocks, gaskets, and so forth, are basic devices that generally have a significant impact on the overall (local and global) performance of a given facade. For instance, once the gaskets start experiencing the plastic deformations, a reduction in the lateral stiffness of the façade can be expected. Consequently, in the subsequent stages, the behavior of the glass facade is also highly influenced by the stiffness of the metal frame. So, care should be taken while modeling the curtain walls for assessing their seismic behavior.

Whilst there are many scholars who have studied the behavior of framed glass facades against earthquakes using numerical approaches, standardized modeling strategies still lack for these building systems, and any modeling assumption could implicitly affect the simulation results. This section critically reports the numerical approaches employed for seismic response of framed glass facades, irrespective of which type of panel (LG and/or IGU) has been used in the analysis.

A numerical strategy to predict the seismic response of framed insulating glass facades was reported by [9, 22]. The ANSYS software was used for the FEA. The glass panel was modeled by using six degrees of freedom (DOFs) per node, based on four-node shell elements. Two-node beam elements were used to model the aluminum transoms and mullions, with two translational DOFs and one rotational DOF per node. The glass–frame interface was modeled by using two-node link elements, with three DOFs for each node.

However, intolerable discrepancies were observed between the experimental results and the presented numerical results. The comparative results in terms of maximum principal strain not only differed in magnitude but also in the mechanical behavior (i.e., compression and tension). For instance, the maximum principal strain at the top of the glass panel was found to be +0.0001258 (tension) from the experiment, while the numerical analysis resulted in −0.000039 (compression). Despite such a difference in the comparative results, the authors did not mention any reason to justify this scatter. This difference could indeed be associated with improper modeling assumptions of the numerical model. Additionally, the authors did not consider the importance of proper modeling of the connection components, given that the numerical study ignored the presence and mechanical contribution of the setting block. Moreover, during simulations, the rigid body movement of the system was also disregarded, and the researcher did not consider the friction offered by the gasket to the glass during the movement of the glass to the frame. However, the frictional resistance and local stiffness that the gaskets provide until the clearance between glass and frame is covered cannot be ignored.

On the other hand [23], presented a numerical simulation for similar purposes, and the authors took into consideration the behavior of connection components to predict the mechanical response of the glass panel against the imposed drifts. The FEA of the curtain wall panel was performed by using ANSYS. The side blocks and setting blocks were also modeled as four-node shell elements. Suitable link elements were used for defining the behavior of the aluminum frame, the friction effect of the gasket, and to simulate the connection between the metal frame and the glass panel. The monotonic in-plane drift was applied at the top of the mullion-transom connection. Boundaries for this panel were set as rigid for the bottom mullion-transom connection nodes ($U_x = 0$, $U_y = 0$, $U_z = 0$), while for top mullion-transom connection nodes, the in-plane displacement in the x-direction was kept free ($U_y = 0$, $U_z = 0$), see Figure 7.

The influencing factor in this study was the properties assigned to the Link elements used for the rubber gasket and the properties of Link 10 modeled for the connection between the glass and frame. The FEA results also confirmed that the seismic response of the facade highly depends upon the geometry and aspect ratio of the panel as well. For instance, for a glass panel with dimensions 1219 mm high × 2438 wide, the first and second contact between glass and frame occurred at a drift value of 20–25 and 30–35 mm, respectively. And when the panel was laid as a glass panel with a size of 2438 mm high × 1219 wide, the first and second contact between glass and frame occurred at a drift value of 40 and 80 mm, respectively. The difference between the results of the two geometrically different panels is clearly visible in Figure 8A,B.

The influencing factor in this study was the properties assigned to the Link elements used for the rubber gasket and the connection between the glass and frame. For instance, the model was checked by varying the modulus of elasticity (E) and stiffness (K) values. Starting from tentative values of E (691, 1000, and 2000 kPa) and K (50, 35, 25, and 14.6 kN/mm), the numerical and experimental results approximately matched at $E = 1000$ kPa and $K = 25$ kN/mm. Although the overall predictions were close to experimental results, about a 16%–20%

TABLE 1 | Summary of selected literature studies on metal-framed glass facades.

Facade size (m)	Glass panel	Software	Type of elements	Type of analysis	Materials	Experimental validation	Accuracy	Key parameters affecting results	Literature/ source
1.52 × 2.06	Monolithic	ANSYS	Shell, beam, link	Static	Linear elastic	No	Low	Friction and stiffness of the setting block and gasket, exclusion of rigid body movement	[9, 22]
2.438 × 1.219 1.524 × 1.829	Monolithic	ANSYS	Shell, beam, link	Static	Linear elastic	Yes	Excellent	Glass aspect ratio: Varying stiffness of gasket and contact link	[23]
2.96 × 2.2	Monolithic	SAP2000	Shell, link (gap, wen)	Static	Linear elastic	Yes	Low to moderate	The gap between frame and panel, rigid connections, ratio of relative displacement calculated using the model and analytical formula	[21]
5.641 × 7.291	LG	SAP2000	Shell, beam, link, rod	Static	Linear elastic	Yes	Excellent	Influence of the connection between panel and frame, gasket friction, transom and mullion connection (fixed/ hinged), interstorey height	[19]
5.38 × 7.8	L-IGU	SAP2000	Shell, beam, link, rod	Static and dynamic	Linear elastic	Yes	Excellent	Two moving beams in opposite directions, position of glass panels, boundary conditions, role of setting blocks	[13]
5.38 × 7.8	L-IGU	SAP2000	Shell, beam, link, rod	Static	Linear elastic	Yes	Good	Top and bottom beam fixed, middle beam moving	[24]
A (5.641 × 7.291) B (5.63 × 7.262)	L-IGU	ABAQUS	C3D8R brick, 1D link	Dynamic	Linear elastic	Yes	Good	Aspect ratio, refinement of software	[11]
5.6 × 7.2	L-IGU	ABAQUS	C3D8R brick, nonlinear link elements	Dynamic	Nonlinear	Yes	Excellent	Frame geometry: rotational stiffness of transom and mullion joint, gasket	[25]
10 × 12	L-IGU	ABAQUS	Shell, 1D beam, link	Dynamic	Linear elastic	No	Good	Multihazard analysis, vibration control analysis, cracking damage model consideration, elastoplastic dampers	[24, 26]
20 × 12, 10 × 12	L-IGU (indoor) and monolithic indoor	ABAQUS	Shell, beam elements, and connectors	Dynamic	Linear elastic	No	Good	Vibration control analysis, connector properties	[27]

(Continues)

TABLE 1 | (Continued)

Facade size (m)	Glass panel	Software	Type of elements	Type of analysis	Materials	Experimental validation	Accuracy	Key parameters affecting results	Literature/source
2.69 × 3.4	IGU	ABAQUS and SAP2000	C3D8R brick, 1D beam, shell, link (gap, wen)	Dynamic	Linear elastic	Yes (to some extent)	Good	Boundary conditions, position of the moving beam, type of software	[1, 28]
1.524 × 1.829	Monolithic	ABAQUS	C3D8R brick, shell	Static and dynamic	Linear elastic	Yes	Good	Position of setting and side blocks, modeling of frame components, global and local mesh size	[29]
5.07 × 3.5	IGU	ABAQUS	C3D8R brick, connectors	Static and dynamic	Linear elastic/elastoplastic	Yes	Good	Bidirectional load, coupled loads, mesh size, connection properties	[30]
5.38 × 7.8	IGU	ABAQUS	Shell, 1D beam, connectors	Dynamic	Linear elastic	Yes (to some extent)	Good	Position of the moving beam, properties of connectors, boundary conditions	[4]

Abbreviations: 1D, one-dimensional, IGU, insulated glass unit, LG, laminated glass, L-IGU, laminated-insulating glass unit.

discrepancy was found, and a scatter above 10% can be questionable. It is evident from the research conducted by [21], where SAP2000 software was used for analyzing the interstory drift of an LG panel supported by a frame. When the possible movement of frame supports was considered in modeling, about 15% of error was observed between the comparative results. Thus, the supports were considered perfectly rigid to get approximately closer comparisons. Additionally, the transom-mullion connection was considered rigid. However, such an assumption raises the question of whether this behavior actually matches the real phenomenon or not.

To assess the importance of proper modeling of gasket and connection behavior for the seismic response of the facade, a study was conducted by [19] on the LG facade. The authors used SAP2000 software and modeled transoms and mullions using "beam" elements. To this aim, the cross-section of transoms and mullions was modeled with equivalent inertial features to reproduce their real properties, while shell elements were used for the glass panels (with a monolithic thickness equal to the sum of all layers). To conduct a nonlinear pushover analysis, a lateral force was applied to the mullion, and the schematic approach shown in Figure 9A was employed for the analysis. Similar to other studies, the analysis took into account the interaction between glass, frame, gaskets, and other components. The analysis was performed on two different facades (A and B types) with different stiffness values for the gaskets and connection behavior. In facade A, a fixed connection was considered between mullions and transoms, while in scheme B, the connection was assumed to be hinged. Most importantly, the gasket-to-glass friction contribution was taken into account. The scatter between numerical and experimental results was found to be about 5%–10% in both cases.

Although the numerical and experimental results were in good agreement, the two facades behaved differently in terms of gasket and frame response (see Figure 10). The frame of facade A was found to be much stiffer than that of facade B. This might be due to a change in thickness, cross-sections, and stiffness properties assigned to connections in the two facades. Especially, the gasket in facade B added more initial stiffness and strength than the gasket in facade A because in facade B, the gasket was provided along the whole edge in and out, unlike facade A, where the gasket was provided on the inner glass layer only. This study again emphasized the importance of the gasket and the correct modeling of the gasket and connection behaviors that highly affected the overall final result of the analysis. Although the researcher checked the seismic response of facades with different properties of connection components and connection behavior, the comparison between the two facades could have been better if the transom-mullion connection had the same behavior, either hinged or fixed, to correctly judge the impact of the gasket on the final load-drift results. Additionally, the setting block was not modeled. The setting block contributes to the initial stiffness and direct load transfer even before the gasket, and a better match has been obtained by modeling this element.

The same strategy was originally used by [13] for the analysis of insulating double-glazing units with LG panes having 0.38 mm PVB, and the authors also took setting blocks into account using a zero-gap element value. A refined meshing size was imposed on the model components to get accurate results. The schematic approach shown in Figure 9B was used for the analysis. It is important to observe that a previous study conducted by [19]

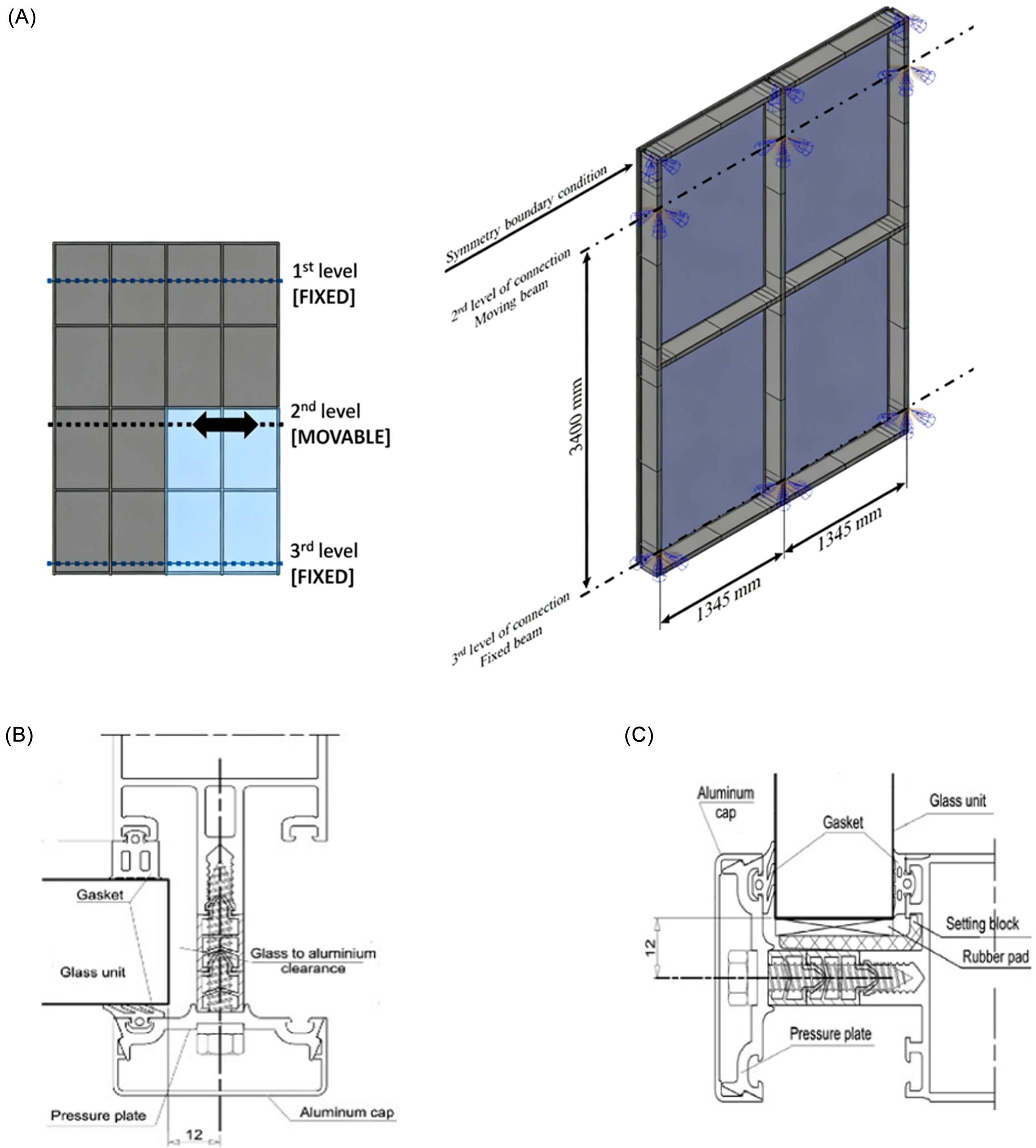

FIGURE 6 | Example of (A) refined numerical modeling of a framed glass facade, with (B) glass-to-mullion and (C) glass-to-transom details (cross-sections with dimensions in mm). (A) Reproduced from [7] under terms of the CC BY 4.0 license, and (B, C) reproduced from [4, 13] with permission from Elsevier©, license number 6110680457389 (September 2025).

compared two facades using a transom-mullion hinge and a fixed connection, respectively. In that case, the hinge connection was found to be more suitable and realistic. The model was, in fact, found to be able to get approximately equal experimental and numerical results. However, this research did not take into account the postbreakage behavior of the glass panel (an indefinitely linear elastic mechanical model), and thus, a similar modeling approach can be useful only until the first cracks occur [34].

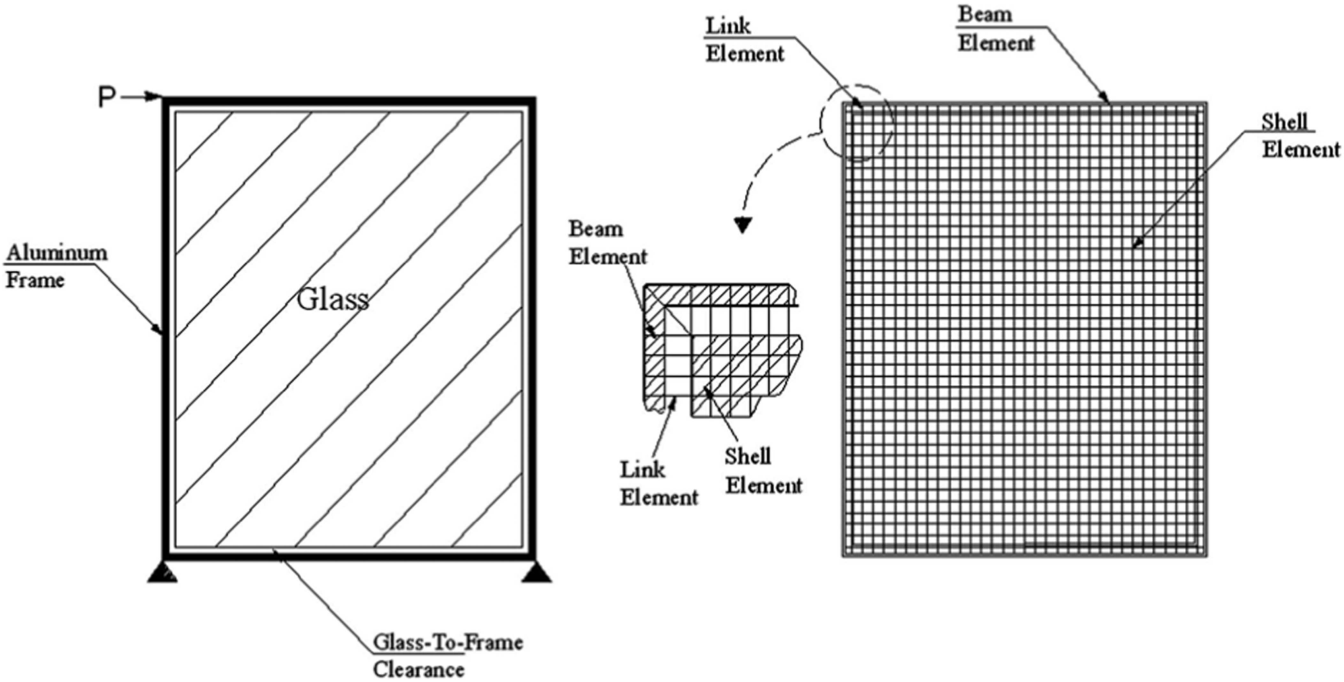

FIGURE 7 | General view and assembly details for the finite element analysis of a glass panel extracted from a curtain wall. Figure reproduced from [23] with permission from ASCE©, license number 1651978 (September 2025).

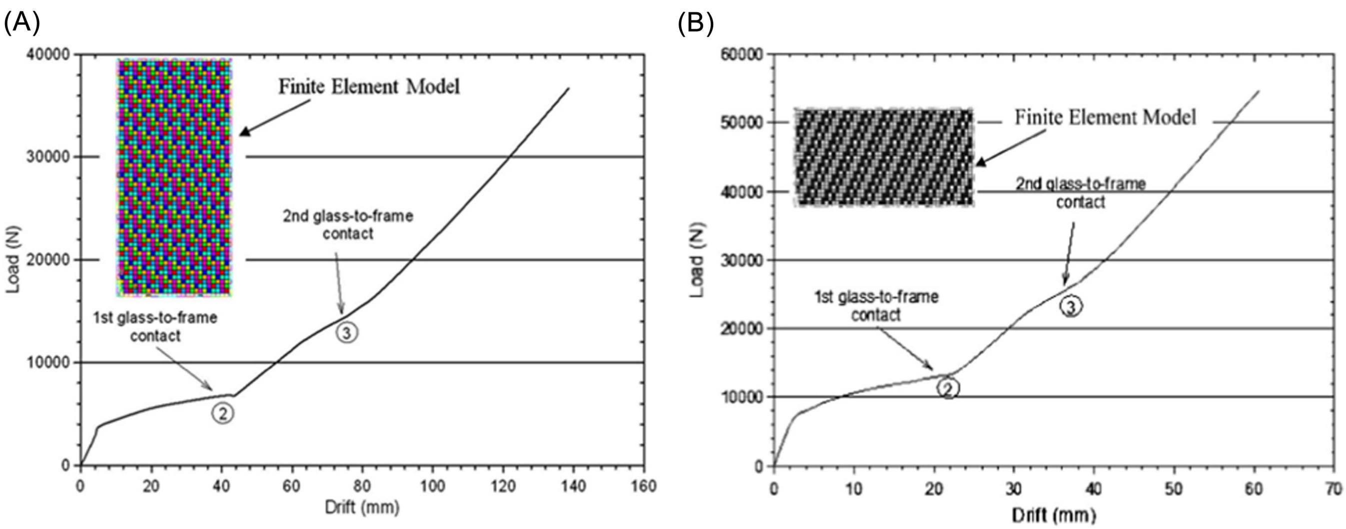

FIGURE 8 | Force-to-drift graph obtained from the finite element analysis of glass facade panels with different aspect ratios: (A) 2:1, and (B) 1:2. Figures reproduced from [23] with permission from ASCE©, license number 1651978 (September 2025).

At the same time, the modeling lacked precision to get an accurate local behavior of the glass panel. Although the experimental work showed glass breakage at the bottom left corner due to local concentration of shear and normal stresses, this mechanism was not perfectly interpreted in the FE model. Nevertheless, the model identified the region of maximum principal stress where glass breakage occurs. Additionally, the study in [13] found for such a modeling simulation that the numerical models and the experimental results had a good match until ± 50 mm, whilst the FE results were not reliable for larger displacements (see Figure 11). The same simulation strategy was also followed by [33], but without considering the setting blocks, which indeed offer a resistance support to prevent the possible risk of premature glass cracking.

Nevertheless, to detect the local behavior, the interactions between different frame parameters and their effects on the overall facade response should be properly considered. For this purpose, a numerical simulation was performed by [11] using ABAQUS to simulate the seismic behavior of monolithic glass panels of typical use in curtain walls. Like in the previously cited studies, researchers focused on the rotational stiffness of the transom-mullion connection, clearance between glass and frame, gasket behavior, and glass-to-frame interaction. The analysis was performed by considering both material and geometrical non-linearities, and C3D8R (eight-node linear brick) type elements were used for glass, transoms, mullions, and so forth. The schematic approach shown in Figure 9A was followed. The numerical

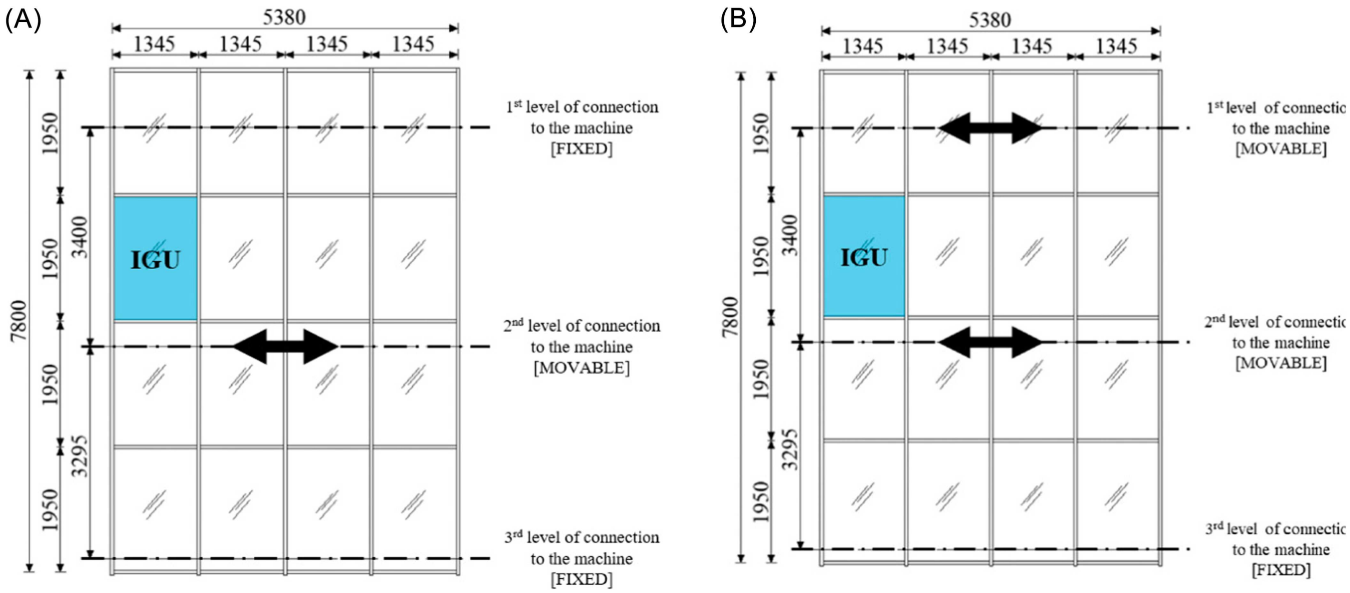

FIGURE 9 | Experimental setup for the experimental in-plane seismic response assessment of glass facades according to [4, 19, 33], and reproduced in [7] for numerical simulations: (A) quasi-static cyclic, and (B) crescendo dynamic tests. Figures reproduced by [7] under the terms of the CC BY 4.0 license. IGU, Insulated Glass Unit.

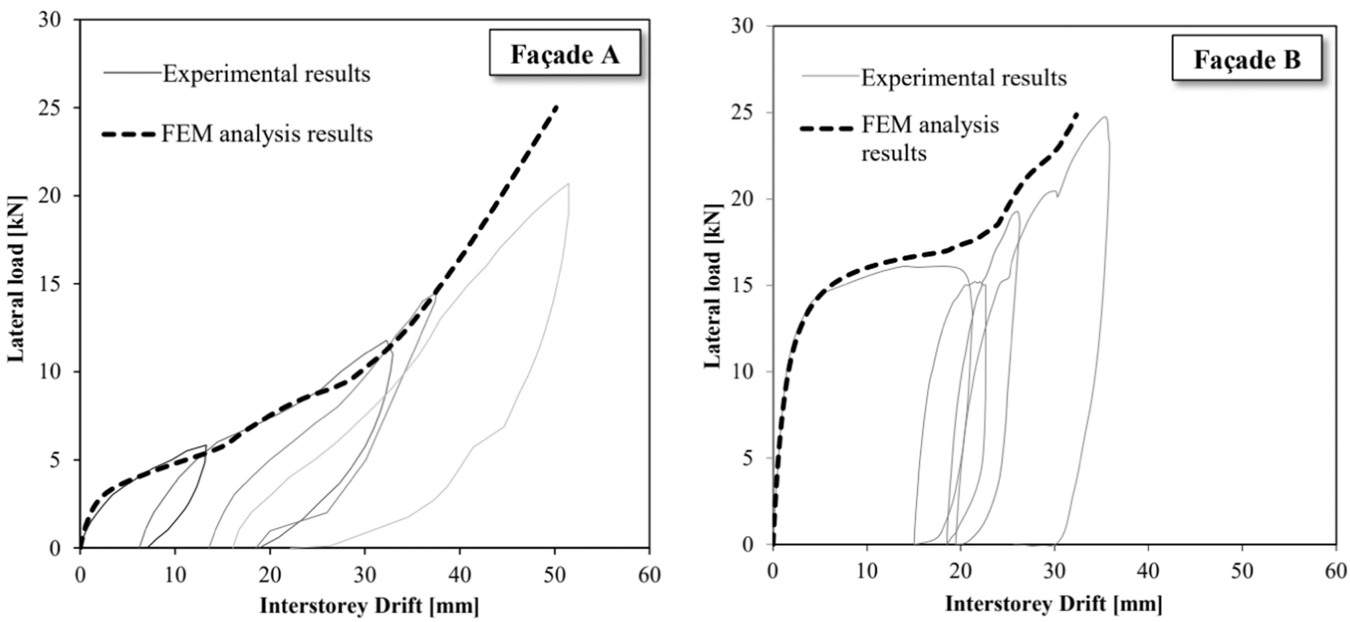

FIGURE 10 | Comparison of experimental and numerical results from the study carried out by Caterino et al. [11, 19]. Figures reproduced from [11] with permission from Elsevier©, license number 6198230368250 (January 2026). FEM, finite element method.

predictions were found to be more in line with the experimental results, and the model also depicted the local behavior of the facade. However, the authors did not mention anything about the setting blocks, and a question also arises whether the modeling of the setting blocks is important or not, for the presented results. Although the minimum number of elements, the minimum will be the computational cost, but inclusion of the setting block in modeling should not be ignored, particularly when the local response of the facade is also important.

A study to predict the seismic behavior of an IGU was also conducted by [24, 26]. The authors modeled the glass panel (with an interposed cavity) as an equivalent monolithic shell, while the frame was modeled by using 1D elements with a box cross-section in ABAQUS. Mechanical joints (connectors) were used to simulate the glass-and-frame connection and the glass-to-gasket connection. The important thing worth noting was that the authors mentioned the behavior of connectors such as "Cartesian + rotation" to simulate glass-to-frame connections. Although the setting block was not modeled, the study indicated that assigning the proper behavior to connectors in ABAQUS (or equivalent link elements in SAP) is the key aspect of getting a true seismic response of similar glass facades.

Accordingly [28], assessed the seismic behavior of glass facades using ABAQUS and SAP software packages. A special

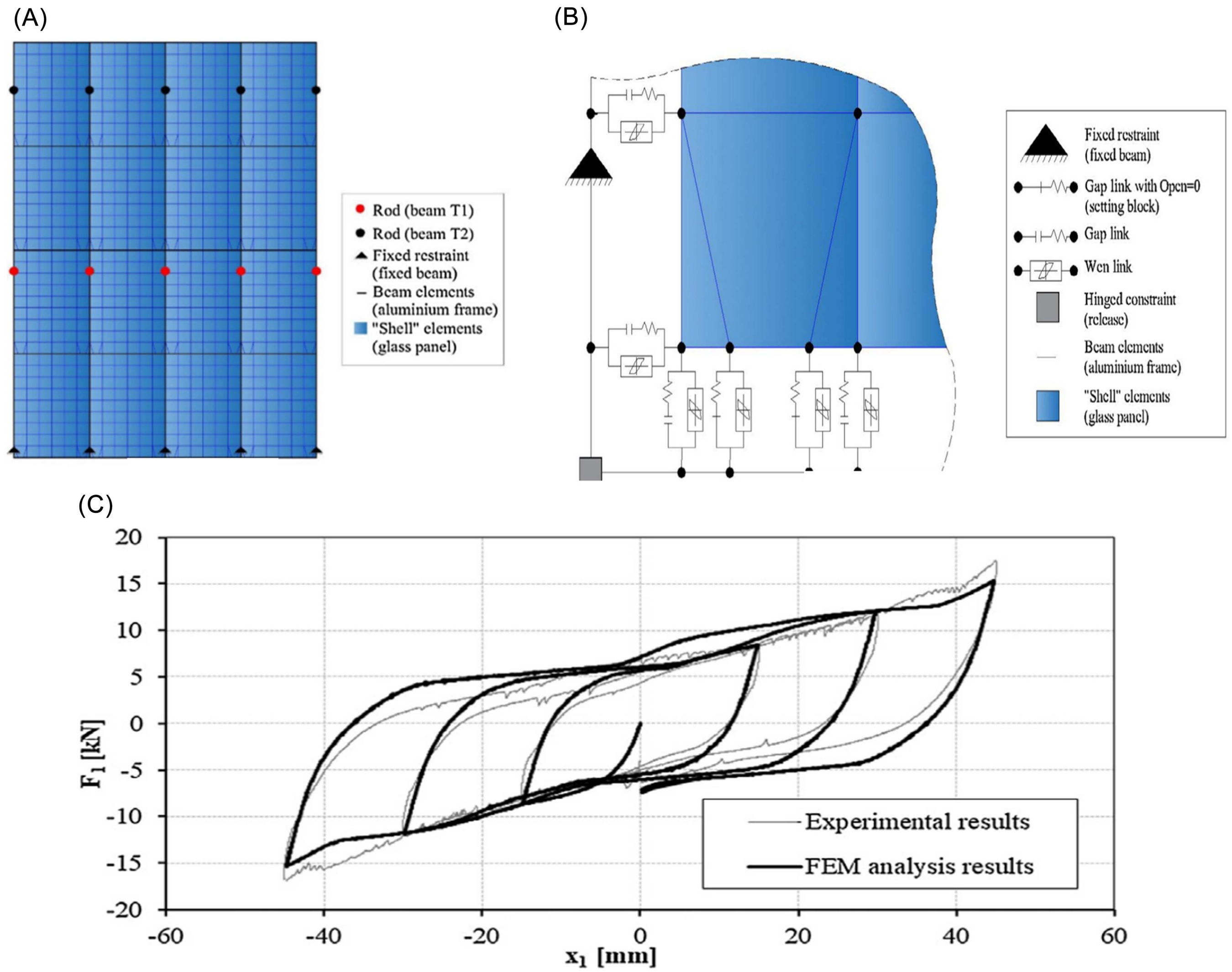

FIGURE 11 | Numerical strategy employed in [13] using SAP2000: (A, B) model features, and (C) comparison of experimental and numerical results. Figures reproduced from [13] with permission from Elsevier©, license number 6110680457389 (September 2025). FEM, finite element method.

importance was given to modeling the facade components, such as accurate reproduction of IGU, frame details (gasket, setting block, transom, mullion), pressure plates, and so forth, and their mechanical interactions when subjected to in-plane seismic loads. While using ABAQUS, the authors selected a static general step followed by a dynamic implicit solution rather than an explicit solution. Dynamic implicit might have been selected by the authors to avoid possible computational errors and high computational costs. Only one-fourth of the whole facade was considered, and the facade was subjected to in-plane displacement at the top nodes of connection. While using ABAQUS, the C3D8R-type elements were used for the glass panel and frame elements. The surface-to-surface contacts with penalty and hard contact options were introduced along all relevant interfaces. However, the study did not explicitly explain how the behavior of the gasket-to-glass contact, frame-to-glass connection, and setting block was simulated. When using SAP2000, the authors followed strategies set by [13] and shell elements were used for the glass panel, and link elements for frame components.

This study revealed that the results obtained from the ABAQUS had a good match with experimental results throughout the load–displacement curve, except at the final stiffness value (40 mm), see Figure 12. However, the SAP2000 simulation underestimated stiffness and strength, particularly in the range between 5 and 30 mm. The study showed that a better match in results can be obtained while using ABAQUS than SAP2000; however, this cannot be concluded on the basis of a single comparison. Additionally, these underestimated and overestimated results show why the proper modeling of facade components and their interaction is important. Also, the refinements in mesh size and properties of frame components also affect the final results, and thus, sensitivity analysis can make results more reliable if all elements are properly modeled.

A similar pattern was also followed by [1], and unexpected discrepancies were found in results obtained from the analysis using the SAP2000 and ABAQUS software packages, particularly the difference of results in the rotation and displacement curves (see Figure 13). However, the most important part of this study was a sensitivity analysis that was conducted to check the difference in facade response with changing: coefficient of friction between glass and gaskets; in-plane lateral stiffness of the aluminum frame, the clearance between frame and glass,

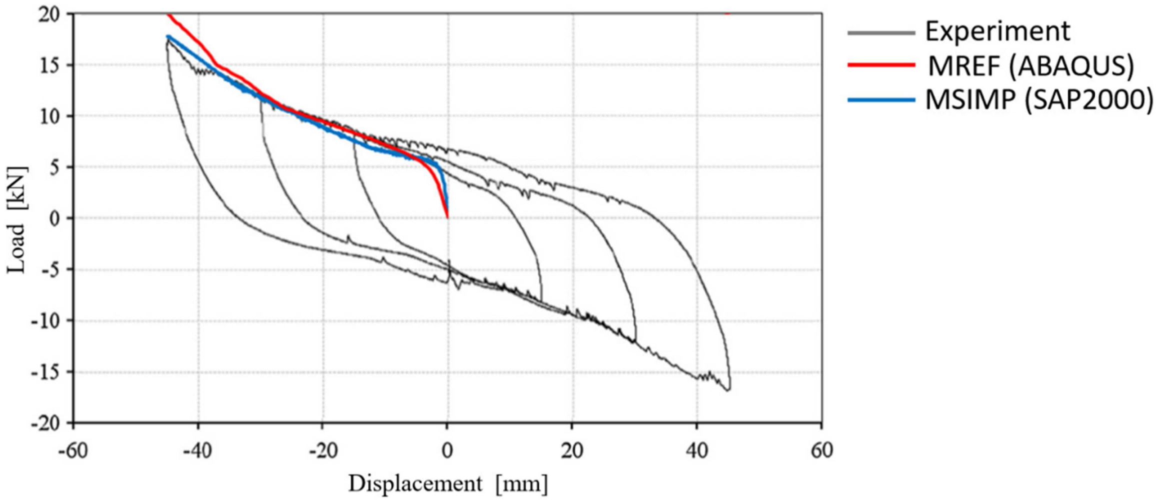

FIGURE 12 | Comparison of experimental and numerical results from the study presented in [28]. Figure reproduced from [28] under terms of the CC BY 4.0 license.

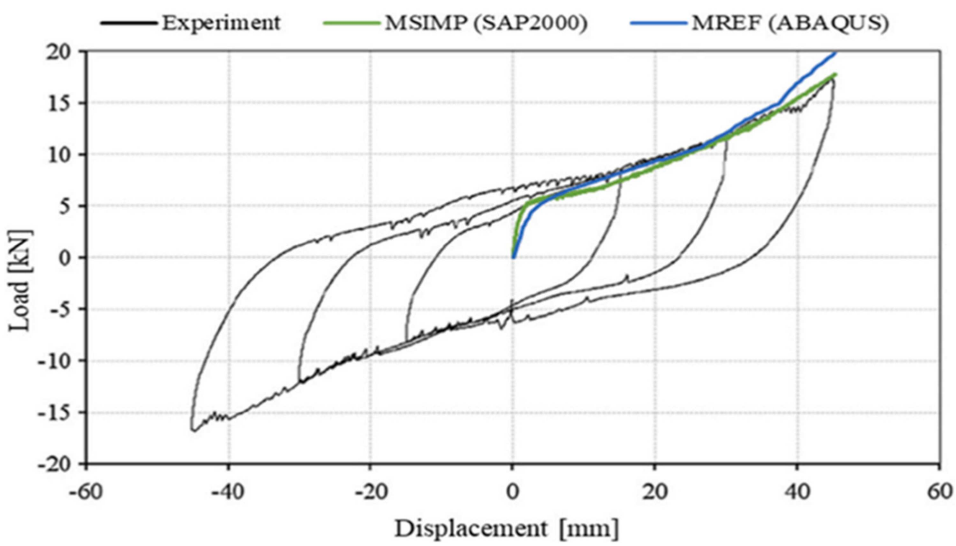

FIGURE 13 | Comparison of experimental and different numerical results (using SAP200 and ABAQUS models) in the study presented in [1]. Figure reproduced from [1] under the terms of the CC BY 4.0 license.

and stiffness of the setting block. The results revealed that the response of the facade is extremely influenced by the frame in-plane lateral stiffness, glass-to-frame clearance, and setting block stiffness. For instance, when the stiffness of the setting block changed from 2 to 50 MPa, the load resistance capacity of the facade increased by 29%. Similarly, when the clearance between glass and frame was reduced from 6 to 4 mm, results indicated the glass would touch the frame at a 26% smaller displacement than at 6 mm, and when the clearance between glass and frame was increased from 6 to 8 mm results indicated the glass would touch the frame at a 23% more displacement than at 6 mm. This meant that for the facade in the first case, glass quickly gained an increase in stiffness compared with the glass in the second case. This study also identified the importance of the properties of various frame components that impact glass behavior under seismic actions. Second, the results of this study also showed that the accuracy of the results was not highly influenced by the simulation tool, but by the proper modeling of facade components. For instance, the maximum concentration of principal stress in the glass panel obtained by [1] using ABAQUS was found at the same region (right top and left bottom corners), as reported by [13].

Most of the above-mentioned research focused on the in-plane seismic response of glass facades. However, studies like [30] also assessed the out-of-plane seismic response of the facade using the same strategy of [29] and many others. The glass panels, transoms, mullions, setting blocks, gaskets, and connecting plates were modeled in ABAQUS using C3D8R elements, and pressure loads were applied on the connecting plates to simulate the local effect of bolts. Certainly, such a strategy consumes more computational time than the modeling of frame components as a connector or 1D beam elements. To avoid a further increase in computational time, the authors used connector elements to simulate the semi-rigid relation of transom-mullion connections. The rubber and steel components were modeled as elastic materials, while the aluminum frame was modeled as an elastic–plastic material. Unlike other

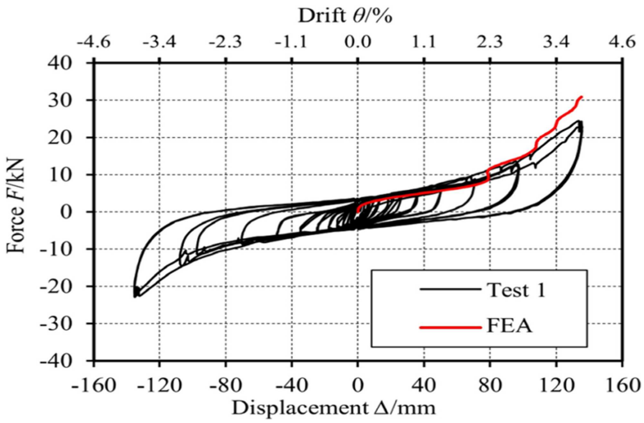

FIGURE 14 | Validation of experimental and numerical results in the study in [30]. Figure reproduced from [30] with permission from John Wiley and Sons©, license number 6174110289274 (December 2025). FEA, finite element analysis.

research, the tie constraints were used between different interfaces. A local meshing refinement strategy was implemented, and the setting blocks were reduced to a 2-mm meshing size, while the mesh size at the diagonal corners of the panel was kept at 25 mm, that is, half of the maximum meshing size for the glass panel (50 mm). The diagonal corners of the glass panel were assigned a finer mesh size because the higher stress concentration was expected to occur there. Boundary conditions like [23] were applied to connections. The results revealed a good match between the force–displacement experimental and numerical results (see Figure 14); however, a similar trend was observed as reported by [28] for the last step. Additionally, results contradicted the experimental and analytical approach and showed that the first glass-to-frame contact happened at the top right corner, followed by the bottom left corner. Contrary to experimental results where 3 out of 20 glass panels got damaged at a 3.9% drift ratio, the numerical results showed no glass panel yielded to the maximum principal stress exceeding the tensile strength of glass. Such errors are expected because prior microcracks in panels are not considered in modeling. Moreover, the top and bottom glass panels in the facade did not show the same behavior in terms of principal stress; this might be because not the same connection properties were assigned to the top and bottom transom-mullion connection nodes. Despite all such possible errors, the FEA using this strategy can also be a useful tool for predicting the approximate seismic response of the glass facade.

The study in [4] proposed a detailed strategy for the seismic response analysis of glass facade, with an effort to get better results with minimum computational cost. In studying the behavior of Gasket, setting block, interactions between glass and frame, and the transom-mullion connection was simulated by using different connectors, that is, Axial connectors were used for the setting blocks, hinge connectors for the transom-mullion connection, and "Cartesian" connectors for the interaction between the glass and the gasket, as well as for the interaction between the glass and the frames. However, the selection of the Cartesian connector for simulating interaction between glass and gasket, and also for interaction between glass and frames, contradicts the simulation approach reported in [24, 26], where "Cartesian + rotation" joints were selected, and their relative rotations were restrained. In this case, researchers allowed the rotation between two nodes, but it was unclear whether the rotation was free until the glass corner touched the frame or was totally free throughout the analysis. A displacement-controlled scheme as used by [19] was employed, and a static general step followed by a dynamic implicit step was applied using ABAQUS. The results showed discrepancies, particularly a high difference in terms of the cyclic–force–displacement curve. The mean scatter between the comparative results was found to be about 12%. However, for the last cyclic load, the scatter was equal to 36%, and thus beyond the tolerable range.

Overall, the literature found that the accuracy of the numerical model depends upon the pattern in which force or displacement is applied, the selection of simulation elements, like, 3D, 2D, or 1D, and most importantly, the connection components (such as gaskets, setting blocks, etc.) involved in modeling.

3.4 | Seismic Analysis of Timber-Framed Glass Facades

One of the innovative approaches to sustainable solutions in the construction industry is the introduction of timber frames in facades. This approach not only serves esthetic purposes but also exhibits improved mechanical properties against various loads, including seismic forces. Figure 15 presents some examples of glazing details of a timber-framed glass facade and its connection system. According to [36], Cross-Laminated Timber–glass facades demonstrated better response against earthquakes.

Furthermore, many researchers, such as [37, 38], have also found that glass timber frames successfully receive loads from glass panels and can mechanically behave similarly to a traditional metal frame system. Additional examples are discussed in [35, 39]. Therefore, the seismic response of timber-type frames has been evaluated numerically and experimentally to further optimize the concept and ensure the structural safety of such facades. However, also in this case, numerical results highly depend upon proper modeling of the timber frame and its connection with the glass components.

Unlike a metal frame, timber is an orthotropic material and modeling needs properties in each direction, which is why timber simulation requires proper attention; otherwise, results can be inaccurate.

This review document drew attention to the literature works recalled in Table 2.

For instance, a study was conducted by [35] in which the seismic response of the timber-framed glass panel was also modeled using ABAQUS; however, the authors did not find correct results due to an improper strategy of modeling the framed glass panel. Most of the researchers (including [36, 39]) modeled the glass panel as 3D solid elements; other accessories, like, purlins, bolts, and so forth, have also been modeled as solid 3D elements.

The nonlinear FEA for the in-plane loading was conducted in [39], where solid elements were used for glass and timber members, and adhesives were modeled by using HYPER86 (eight-node solid) elements. The interaction between glass and timber members was represented by surface-to-surface

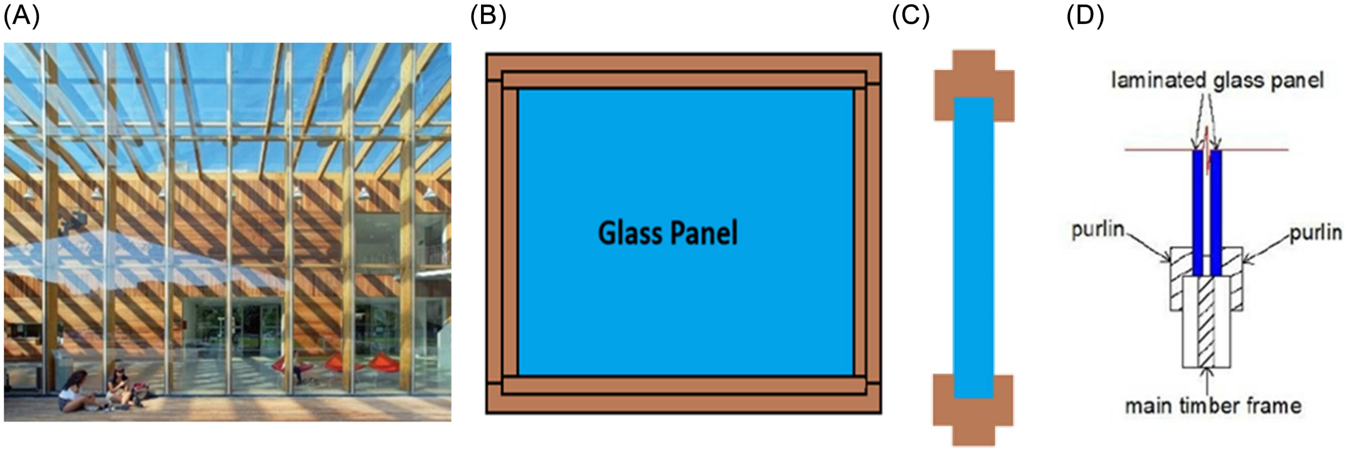

FIGURE 15 | Examples of (A) timber-framed glass facade, and (B–D) glass-to-timber connection. Figure (A) reproduced from [35] under terms of the CC BY-SA 4.0 license. The authors own the copyright of figures (B)–(D).

nonlinear contact elements, and meshing was calibrated until results came closer to experimental results. Both the numerical and experimental results were in good agreement. This study also identified the importance of the adhesive layer used between the glass panel and timber members, and the position of the glass in the frame. It was observed that the closer the glass is to the midplane of the frame, the more even the stress distribution is.

The shaking table and cyclic loading analysis of a timber-framed glass structure were conducted by [40], in which IGU was modeled as a shell, and the Timber frame was reproduced using solid 3D tetrahedral elements in SolidWorks software. Two models were assessed for analyzing the seismic response: a single IGU as a one piece, and another model with the same dimensions, but with two IGU panels separated by a stud between them. To reduce computational cost, the connection between frame and glass was modeled using linear springs; similarly, the axial connectors were used by [45] for adhesion layers. The top timber purlins were assigned roller support properties, while the bottom purlins were kept fixed. The study declared that the mathematical modeling showed good agreement between experimental and numerical results for the single panel, while for the double panel assembly, the results showed discrepancies. Contrary to this study, another numerical analysis was carried out by [42] on the double skin glass facade in which the timber members were modeled using a 1D beam element rather than a 3D solid element, glass as a shell composite, and adhesive glazing as spring link elements. Additionally, even though the timber is an anisotropic material, it was considered as an isotropic material, and the average value of the modulus of elasticity was assigned to it. The racking performance of the facades was evaluated, and the results were obtained. The study showed that the racking performance of the facade changed with the dimensions of the adhesive layer. Furthermore, the researchers found that although this adhesive layer had been modeled as a link element in SAP2000, this increased the computational cost of the simulation.

Similarly, Šilih and Premrov [43] also used SAP2000 software to model timber members as isotropic 1D beam elements, and the IGU for the double skin facades was modeled as a composite shell element that allowed multilayered simulation of the IGU. In addition, the adhesive bonding layers and bolts were also reproduced using linear link elements. Only 6% difference in the experimental and numerical results was observed (see Figure 16) for the load–displacement curve and racking value, but the researcher did not provide details about the computational cost of the analyses. A similar pattern was followed by [44].

Although some researchers identified a good response of the timber frame against seismic forces, more work is required to be carried out on this frame, particularly including the whole facade rather than on panels.

3.5 | Seismic Analysis of PFGFs

The PFGF solution (see Figure 17) has become more popular due to its esthetic appearance and transparency. Nevertheless, when compared with a framed facade system, PFGFs are more vulnerable to drifts. Therefore, when checking building safety against earthquakes, it should be ensured that the building's drift demand does not exceed the maximum in-plane capacity of the facade. It is important to note that in PFGFS, a polymer material is provided between the glass panel and steel bolt to avoid a direct connection between the glass and bolt and maintain uniform distribution of tensile stresses around holes. The clearance between the bolt and glass edges also highly affects the overall seismic response of the glass facade. Additionally, the seismic behavior of PFGF is highly influenced by the type of spider arm and diameter of the glass hole and bolt (whether circular or slotted). Thus, the behavior of polymer material, clearance provided between glass panel and steel bolt, type of spider, and the diameter of bolt, cannot be ignored in numerical modeling as well.

Like framed glass facades, the seismic response of PFGFs for a long time had been evaluated through experimental and analytical approaches only. However, numerical approaches have also gained more popularity in the last 10–15 years. In parallel, numerical approaches also have gained fame for the analysis of PFGFs against thermal [47], seismic, and other forces. For instance [46], conducted a study using all three approaches (experimental, analytical, and numerical) and assessed the in-plane load response of PFGFs, specifically focusing on the stress concentration near the holes. MSC Visual Nastran (an older, Windows-based version of the MSC Nastran FEA software) was

TABLE 2 | Summary of selected literature studies on timber-framed glass facades.

Facade size	Glass panel	Software	Type of elements	Type of analysis	Materials	Experimental validation	Accuracy	Key parameters affecting results	Literature/source
3.222 × 2.72	LG	ABAQUS	C3D8I	Dynamic	Linear elastic	No	Inaccurate	Improper modeling of frame connections	[35]
2.11 × 2.03	Monolithic	ANSYS	CONTA174, HYPER86, SOLID95	Static	Linear elastic	Yes	Good	Monotonic in-plane loading, quasi-static cyclic loads, types of adhesives, mesh analysis	[39]
2.11 × 2.03	IGU	Solidwork	3D solids, shell, Springs	Both	Linear elastic	Yes (to some extent)	Very low	Boundary conditions, size of glass panel, type of adhesive	[40]
2.4 × 2.4	IGU	SAP2000	Shell, 1D beam, Springs	Both	Linear elastic	Yes	Good	Double skin façade (DSF), bonding between panel and frame, assumption of façade as load-bearing element	[41, 42]
1.25 × 2.34	DSF	SAP2000	Shell, 1D beam, Springs	Static	Linear elastic	Yes	Good	DSF, type of bonding, adhesive thickness	[43, 44]

Abbreviations: 1D, one-dimensional; IGU, insulated glass unit; LG, laminated glass.

used for numerical simulations. The researcher obtained results closer to analytical and experimental ones and concluded that the numerical model must be verified step by step. PLATE 64 (finer mesh) elements should be used rather than PLATE 32 in the circumference of the holes; and 3D SOLID elements should be used rather than 2D elements.

This document drew attention to the literature works recalled in Table 3.

The seismic response of PFGFs was presented in [48–50] using ANSYS software. The analysis incorporated the bending and axial effects from the countersunk bolts. However, the bolt head and hole in glass were considered to have uniform diameters instead of a countersunk bolt head. Shell-type elements were assumed for the glass panel and the bolt head. The hole in the glass panel was also assumed to be cylindrical with the same diameter. Different types of springs were used to model the spider arm, support structure, and connection between two elements (see Figure 18A). The nonlinear springs were used to model the behavior of the spider arm to rotate when interacting with the internal frictional force at the structural support connections. The Silicon-sealant was also modeled by using the Blatz-Ko formulation, a material model specified in the ANSYS [58]. The BEAM3 element types were used to model the shank of the bolt fittings. Spider arm was modeled as linear elastic to avoid complexities.

According to Figure 18, spiders and structural supports were connected using three COMBIN39 nonlinear spring elements, where springs in x and y were modeled using a load–displacement curve, and the spring in z was kept rigid to restrict out-of-plane movements. Keeping the geometrical nonlinearity into consideration, a 60-mm displacement was applied at the top of the structural frame with restraining support frame and spider arm in the x-, y-, and z-directions, and restraining rotation of bolt and spider arm about x and y at the spider arm bases (see Figure 18B). The experimental and numerical results were found in good agreement, see Figure 19A. From the analysis results, the bending stresses developed in out-of-plane were observed as the key factor for the glass failure, and such stresses were extremely influenced by the properties of the spider arm. The same modeling pattern was followed by [51, 10], for results see Figure 19B.

The seismic behavior of PFGFs was assessed by [52] using the ABAQUS software. Different LG panels (a few of which had a composition of 10 + 1.52 + 8, and some with 12 + 1.52 + 12 sections) were used in the study, with different types of interlayers (PVB and SentryGlas). The LG section was modeled by using 3D eight-node elements. The global mesh size for the glass panel was kept at 20 mm, while near the glass holes, it was reduced to 10 mm. The researcher did not define the exact boundary conditions, and these were selected using a hit-and-trial rule until the results represented the actual support condition. The beam elements were used to connect the panel to the support. Although the authors concluded the results were in good agreement with analytical results, they did not show the comparison between the two results to identify the discrepancies. Additionally, meshing near holes does not look like it was properly done, and such a meshing shape does not provide accurate results and causes convergence problems as well.

The study reported in [53] analyzed the in-plane behavior of bonded and bolted LG panels. The top of the LG panel was subjected to the distributed load of 8 kPa. The facade was subjected to

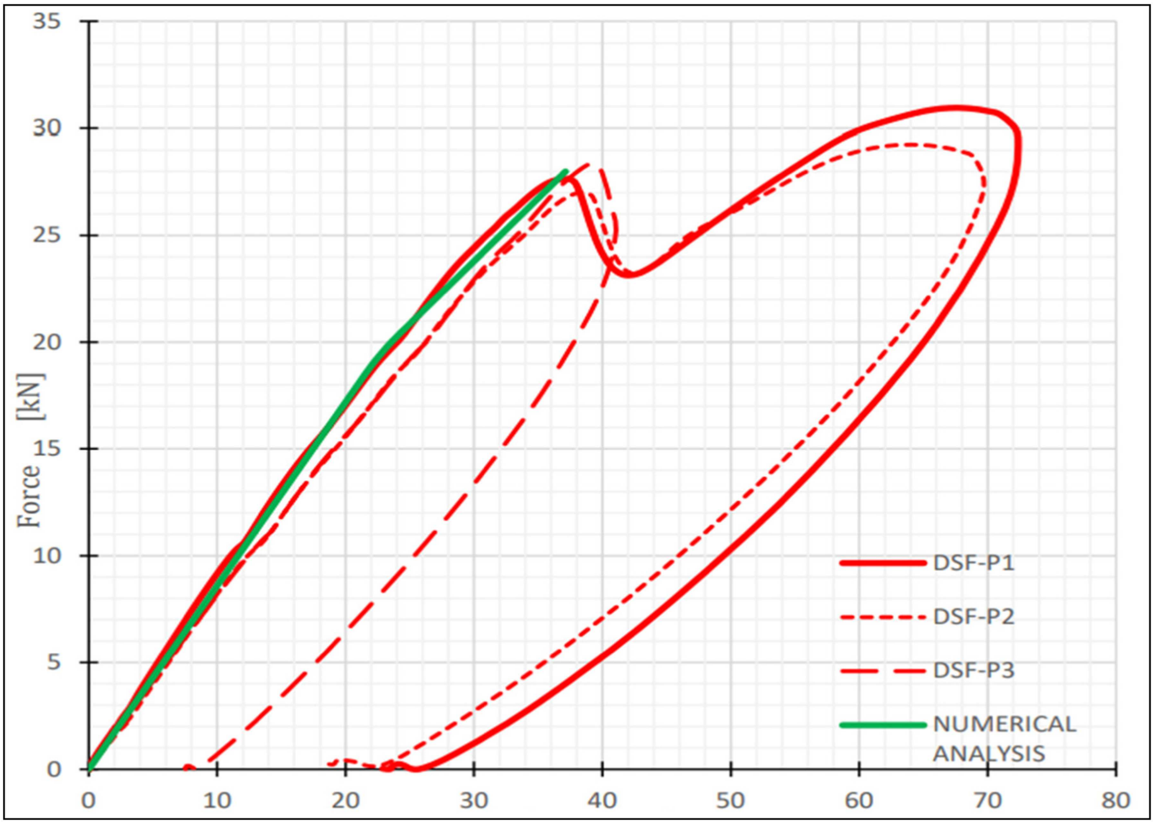

FIGURE 16 | Validation of experimental and numerical results from the study in [43]. Figure reproduced from [43] under terms of the CC BY 4.0 license. DSF, double skin façade.

in-plane and out-of-plane displacement. The C3D8R elements were used for the glass panel and bolts. However, this article did not provide an explicit detail of the analysis and whether the results accurately matched the experiment or differed by a certain percentage. Similarly, the behavior of bolted-type LG panels was analyzed by [12] for seismic loads. The C3D8R elements were used to model glass, interlayer, steel shaft, and bolt head. The interaction properties for bonding the interlayer and glass were done using surface-to-surface interaction, and for allowing the bolt's head to have rotation capacity when interacting with glass, a two-node linear beam element was used with MPC constraints. Maximum mesh size was selected as 20 mm, with two elements per layer thickness of the layers. Following the experimental setup, the shaft was considered to have a fixed boundary condition at its outer faces. It was a comparative study between dissipative (with clearance) and nondissipative (fixed) spider arms, and the main aim of the study was to investigate the seismic response of the bolted (countersunk) LG panels subjected to quasi-static lateral loads. Although the bolt head and shaft were modeled as solid elements, to assign clearance behavior of dissipative spider arms, connectors were used between the shaft and the bolt's head. The results identified lesser stresses near holes while using dissipative spider arms than vice versa. The important part of modeling for getting true results was the proper selection of connectors and properties assigned to them. Although the authors did not define which type of connectors were employed, Cartesian connectors seem more reasonable for modeling the behavior of dissipative and nondissipative spider arms.

The researchers in [54] also conducted a comparative study on the traditional connection holes to innovative (slotted) connection holes using SAP and ABAQUS software packages. ABAQUS was used for analyzing the frictional behavior of different elements, while SAP200 was used for analyzing the seismic response of the overall facade. The panel size was considered 2 m × 3.8 m, with 12-mm-thick toughened glass. A 2D nonlinear modeling was done for experimental works using linear shell elements for glass (elastic material) and multilinear link elements for silicon sealant (elastic–plastic material). To cut computation cost, the multilinear elastic link elements were used in SAP2000 to replace nonlinear shell elements in ABAQUS. The countersunk type bolts and bolt fixings were adopted and modeled using shell elements. The bolt shank was modeled using frame elements, and nonlinear link elements were used for modeling the interaction between bolted fixing and the spider arm. The static pushover analysis was performed using the force-displacement curve of the PFGFs. Although the results of the overall facade with an innovative solution showed improvement in the interstorey drift ratio of the facade, this simulation was only recommended for a similar type of facade having the same dimensions, because facade response depends upon panel dimensions and aspect ratio. A similar type of simulation strategy was followed by [14] with the same panel size and aspect ratio.

The numerical simulation approach was also performed by [3] for the PFGFs. The glass panel, shaft, nylon rubber, and bolt were modeled using C3D8R elements. All materials (glass, EVASAFE, and steel) were described as linear elastic materials. The tie constraints were used between interlayer and glass, Nylon cap (used between glass and bolt), and glass, while MPC beam type contact was used for the interaction between beam and bolt's head, and shaft end to beam (see Figure 20). All the

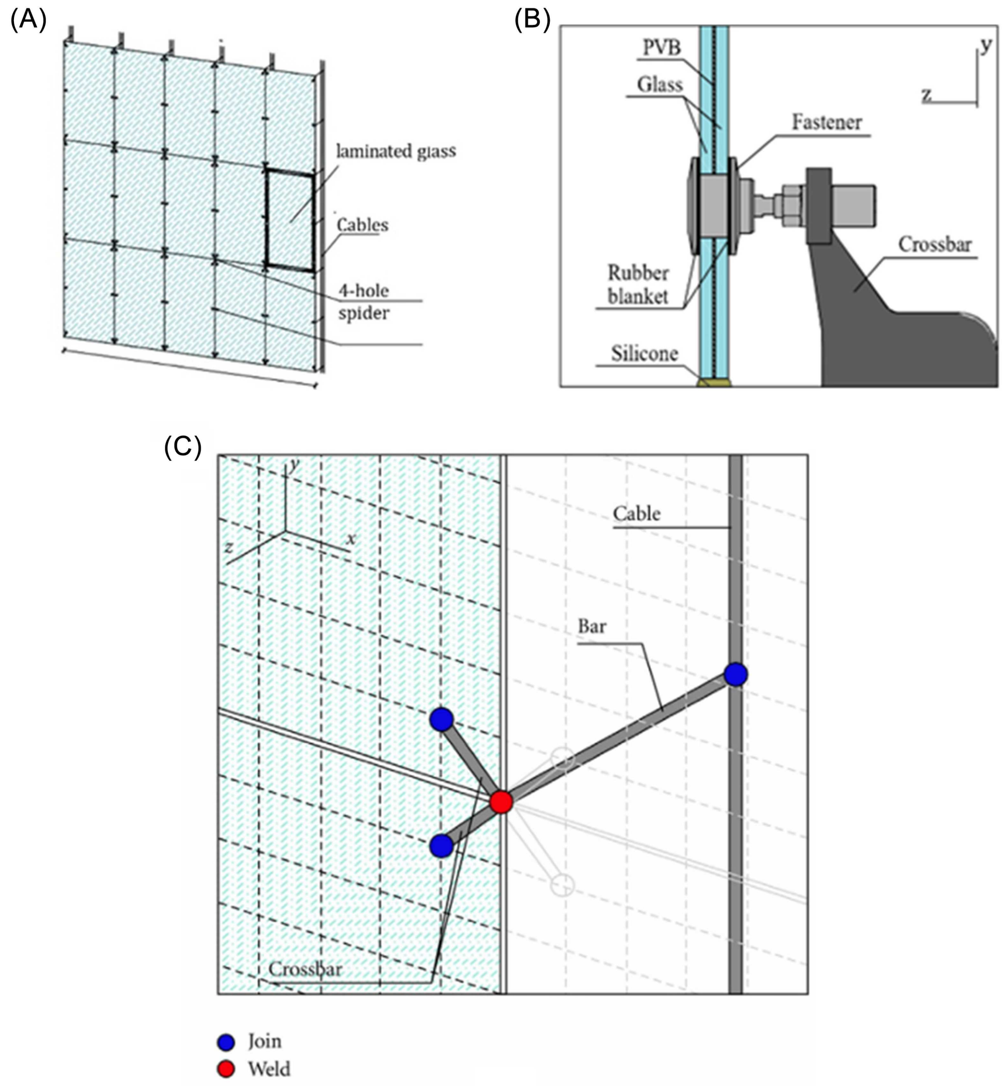

FIGURE 17 | Example of numerical modeling strategy for a cable-supported point-fixed glass facade system: (A, B) assembly and connection details according to [46], and (C) numerical modeling strategy. Figures reproduced from [46] under terms of the CC BY 3.0 license.

translations and rotations were restrained at the shaft's face, and different uniform distribution pressure loads (2, 4, and 8 kPa) were applied on the outer face of the LG panel. The panel was analyzed for out-of-plane displacement and longitudinal strain. The FEA results were compared with experimental results. The discrepancies in longitudinal strain and out-of-plane displacements were found near the edges of the LG panel for a load above 4 kPa. This study also declares that modeling all elements as a C3D8R increases the computational cost. The simulation in this study did not define whether dissipative-type spiders were used or fixed-type. The most significant point in FEA was that the researcher conducted a mesh sensitivity analysis and identified the impact of mesh size on the results.

The ABAQUS software was used by [55] for the global (the whole building) model and the sub-(glass panel) models, MATLAB tools were used to analyze results after the modeling had been done. Different structural elements of the building were modeled by using both the shell and beam elements. The two-node beam elements were used to model beams and columns of the building, while three-node beam elements were employed to model spider joints. Additionally, the slab and glass panel were modeled by using S4R and S8R elements, respectively. In this comparative study, innovative connectors were found to be stronger than conventional. However, in this study, the sealant contribution was ignored, and the study only focused on the seismic response of the glass and connector system. Moreover, a rubber-type material is usually placed between the glass and the bolt modeled by other researchers; this study suggested that modeling such a bushing material was not necessary. This analysis was also not validated by any experimental setup, and only an in-plane analysis was carried out.

Unlike [55], where ABAQUS was used for the global model, the ANSYS tool was used by [56] for the submodel, and ETABS was used for the global model to assess the behavior of the glass facade against earthquake. Additionally, the researcher did not neglect the silicone sealants in modeling, and they were modeled using shell elements. The spider connectors were modeled using a frame for the spider arm and link elements for bolts in ETAB. The connection between the glass panel and connectors was made using a shell-thin element, and the clearance between the glass and connection was maintained at an offset of 5 mm. The shell element was meshed at connection points to ensure connectivity

TABLE 3 | Summary of selected literature studies on PFGFs.

Document	Facade size	Glass panel	Software	Type of elements	Type of analysis	Materials	Experimental validation	Accuracy	Key parameters affecting results	Literature/ source
[48–50]	2.48 × 2.72	LG	ANSYS	Shell, beam, springs	Static	Linear elastic	Yes	Good	The effect of sealant was ignored, geometry of façade, boundary conditions of spider arm	[48–50]
[10, 51]	2.48 × 2.72	LG	ANSYS	Shell, beam, springs	Static	Linear elastic	Yes	Good	Drift capacity, size of façade, type of bolts	[10, 51]
[52]	2.35 × 2.3	LG	ABAQUS	C3D8R, beam elements	Dynamic	Linear elastic	Yes	Reasonably good	Response spectrum analysis, postbreakage behavior, type of interlayer, type of glass	[52]
[53]	1.5 × 1.5	LG	ABAQUS	C3D8R	Dynamic	Linear elastic	No	No experimental confirmation	Type of bolt fixings, type of interlayer, silicon sealant, laboratory temperature	[53]
[12]	1.49 × 1.49	LG	ABAQUS	C3D8R, two-node beam, MPC	Static	Linear elastic	No	Good for loads below 4 kPa	Articulated point fixing, type of bolt fixings, type of interlayer	[12]
[14, 54]	8 × 15.2	LG	SAP2000	Shell, link	Static	Linear elastic	Yes	Good	Type of spider arm, modeling of connection elements, consideration of sealant in modeling	[14, 54]
[3]	1.49 × 1.49	LG	ABAQUS	C3D8R, MPC beam	Static	Linear elastic	Yes	Good	Spider clearance, dissipative capacity in the system, types of spider arms	[3]
[55]	0.4 × 0.4	LG	ABAQUS and MATLAB	S8R, B32	Static	Linear elastic	No	Required more realistic modeling	Load event (single/ double), static fatigue, type of glass	[55]
[56]	8.7 × 3	LG	ANSYS and ETAB	Shell, link	Dynamic	Linear elastic	Yes	Good	Type of spider arms, boundary conditions, type of building	[56]
[57]	4.5 × 4.49	LG	SAP2000	Shell, link (gap, wen)	Dynamic	Linear elastic	Yes	Good	Type of fixing: lamination of foil, glass modeling	[57]

Abbreviations: LG, laminated glass; PFGFs, point-fixed glass facades.

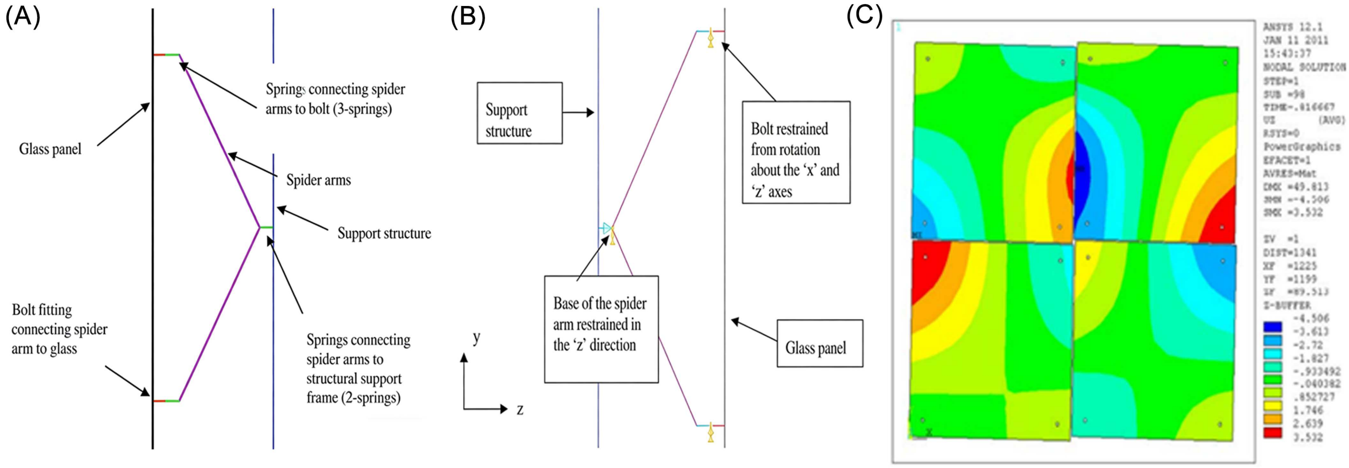

FIGURE 18 | Examples of modeling strategy and details: (A) assembly of the connection system, (B) boundary conditions, and (C) out-of-plane movement of the façade. Figures adapted by the authors from ©Sivagnanasundram et al. [48–50]. The authors own the copyright.

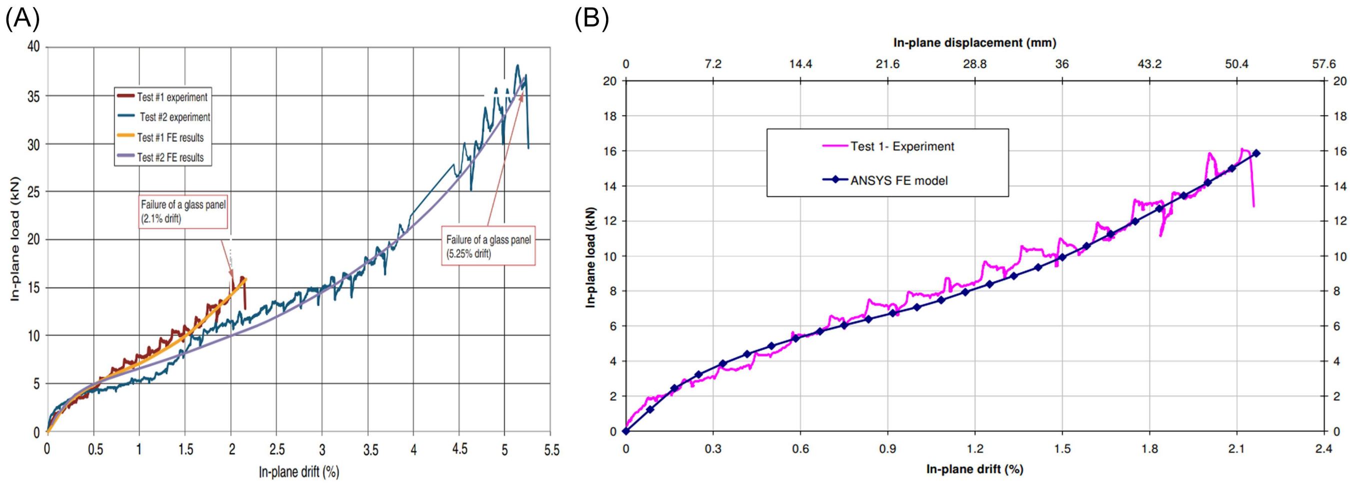

FIGURE 19 | Examples of comparison between experimental and numerical results in the study by [48, 49]. Figures adapted from (A) ©Sivanerupan et al. [51] and (B) ©Sivagnanasundram [48]. The authors own the copyright. FE, finite element.

between the spider screws and the links. The overall results of the facade subjected to in-plane seismic loadings were similar to previous findings. The ANSYS software was used to detect seismic response at the micro level, while ETAB was used to analyze the whole building. ANSYS was used only for analyzing connectors; it might be because for the whole building analysis, ANSYS would have a high computational cost as compared with ETABS. This hybrid-type analysis approach was used to balance the accuracy and practicality of the analysis.

According to [57] analyzing the seismic response of PFGFs is a complex job to do because the behavior of PFGFs depends upon many things, including material properties, semi-rigid joints, soft-core sandwich-type glass elements, nonlinear dissipative mechanisms, and so forth. Furthermore, to deal with geometrical and material nonlinearities, the nonlinear analysis is performed for predicting the true response. On the other hand, current design codes do not provide simplified design tools for PFGFs when subjected to earthquakes. Therefore, it is essential to develop simplified models for a pre-design of the PFGFs. However, such modeling needs a strong basis to correctly develop models to get true predictions of behavior [57]. modeled and the PFGFS for seismic response using SAP2000. The two PFGFs connection systems were evaluated, that is, partially through the bolt fixing system and fully through the point fixing system. Unlike studies done by [56, 55] where ETAB and ABAQUS were used for the global model, here SAP2000 was used for the same. All materials except glass were assigned bilinear mechanical properties. The steel frame was modeled using beam elements with six DOFs per node.

Furthermore, the spider arm and bolt shank were also modeled using link elements, while the glass was modeled as a shell, but ignoring the lamination. It is important to note that the glass was modeled as a monolithic panel equal to the total thickness of LG; this was done to reduce computational cost, and the total computational time was limited to 2 h. Although the model was simple, the maximum drift percentages obtained using FEA were reasonably closer to those obtained by laboratory work for both cases. However, the model did not fully reproduce the same results for the nonlinearity of the hysteretic as the experimental results (see Figure 21).

Overall, the reviewed literature revealed that in the case of PFGFs, which includes spider, bolts, washers, shafts, columns, and so forth, modeling all such elements not only makes the modeling complex but also time-consuming. However, to make the analysis easy and quick, the behavior of connection components, such as columns, bolts, washers, spiders, and so forth, can be modeled by using connectors or link elements, and such a quick and easy analysis can be a unique approach for researchers working on the PFGFs.

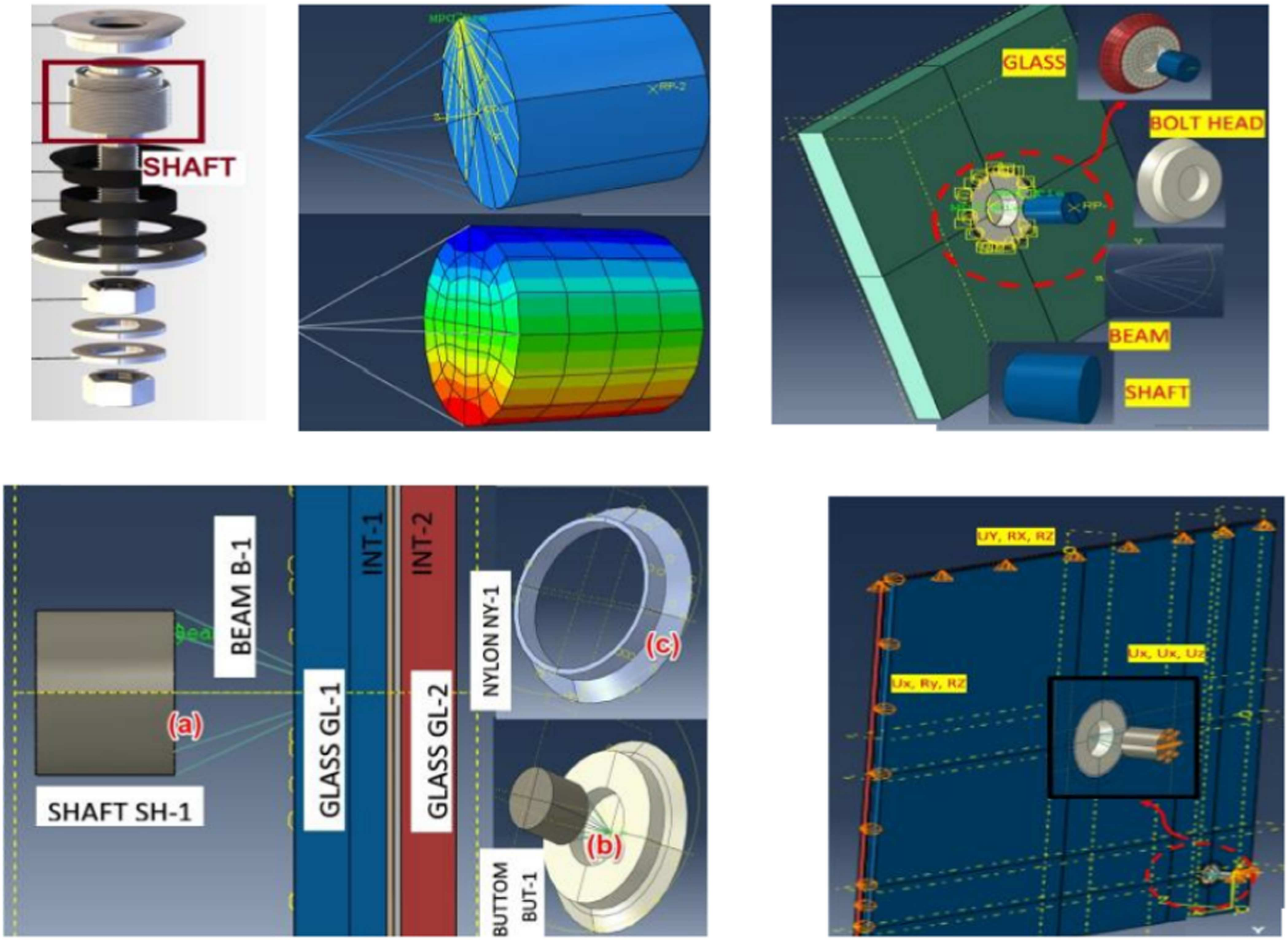

FIGURE 20 | Numerical strategy for point-fixed glass facade employed in [3]. Figure reproduced from [3] under the terms of the CC BY-NC 4.0 license.

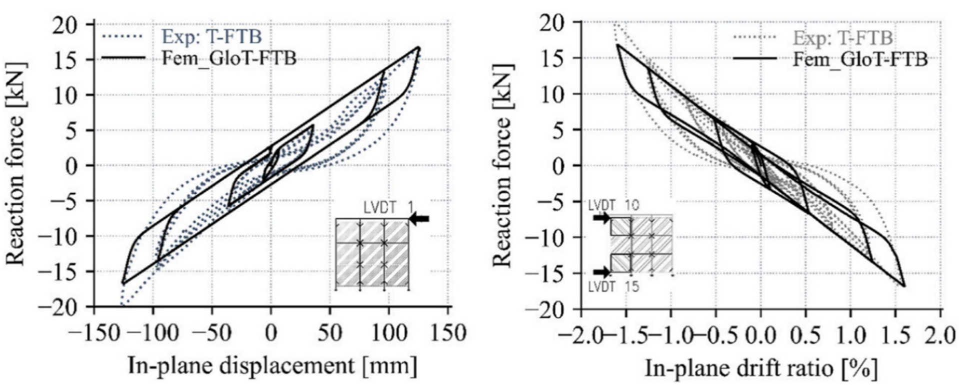

FIGURE 21 | Examples of comparison between experimental and numerical results in the study by Inca [57]. Figure reproduced from [57] under the terms of the CC BY 4.0 license.

4 | Identification of Modeling Generalized Strategies

Many researchers have used the FEA analysis approaches for validating the experimental results of seismic analysis for glass facades. Although different software packages (ANSYS, ETAB, SAP, ABAQUS, etc.) have been used, the model simplification, refinement, and computational cost have been given high importance. Furthermore, the panel size and loading schemes may vary for the said purpose, but the modeling procedure should be such that other researchers should not feel difficulty and follow the same strategy as done by prior researchers. This section identifies whether the researcher followed the same modeling strategy or if there is no generalized set of rules for each glass facade system.

Literature revealed that not all the authors followed the same simulation strategy for the same purpose, even using the same software package for both framed and frameless glass facades (see Table 4). When modeling the framed glass facade, high importance should have been given to frame components, such as gasket, setting block, and so forth. However, some authors modeled connection components, and others neglected behavior of such components in modeling. For instance, studies reported in [9, 19, 22, 33] did not include the setting blocks in modeling, while [19, 23] did, for obtaining a more accurate facade response. Moreover [21], considered the transom-mullion connection to be rigid, while many others, like [4] assumed this connection as a hinge. It should be noted that if the transom-mullion connection was considered fixed, it showed less drift than the hinge with the same load. It was also observed by researchers that when the glass and frame come in contact during simulation, the stiffness increased drastically; however. In reality, the gradual increase in stiffness was observed.

Additionally, the interaction between different components of facades can have a high influence on the associated numerical outcomes, particularly on the results of dynamic or seismic analysis, yet different interaction properties have been used by many scholars. Some researchers, like [30] reproduced the interaction between different frame elements, such as gasket, setting block, transom, and mullion, using tie constraints, while some authors, like [11] used surface-to-surface contact by means of master to slave interfaces, allowing the relative sliding interaction. However, using tie constraints for the gasket and setting block can be unrealistic because such elements are not rigidly connected to glass, and using surface-to-surface interaction between the interlayer and glass can underestimate the global stiffness and composite action as well.

Similarly, for timber-framed glass facades, some authors assumed purlins as link elements, while others assumed 3D elements. Although assigning a calibrated mechanical behavior to links or connectors can be a complex task, authors have also found that using spring elements in timber frame modeling increases the computational time.

A similar unlikeness was also observed in the seismic analysis of PFGFs. A study was conducted by [12], where surface-to-surface contact between glass and interlayer was assumed, while [3] used tie constraints for all elements (glass, interlayer, bolthead, Nylon cap). Additionally, silicone sealant provided between glass panels plays a vital role, and if not provided,

TABLE 4 | Summary of general strategies followed by different researchers.

Component	Material	Element types	Computational cost	Advantages	Limitations	Suitable for…
Glass panel	Linear elastic	Shell element	Low	Easy to model	No detection of cracks	Global response within the serviceable limit state
Glass panel	Linear elastic/ nonlinear elastic	3D solid element	High	Detection of overall failure	detection of cracks	Local response within ultimate limit state
Frame	Linear/nonlinear	Beam elements	Low	Highly efficient	Local effect ignored	Suitable for global response
Frame	Linear/nonlinear	Shell	High	Can represent the true shape of members	Requires high detailing and good mesh quality	More realistic results
Frame	Linear/nonlinear	3D solids	High	Highly accurate	Requires more detailing to model a true hollow section	More realistic local results
Point-fixing components	Linear/nonlinear	3D Solid	High	High accuracy and realistic articulation flexibility	Requires a lot of calibration details	Detection of the overall true behavior of all fixing components
Point-fixing components	Linear/nonlinear	Connectors	Low	High accuracy	Difficult to assign true properties to each component	Quick analysis of large facades

may alter seismic behavior [59]. Even though silicone sealant contributes to energy dissipation and stress transfer, many researchers like [1, 4, 18] did not include it in modeling. However, while analyzing the PFGF, the [56] did not neglect the silicone sealants in modeling, and they modeled it using shell elements.

Furthermore, frame elements have been modeled by using 2D shell elements [4], 3D brick elements [1], and a 1D beam [13] by different scholars. The selection depends upon the accuracy required and computational cost. Additionally, 2D shell elements and 3D brick elements have been used for modeling the LG and IGU [31]. Many authors, such as [28], have modeled the IGU as a 3D brick element while using ABAQUS and provided a cavity, while in SAP2000, the IGU was modeled as a simple single shell with equal thickness of all the elements. However, modeling the IGU as a monolithic shell element can be one of the reasons that the results obtained by [4] were not reasonable, particularly for the last step. Such a modeling approach does not take into account the role of the interlayer.

Overall, the literature indicated that, although experimental and numerical results in many cases did not show high discrepancies, different strategies affected the local behavior of the facade. It is also evident from prior research work that facades are complex to model, and generalized modeling strategies do not exist.

5 | Conclusions

Glass is a fragile material, and due to its brittle behavior, it is always difficult to perfectly predict its response, particularly against seismic forces. Although the experimental work carried out in laboratories is a common technique to analyze the seismic behavior of glass facades, numerical approaches also predict the seismic response of the glass facade if a proper modeling strategy has been followed.

There are two different types of glass facades, such as framed glass facades in which the frame can be metal or timber and PFGFs, also called frameless glass facade. The two systems not only vary in connections but also in force resistance response and displacement accommodation capacity.

Therefore, their accurate modeling, including their components, can produce more accurate results.

Thus, keeping the accuracy and computational time of analysis into consideration, a literature review was carried out in this study. The literature revealed that connection components, such as for a framed glass facade the setting block and gasket for a framed glass facade, play a vital role and cannot be ignored in modeling. If improper properties, dimensions, or even meshing size are assigned to such components, huge discrepancies can be observed between numerical and experimental results.

In some research, errors due to the improper position of the setting block were also observed. However, some researchers did not include a setting block in the analysis, and there is a need to check how much difference in results can be obtained with and without modeling the setting block. Similarly, setting blocks and gaskets have been modeled as 3D solid elements by some researchers, while others have modeled them as link elements in SAP2000 or connectors in ABAQUS, but it is unclear which strategy produced the minimum errors. Additionally, literature revealed that in some cases, numerical analysis failed to capture the local behavior of the glass facade.

Similarly, for the numerical analysis of PFGFs, some researchers modeled each connection element, which was a complex and time-consuming strategy. The same analysis can be conducted by using only the link elements or connectors by assigning the same behavior as the behavior of bolts, washers, and spiders, and so forth. On the other hand, the silicone sealant, which is provided between two glass panels, also contributes resistance to tension, compression, shear, and in-plane and out-of-plane forces and according to the literature it has been ignored by many scholars while carrying out facade simulation.

Overall, the literature revealed that not all authors followed the same simulation strategy; therefore, no generalized strategy exists irrespective of the connection system. Additionally, literature showed that limited work has been done on seismic analysis of timber-framed and PFGFs using numerical approaches.

However, from the reviewed literature, it is evident that ABAQUS (or similar) software provides more refined results than other software. LG can be associated to better results if modeled as 3D solid elements. To capture the realistic response of the frame and connection components (such as gaskets, setting blocks, etc.), it is suggested to model them as 3D elements as well. However, to minimize the computational cost, such components can be reduced to 1D beam elements and connectors, while paying more attention to assigning properties (especially to connectors). Similarly, in the case of PFGFs, glass members should be modeled as a 3D solid, to more accurately capture the local behavior near fixings. The other elements (such as spider arms, bolts, and washers between the glass panel and each bolt) should also be modeled as 3D solids for more accurate results. However, especially when only the global response of the facade is more concerned, the shell element solution is also suitable for glass panels. In a nutshell, solid 3D elements give more accurate results but have a high computational cost. On the other hand, shell elements are computationally efficient but cannot predict the true behavior of laminated members, and should be consequently used with a clear view of these intrinsic limits.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. N. Cella and C. Bedon, "Numerical Modelling of Global/Local Mechanisms and Sensitivity Analysis for the Seismic Vulnerability Assessment of Glass Curtain Walls," *Engineering Structures* 319 (2024): 118859, https://doi.org/10.1016/j.engstruct.2024.118859.

2. National Research Council of Italy, Advisory Committee on Technical Recommendations for Construction, *Guide for the Design, Construction and Control of Buildings With Structural Glass Elements* (2013).

3. E. Inca, S. Jordão, C. Bedon, A. Mesquita, and C. Rebelo, "Numerical Analysis of Laminated Glass Panels With Articulared Bolted Point Fixings," *ce/papers* 5, no. 2 (2022): 140–149, https://doi.org/10.1002/cepa.1709.

4. N. Cella and C. Bedon, "Numerical Seismic Fragility Analysis of Glass Curtain Walls: Gaps and Challenges in Modelling Optimization and Limit Performance Indicators," *Buildings* 14, no. 12 (2024): 3863, https://doi.org/10.3390/buildings14123863.

5. R. A. Behr, *Architectural Glass to Resist Seismic and Extreme Climatic Events* (Woodhead Publishing, 2009), https://doi.org/10.1533/9781845696856.

6. S. Taghavi and E. Miranda, *Response Assessment of Nonstructural Building Elements* (Pacific Earthquake Engineering Research Center, University of California, 2003).

7. R. G. S. S. Perera, J. H. A. Ruwanmali, T. Thevega, J. A. S. C. Jayasinghe, C. S. Bandara, and A. J. Dammika, "Thermal Performance of Glass Facade Under Fire Loading: A Numerical Approach," *Sri Lanka Journal of Social Sciences* 52, no. 2 (2024): 229–241, https://doi.org/10.4038/jnsfsr.v52i2.11732.

8. C. G. Galante, *Investigating the Performance of Mechanically Ventilated Double-Skin Facades With Solar Control Devices in the Main Cavity* (2026).

9. A. M. Memari, A. Shirazi, and P. A. Kremer, "Static Finite Element Analysis of Architectural Glass Curtain Walls Under In-Plane Loads and Corresponding Full-Scale Test," *Structural Engineering and Mechanics* 25, no. 4 (2007): 365–382, https://doi.org/10.12989/sem.2007.25.4.365.

10. S. Sivanerupan, J. L. Wilson, E. F. Gad, and N. T. K. Lam, "Analytical Study of Point Fixed Glass Facxade Systems Under Monotonic In-Plane Loading," *Advances in Structural Engineering* 19, no. 4 (2016), https://doi.org/10.1177/1369433216630192.

11. L. Casagrande, A. Bonati, A. Occhiuzzi, N. Caterino, and F. Auricchio, "Numerical Investigation on the Seismic Dissipation of Glazed Curtain Wall Equipped on High-Rise Buildings," *Engineering Structures* 179 (2019): 225–245, https://doi.org/10.1016/j.engstruct.2018.10.086.

12. I. Eliana, J. Sandra, B. Chiara, M. Afonso, and R. Carlos, "Numerical Analysis of Bolted Point Fixed Laminated Glass Panels Subjected to Seismic Loads," in *ECCM 2022—Proceedings of the 20th European Conference on Composite Materials: Composites Meet Sustainability* (2022).

13. C. Aiello, N. Caterino, G. Maddaloni, A. Bonati, A. Franco, and A. Occhiuzzi, "Experimental and Numerical Investigation of Cyclic Response of a Glass Curtain Wall for Seismic Performance Assessment," *Construction and Building Materials* 187 (2018): 596–609, https://doi.org/10.1016/j.conbuildmat.2018.07.237.

14. S. D'Amore, S. Bianchi, J. Ciurlanti, and S. Pampanin, "Seismic Assessment and Finite Element Modeling of Traditional vs Innovative Point Fixed Glass Facade Systems (PFGFs)," *Bulletin of Earthquake Engineering* 21, no. 5 (2023): 2657–2689, https://doi.org/10.1007/s10518-023-01622-0.

15. C. P. Pantelides, K. Z. Truman, R. A. Behr, and A. Belarbi, "Development of a Loading History for Seismic Testing of Architectural Glass in a Shop-Front Wall System," *Engineering Structures* 18, no. 12 (1996): 917–935, https://doi.org/10.1016/0141-0296(95)00224-3.

16. U. Galli, Seismic Behaviour of Curtain Wall Facades: a Comparison Between Experimental Mock-Up Test and Finite Element Method Analysis, MSc Thesis (Politecnico of Milano, 2010), https://hdl.handle.net/10589/52381.

17. M. Momeni and C. Bedon, "Review on Glass Curtain Walls Under Different Dynamic Mechanical Loads: Regulations, Experimental Methods and Numerical Tools," in *Facade Design* (IntechOpen, 2024), https://doi.org/10.5772/intechopen.113266.

18. E. Inca-Cabrera, S. Jordão, C. Rebelo, C. Bedon, A. Mesquita, and S. A. Hosseini, "Experimental and Numerical Investigation of In-Plane Cyclic Response of a Point-Fixed Glass Façade System for Seismic Performance Assessment," *Journal of Building Engineering* 108 (2025): 112956, https://doi.org/10.1016/j.jobe.2025.112956.

19. N. Caterino, M. D. Zoppo, G. Maddaloni, A. Bonati, G. Cavanna, and A. Occhiuzzi, "Seismic Assessment and Finite Element Modelling of Glazed Curtain Walls," *Structural Engineering and Mechanics* 61, no. 1 (2017): 77–90, https://doi.org/10.12989/sem.2017.61.1.077.

20. R. A. Behr and A. Belarbi, "Seismic Test Methods for Architectural Glazing Systems," *Earthquake Spectra* 12, no. 1 (1996), https://doi.org/10.1193/1.1585871.

21. M. Bârnaure and M. Voiculescu, "The Seismic Behaviour of Curtain Walls: An Analysis Based on Numerical Modelling," *Mathematical Modelling in Civil Engineering* 9, no. 4 (2013): 1–8, https://doi.org/10.2478/mmce-2013-0013.

22. J. Wilson, E. Gad, N. Lam, and S. Sivanerupan, *Drift Performance of Façade Systems* (2008), accessed August 18, 2025, https://figshare.swinburne.edu.au/articles/conference_contribution/Drift_performance_of_facade_systems/26224616?file=47531222.

23. A. M. Memari, A. Shirazi, P. A. Kremer, and R. A. Behr, "Development of Finite-Element Modeling Approach for Lateral Load Analysis of Dry-Glazed Curtain Walls," *Journal of Architectural Engineering* 17, no. 1 (2011): 24–33, https://doi.org/10.1061/(asce)ae.1943-5568.0000027.

24. C. Bedon and C. Amadio, "Numerical Assessment of Vibration Control Systems for Multi-Hazard Design and Mitigation of Glass Curtain Walls," *Journal of Building Engineering* 15 (2018): 1–13, https://doi.org/10.1016/j.jobe.2017.11.004.

25. L. Casagrande, A. Bonati, F. Auricchio, and A. Occhiuzzi, "Dissipating Effect of Glazed Curtain Wall Stick System Installed on High-Rise Mega-Braced Frame-Core Buildings Under Nonlinear Seismic Excitation," in *COMPDYN 2017—Proceedings of the 6th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, National Technical University of Athens* (2017), 3711–3727, https://doi.org/10.7712/120117.5677.17166.

26. C. Bedon and C. Amadio, "Glass Facades Under Seismic Events and Explosions: A Novel Distributed-TMD Design Concept for Building Protection," *Glass Structures & Engineering* 3, no. 2 (2018): 257–274, https://doi.org/10.1007/s40940-018-0058-9.

27. C. Bedon and C. Amadio, "Enhancement of the Seismic Performance of Multi-Storey Buildings by Means of Dissipative Glazing Curtain Walls," *Engineering Structures* 152 (2017): 320–334, https://doi.org/10.1016/j.engstruct.2017.09.028.

28. N. Cella and C. Bedon, "Role of Secondary Components in the Numerical Analysis and In-Plane Seismic Performance Assessment of Glass Curtain Walls," *Vibroengineering Procedia, EXTRICA* 50 (2023): 35–41, https://doi.org/10.21595/vp.2023.23453.

29. E. Gil and M. M. Flint, *Computational Modeling of Glass Curtain Wall Systems to Support Fragility Curve Development* (2019).

30. X. Ji, Y. Zhuang, W. Lim, and Z. Qu, "Seismic Behavior of a Fully Tempered Insulating Glass Curtain Wall System Under Various Loading Protocols," *Earthquake Engineering & Structural Dynamics* 53, no. 1 (2024): 68–88, https://doi.org/10.1002/eqe.4017.

31. J. Bouwkamp, *Behavior of Window Panels Under In-Plane Forces* (University of California, 1960).

32. C. Eva and T. C. Hutchinson, "Experimental Evaluation of the In-Plane Seismic Behavior of Storefront Window Systems," *Earthquake Spectra* 27, no. 4 (2011): 997–1021, https://doi.org/10.1193/1.3651407.

33. C. Aiello, "In-Plane Seismic Response of a Glazed Curtain Wall: Full-Scale Laboratory Test and Non-Linear Modelling," in *COMPDYN Proceedings* (2019), https://doi.org/10.7712/120119.6918.19258.

34. H. Lee, M. Oh, J. Seo, and W. Kim, "Seismic and Energy Performance Evaluation of Large-Scale Curtain Walls Subjected to Displacement Control Fasteners," *Applied Sciences (Switzerland)* 11, no. 15 (2021): 6725, https://doi.org/10.3390/app11156725.

35. D. Antolinc, R. Žarnic, F. Cepon, V. Rajcic, and M. Stepinac, "Laminated Glass Panels in Combination With Timber Frame as a Shear Wall in Earthquake Resistant Building Design," in *Challenging Glass 3: Conference on Architectural and Structural Applications of Glass, CGC 2012*, eds. B. Louter and N. Veer (IOS Press, 2012), 623–631, https://doi.org/10.3233/978-1-61499-061-1-623.

36. V. Rajčić, C. Bedon, J. Barbalić, and N. Perković, "Numerical Analysis and Experimental Verification of the Thermal Performance of Hybrid Cross-Laminated Timber (CLT)-Glass Facade Elements," *Challenging Glass Conference Proceedings* 7 (2020), https://doi.org/10.7480/cgc.7.4459.

37. P. J. S. Cruz, J. Pequeno, J-P. Lebet, and D. Mocibob, "Mechanical Modelling of In-Plane Loaded Glass Panes," in *Challenging Glass 2: Conference ong Architectural and Structural Applications of Glass* (CGC, 2010), https://doi.org/10.7480/cgc.2.2419.

38. W. Hochhauser, A. Fadai, M. Rinnhofer, and W. Winter, "Timber-Glass Composites: Calculation and Sizing Concept," in *WCTE 2016—World Conference on Timber Engineering* (2016).

39. B. Ber, M. Premrov, and A. Štrukelj, "Finite Element Analysis of Timber-Glass Walls," *Glass Structures & Engineering* 1, no. 1 (2016): 19–37, https://doi.org/10.1007/s40940-016-0015-4.

40. M. Premrov, B. Ber, and A. Štrukelj, "Cyclic and Shaking-Table Tests of Timber–Glass Buildings," *International Journal of Computational Methods and Experimental Measurements* 5, no. 6 (2017): 928–939, https://doi.org/10.2495/CMEM-V5-N6-928-939.

41. B. Ber, G. Finžgar, M. Premrov, and A. Štrukelj, "On Parameters Affecting the Racking Stiffness of Timber-Glass Walls," *Glass Structures and Engineering* 4, no. 1 (2019): 69–82, https://doi.org/10.1007/s40940-018-0086-5.

42. M. Premrov and E. Kozem Šilih, "Numerical Analysis of the Racking Behaviour of Multi-Storey Timber-Framed Buildings Considering Load-Bearing Function of Double-Skin Façade Elements," *Sustainability (Switzerland)* 15, no. 8 (2023): 6379, https://doi.org/10.3390/su15086379.

43. E. K. Šilih and M. Premrov, "Numerical Study of Racking Resistance of Timber-Made Double-Skin Façade Elements," *Advances in Production Engineering and Management* 17, no. 2 (2022): 231–242, https://doi.org/10.14743/apem2022.2.433.

44. K. E. Šilih and M. Premrov, "Enhancing Racking Stiffness in Tall Timber Buildings Using Double-Skin Façades: A Numerical Investigation," *Advances in Production Engineering and Management* 20, no. 1 (2025): 116–130, https://doi.org/10.14743/apem2025.1.531.

45. C. Bedon and C. Amadio, "Exploratory Finite-Element Investigation and Assessment of Standardized Design Buckling Criteria for Two-Side Linear Adhesively Supported Glass Panels Under In-Plane Shear Loads," *Engineering Structures* 106 (2016): 273–287, https://doi.org/10.1016/j.engstruct.2015.10.033.

46. I. Maniatis and G. A. R. Parke, "Numerical and Experimental Investigations on the Stress Distribution of Bolted Glass Connections Under In-Plane Loads" (PhD diss., 2008).

47. Y. Wang, Q. Wang, J. Sun, L. He, and K. M. Liew, "Effects of Fixing Point Positions on Thermal Response of Four Point-Supported Glass Façades," *Construction and Building Materials* 73 (2014): 235–246, https://doi.org/10.1016/j.conbuildmat.2014.09.085.

48. S. Sivagnanasundram, *In-Plane Seismic Performance of Glass Façade Systems* (2011).

49. J. L. Wilson, E. F. Gad, N. T. K. Lam, and S. Sivanerupan, *In-Plane Drift Capacity of Point Fixed Glass Façade Systems* (2010).

50. S. Sivanerupan, J. L. Wilson, E. F. Gad, and N. T. K. Lam, "In-Plane Drift Capacity of Contemporary Point Fixed Glass Facade Systems," *Journal of Architectural Engineering* 20, no. 1 (2014), https://doi.org/10.1061/(asce)ae.1943-5568.0000130.

51. S. Sivanerupan, J. L. Wilson, E. F. Gad, and N. T. K. Lam, "Drift Performance of Point Fixed Glass Façade Systems," *Advances in Structural Engineering* 17, no. 10 (2014): 1481–1495, https://doi.org/10.1260/1369-4332.17.10.1481.

52. L. Martins, R. Delgado, R. Camposinhos, and T. Silva, "Seismic Behaviour of Point Supported Glass Panels," in *Challenging Glass 3: Conference on Architectural and Structural Applications of Glass, CGC 2012* (IOS Press, 2012), 281–292, https://doi.org/10.3233/978-1-61499-061-1-281.

53. E. Inca, C. Bedon, S. Jordão, and C. Rebelo, "Seismic Behaviour of Bolted and Bonded Point Fixed Laminated Glass Panels," *MATEC Web of Conferences* 352 (2021): 00013, https://doi.org/10.1051/matecconf/202135200013.

54. S. D'Amore, J. C. Bianchi, and S. Pampanin, *Seismic Performance of Point Fixed Glass Facade Systems Through Finite Element Modelling and Proposal of a Low-Damage Connection System* (2022).

55. G. Sciacca, E. Katsanos, and J. H. Nielsen, "Damage Accumulation in Point Supported Glass Panels Subjected to Earthquake Excitations via a Simplified Stepwise Approach," *Glass Structures & Engineering* 7, no. 4 (2022): 661–679, https://doi.org/10.1007/s40940-022-00215-8.

56. N. Breuil, H. Wu, and M. Mouazzam, "Seismic Performance Analysis of Horizontally Isolated Point-Fixed Glass Façade System Incorporated in Self-Centering Wall Structure," *Structures* 80 (2025): 109983, https://doi.org/10.1016/j.istruc.2025.109983.

57. E. Inca-Cabrera, S. Jordão, C. Rebelo, C. Bedon, A. Mesquita, and S.-A. Hosseini, "Experimental and Numerical Investigation of In-Plane Cyclic Response of a Point-Fixed Glass Façade System for Seismic Performance Assessment," *Journal of Building Engineering* 108 (2025): 112956, https://doi.org/10.1016/j.jobe.2025.112956.

58. S. Bondi and N. McClelland, *Capturing Structural Silicone Non-Linear Behavior via the Finite Element Method* (Glass Performance Days, 2009), 183–185.

59. B. Dal Lago, F. Biondini, G. Toniolo, and M. Lamperti Tornaghi, "Experimental Investigation on the Influence of Silicone Sealant on the Seismic Behaviour of Precast Façades," *Bulletin of Earthquake Engineering* 15, no. 4 (2017): 1771–1787, https://doi.org/10.1007/s10518-016-0045-y.