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Review paper

Challenges in curtain wall systems technology

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ABSTRACT
This review synthesizes current research on the mechanical and environmental performance of glass curtain wall (GCW) systems, focusing on seismic vulnerability, wind engineering, material degradation, and computational modeling. This study addresses the critical disconnect between conservative design code limits and the actual structural capacity of modern flexible façade systems, demonstrating that performance-based design approaches can enable safer and more economical solutions. The key strengths include the comprehensive scope spanning four interdisciplinary domains, the identification of unresolved contradictions between international standards and experimental evidence, and the structured synthesis of advanced numerical modeling strategies.

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1 Introduction

1.1 Historical development

The use of lightweight facade systems in modern high-rise buildings has increased in recent years, gradually replacing conventional facade systems. Curtain wall (CW) systems are among the most commonly used facade systems because they provide a modern appearance and greater flexibility in architectural designs. The curtain wall is constructed from prefabricated elements. The structural elements of the CW can be made of steel or aluminum, while the cladding can consist of various materials, such as stone, aluminum, or glass. Examples of the system and the facade's appearance are shown in Figures 1 and 2. These facades represent very complex and attractive structures because their role is no longer just to be an envelope protecting the building from external influences, but also an authentic architectural stamp, as can be seen in the Figures 3 and 4. Precisely because of their complex function, these structures require attention in design, as well as a fertile field for continuous theoretical and experimental research [1-5].

The history of the curtain wall is considered to have begun in 1851 with the construction of the Crystal Palace in London. The development of these systems began with the development of reinforced concrete and structural steel construction technology. The curtain wall as an official form of construction was first suggested by Frederick Baumann (1826-1921) in 1884 and was implemented in 1895 during the construction of the Reliance Building in Chicago. The curtain walls known today have been developed through decades of innovation and differ greatly from the initially defined idea [6]. The origin of the forms of the curtain wall known today is considered to be due to Walter Gropius (1883-1969), a German professor at the famous Bauhaus

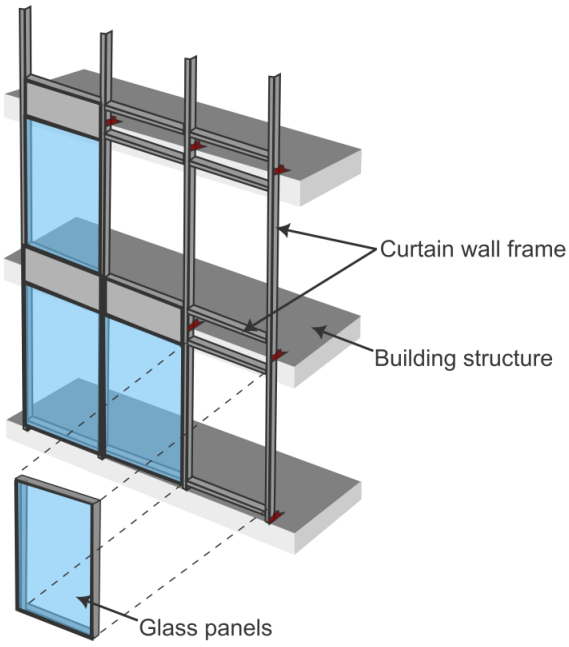


Figure 1. Typical curtain wall system.

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Figure 2. The Science and Technology Park Niš, Serbia. (Source: Authors' own photos. Photo credit: K. Slavković. Date: November 22, 2024)



Figure 3. The Axel Springer Neubau in Berlin, Germany. (Source: Authors' own photos. Photo credit: K. Slavković. Date: May 21, 2025)



Figure 4. Potsdamer Platz in Berlin, Germany. (Source: Authors' own photos. Photo credit: K. Slavković. Date: May 18, 2025)

school of architecture for which he designed a new campus with an innovative facade system [7, 8]. The key forerunner of the curtain wall system in the United States was the 1909 Boley Building in Kansas City [9]. After World War II, the use of these systems increased. Today, curtain walls are multifunctional envelopes responsible for managing heat, air, water, and sound, often accounting for up to 40% of a building's total cost [2].

1.2 Engineering and environmental challenges

Despite their attractive aesthetics and functional role, these structures are architecturally and engineering challenging endeavors. As previously noted, these composite systems consist of multiple materials, most commonly aluminum or steel, which are both durable and elastic, glass, which can be sensitive and brittle, and various structural systems and elastic seals to achieve and maintain the integrity of the connections. Due to their complexity, these systems can be very sensitive to common and extreme influences over the course of a lifetime [4, 10].

This study highlights four main areas that need to be considered during the design phase, Figure 5.

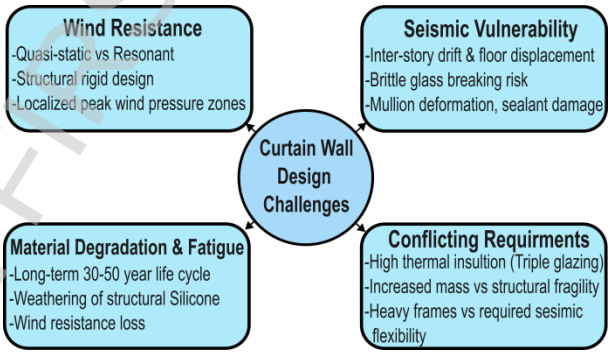


Figure 5. The four main challenges in CW design

The wind resistance and dynamic response of curtain wall systems to wind action are critical factors. Wind action is the primary influence in the design of these systems. Wind action on curtain wall systems has traditionally been considered a quasi-static action because facades usually have high natural frequencies, and the wind energy at these high frequencies is considered small [11-13]. According to ASCE 7 (2022) [14], facades are treated as "rigid" structures if their natural frequency is above 1 Hz, which is why resonant responses under wind action are ignored [15]. However, recent wind tunnel studies suggest the occurrence of significant resonant vibrations at frequencies higher than 1 Hz, i.e., between 8 and 14 Hz [16-17]

Seismic vulnerability also presents one of the challenges in the design of curtain wall systems. These systems are susceptible to damage during earthquakes, primarily because of the incompatibility between the relative floor displacements of the primary structure and the limited deformation capacity of the facade structure. Conventional fastening methods often fail to absorb external forces, resulting in glass breakage during block installation, damage to the mullions and seals, or the loss of entire panels [4, 18, 19].

Material degradation and fatigue can be regarded as a third factor to be considered when designing these systems. Because curtain walls represent the external facade of a building, they are exposed to constant atmospheric influences and dynamic wind action. These influences cause

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material degradation due to changes in temperature, humidity, water, and frost. In addition, the constant change in wind intensity causes a change in the stress state of the materials, which results in their fatigue [10, 20-24]. There is a significant difference between the performance of new material samples and their behavior in real operational conditions during a life cycle of 30 to 50 years. Environmental fatigue and aging of silicone sealants and EPDM gaskets can lead to a loss of performance of up to 54% in air infiltration resistance and 18.5% in wind pressure resistance over time [25].

The fourth issue is the conflicting performance requirements. The latest energy codes require high thermal insulation (low U-values), which results in the need for thicker triple glazing units (IGUs) and thermal breaks. However, these components can increase structural fragility and add additional loads or create stress concentration points, which conflicts with the need for structural flexibility in seismic areass [18, 25, 26].

1.3 Objective of this review

The primary objective of this review was to synthesize the current research on the mechanical and environmental performances of curtain wall systems. Although existing standards (such as ASCE 7 [14] and Eurocode 8 [13]) rely on rigid and often overly restrictive constraints for inter-storey displacement, this review evaluates advanced numerical modeling strategies and experimental analyses that suggest that curtain walls can withstand higher capacities than those currently codified. Additionally, the aim was also to explore next-generation technologies, such as motion control fasteners and adaptive sun protection systems, designed to balance structural safety with energy efficiency.

This review identifies unresolved contradictions in current technology and design standards and provides a comprehensive framework for designers, engineers, and researchers to optimize the safety and durability of modern building envelopes.

2 Seismic vulnerability and performance-based design

The seismic analysis of glass curtain wall (GCW) systems was previously viewed as simply adding additional loads to the load-bearing structure of a building. However, the analysis of the behavior of these systems has evolved into highly accurate numerical and experimental performance-based processes. This evolution has been driven by the recognition of GCWs as non-structural components that are highly sensitive to displacements; the failure of these components, although not compromising the primary load-bearing capacity of the building, poses a significant threat to human life safety and results in large economic losses [4, 27, 28].

Thus, performance-based design (PBD) is a modern engineering approach that focuses on achieving specific performance objectives (such as life safety or continuity of function) under specific load levels, rather than simply adhering to conservative, prescriptive building code rule [28, 29]

Regulations such as Eurocode 8 [13] or ASCE 7 [14] usually define fixed and often very conservative design assumptions, such as inter-storey displacement limits (IDRs), to prevent damage to non-structural elements. Performance-based design (PBD) assumes that these general limits often do not reflect the actual capacity of modern and flexible facade systems. PBD allows engineers to demonstrate that the system can withstand significantly larger displacements than prescribed, without the risk of glass falling out or compromising human safety [4, 28].

The definition of these limits began with the pioneering studies of Bouvkamp and Meehan (1960) [30] and Bouvkamp (1961) [31], which determined that the seismic response of a curtain wall system depends on the type of frame selected and the potential displacement of the glass panels during an earthquake. This early research suggested that glass panels could theoretically accommodate relative inter-storey displacements of up to 8% if the column-to-glass spacing was sufficiently large [32].

According to most design standards worldwide, curtain wall facade systems are considered non-structural elements. Also, according to the above standards, non-structural elements are expected to have the same inter-storey drift during seismic displacement as the supporting structure, i.e. to follow the displacements of the building itself. To limit damage to the structure itself and all non-structural elements, limits on maximum structural displacements have been defined.

Typical values of the maximum allowable inter-storey drift according to EC8 [13] depending on the type of non-structural element, and the exact values are listed in Table 1.

According to American regulations ASCE 7 [14], these limits are defined slightly differently. According to these regulations, the GCW must follow the relative displacements of the building ($\Delta_{fallout}$), which are given by the following equation:

$$\Delta_{fallout} \geq \max (1.25 \cdot Ie \cdot Dp; 13\ mm) \quad (1)$$

where I_e is the importance factor, and D_p is te relative seismic displacement. In contrast, American FEMA 27 [33, 34] provides values of 2% for life safety and 1% and for immediate occupancy performance levels.

Canadian regulations CSA-S832 [35], provide the same value for all cases, which is 2.0%.

Japan JASS14 [36] and New Zealand NZD 1170.5 [37] codes establish limits based on earthquake intensity. The limitations based on JASS14 [36] are listed in Table 1.

According to NZS 1170.5 [37], the inter-storey drift at the ultimate limit state is limited to 2.5% of the corresponding storey height. For the serviceability limit state, the inter-storey drift should be restricted to prevent adverse effects on other building components. For facade systems, including curtain walls, more restrictive serviceability criteria are commonly adopted, where the drift limit is governed by the available clearance between the glazing and frame, typically expressed as 0.4% of the storey height or twice the glass clearance, whichever is more critical.

According to the Chinese technical codes JGJ 102 [38] and DGJ 08-56 [39], the in-plane deformation capacity of curtain wall systems should not be less than three times the elastic inter-storey drift of the main building structure. This requirement ensures sufficient deformation compatibility between the facade system and the supporting structure during seismic loading.

A global comparison of seismic inter-story drift (IDR/h) limits and criteria for non-structural glass wall systems is summarized in Table 1 for all the standards addressed.

Some basic seismic design requirements have been outlined to date. However, there is a noticeable discrepancy between traditional code-based design and recent performance-based research. Cella and Bedon (2024) [4] and Caterino (2023) [28] argue that current code-defined IDR limits are too restrictive and outdated for modern high-rise

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Table 1. Global comparison of seismic inter-storey drift ratio (IDR/h) limits and criteria for non-structural glass curtain wall systems

Standard	Country	Classification (Performance Level)	Allowable Drift Limit (IDR/h)
Eurocode 8 [13]	Europe	Brittle non-structural elements Ductile non-structural elements Non-structural elements not interfering with structure deformation	0.0050 0.0075 0.0100
ASCE [14]	United States	Relative seismic displacement requirement	$\Delta_{fallout} \geq \max(1.25 \cdot Ie \cdot Dp; 13\ mm)$
FEMA 27 [33, 34]	United States	Immediate Occupancy (IO) Life Safety	1.0% (0.0100) 2.0% (0.0200)
CSA-S832 [35]	Canada	All standard cases	2.0% (0.0200)
JASS 14 [36]	Japan	Level 1: Frequent earthquakes Level 2: Large-scale earthquakes happened in the past Level 3: Severe earthquakes	1/300 (0.0033) 1/200 (0.0050) 1/100 (0.0100)
NZS 1170.5 [37]	New Zealand	Ultimate Limit State (ULS) Serviceability Limit State (SLS)	2.5% (0.0250) 0.4% or 2 · clearance
JGJ 102 [38] **DGJ 08-56 [39]**	China	In-plane deformation capacity	≥ 3 · elastic inter-storey drift of main structure

facades. Their research indicates that flexible GCW systems often have a higher displacement capacity than the code-defined limits. However, current codes are often chosen as a necessary conservative basis, although researchers note that they lack specific provisions for determining the actual deformation capacity of different GCW typologies.

Performance-based design in seismic engineering emphasizes that the facade, although considered a non-structural element, significantly interacts with the primary structure of the building. This approach considers how the flexibility of the facade and its details (such as seals and shims) can absorb energy and affect the overall damping of the building. For example, integration of a facade into a seismic analysis can show that it contributes to energy dissipation, which can reduce peak story displacement [29].

One of the key tools in the Performance Based approach are the fragility curves, Figure 6. Engineers use advanced numerical models (e.g., software such as ABAQUS [40]) to create fragility curves. These curves statistically show the probability that a facade system will reach a certain state of damage at different intensities of seismic acceleration [4].

Furthermore, the failure mechanism analysis of curtain wall systems has been developed over the years. Failure mechanism analysis has evolved from basic simple models to very complex models that involve the identification of complex local stress concentrations.

Early models (1960s – 1990s) focused on the rigid translation of the glass panel within the frame until clearance closure. The failure was viewed as a geometric event in which contact at two opposite corners initiated in-plane rotation [31, 41].

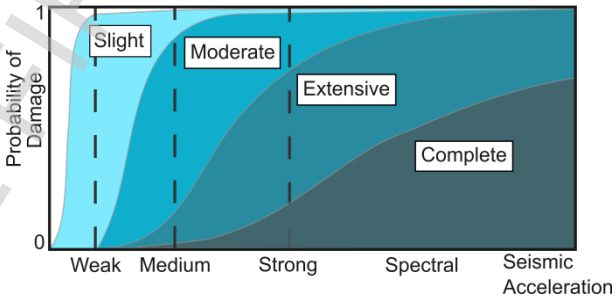


Figure 6. Schematic representation of fragility curves

A new approach emerged between 1990 and 2010. For example, in the work of Sucuoglu and Vallabhan (1997) [42], it was suggested that the analysis of the fracture mechanism could be based on the analysis of the compressed diagonal that occurs when the panel is rotated, Figure 7. When the panel is in a certain configuration and the compressed diagonal reaches certain stress values, brittle fracture of the glass or support occurs. Behr (1998) [43] defined the mechanism of glass failure through geometric contact at opposite corners due to the distortion of the aluminum frame into a parallelogram. Failure occurs when the displacement exceeds the clearance, leading to local crushing of the corners and radial crack propagation, Figure 8.

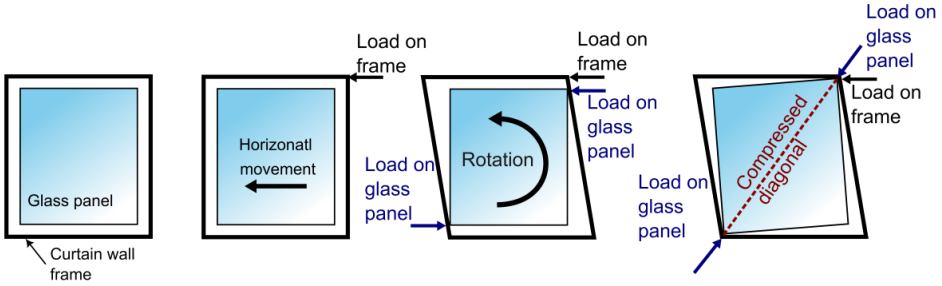


Figure 7. Typical movement of the glass panel within the frame under in-plane seismic action

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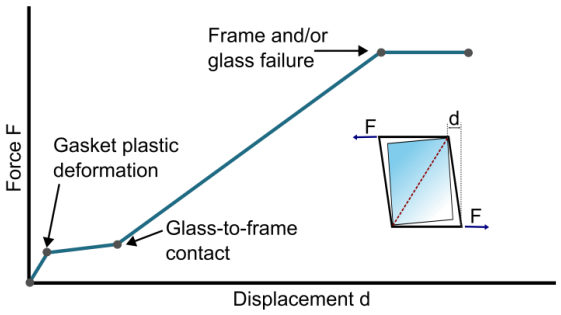


Figure 8. Schematic representation of the in-plane load–displacement behavior of a glass facade

Ali M. Memari [44, 45] is one of the most cited authors in this field. Memari used an advanced numerical approach, finite element method (FEM), and focused on local contacts and corner geometry for the seismic analysis of glass panels. His model tracks the movement of the panels in detail, simulating the impact of the glass on the frame after the gap is exhausted and the stress concentration at the edges. Recent full-scale "Crescendo" tests conducted by Aiello et al. (2018/2019) [27, 32] have detailed the exact physical phenomena at the component level. Glass breakage and cracking are often localized at the bottom edge of the panel where the mounting blocks provide a rigid reaction point, causing stress peaks that are 4 to 5 times larger than suggested by global simplified models.

A summarized overview of the chronological development and analysis of failure mechanisms for glass facade wall systems is presented in Table 2.

Over the years, in addition to the development of the calculation principles of curtain wall systems in seismically active areas, the design principles have also evolved. Innovative special dissipative systems have been developed to mitigate the seismic forces and displacements of curtain wall systems.

Lee et al. (2021) [18] demonstrated through full-scale experimental testing their innovative fastener design that can accommodate dynamic displacements of ±150 mm (3.75% IDR) without any glass fallout or gasket breakage, effectively isolating the facade from floor slab vibrations. Figure 9 shows simplified schematics of the dissipative system proposed in [18].

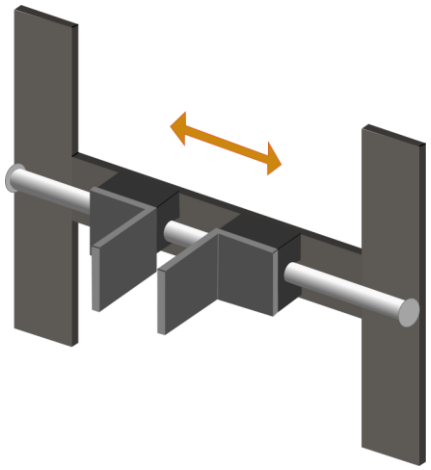


Figure 9. Schematic representation of innovative dissipative connection systems (adapted from [18])

Brueggeman et al. (2000) applied a seismic isolation system at the facade construction level based on the physical separation of glass panels and aluminum frames from the primary building structure. This system uses increased gaps, special seismic verticals, and sliding connections to allow significant relative displacements without damaging the glass [45]. A schematic representation of Bruggeman's connection proposal is shown in Figure 10.

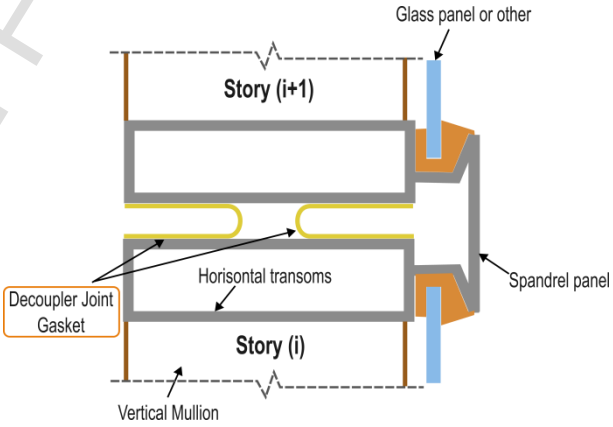


Figure 10. Schematic representation of Brueggeman's connection (adapted from [45])

Table 2. Chronological evolution of failure mechanism analyses for glass curtain wall systems

Period	Key Researchers	Analytical Approach	Failure Criteria & Focus
1960s – 1990s	Bouvkamp and Meehan (1960) [30] and Bouvkamp (1961) [31]	Rigid body translation within the aluminum frame until clearance closure.	Geometric event; contact at two opposite corners initiates in-plane rotation.
1990s - 2010	Sucuoglu & Vallabhan (1997) [42], Behr (1998) [43]	Compressed diagonal mechanism due to panel rotation and frame distortion.	Brittle fracture of glass or support occurs when diagonal stresses exceed limits.
Modern Era	Cella and Bedon (2024) [4], Caterino (2023) [28], M. Memari [44, 45]	Advanced Performance-Based Numerical Models (e.g., ABAQUS) and Fragility Curves.	Local stress concentrations, energy dissipation, seals/shims interaction, and statistical damage probabilities.

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Another possible solution for earthquake mitigation is advanced unitized joint technology. The literature suggests that unitized (panel) systems are superior to rod systems in terms of their seismic resistance. Their “pin and turn” interconnection methodology allows the units to move independently, whereas rod systems rely on in-situ joints that are highly susceptible to installation failures [10, 46].

3 Wind engineering and aerodynamic behavior

The aerodynamic analysis of glass curtain wall (GCW) systems has evolved over the years from the application of simple uniform quasi-static wind pressures in the calculations, as shown schematically in the Figure 11, to very sophisticated dynamic analyses that consider non-Gaussian turbulence and complex fluid–structure interactions. As modern buildings are designed with increasing storeys and attractive large-scale facades with complex geometries, incompleteness and limitations in regulations have become one of the central themes in the literature related to wind engineering [2, 10, 29].

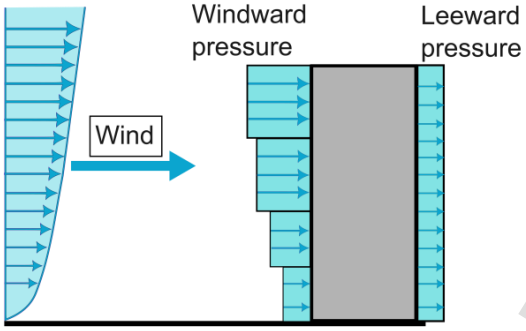


Figure 11. Schematic representation of wind pressure distribution on a high-rise building

The literature indicates discrepancies between the predictions provided by standard wind codes (e.g. ASCE 7 [14], Eurocode 1 [47], GB 50009 [48]) and the actual localized peak pressures recorded during experimental wind tunnel testing. In other words, while the wind loads on low to medium-height structures can be reliably determined, the intensity of tall structures remains a significant challenge, especially with regard to suction forces. One of the shortcomings observed is the underestimation of the suction force at the corners of the building. Negative wind pressures (suction) at the corners of buildings and roof edges are significantly higher than the pressures in the center of the facade. However, for tall buildings, these negative pressures can be more than twice as high as the pressure force (positive) load [4, 2].

The terrain configuration also plays an important role in wind analysis. Recent studies on airport terminals in mountainous areas revealed that standard impact factors are insufficient. Studies show that extreme wind pressures on mountainous terrain can increase by up to 90% compared to those on flat ground [49].

Another factor that, in addition to the terrain, can significantly change the impact of wind on a structure are geometric discontinuities on the facade. The impact of architectural protrusions, terraces, and decorations on facades should be further analyzed. Geometric discontinuities and vertical protrusions attached to the structure for aesthetic reasons can negatively affect the dynamic response caused by wind, acting as aerodynamic triggers for increased vibrations [15].

Over the years, the methodology for assessing wind loads has evolved from empirical static tests to wind tunnel testing, and now integrated hybrid approaches are becoming increasingly popular, Figure 12 [10, 15, 29].

Early literature relied heavily on full-scale performance testing, which involved a quasi-static approach, i.e., using air-pressurized chambers to simulate static or cyclic pressures [50, 51]. In contrast, industry conducts standardized tests using monotonic static or cyclic tests in accordance with test guidelines given in standards such as ASTM E330/E330M-14 (2021) [52], ICC TAS 202-94 (2017) [12], EN 16612 (2019) [53], and AAMA 501.1 (2005) [54].

These standards mainly consider the quasi-static response of facade systems and may not fully reflect their behavior under extreme wind actions, such as strong wind gusts or region-specific hurricane events, where extreme wind actions induce dynamic effects that can lead to different damage mechanisms in curtain-wall systems [55].

For example, full-scale studies have been conducted on curtain wall systems using uniform static pressure, which concluded that the tests had limitations in that they did not provide a realistic assessment of the dynamic characteristics of the structure, suggesting that more realistic full-scale wind tunnel tests are required [56].

Momeni and Bedon (2024) [10] also note that these traditional methods often do not provide satisfactory answers for complex designs, making wind tunnel experiments the primary alternative. For this reason, wind tunnel testing is becoming the “gold standard” for accurate wind impact assessment when considering possible wind gust scenarios that are not covered by the standard or that require more precise assessment, such as building importance or non-standard geometric discontinuities. In wind tunnels, scaled-down models of the structure are constructed, terrain replicas are created, and the required wind action is determined in accordance with the model. In this way, all necessary characteristics, such as wind speed, structural effects, stresses, and deformations, can be measured.

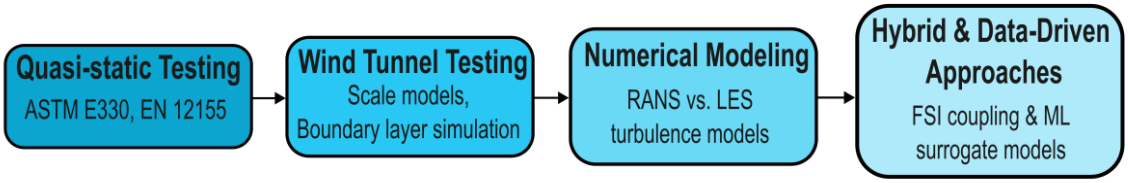


Figure 12. Methodological timeline and evolution of wind load assessment for glass curtain wall systems, transitioning from traditional quasi-static chamber tests to high-fidelity hybrid and data-driven computational frameworks

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Chen et al. (2023) [57] used a wind tunnel with a 1:320 scale model to determine the local shape coefficients on 21 sets of glass panels, finding that the wind direction (especially 0°) dictated the most unfavorable responses. On the other hand, Bakhtiari et al. (2024) [15] also used wind tunnels to reproduce Category 5 hurricane winds in full-scale models, noting that reduced-scale models often have limitations due to a lack of low-frequency turbulence.

Recent developments in wind engineering increasingly rely on hybrid approaches that combine experimental testing, numerical simulations and data-driven methods. One common example is the integration of wind tunnel testing with computational fluid dynamics (CFD), where experimental measurements are used to validate and calibrate the CFD models. CFD is a numerical method used to simulate the airflow around buildings. Various turbulence modeling approaches have been employed in CFD. One of the most widely used models is the Reynolds - Averaged Navier - Stokes (RANS) model, which predicts the mean characteristics of turbulent airflow and is commonly adopted in engineering practice because of its computational efficiency. Another approach is large-eddy simulation (LES), which explicitly resolves large turbulent eddies and provides more accurate predictions of unsteady flow phenomena, including vortex shedding and flow separation around buildings. However, LES simulations require substantially greater computational resources than RANS models [58-64].

More recently, these high-fidelity numerical simulations have been increasingly combined with machine learning (ML) techniques, including artificial neural networks (ANN), convolutional neural networks (CNN), deep neural networks (DNN), graph neural networks (GNN), radial basis function (RBF) neural networks, and Gaussian process regression (GPR). The training datasets are typically obtained from wind tunnel experiments or high-fidelity CFD simulations. Such approaches are increasingly employed when hundreds or even thousands of wind loading scenarios must be analyzed, as performing conventional experiments or high-fidelity CFD simulations for each case would be computationally expensive and time-consuming. By employing data-driven surrogate models, it is possible to significantly reduce the computational cost and analysis time while maintaining satisfactory prediction accuracy, provided that representative and high-quality training datasets are available [65-69].

Ultimately, recent research increasingly examines the dynamic response of GCW systems through the lens of fluid–structure interaction (FSI), challenging the traditional assumption that facade elements behave as purely rigid components [15, 23]. In high-rise structures, the interaction between the primary structural frame and secondary cladding is particularly critical. For instance, Chen et al. (2023) demonstrated that wind-induced deformations of the main structural frame impose substantial additional stress and displacement on the glass panels. Their FEM model revealed that incorporating the global sway and deformation of a tall building increases the peak displacement of the entire GCW system by up to 40.5%, with stress concentrations being particularly severe along the upper and lower edges of the glass panels. These findings underscore the necessity of moving beyond isolated cladding analyses toward fully coupled FSI models to accurately predict the structural integrity of modern facades [57].

4 Durability, material aging, and field failure observations

A major challenge in modern facade engineering is the growing discrepancy between the performance of curtain wall systems under controlled laboratory conditions and their actual behavior over decades of service, which involves cyclical loading. Standard industry practice dictates that verification of curtain wall system performance, including air permeability, water tightness, and structural integrity, be performed on full-scale models of brand-new models. However, these laboratory specimens are typically fabricated under strict supervision and with ideal workmanship, which is not guaranteed during on-site assembly on large projects [25]. Consequently, the current reliance on static pressure tests and initial certification does not account for the dynamic degradation that occurs over the 30 to 50-year lifespan of a building [70]. As building envelopes are increasingly exposed to extreme weather, rainstorms, and atmospheric pollution, materials and joints suffer cumulative stress that is not captured by standard pre-construction assessments [7]. This gap highlights the critical need to move to durability-focused testing protocols that simulate weather effects, i.e., environmental exposure, rather than mere initial regulatory compliance [10, 25].

Field investigations of existing buildings provide a clear diagnosis of the vulnerability of modern curtain wall systems; for example, this is included in the research conducted by the group of authors in the paper Ilter et al. 2016 [70]. Thus, the research covers 29 high-rise buildings in Istanbul built between 1996 and 2012, where the vulnerability of the system was analyzed. The results obtained reveal that defects arising from the design process account for a significant 67% of the observed failures, followed by defects in use and maintenance with 22%. The key finding is the difference between the typologies of the systems; "stick" systems are significantly more susceptible to failures, representing 59% of the failures examined, while unitized (panel) systems showed greater resilience due to controlled factory assembly. Field observations emphasize that most performance-related problems involve catastrophic losses of air and water tightness, often exacerbated by the thermal effects of the sun and repeated wind exposure.

The degradation of the curtain wall performance is primarily driven by fatigue due to environmental factors, a mechanical and physical phenomenon resulting from repeated variable wind loads and thermal cycles. Comparative experimental testing between reference samples and those exposed to fatigue reveals measurable performance losses; specifically, environmental fatigue can lead to documented losses in air infiltration resistance of up to 54%. In addition, the resistance to wind pressure showed a significant decrease, with frontal deflections increasing by 18.53% for the fatigue-exposed specimens compared to 6.67% for the reference units [25].

The most common mechanism behind these failures involves the cyclical opening and closing of the joints, which eventually leads to the dislodgement and tearing of the seals. This fatigue causes the water leakage limits to be exceeded much earlier in the life cycle of the system than predicted by the initial calculations, confirming that wind-induced vibration and cyclic pressures are the primary drivers of weathering loss in tall buildings [23].

The long-term integrity of glass curtain walls relies almost exclusively on the durability of polymer components, particularly silicone structural glazing (SSG) sealants and EPDM gaskets. These materials undergo complex chemical

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and mechanical degradation when exposed to synergistic stresses. Ultraviolet (UV) radiation has been identified as the primary aging factor, as its high energy is capable of breaking the lateral Si-C and C-H bonds of polysiloxane, leading to surface embrittlement and the formation of microcracks. Although these photo-aging reactions involve the breaking of molecular chains, they are simultaneously accompanied by re-crosslinking reactions that can initially increase the tensile strength of the joint before the eventual dominance of degradation, leading to a systematic decrease in strength. Moisture molecules further aggravate this process by diffusing into the polymer matrix and causing hydrolytic degradation of the Si-O-Si skeletal chains. The intensity of these effects follows a hierarchical order where UV radiation has the strongest influence, followed by temperature, humidity, and mechanical stress [24, 71, 72]. A conceptual map highlighting the synergistic degradation mechanism of SSG and EPDM is shown in Figure 13.

Newer research emphasizes that these environmental factors do not act in isolation but through significant synergistic effects; for example, microcracks on the surface caused by UV radiation significantly accelerate the penetration and diffusion of moisture, whereas elevated temperatures reduce the activation energy for both hydrolysis and photo-oxidation. This synergy is critical in tall buildings where mechanical wind cycles act simultaneously with UV and thermal stress, accelerating polymer degradation at a rate significantly greater than that in insulated buildings. To bridge the gap between artificial aging and real-world behavior, modern service life prediction (SLP) methodologies now use recursive algorithms combined with the Markov Chain Monte Carlo (MCMC) method. These hybrid models use multi-gradient matrix aging tests to calculate tensile-time curves, which can then be correlated with three-year outdoor environmental records to predict performance for up to 40 years of exploitation. Such predictive accuracy is necessary to develop maintenance strategies that ensure that the tensile strength of the hidden-frame facade connection remains above safety limits throughout the building's operating cycle [24, 73-75].

5 Advanced computational modeling and future adaptive technologies

The structural analysis of the curtain wall system has evolved from simple traditional quasi-static analysis to highly sophisticated numerical simulations using the finite element method and performance-based engineering. This evolution was driven by the need to analyze the complex dynamic requirements imposed by earthquakes, extreme wind, and random impacts [4, 10, 76].

The literature defines clear contrasts between simplified numerical macromodels (MSIMP) and refined micromodels (MREF). Simplified models, typically implemented in software such as SAP2000 [77], use 1D beam elements for frames and monolithic 2D shell elements for insulating glass units (IGUs), often neglecting cavity thickness and secondary components to improve computational efficiency. Although these models are generally robust in predicting the global load-displacement response and force-displacement relationships, they exhibit significant limitations in capturing the localized mechanical interactions that govern failure [4, 76, 78].

In contrast, more sophisticated modeling methods using software such as ABAQUS [40] or ANSYS [79] allow for more advanced 3D finite element modeling, e.g. with C3D8R elements. Alternatively, hybrid finite elements can be defined using subsurfaces. Research by Cella and Bedon (2024) [4] and Aiello et al. (2018) [19] show that more advanced modeling is mathematically and physically necessary because simplified assemblies tend to drastically overestimate localized stress concentrations. In particular, compressive stress peaks in glass panels near the edges can be four to five times higher in refined models compared to simplified models. Ignoring these components leads to catastrophic underestimation of load-bearing capacity and possible system failure, because, for example, the elements used to mount the glass panels are rigid reaction points that trigger brittle crushing when the gap between the glass and the frame closes [4, 10, 18, 27, 78, 80].

The literature highlights a critical trade-off between computational cost and engineering accuracy. Advanced 3D

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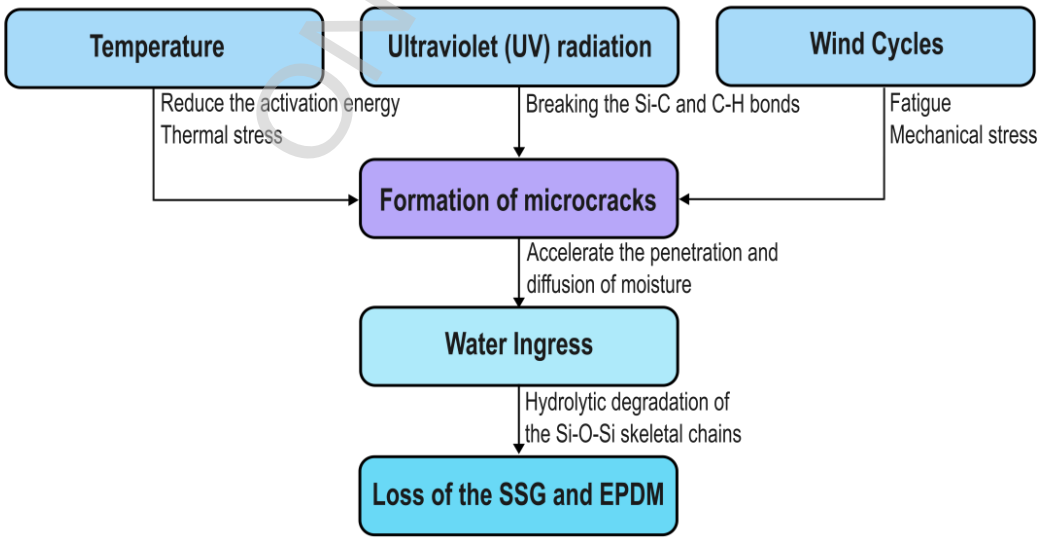


Figure 13. A conceptual map that highlights the synergistic degradation mechanism of SSG and EPDM

models, while highly accurate, are extremely demanding, requiring thousands of degrees of freedom (DOF) even for a partial facade structure. Consequently, the industry often adopts 12-DOF beam elements or “facade-only” models without modeling the entire structure to maintain acceptable computational times. However, Bakhtiari et al. (2024) [15] demonstrated that excluding the primary structure of a building can lead to overlooking facade-structure interactions, missing critical natural frequencies, and underestimating wind-induced resonant responses. To mitigate these shortcomings, state-of-the-art numerical models are rigorously calibrated against physical laboratory tests, such as the AAMA 501.6 “Crescendo” protocol for seismic displacements [81] or Wall of Wind experiments for hurricane-force winds. Validation metrics typically require that numerical responses - such as power spectral densities (PSDs) or root-mean-square acceleration (RMS) - remain within 10% of experimental data to be considered comparable for professional design purposes. This synergy between advanced computing and experimental validation remains a cornerstone of modern facade engineering, ensuring the safety of increasingly complex and adaptive building envelopes [4, 10, 15, 29, 76, 78, 82].

A synthesis of contemporary research reveals a definite shift from deterministic models of life-time prediction to probabilistic frameworks that consider stochastic variables in material aging. A key advance in this area is the derivation of analytical fragility curves via “Cloud Analysis”. This method uses a set of unscaled accelerograms to perform nonlinear dynamic analyses, allowing engineers to predict the probability that a facade system will exceed certain thresholds of damage states, such as gasket degradation or glass failure, under different earthquake intensities [24, 76, 83-85].

For material-level durability, particularly for silicone structural glazing (SSG), the MCMC algorithm has emerged as a state-of-the-art tool for estimating degradation parameters. In this context, MCMC is a Bayesian statistical method used to calculate unknown parameters in complex multi-factor degradation models, where traditional analytical solutions are infeasible. By iteratively sampling from a parameter space, MCMC allows researchers to integrate the synergistic effects of ultraviolet (UV) irradiance, temperature, humidity, and mechanical stress into a unified tensile bond strength model. This algorithm is uniquely capable of handling the statistical uncertainties inherent in long-term environmental exposure, enabling service life predictions of up to 40 years with a high degree of correlation to real-world outdoor aging data, Figure 14 [24, 84].

The next generation of building facades is characterized by adaptive facades that dynamically respond to environmental influences. A prominent innovation in this field is the development of flexurally active glass fiber-reinforced polymer (GFRP) panels integrated into unique curtain walls. Unlike rigid body mechanisms that require heavy, energy-intensive actuators, these systems rely on the reversible elastic deformability of GFRP elements. Their kinematics are controlled by scissor-like element supports that induce elastic curvature in the panels to provide varying levels of solar protection. The computational shape finding for these systems uses third-order nonlinear theory to ensure that the induced stresses remain well below the yield strength (500 MPa) of the GFRP material, even at maximum actuation angles [86-89].

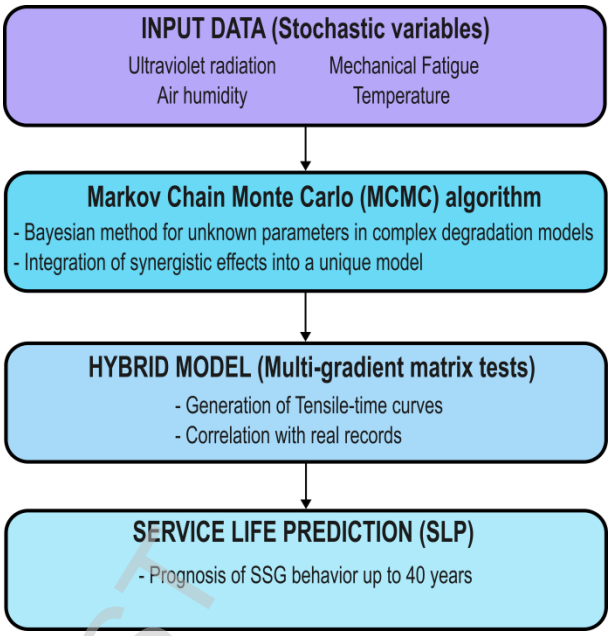


Figure 14. Flowchart of predictive model development

6 Conclusions

The key challenges and contradictions are now discussed in this section as part of the broader concluding synthesis, which addresses the key challenges in curtain wall design. It will also list some of the contradictions that have been observed where literature, regulations, and experimental research do not follow each other.

An analysis of the conclusions and limitations of the provided research papers revealed several critical unresolved contradictions and research gaps in GCW technology. Although there is a broad consensus on the fundamental vulnerabilities of these systems, specifically their brittle nature and susceptibility to seismic and wind-induced damage, the literature diverges significantly on how to accurately model, test, and regulate these components for long-term performance.

The following are the top unresolved contradictions and research gaps identified across the sources.

6.1 Disconnection between design standard limits and real structural capacity

The most prominent contradiction lies in the IDR limits prescribed by international standards (such as ASCE 7 [14] and Eurocode 8 [13]). Recent fragility analyses suggest that the generic IDR limits recommended by construction standards are overly restrictive and do not correlate with the actual seismic capacity of flexible GCW systems.

Researchers agree that GCWs are "non-structural" but highly vulnerable to damage during earthquakes due to incompatibility between the primary structure's deformation and the facade's capacity.

Standards rely on rigid drift limits to prevent damage; however, refined numerical simulations show that flexible curtain walls can often withstand displacements far exceeding these limits without glass fallout. This gap highlights a need for performance-based design and specific IDR limitations tailored to facade typologies rather than generic structural values.

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6.2 Accuracy gap in numerical modeling: Global vs. Local mechanisms

There is an unresolved tension between the computational efficiency of simplified models and the accuracy of refined models in predicting the local stress peaks.

Both simplified (e.g., SAP2000 [77]) and refined (e.g., ABAQUS [40]) models can accurately predict the global load-displacement response of a building facade.

Simplified models, which are industry standards, fail to capture the complex mechanical interactions at the component level. Refined models reveal that stress concentrations at setting blocks and gaskets can be 4–5 times higher than those predicted by simplified models. The role of these "secondary" components (rubber pads, fasteners, and sealant aging) remains a major research gap, as they are often neglected in structural design but are the primary drivers of local glass crushing and failure.

6.3 Initial performance vs. Long-term environmental fatigue

Current industry practice relies heavily on full-scale mock-up testing to certify facade performance; however, these tests typically only reflect the system in its brand-new condition.

Mock-up testing is essential for verifying the air-tightness, water-tightness, and structural integrity under design loads.

Long-term studies have shown that environmental fatigue and material degradation (specifically the aging of silicone sealants and EPDM gaskets) cause performance losses of up to 54% in air infiltration and 18.5% in wind pressure resistance over time. There is a significant research gap in developing standardized test procedures that incorporate environmental fatigue into initial performance assessments to predict real-life behavior over a 30–50-year building life cycle.

6.4 Conflict between thermal performance and structural/seismic integrity

A technical contradiction exists between the requirements for high energy efficiency and the need for structural flexibility in seismic-prone regions.

Energy regulations increasingly demand low heat transmission rates (U-values below 1.0 W/m²K) and high air-tightness.

Achieving high thermal insulation often involves complex thermal breaks (e.g., synthetic resins or polyamides) and IGUs. However, these components can introduce brittleness or stress concentration points that reduce the ability of the system to absorb seismic energy or accommodate large drifts. Although some researchers have developed "mobile fasteners" to balance these needs, finding an optimal design that provides simultaneous high insulation and seismic dissipation without increasing local stress remains a challenge.

6.5 Summary of agreement and divergence

The synthesis of current GCW research highlights fundamental structural differences between system typologies and a major unresolved contradiction in wind engineering codes. In the realm of wind engineering, a significant contradiction exists: standard codes, such as ASCE 7 [14], frequently treat GCW components as rigid structures. However, high-fidelity wind tunnel data prove this assumption inadequate, as building envelopes consistently experience severe resonant vibrations at frequencies between 8 and 14 Hz. Furthermore, the observed Dynamic Amplification Factor (DAF) suggests that current quasi-static wind load criteria fundamentally overlook critical dynamic effects and facade-structure interactions, which can increase peak displacements by more than 40%. This evidence necessitates a rigorous re-evaluation of wind load standards to account for the resonant behavior of modern high-rise facades.

The analysis revealed critical gaps and contradictions in current building performance assessments and regulatory standards. Notably, the absence of standardized test procedures incorporating environmental fatigue limits the ability to predict the long-term behavior of a building's life cycle. Additionally, the conflict between achieving high thermal performance and maintaining structural and seismic integrity remains unresolved, as existing solutions often compromise one aspect to account for the other one. In wind engineering, prevailing codes inadequately address the dynamic responses of facades, overlooking significant resonant vibrations and interactions that amplify displacements beyond current design assumptions. These findings underscore the need for comprehensive revisions of testing protocols and design standards to holistically integrate thermal, structural, seismic, and dynamic wind load considerations for resilient and energy-efficient building facades.

Use of AI Tools

Artificial intelligence tools were used to assist with grammar correction, language refinement, and clarity enhancement. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Srđan Živković (SŽ): Supervision, critical reviewing and approval of the final manuscript.

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