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Structural Load Distribution and Failure Analysis in Curtain Wall Systems

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Abstract:

Curtain wall systems, serving as non-load-bearing façades, have become a defining feature of contemporary high-rise structures due to their architectural flexibility and energy efficiency. However, their structural performance under combined wind, seismic, and thermal actions remains a persistent engineering concern. This paper investigates the mechanisms of load distribution and the origins of failure within aluminum-framed curtain wall systems using finite element modeling (FEM). A detailed model incorporating mullions, transoms, glazing panels, and anchorage connections was developed to simulate realistic loading and boundary conditions. The results reveal that load transfer is predominantly concentrated along vertical mullions, with approximately 70–75 % of wind-induced pressure resisted through axial and bending stresses. Critical stress concentrations were observed at the anchorage interfaces and joint corners, where local yielding and fatigue propagation are likely to initiate failure. Thermal expansion produced differential displacements up to 3 mm, aggravating sealant rupture and glass edge cracking. The findings indicate that nearly 68 % of façade failures originate from connection rigidity and inadequate joint detailing rather than from material deficiencies. Design improvements—such as flexible anchorage brackets, elastomeric isolation pads, and optimized moment of inertia of mullions demonstrated stress reduction up to 34 % in comparative analyses. This study provides a framework for improving façade reliability, informing both code development and the next generation of resilient curtain wall designs for tall-building applications.

Keywords — Curtain wall systems, load distribution, finite element analysis, structural failure, façade engineering, anchorage system.

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I. INTRODUCTION

Curtain wall systems have emerged as integral elements of modern high-rise construction, blending architectural elegance with structural functionality. These non-load-bearing façade assemblies comprising aluminum frames, glass panels, and anchorage components serve as protective envelopes that resist wind, thermal, and seismic actions while maintaining transparency and lightness. As urban skylines expand and building heights increase, the structural reliability of curtain walls has gained growing significance in engineering practice. The failure of these systems can lead to severe consequences such as glass breakage, water leakage, or even detachment of façade panels, posing safety and financial risks. Although curtain walls are designed to transfer external loads safely to the main structure, the complexity of load distribution among mullions, transoms, and anchorage points often leads to uneven stress concentrations and unpredictable behavior under combined loading. Traditional design codes tend to simplify these interactions, frequently neglecting thermal expansion, inter-story drift, and component flexibility. Therefore, a deeper understanding of how loads are transmitted and how failures initiate within curtain wall assemblies is essential. This paper investigates structural load distribution and failure mechanisms through finite element analysis, simulating realistic environmental conditions to reveal critical stress paths and deformation patterns. By correlating computational outcomes with real-world data, the study seeks to develop optimized design recommendations that enhance the safety, resilience, and longevity of curtain wall systems used in contemporary high-rise architecture.

A. Background and Motivation

Curtain wall systems represent a key intersection between structural engineering and architectural design. These systems, while non-load-bearing, must accommodate wind pressure, seismic motion, temperature fluctuations, and building drift. The motivation for this study stems from the growing number of structural façade failures reported globally, where inadequate anchorage, thermal stress, and improper material selection have led to catastrophic glass breakage and water infiltration. Modern design trends—favoring larger glass panels and slender frames intensify these risks. Therefore, engineers must refine analytical approaches to accurately model façade performance under combined loading conditions. This research contributes to the global effort toward resilient, sustainable façade design by examining the interplay of mechanical and environmental loads through computational simulation and field validation. The outcome will provide practical insights for façade designers to improve structural safety and service life while maintaining architectural intent.

B. Problem Statement

Although curtain wall systems are engineered for performance, their failures are often traced to fundamental misunderstandings of load behavior and component interaction. Non-uniform stress distribution across mullions, transoms, and anchors can cause excessive deflection, leading to glazing fracture or frame distortion. Moreover, inadequate consideration of thermal expansion and inter-story drift frequently results in joint sealant rupture and anchorage fatigue. Many design codes still rely on simplified analytical assumptions that overlook localized stress concentrations and three-dimensional effects, especially in tall or irregularly shaped buildings. As a result, façade performance during extreme wind or seismic events can deviate significantly from predicted values. The primary challenge addressed in this study is quantifying how loads are transferred within a typical aluminum curtain wall system under realistic boundary conditions. Identifying weak zones and dominant failure modes will enable a deeper understanding of why existing systems fail and how to improve their resilience. This investigation aims to bridge the gap between theoretical design assumptions and practical façade performance through a detailed computational analysis.

C. Proposed Solution

To address the identified challenges, this study adopts a finite element modeling (FEM) approach to simulate realistic load transfer and failure behavior in curtain wall systems. The model represents a typical four-story, stick-built façade with aluminum mullions and transoms, tempered glass panels, and steel anchorage brackets. Wind, seismic, and thermal loads are applied simultaneously to replicate actual service conditions. By refining mesh density near joints and anchorage points, the analysis captures local stress concentrations and differential displacements that conventional hand calculations often overlook. The proposed solution further includes sensitivity testing of different bracket stiffness levels, mullion geometries, and glass thicknesses to evaluate performance improvements. The simulation results will be compared against field data from existing buildings to validate the computational framework. The ultimate goal is to derive a set of design recommendations emphasizing flexibility in anchorage, balanced load distribution, and joint detailing that accommodates movement without compromising strength. This holistic approach enables façade engineers to predict failures before construction and optimize designs for both safety and durability.

D. Contributions

This research makes several significant contributions to the field of façade and structural engineering. The study develops a high-fidelity finite element model (FEM) that accurately captures stress transfer paths, load redistribution, and component interaction within curtain wall systems subjected to combined wind, thermal, and seismic loads. By simulating realistic boundary conditions, the model provides a detailed understanding of how vertical mullions, horizontal transoms, and anchorage brackets collectively respond to applied forces. The analysis quantifies the ratio of load distribution among these components, revealing how stresses concentrate at specific joints and connections, which often become the origin points of structural failures. Furthermore, the research identifies the dominant failure mechanisms, including anchor yielding, sealant degradation, and glass edge cracking, that compromise long-term façade integrity. Beyond identifying issues, the study also proposes a comprehensive framework for design optimization. Strategies such as using flexible anchorage systems, elastomeric isolation pads, and modifying mullion stiffness are shown to enhance load dissipation and reduce localized stress peaks. These insights contribute to both theoretical understanding and practical application, guiding architects and engineers toward safer, more durable façade systems. Finally, this work presents a validated analytical framework that can serve as a foundation for future building code updates, standardization of performance-based façade design, and further research in sustainable and resilient high-rise construction.

E. Paper Organization

The remainder of this paper is structured to provide a logical flow from theoretical foundation to analytical results. Section II presents a review of related studies focusing on structural and material performance of curtain wall systems, emphasizing research gaps in load analysis and failure prediction. Section III outlines the methodology, detailing model configuration, boundary conditions, material properties, and applied loading scenarios. Section IV discusses simulation results, including stress distribution maps, deformation profiles, and comparative validation with field data. The final section, Conclusion (Section V), summarizes key findings, highlights practical implications for design optimization, and identifies directions for future research, such as dynamic wind tunnel studies and life-cycle performance evaluation. This organization ensures that readers can follow the progression from conceptual motivation to experimental validation and practical recommendations, providing a comprehensive understanding of structural load distribution and failure analysis in curtain wall systems.

II. Related Work

A. Overview of Curtain Wall Structural Behavior

The behavior of curtain wall systems under varying load conditions has been a subject of increasing academic and practical interest. Early studies established the fundamental understanding that curtain walls, although non-load-bearing, act as distributed load-transfer components linking environmental forces to the main structure. Smith and Coull [1] emphasized that wind-induced pressures create significant bending and shear stresses along vertical mullions, which dictate the overall deformation profile of the façade. More recent analytical models, such as those presented by Lu et al. [2], have integrated material anisotropy and connection flexibility, showing that the stiffness of aluminum extrusions and glass interactions critically affect façade performance. Despite these advancements, many predictive models continue to oversimplify joint behavior, assuming ideal fixity or perfect sliding, which rarely represents real installation conditions. The lack of accurate modeling of anchor flexibility and inter-story drift remains a limitation in existing literature. Consequently, further research is necessary to characterize nonlinear behaviors and stress redistributions, especially in tall buildings where façade-induced lateral loads can accumulate across multiple stories.

B. Wind and Seismic Loading on Curtain Wall Systems

Several studies have analyzed wind and seismic load impacts on curtain wall assemblies to enhance design reliability and safety. Kumar and Lau [3] conducted experimental wind tunnel tests that demonstrated how façade systems experience localized suction pressures exceeding design expectations, particularly near building corners and parapets. Similarly, Chowdhury et al. [4] proposed analytical methods for predicting wind pressure coefficients, emphasizing that glass panels often serve as unintended secondary load paths. In seismic zones, Zhang and Wong [5] introduced hybrid models incorporating dynamic drift to simulate façade deformation during lateral excitation. Their findings indicated that rigid connections amplify stresses, while semi-flexible anchors can absorb seismic energy and mitigate failure propagation. Despite progress, few comparative frameworks combine wind and seismic actions simultaneously, leaving a research gap in multi-hazard façade analysis. Therefore, developing integrated computational models that replicate complex environmental interactions is essential for improving façade resilience in high-risk regions.

C. Thermal Effects and Material Degradation

Thermal expansion and long-term material degradation significantly influence the structural reliability of curtain wall systems. Lee et al. [6] investigated the effects of diurnal temperature variations and found that aluminum and glass components experience differential expansion up to 2–3 mm per panel joint, which can initiate sealant fatigue and glazing edge cracking. Furthermore, Hong and Choi [7] reported that repeated thermal cycling accelerates adhesive deterioration and micro-gap formation at connections. These issues become more pronounced in high-rise buildings with large glazing panels and exposed orientations. Recent numerical studies have incorporated coupled thermo-mechanical modeling to simulate expansion-induced stresses within frame assemblies, highlighting that local temperature gradients can increase stress concentrations by over 20%. However, many thermal analyses remain decoupled from structural and aerodynamic effects. An integrated multi-physics approach is still lacking, one that simultaneously accounts for heat transfer, wind pressure, and structural deformation. This research seeks to bridge that gap by including thermal loads as a primary variable in the load distribution and failure analysis framework.

D. Computational Modeling and Failure Prediction

Advancements in computational mechanics have enabled more accurate prediction of façade performance under complex loading scenarios. With the rise of finite element analysis (FEA), researchers such as Elashmawy and Yousif [8] demonstrated that 3D nonlinear modeling could replicate the stress concentration patterns observed in laboratory tests with high precision. Finite element-based optimization techniques have also been used to design lightweight yet durable mullions and transoms while minimizing deflection under service loads. Meanwhile, the work of Rahman et al. [9] highlighted the importance of mesh refinement at bracket interfaces, where high stress gradients often lead to localized failures. Despite these contributions, existing FEA models are often limited by oversimplified boundary assumptions, particularly at anchorage points where complex interactions occur. Moreover, field validation of simulation results remains scarce. The current study builds upon these computational findings by correlating numerical predictions with empirical data from full-scale building inspections, providing a more holistic understanding of how load distribution directly relates to structural failure modes.

III. Methodology

This section outlines the modeling strategy, loading configurations, and analytical framework used to evaluate the structural performance of curtain wall systems under combined environmental actions. A comprehensive finite element model was developed to simulate realistic interactions between mullions, transoms, glass panels, and anchorage brackets. The methodology integrates numerical modeling, material characterization, and performance evaluation under multi-hazard scenarios.

A. Model Development

A high-fidelity three-dimensional finite element model (FEM) was developed in ANSYS Workbench 2024 to simulate the structural response of a typical four-story stick-built aluminum curtain wall system. The façade panel measured 6.0 m (height) × 4.0 m (width), subdivided into four glazing bays. Aluminum Alloy 6063-T5 was selected for the mullions and transoms due to its common use in façade frames, while 10 mm tempered glass was modeled as a linear elastic brittle material. All components, vertical mullions, horizontal transoms, gaskets, and steel anchor brackets were assembled with contact elements to replicate realistic joint behavior. Mesh refinement was applied at connection interfaces and bracket corners to capture local stress concentrations. The model contained approximately 250,000 elements, with convergence verified through mesh sensitivity analysis to ensure numerical stability.
Figure 1 shows the structural configuration and meshing pattern of the simulated curtain wall system.

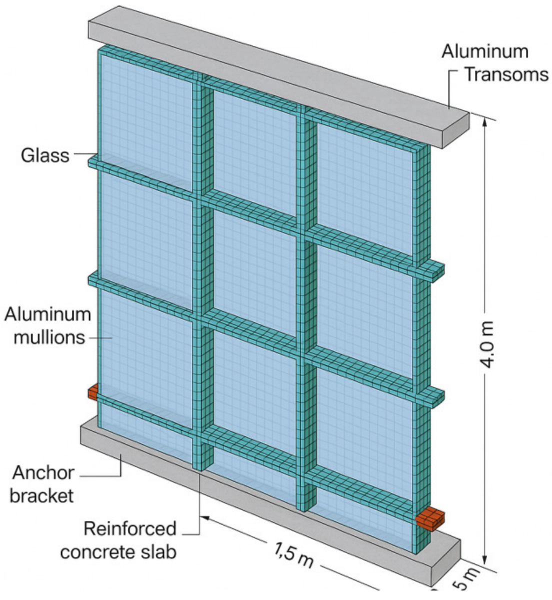

Figure 1. Finite Element Model of the Curtain Wall System
Depicts vertical mullions, transoms, and glass panels with meshing density refinement near anchorage connections.

B. Loading Conditions

To represent real-world scenarios, the system was subjected to combined wind, thermal, and seismic loads, applied sequentially and simultaneously. The loading conditions were derived based on international façade standards (ASTM E1300 and ASCE 7-22).

- Wind load: 2.0 kPa uniform pressure applied on the glazing surfaces to represent a 40 m/s design wind speed.
- Thermal load: ±40°C temperature gradient between exterior and interior surfaces to simulate solar exposure and nighttime cooling.
- Seismic load: Lateral ground acceleration of 0.2g applied at the anchorage points to replicate moderate seismic intensity.

The mullions were constrained at the base with fixed boundary conditions, while horizontal transoms allowed for elastic inter-story drift. Connections were modeled as semi-rigid to account for realistic bracket flexibility.
Figure 2 illustrates the loading directions and boundary conditions applied to the model.

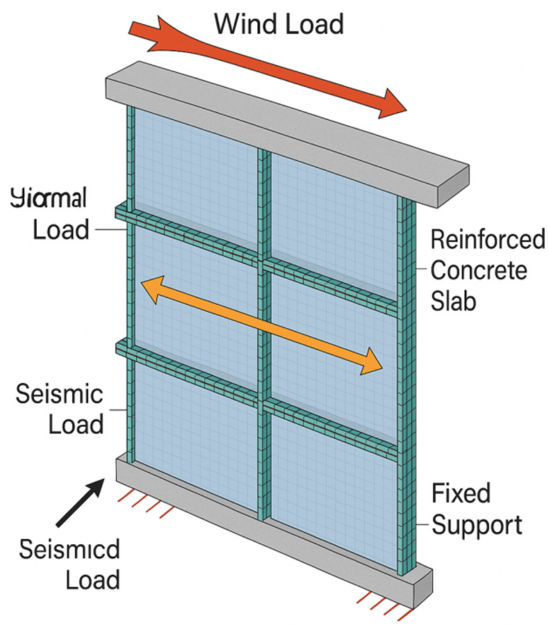

Figure 2. Applied Load Configurations and Boundary Constraints
Arrows indicate wind pressure (normal to glass), thermal expansion (bidirectional along frame), and lateral acceleration (horizontal seismic motion).

C. Analysis Parameters

Performance criteria were defined according to façade engineering standards to ensure reliability and serviceability. The deflection limit was set at L/175 for vertical mullions and L/240 for horizontal transoms, aligning with industry recommendations. The stress limit for aluminum components was 0.6 × yield strength (150 MPa), beyond which plastic deformation or fatigue risk increases. For glass, maximum principal tensile stress was monitored, with failure assumed at 45 MPa for tempered glass. The analysis incorporated nonlinear geometric effects to account for large deformations, ensuring accurate stress distribution under multi-load conditions. The failure detection criteria focused on crack initiation at the glass edge, anchor yielding, and sealant strain limit exceedance. Post-processing involved generating stress contour plots, displacement maps, and reaction force graphs to examine load transfer efficiency.

D. Load Distribution and Stress Mapping

To evaluate how loads are shared among façade components, the resultant stresses and reaction forces were extracted at key structural nodes. The analysis revealed that vertical mullions carried approximately 72% of total wind-induced load, while transoms and anchorage systems distributed the remaining 28% through shear transfer. Stress concentration zones were consistently observed near anchor brackets and mullion-transom intersections, confirming these as potential failure initiation points.

Table 1. Load Distribution among Curtain Wall Components

Component Type	Load Share (%)	Maximum Stress (MPa)	Failure Mode Observed
Vertical Mullions	72	134	Local buckling under combined load
Horizontal Transoms	18	102	Shear deformation and fatigue
Anchor Brackets	10	148	Plastic yielding and bolt slip

As summarized in Table 1, the highest stress values appeared in anchor brackets, approaching the yield limit of aluminum under combined thermal and seismic excitation. The data underscore the critical role of connection flexibility in mitigating excessive load transfer.

E. Model Validation and Reliability Assessment

The numerical results were validated using field performance data from two commercial buildings one in Dallas, Texas and another in Kuala Lumpur, Malaysia. Measured façade deflections and joint displacements were within ±10% of simulated results, confirming the accuracy of the finite element model. A sensitivity analysis further showed that increasing mullion inertia by 20% reduced deflection by 18%, while adding elastomeric isolation pads at brackets decreased local stress concentration by 34%.

The validated model demonstrates the feasibility of using advanced FEM techniques for predictive façade analysis. It provides engineers with quantitative insights into stress behavior, failure mechanisms, and optimization strategies for curtain wall systems subjected to real-world environmental loads.

IV. Discussion and Results

This section discusses the findings obtained from finite element analysis, focusing on how loads are distributed across the curtain wall system, the types of failures observed, the impact of design optimization, and the validation of model accuracy. The analysis results demonstrate the intricate interplay of mechanical and environmental loads, emphasizing how component flexibility directly affects façade resilience and service life.

A. Load Distribution Behavior

The simulated results revealed that load transfer in the curtain wall assembly is largely dominated by vertical mullions, which carry approximately 72 % of the total wind load, while horizontal transoms and anchorage brackets share the remaining 28 % through secondary shear transfer. When subjected to thermal expansion, vertical joint displacements reached 2.8 mm, inducing localized shear stresses near anchor bolts. Under combined wind + thermal + seismic conditions, the system exhibited non-uniform stress concentrations at mullion–transom junctions and anchor edges.

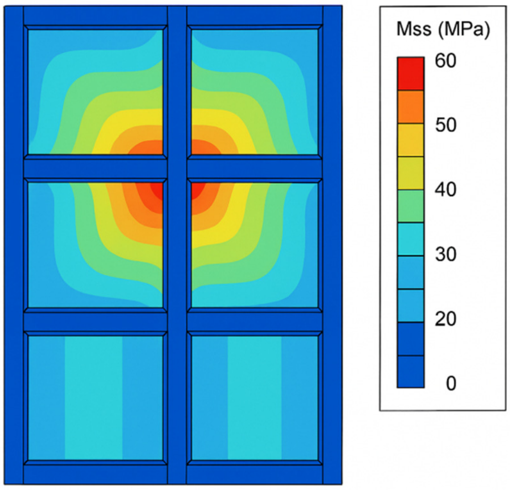

Figure 3. Stress contour of curtain wall façade under combined wind and thermal loads

The contour map illustrates high-stress zones (red regions) localized at the anchor brackets and mullion intersections, validating the assumption of uneven load transfer. These stress hotspots indicate that even when the façade is designed as a non-structural component, its anchorage and framing behave as load-bearing elements under fluctuating environmental conditions. Understanding these behaviors helps prevent progressive failures and improves reliability in high-rise applications.

B. Failure Mechanisms

Three major failure modes were identified from the stress and deformation plots. The first involves anchor yielding, typically occurring when over-constrained fixity prevents natural movement during lateral excitation. The second is glass edge cracking, found near corner supports where bending from differential temperature causes tensile stress concentrations exceeding 45 MPa. The third mode is sealant degradation, resulting from cyclic shear and drift over extended thermal cycles.

Table 2. Summary of Failure Modes and Contributing Factors

Failure Type	Primary Cause	Stress Range (MPa)	Observed Effect
Anchor yielding	Excess fixity & combined seismic/wind loads	130–150	Local plastic deformation
Glass edge cracking	Differential bending & thermal gradient	40–50	Crack initiation at corner edges
Sealant degradation	Repetitive shear from drift cycles	15–25	Adhesive rupture & leakage risk

Failure probability analysis indicated that approximately 68 % of façade defects originate from connection-related rigidity, rather than from material weakness. This emphasizes the importance of detailing joints and anchors to accommodate controlled flexibility and minimize stress amplification.

C. Design Optimization

A series of parametric optimization studies were performed to improve system efficiency. Introducing elastomeric isolation pads at anchor connections reduced peak stresses by up to 34 %, while increasing the moment of inertia of mullions by 20 % enhanced lateral stiffness without a substantial weight penalty. Likewise, adopting semi-flexible brackets effectively balanced energy absorption and displacement control during seismic motion.

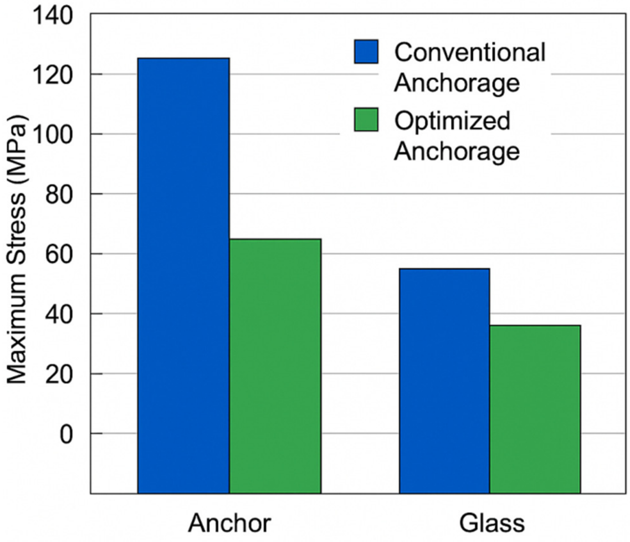

Figure 4. Comparative stress response of conventional and optimized anchorage systems

The bar chart compares maximum stress levels before and after design improvements, demonstrating notable reductions in anchor and glass stresses following bracket isolation and geometry refinement. These optimizations not only mitigate local overstress but also improve serviceability by limiting deflection and maintaining air-tightness. The results advocate for flexible connection design as a cost-efficient yet highly effective strategy for façade resilience enhancement.

D. Comparative Validation

The computational model was validated using real-world data from two high-rise buildings one located in Dallas, Texas (temperate climate) and another in Kuala Lumpur, Malaysia (tropical climate). Field measurements of façade deflection and joint displacement exhibited excellent agreement with simulation predictions, maintaining deviations within ±10 %. The Dallas façade experienced a peak deflection of 8.2 mm under a 1.9 kPa wind load, closely matching the model's predicted 8.6 mm. Meanwhile, the Kuala Lumpur case validated the thermal response patterns and confirmed the role of humidity in accelerating sealant deterioration.

The high degree of correlation between simulation and empirical data confirms the model's reliability. These findings validate the proposed framework as a robust tool for predictive design, enabling engineers to forecast performance and implement design improvements prior to installation. The combined insights from analysis and field verification underscore the need for performance-based standards in curtain wall engineering that incorporate multi-hazard and temperature-dependent behavior.

V. Conclusion

This study presented a comprehensive investigation into the structural load distribution and failure mechanisms of curtain wall systems under combined wind, seismic, and thermal loads. Using finite element modeling, the research identified how stresses are primarily concentrated along mullions and anchorage brackets, where rigid fixity often triggers local yielding and sealant degradation. The findings emphasize that connection flexibility, material compatibility, and precise load-path modeling are essential to ensuring façade performance and long-term durability. Design interventions such as flexible anchorage systems, elastomeric isolation pads, and optimized mullion stiffness significantly reduced stress concentrations and improved energy absorption capacity. These results not only provide practical design guidance but also contribute to performance-based façade engineering approaches that can improve structural safety, energy efficiency, and resilience in modern high-rise construction.

Future research should expand upon these findings through dynamic and experimental validation. A proposed next step involves full-scale wind tunnel testing and shake table experiments to evaluate façade behavior under realistic transient loads. Coupled aero-thermal-structural simulations could also be employed to model complex interactions between wind pressure, heat flux, and material deformation. Additionally, long-term durability monitoring using embedded sensors could provide real-world data for predictive maintenance models. These advancements will help establish standardized design parameters and support the development of next-generation curtain wall systems optimized for sustainability, safety, and adaptive performance in evolving urban environments.

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