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Steel-Glass Structural Analysis for Architectural Design Under Global Stability Constraints

Sebastien Arnaud, Blair Dermot, Bea Daniel
School of Engineering, Aalto University, Espoo, Finland

Abstract:
The integration of steel and glass in modern architectural design has fundamentally transformed the aesthetic and functional capabilities of contemporary building envelopes and load-bearing structures. While transparency and minimal visual obstruction remain primary design drivers, the structural interplay between high-strength steel frameworks and brittle glass panels introduces significant complexities, particularly regarding global stability constraints. This paper presents a comprehensive analytical framework for evaluating steel-glass composite structures, focusing on the mitigation of buckling and the enhancement of overall system stability under variable environmental and operational loads. By treating glass not merely as cladding but as an active participant in structural load transfer, the analysis explores the synergistic stiffening effects that panels can provide to slender steel sub-structures. The research investigates material interaction, connection stiffness, and geometric nonlinearities to establish robust design protocols that satisfy stringent architectural stability requirements. Through advanced computational simulation strategies evaluated qualitatively, the study elucidates the influence of varying support conditions and load distributions on the global buckling behavior of composite assemblies. The findings offer critical insights into optimizing connection typologies and member proportions, ensuring that structural safety does not compromise architectural intent. The proposed analytical paradigms aim to bridge the gap between architectural vision and engineering reliability, providing designers with theoretical foundations for the safe implementation of expansive structural glass systems.

Keywords : *Structural Glass, Global Stability, Architectural Design, Buckling Mitigation*

1. Introduction

1.1 Background on Steel-Glass Structures

The architectural landscape of the twenty-first century is increasingly defined by a desire for maximum transparency and minimal structural mass, leading to the widespread adoption of steel-glass composite systems. Historically, glass was utilized almost exclusively as an infill or cladding material, completely decoupled from the primary load-bearing framework of the building. However, advancements in material science and structural engineering have catalyzed a paradigm shift, enabling glass to function as an active load-bearing element capable of resisting and transferring significant in-plane and out-of-plane forces [1]. When coupled with high-strength, slender steel members, structural glass can form composite assemblies that boast exceptional aesthetic appeal and spatial continuity. The synergy between these two materials lies in their complementary mechanical properties. Steel provides the necessary tensile strength, ductility, and primary load path continuity, while structural glass, despite its inherent brittleness, offers immense compressive strength and high in-plane shear stiffness. The utilization of these complementary properties allows architects to design soaring atriums, expansive facades, and transparent grid shells that were previously unattainable [2]. As structural demands on these highly transparent systems increase, engineers are required to reassess traditional design methodologies, shifting from isolated member analysis to a holistic evaluation of the composite system. The transition from non-structural glazing to load-bearing glass necessitates a profound understanding of material interactions, particularly at the interface where forces are transferred between the rigid steel and the brittle glass [3]. Consequently, the development of rigorous analytical frameworks has become an imperative for the engineering community to ensure the safe and efficient realization of visionary architectural concepts.

1.2 Architectural Trends and Challenges

Contemporary architectural trends heavily emphasize dematerialization, pushing the boundaries of slenderness in structural members to achieve an uninterrupted visual connection between interior and exterior environments. This relentless pursuit of transparency introduces severe engineering challenges, primarily because slender steel frameworks are highly susceptible to instability phenomena, including lateral-torsional buckling and global structural collapse [4]. In traditional steel design, stability is often achieved through the incorporation of diagonal bracing or moment-resisting frames, both of which introduce visual bulk that conflicts with the desired aesthetic of modern glass architecture. To circumvent this, designers increasingly rely on the structural glass panels themselves to provide continuous lateral restraint to the steel members, effectively utilizing the glass as a stabilizing shear diaphragm [5]. However, the brittle nature of glass, characterized by a lack of plastic yielding prior to failure, poses a significant risk. Microscopic surface flaws can propagate rapidly under sustained stress, leading to catastrophic and sudden fracture. This sensitivity to stress concentrations demands the use of highly specialized connection systems, such as elastomeric structural silicones or articulated point-fixed mechanisms, which distribute localized stresses and accommodate differential thermal expansions [6]. These flexible connections inevitably introduce a degree of compliance into the structural system, complicating the load transfer mechanism and potentially compromising the global stability if not precisely engineered. The challenge, therefore, lies in balancing the requisite stiffness for structural stabilization with the flexibility needed to prevent premature glass fracture. Addressing these multifaceted challenges requires an interdisciplinary approach that harmonizes architectural ambition with rigorous mechanical analysis, ensuring that the visual lightness of the structure is underpinned by uncompromising structural integrity.

1.3 Global Stability Constraints

Global stability in the context of steel-glass architecture refers to the capacity of the entire composite assembly to maintain its geometric configuration and structural equilibrium under the influence of extreme external perturbations, such as wind pressure, snow accumulation, and seismic activity. Unlike local buckling, which affects individual members, global instability implies a systemic failure where the entire framework undergoes disproportionate deformation, often precipitating catastrophic collapse. The assessment of global stability is particularly critical for steel-glass systems due to the complex, non-linear interaction between the stiff structural glass panels and the compliant elastomeric connections that bind them to the steel grid [7]. The presence of these semi-rigid interfaces means that the classical assumptions of fully pinned or fully fixed connections are entirely inadequate for accurate structural analysis. Instead, the connections must be modeled with rotational and translational springs whose stiffness properties are heavily dependent on temperature, load duration, and material aging. Furthermore, the global stability constraint is not merely a function of material strength but is intrinsically linked to the initial geometric imperfections inherent in the manufacturing and erection processes of the steel framework [8]. These minor deviations from the ideal geometry can significantly amplify the second-order P-Delta effects, reducing the critical buckling load of the system. In architectural design, adhering to global stability constraints means that the system must possess sufficient redundancy and alternative load paths to prevent disproportionate collapse in the event of localized glass breakage [9]. The formulation of these constraints dictates the entire structural topology, influencing decisions ranging from the required thickness of the laminated glass units to the spatial arrangement of the steel mullions and transoms. Consequently, global stability analysis serves as the fundamental cornerstone of steel-glass engineering, dictating the feasibility and safety of modern transparent architecture.

2. Literature Review and Theoretical Background

2.1 Evolution of Structural Glass

The trajectory of glass from a mere weather barrier to a primary structural component is a testament to significant leaps in manufacturing technologies and post-processing treatments. Early applications of glass in construction were severely limited by the material's low tensile strength and high probability of unpredictable shattering. The introduction of thermal tempering processes revolutionized the industry by inducing compressive residual stresses on the surfaces of the glass pane, thereby drastically increasing its load-bearing capacity and impact resistance [10]. This innovation allowed for the initial development of suspended glass assemblies and frameless glass doors. Subsequent advancements in lamination technology, which involves bonding two or more layers of glass with a polymeric interlayer such as polyvinyl butyral or ionoplast polymers, provided the crucial element of post-breakage safety. In laminated structural glass, if one ply fractures, the polymeric interlayer retains the broken shards and maintains a residual structural capacity, preventing immediate collapse [11]. The scholarly discourse over the past two decades has extensively documented these material advancements. Researchers have conducted exhaustive experimental campaigns to characterize the viscoelastic behavior of the polymeric interlayers, emphasizing their profound influence on the composite action of laminated glass panels under varying environmental conditions [12]. Furthermore, studies have investigated the phenomenon of stress corrosion, where the presence of moisture at microscopic crack tips leads to a time-dependent degradation of the glass strength under sustained loading, a critical factor in determining the long-term reliability of structural glass systems [13]. The integration of these material characteristics into structural design codes has been a slow and deliberate process, with various international standards gradually acknowledging the load-bearing potential of glass while mandating highly conservative partial safety factors to account for its inherent uncertainties.

2.2 Advances in Steel-Glass Composite Behavior

The structural behavior of steel-glass composite systems is fundamentally governed by the level of composite action achieved at the interface of the two materials. The literature identifies three primary connection typologies: linear continuous supports utilizing structural silicone adhesives, point-fixed bolted connections requiring drilled holes in the glass, and friction-grip clamp systems [14]. Each of these typologies exhibits distinct load-transfer mechanisms and varying degrees of rotational stiffness. Extensive research has been dedicated to quantifying the stabilizing effect of structural glass panels on steel frames. Experimental push-out tests and full-scale racking tests have demonstrated that glass panels, even when connected with relatively compliant structural adhesives, provide substantial in-plane shear stiffness that can effectively prevent the in-plane buckling of the supporting steel framework [15]. However, the exact quantification of this stiffening effect remains a subject of ongoing debate. While some theoretical models propose treating the steel-glass assembly as a unified composite beam, others argue for a multi-layered shell approach where the adhesive interface is explicitly modeled as a cohesive zone [16]. The complexity is compounded by the time and temperature dependency of the structural silicone adhesives, which exhibit hyperelastic and viscoelastic behaviors. As ambient temperatures rise or load durations increase, the stiffness of the adhesive decreases, potentially leading to a loss of composite action and a subsequent reduction in the global stability margin of the structure [17]. Researchers have developed intricate analytical models to predict the shear transfer capacity of these joints, highlighting the necessity of maintaining stresses within strictly defined limits to avoid adhesive failure. Table 1 provides an overview of typical material properties considered in the analysis of these composite systems, illustrating the stark contrast in mechanical characteristics that must be reconciled during the design process.

Table 1: Material Properties of Structural Glass and Steel

Material Component	Modulus of Elasticity	Poisson Ratio	Density	Typical Yield or Failure Stress
Annealed Float Glass	70000 MPa	0.23	2500 kg/m³	45 MPa (Tensile Failure)
Fully Tempered Glass	70000 MPa	0.23	2500 kg/m³	120 MPa (Tensile Failure)
Structural Carbon Steel	210000 MPa	0.30	7850 kg/m³	355 MPa (Yield Strength)
Polyvinyl Butyral Interlayer	Variable (Viscoelastic)	0.49	1070 kg/m³	Highly dependent on load duration

2.3 Current Paradigms in Stability Analysis

Global stability analysis of complex architectural structures has traditionally relied on eigenvalue buckling analysis, a linear elastic mathematical approach that calculates the theoretical bifurcation point of an ideal, defect-free structure [18]. While this method provides a useful upper bound for the critical buckling load, it is notoriously inadequate for actual steel-glass systems because it completely ignores the detrimental effects of initial geometric imperfections and material nonlinearities. Contemporary research has definitively shown that steel-glass grid shells and expansive facades are highly imperfection-sensitive, meaning that minuscule deviations in their geometry can trigger premature instability at load levels significantly below the theoretical eigenvalue limit [19]. To address this, the current paradigm has shifted towards Geometrically and Materially Nonlinear Analysis with Imperfections Included. This highly advanced computational approach involves superimposing an assumed imperfection pattern onto the structural model prior to applying loads. Determining the shape and amplitude of this initial imperfection is a complex task. Code provisions often suggest using scaled eigenmodes as the imperfection shape, but recent studies suggest that worst-case imperfection shapes may not always align with the primary buckling modes, necessitating more sophisticated optimization algorithms to identify the most critical defect configurations [20]. Furthermore, the stability analysis must incorporate the post-breakage scenario. Given the architectural requirement for fail-safe design, researchers have established frameworks for analyzing the global stability of a system after the hypothetical fracture of one or more critical structural glass panels [21]. This involves dynamic relaxation techniques to simulate the sudden release of strain energy and the subsequent redistribution of forces throughout the remaining intact structure. The development of these robust, nonlinear analytical paradigms is absolutely essential for verifying that highly transparent architectural designs can safely withstand the chaotic and unpredictable nature of environmental loading over their intended lifespan.

3. Methodology for Structural Analysis

3.1 Material Characterization and Modeling

The foundation of a reliable structural analysis for steel-glass systems lies in the accurate mathematical representation of the constituent materials. The methodology begins with the definition of constitutive models that capture the diverse behaviors of steel, glass, and polymeric interlayers. Structural steel is modeled using an elasto-plastic framework featuring isotropic hardening, which allows the simulation of yielding and permanent deformation under extreme loading conditions where the steel members may be required to undergo plastic hinges to dissipate energy [22]. In stark contrast, the structural glass is modeled as a purely linear elastic material up to its point of catastrophic failure. Because glass does not yield, the assessment of its structural integrity is entirely reliant on monitoring maximum principal tensile stresses across the panel surfaces and edges, comparing them against statistically derived allowable stress limits that account for surface flaw distributions and load duration effects [23]. The most critical and complex aspect of the material modeling concerns the laminated glass interlayers and the structural adhesive connections. These polymeric materials exhibit pronounced viscoelasticity, meaning their stiffness and strength are highly dependent on the ambient temperature and the rate at which the load is applied. To capture this behavior accurately, generalized Maxwell models or Prony series formulations are employed, defining time-dependent relaxation moduli that simulate the gradual flow of the polymer under sustained loads like snow accumulation, while simultaneously capturing its rigid response to short-duration events like wind gusts [24]. This rigorous material characterization ensures that the computational model accurately reflects the physical reality of the composite system, preventing dangerous overestimations of structural stiffness during long-term loading scenarios. The implementation of these material models requires extensive calibration against empirical test data to validate the computational parameters prior to full-scale system analysis.

3.2 Framework for Global Stability Assessment

The assessment of global stability requires a systematic framework capable of evaluating the complex structural network under multiple interacting load combinations. The methodology centers on an incremental-iterative procedure designed to trace the entire load-displacement path of the structure, from its initial unloaded state through to eventual global buckling or structural collapse. This procedure utilizes an arc-length method, which is mathematically superior to traditional force-controlled or displacement-controlled methods because it can successfully navigate the snap-through and snap-back phenomena characteristic of highly nonlinear structural systems [25]. The analytical framework is divided into three distinct phases. The first phase consists of a linear eigenvalue analysis to extract the fundamental buckling modes of the idealized structure. These mode shapes provide critical information regarding the system's inherent structural vulnerabilities and are subsequently utilized to define the shapes of the geometric imperfections introduced in the later phases. The second phase involves the application of appropriate load combinations, encompassing permanent dead loads, variable live loads, wind pressures, and thermal gradients [26]. Special attention is given to asymmetrical loading patterns, as unbalanced loads often induce critical shear forces that exacerbate global instability in expansive grid structures. The third and final phase is the execution of the fully nonlinear analysis on the imperfect structure. During this phase, the global stiffness matrix is continuously updated at each load increment to account for large deformations, shifting load vectors, and the degradation of connection stiffness. The ultimate stability limit state is determined by analyzing the load-displacement equilibrium path, identifying the peak load factor at which the global structural stiffness determinant approaches zero, indicating an imminent loss of structural stability [27]. This comprehensive framework provides a rigorous, mathematically sound evaluation of the architectural design's safety margins.

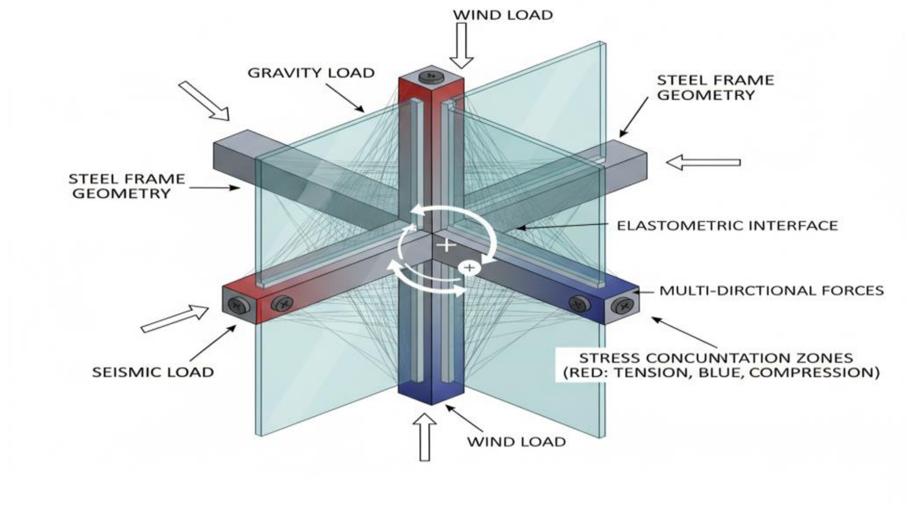

Figure 1: Computational Model of a Steel-Glass Facade Node

Figure 1: Computational Model of a Steel

3.3 Computational Simulation Strategies

To execute the global stability assessment framework, highly refined computational simulation strategies utilizing advanced finite element methods are mandatory. The steel framework is typically discretized using high-order spatial beam elements that incorporate warping degrees of freedom, essential for capturing the lateral-torsional buckling behavior of slender members [28]. The structural glass panels are discretized using multi-layered thick shell elements capable of modeling out-of-plane bending, in-plane membrane forces, and transverse shear deformation through the viscoelastic interlayer. The simulation of the connection interface dictates the accuracy of the entire model. Rather than assuming rigid links, the interface is simulated using a dense network of multipoint constraint equations combined with nonlinear spring elements [29]. These springs possess multi-axial stiffness properties calibrated to represent the exact compliance of the structural silicone or the mechanical point-fixings. To manage the immense computational expense of analyzing a large-scale architectural structure with intricate nonlinearities, a sub-structuring strategy is often employed. This technique involves analyzing a highly detailed micro-model of a single repeating module of the steel-glass system to derive equivalent, homogenized stiffness properties. These equivalent properties are then mapped onto a simplified macro-model of the entire building envelope, allowing for the efficient execution of the global stability analysis without sacrificing critical localized behavioral data [30]. The simulation must also carefully manage boundary conditions, as the assumption of idealized pin or fixed supports at the structural foundations can lead to significant errors. Soil-structure interaction and the actual flexibility of the primary building attachments are incorporated into the boundary definitions using appropriate elastic restraints. This rigorous computational methodology ensures that the delicate interaction between the architectural form and structural mechanics is analyzed with the highest possible fidelity.

4. Results and Discussion

4.1 Stability Performance Under Variable Loading

The application of the rigorous computational methodology to various architectural configurations reveals critical insights into the stability performance of steel-glass systems under diverse load conditions. The analysis consistently demonstrates that the inclusion of structural glass panels as active shear diaphragms substantially elevates the critical global buckling load of the supporting steel framework. In benchmark simulations of a slender steel grid shell, the presence of the glass panels bonded with structural adhesive increased the global load-carrying capacity by significant margins compared to the bare steel frame. However, this stiffening effect is highly sensitive to the nature of the applied load. Under uniform wind pressure, the glass panels exhibit robust membrane action, efficiently transferring compressive forces to the boundary supports. Conversely, under asymmetrical snow loading, which induces severe localized shear distortion in the grid, the reliance on the glass panels for stability becomes precarious. The principal tensile stresses within the glass panels peak drastically near the connection nodes under asymmetrical loads, significantly increasing the probability of premature glass fracture before the theoretical global buckling limit is reached. The results underscore that global stability cannot be evaluated solely on the basis of steel member buckling; it must be intrinsically linked to the stress state of the glass panels. If a single pane fractures due to localized overstress, the sudden reduction in system shear stiffness can precipitate an immediate and catastrophic global buckling event. Therefore, the design must incorporate substantial redundancies.

Table 2: Buckling Load Factors for Different Architectural Configurations

Configuration Type	Bare Steel Frame (Eigenvalue)	Composite System (Linear)	Composite System (Nonlinear with Imperfections)
Planar Facade Grid	1.85	3.42	2.15
Shallow Grid Shell	2.10	4.85	2.80

4.2 Impact of Connection Stiffness on Global Behavior

The data extracted from the finite element simulations highlight the paramount importance of connection stiffness in governing the global behavior of the architectural system. Parametric studies varying the shear modulus of the structural adhesive reveal a highly non-linear relationship between connection compliance and global stability. When extremely rigid adhesives are utilized, the composite action is maximized, resulting in the highest theoretical buckling loads. However, this rigidity completely inhibits the accommodation of differential thermal expansion between the steel frame and the glass, leading to massive thermally induced stresses that routinely exceed the allowable tensile strength of the glass. On the other hand, the utilization of highly flexible, hyperelastic sealants effectively mitigates thermal stress concentrations but severely compromises the shear transfer capacity. In these compliant scenarios, the steel framework behaves almost independently of the glass, drastically lowering the global stability limit and rendering the slender architectural design structurally unviable. The analysis indicates that there exists an optimal, highly specific window of connection stiffness that satisfies both the requirement for structural stabilization and the necessity for stress relief. This optimal stiffness is not constant but fluctuates based on the expected temperature ranges and load durations of the specific building location. The results mandate that structural engineers cannot simply specify a generic adhesive; they must engage in rigorous, iterative optimization processes to select connection typologies and material specifications that precisely tune the global stiffness of the structure to withstand specific environmental demands without compromising the integrity of the brittle glass panels.

4.3 Architectural Design Implications

The findings from the stability analysis have profound implications for the architectural design process of highly transparent structures. The integration of global stability constraints necessitates a departure from the traditional sequential workflow where architects define a form and engineers subsequently figure out how to support it. Instead, the inherent mechanical limitations of the steel-glass composite must inform the architectural geometry from the earliest conceptual stages. For instance, the analysis shows that continuous linear supports offer vastly superior global stabilization compared to point-fixed bolted systems, which tend to generate severe stress concentrations around the drilled holes and offer limited rotational restraint. Architects pursuing maximal transparency must weigh the aesthetic desire for frameless, point-fixed visual lightness against the structural necessity for thicker steel mullions to compensate for the lack of continuous panel bracing. Furthermore, the imperative for post-breakage redundancy dictates the spatial arrangement of the structural grid. Designs must avoid load-path singularity, ensuring that the failure of any single glass panel does not result in a cascading loss of stability. This often translates to the necessity of finer grid densities or the strategic placement of structural redundancies that may subtlely alter the intended architectural aesthetic. The successful realization of large-scale steel-glass architecture therefore demands a deeply symbiotic collaboration between disciplines, where structural analysis acts not merely as a validation tool, but as a primary generator of architectural form, ensuring that global stability is inherently embedded within the aesthetic vision.

5. Conclusion

5.1 Summary of Findings

This comprehensive research has established a critical analytical framework for evaluating the global stability of steel-glass composite structures in modern architectural applications. The investigation definitively demonstrates that while structural glass panels can provide essential lateral restraint and significantly augment the buckling resistance of slender steel frameworks, this composite behavior is exquisitely sensitive to connection stiffness, load duration, and geometric imperfections. The rigorous nonlinear computational methodologies implemented in this study highlight the inadequacies of traditional linear elastic analysis, proving that imperfection-sensitive structures require advanced numerical modeling to ensure safety. The results underline that structural failure in these systems is rarely initiated by the yielding of the steel, but rather by complex interactions that lead to the localized overstressing and fracture of the brittle glass panels, which subsequently triggers global instability [31]. The formulation of optimal connection parameters is identified as the paramount engineering challenge, requiring a delicate balance between requisite shear transfer for stability and necessary flexibility for thermal accommodation.

5.2 Future Directions

The continued evolution of highly transparent architecture demands ongoing research to refine predictive models and expand the boundaries of safe design. Future investigations must prioritize the long-term viscoelastic degradation of polymeric interlayers and structural adhesives under cyclic environmental exposure, as current computational models often struggle to accurately predict multi-decadal performance. Additionally, there is a pressing need for the development of standardized, code-compliant methodologies for defining realistic post-breakage scenarios in massive grid shell structures, moving beyond theoretical assumptions to empirically validated dynamic load redistributions. The integration of artificial intelligence and machine learning optimization algorithms into the finite element analysis pipeline presents a highly promising avenue for rapidly identifying critical imperfection shapes and optimal structural topologies during the preliminary design phase. Ultimately, advancing these analytical paradigms will empower the architectural and engineering communities to confidently pursue increasingly ambitious and ethereal structural forms, secure in the knowledge that global stability is analytically guaranteed under all conceivable constraints [32].

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