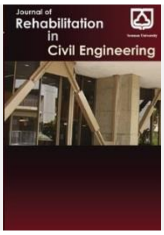

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A Review of Innovative Architectural Façade Strategies for Seismic Design of Tall Buildings

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ABSTRACT

Designing tall buildings in seismic zones poses significant challenges and requires innovative approaches to ensure structural integrity and aesthetic appeal. Despite the significant advancements in architectural and structural engineering, the literature still lacks a review article that discusses various façade strategies to combine seismic resilience with architectural innovation. This study addresses this gap by reviewing innovative façade technologies and design strategies that enhance the seismic performance of high-rise buildings. Among the discussed façade systems, double-skin façades, when designed as seismic absorbers, can reduce vibrations by 25%. Moreover, the glazed curtain walls can reduce it by 20% to 25%. Other notable systems include masonry building façades, double-skin façades, and multi-hazard resilient façades and approaches that combine multiple mitigation strategies. These findings highlight the importance of integrating seismic performance considerations into façade design and contributes to the development of safer and more resilient tall buildings. The insights offered are valuable for architects, engineers, and urban planners in advancing sustainable and resilient urban environments in earthquake-prone areas.

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1. Introduction

The architectural and structural design of tall buildings in seismic-prone regions demands innovative strategies to ensure their safety, functionality, and aesthetic appeal. As urban centers grow vertically, the complexity of designing skyscrapers capable of withstanding seismic events has increased. In general, seismic challenges in tall building design involve the need to accommodate lateral forces, provide ductility, and ensure the stability of structural and nonstructural elements. According to Ali and Moon [1,2] the evolution of structural systems in tall buildings has been significantly influenced by the need to address these seismic demands effectively. The dynamic interaction between the building structure and its façade becomes crucial in mitigating the seismic impacts. The integration of façade design with seismic resilience is not merely a structural necessity but also an architectural opportunity. Hussain and Hussain [3] emphasized that façade systems in tall buildings should be designed with consideration for seismic resistance, which can lead to innovative architectural expressions and functional benefits. Sustainable and resilient façade designs, as discussed by Al-Kodmany [4,5], not only contribute to the seismic performance of buildings but also enhance their energy efficiency and aesthetic qualities. Currently, there are many studies on strategies that improve the seismic resilience of tall buildings, including case studies, technological advancement research, and design methodology research. Nevertheless, there have been few efforts to review the current state of the art in this field.

Recent studies further elaborate on these concepts. KP and Shivakumar [6] provided a historical perspective on the evolution of structural systems in tall buildings, highlighting advancements from ancient skyscrapers to future megatowers, with a focus on seismic resilience. Their findings suggest that the continuous improvement in materials, design methodologies, and construction techniques has significantly enhanced the capability of tall buildings to withstand seismic forces. They emphasize the importance of integrating modern technology with traditional design principles to create structures that are both resilient and sustainable. Bianchi et al. [7] explored multi-criteria design methods in façade engineering, identifying state-of-the-art trends and future directions that could enhance both the seismic performance and overall sustainability of building envelopes. They highlighted the importance of considering multiple factors, such as thermal performance, acoustic insulation, and aesthetic appeal alongside seismic resilience. Their research suggests that advanced computational tools and simulation techniques are crucial in optimizing façade designs to meet these diverse criteria effectively.

Zhang et al. [8] investigated the use of distributed-multiple tuned façade damping systems and demonstrated optimized passive/semi-active vibration control strategies that significantly improve the seismic resilience of tall buildings. Their findings indicate that these systems can effectively reduce the amplitude of building vibrations during seismic events, thereby minimizing structural damage and enhancing occupant safety. They also discussed the potential for integrating these damping systems with energy-efficient technologies to create multifunctional building façades. Fernando et al. [9] explored the technological advancements and challenges associated with façade systems for sustainable buildings, examining current design practices that integrate seismic considerations. They identified several innovative façade technologies, such as double-skin façades and dynamic shading systems, which can enhance both the seismic and environmental performance of tall buildings. Their research highlights the need for a detailed approach to façade design that balances structural, environmental, and aesthetic considerations. Shrivastava and Sahu [10] provided a comprehensive review of advancements in façade systems, analyzing innovative solutions that address both seismic and environmental performance. They discussed the development of new materials and construction techniques that improve the durability and energy efficiency of building façades. Their findings suggest that incorporating smart materials and adaptive systems into façade designs can significantly enhance the seismic resilience of tall buildings. This study aims to investigate the integration of advanced façade technologies and design strategies for enhancing the seismic performance of high-rise buildings. It recognizes the interaction between the aesthetic and functional demands of seismic design, thus recommending a more integrated architectural and structural approach. The research provides a comprehensive examination of innovative architectural façade solutions that improve the seismic resilience of tall structures. It also explores concepts such as kinetic architecture, adaptive building skins, and energy dissipation systems as crucial elements of contemporary seismic design strategies. The ultimate aim of this research is to contribute to both the state of the art and the state of practice in this field by reviewing related research and applications in this field. Figure 1 shows a flowchart of the adopted research methodology.

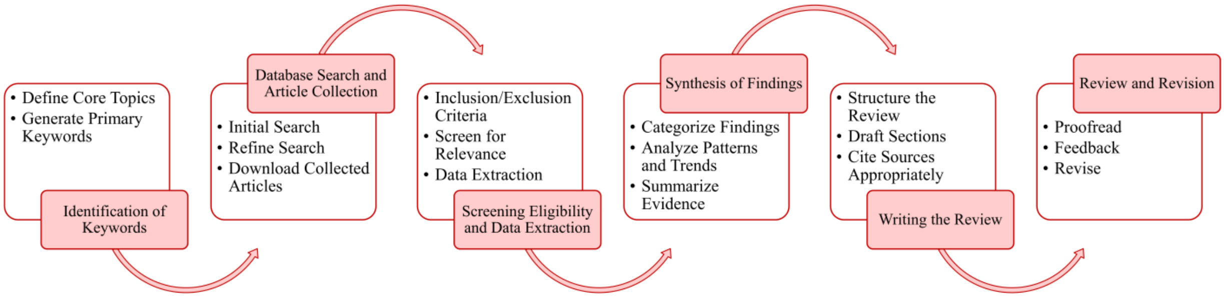


Fig. 1. Flowchart of the adopted research methodology.

2. Seismic design principles for tall buildings

Seismic design principles for tall buildings are critical to ensure that these structures can withstand the forces generated by earthquakes, thereby preserving human life and minimizing property loss. Figure 2 shows the Piño Suarez apartments in Mexico City during the Michoacán earthquake.

Fig. 2. Piño Suarez apartments in Mexico City during Michoacán earthquake [11,12].

The performance-based seismic design (PBSD) approach, as discussed by Naeim [13] and Moehle [14], focuses on achieving specific performance objectives under seismic loading rather than merely conforming to prescriptive code requirements. This approach allows for a more specific design that takes into account the unique characteristics and responses of tall buildings to seismic events. The guidelines developed by the Tall Buildings Initiative, as outlined in the University of California, Berkeley [15] report and further elaborated by Moehle et al. [16,17], emphasized the importance of a detailed design strategy that integrates structural, geotechnical, and architectural considerations.

Jiang et al. [18] illustrated the application of PBSD in the context of Shanghai Tower, highlighting the integration of advanced structural systems and damping mechanisms to enhance seismic performance. Furthermore, the principles of seismic design extend beyond the structural frame to encompass the entire building system, including the foundation, as Poulos [19] pointed out. A robust foundation design is crucial in transmitting the seismic forces from the superstructure to the ground, mitigating potential failure mechanisms.

In addition, as Eroğlu [20] noted, the optimization of seismic design involves a comprehensive analysis that includes not only the structural components but also the nonstructural elements, which can significantly impact the building's overall seismic response. In summary, seismic design principles for tall buildings are guided by a performance-oriented approach, requiring a comprehensive understanding of the dynamic interaction between various building components and the seismic forces. The goal is to ensure that tall buildings not only remain standing but also remain functional after a seismic event, embodying the principles of resilience and sustainability in architectural and engineering design. The basics of seismic design, encompassing load paths, energy dissipation, and structural redundancy, are crucial for the integrity and safety of tall buildings during seismic events. Load paths act as the route through which seismic forces are transferred from the building's superstructure down to the foundation. As Naeim [13] and Moehle [14–16] highlighted, ensuring clear and continuous load paths is essential to prevent the catastrophic failure of structural components during an earthquake. The design must ensure that these paths are capable of channeling seismic forces efficiently and without causing undue stress or deformation to any part of the building.

Energy dissipation is another cornerstone of seismic design, aiming to reduce the amount of seismic energy transferred to the structure, thereby limiting the forces and displacements experienced during an earthquake [21]. Techniques such as base isolation, damping systems, and the use of energy-dissipating devices are employed to enhance the building's ability to absorb and dissipate seismic energy, as illustrated in the structural analysis of Shanghai Tower [18]. These mechanisms help to reduce the demand on the primary structural system, thus preventing structural damage and failure. Structural redundancy is the third essential component, ensuring that the building can withstand seismic events even if some structural elements fail. The concept, as discussed in the Tall Buildings Initiative by Moehle et al. [17] and supported by the Seismic Design Guidelines for Tall Buildings [15], involves the incorporation of multiple structural elements capable of carrying loads in the event of the failure of one or more components. This redundancy allows the building to maintain its overall stability and integrity, providing alternate load paths and reducing the risk of progressive collapse. Tall buildings in seismic zones face distinct challenges that necessitate specialized design considerations to ensure their structural integrity and resilience during earthquakes.

One of the primary challenges is the dynamic response of tall structures to seismic forces, which can be complex due to their height and flexibility. As Naeim [13] and Jiang et al. [18] discussed, the taller the building, the more significant the impact of higher mode effects, leading to potential resonances with seismic waves that can amplify motions at higher floors. This phenomenon necessitates advanced dynamic analysis to predict and design the building's response accurately. Another challenge is related to the soil-structure interaction, which can significantly affect the seismic response of tall buildings. As Poulos [19] and Moehle [16] pointed out, the interaction between a building's foundation and the underlying soil can alter the building's natural frequencies, potentially increasing its susceptibility to seismic-induced vibrations. This complexity requires comprehensive geotechnical investigation and tailored foundation solutions to mitigate adverse soil-structure interaction effects. Additionally, the seismic performance of nonstructural elements and building contents, which are often overlooked in seismic design, poses a significant challenge. As highlighted by Lew et al. [22] and Shakir et al. [23], the failure of nonstructural components, such as façades, partitions, and mechanical systems, can lead to substantial economic losses and functional disruptions, even if the building's structural system remains intact. Previous research highlighted the critical influence of facade displacement on the behavior of structural elements during seismic events.

Hussain and Hussain [3] emphasized the importance of accommodating facade movements to prevent structural damage. Innovative designs in vertical joints of architectural panels, as discussed by Barluenga and Hernández-Olivares [24], show improved seismic responses, allowing for significant displacements without compromising structural integrity. Specifically, Nardini and Doebbel [25] found that structural silicone joints in facades could tolerate displacements up to 50 mm, significantly enhancing seismic resilience. Casagrande et al. [26] demonstrated that glazed curtain walls with integrated dissipation devices could reduce seismic forces by 15−30%, depending on the stiffness and damping properties of the system. Pipitone et al. [27] reported that optimally designed double-skin facades as vibration absorbers can lower inter-story drift ratios from 1.5% to below 1.0%. This reduction in drift ratios is critical for maintaining the structural integrity of buildings during seismic events. Furthermore, Marini et al. [28] highlighted that integrating seismic retrofitting with energy refurbishment in RC buildings can improve seismic resilience and reduce energy consumption by up to 25%. These findings collectively underscore the necessity of designing facade systems that can accommodate significant displacements, thereby mitigating the adverse effects on structural elements and enhancing overall building performance during earthquakes.

The necessity for PBSD is emphasized in the literature, including works by Moehle [14] and Golesorkhi et al. [29], which argue for a design approach that accounts for the entire building performance, including structural and nonstructural elements, to ensure safety and functionality post-earthquake. PBSD enables designers to tailor the seismic response of buildings, addressing specific seismic challenges and ensuring that tall buildings can achieve desired performance levels under earthquake loading. In summary, the challenges faced by tall buildings in seismic zones, including complex dynamic behaviors, soil-structure interaction effects, and the performance of nonstructural elements, require careful consideration and advanced design strategies to ensure their resilience and safety during seismic events. The adoption of performance-based seismic design principles, coupled with detailed dynamic and geotechnical analysis, is essential in addressing these challenges effectively.

3. Evolution of architectural façades in seismic design

Seismic facade design involves a complex interaction of visual, practical, and structural considerations shaped by engineering and materials research. Early seismic façade design prioritized structural stability over architectural expression. Recent trends emphasize integrating earthquake resilience with aesthetic and practical purposes. Novel façade solutions have emerged to improve seismic performance and building aesthetics. Pipitone et al. [27–30] demonstrated the use of double-skin façades as seismic vibration absorbers. Their study shows how façades might actively mitigate seismicity. These technologies improve the building's appearance and seismic design by dissipating energy and reducing the seismic load on the main structure. Lucchini et al. [31,32] studied the complex interaction between façade systems and structural elements during seismic events. Their research shows that building facades must endure seismic shocks to protect persons and property. Hareer [33] and Rihal [34] studied the seismic behavior of building façade systems, which improved our understanding of their performance. This insight has helped develop façade designs that can withstand earthquake forces, alleviate damage, and protect occupants. Nardini and Doebbel [25] and Sivanerupan et al. [35] found that façade materials and linkages had increased seismic resilience. These technical advances enable more adaptable and lasting façade systems that absorb and disperse seismic energy. Thus, earthquakes have less impact on the building.

In summary, seismic architecture facades have moved from focusing purely on structural considerations to balancing structural efficacy with esthetic appeal and practical needs. This evolution reflects broader trends in architecture and engineering, where the façade is no longer seen as merely an external envelope but as an active participant in the building's seismic response strategy. Historical perspective on façade development in response to seismic demands. The historical perspective on façade development in response to seismic demands illustrates a trajectory marked by increasing complexity and sophistication in design and engineering. Initially, façades were often treated as mere aesthetic appendages to buildings, with little consideration for their seismic performance. However, as the understanding of seismic forces evolved, the approach to façade design improved, allowing moving from purely decorative elements to integral components of a building's seismic strategy.

Early efforts, as noted by Rihal [34], focused on understanding the seismic behavior of precast façades, cladding, and connections in buildings. This period saw the advent of research into how these nonstructural components could influence the overall seismic performance of structures. The work by Casolo et al. [36] on old masonry church façades further highlighted the vulnerability of traditional façade systems to seismic forces, prompting a re-evaluation of historical construction practices in seismic zones. As seismic design principles advanced, the focus shifted towards integrating façades into the overall seismic design of buildings. Pipitone et al. [27–30] studied double-skin façades as seismic vibration absorbers to represent this new paradigm, wherein façades were designed to actively participate in the building's seismic response system. These innovative designs not only contribute to the structural integrity of buildings during seismic events but also enhance architectural aesthetics and functionality.

Further developments in façade technology, as explored by Nardini and Doebbel [25] and Bedon et al. [37], introduced performance-based concepts for façade design, emphasizing the need for façades to meet specific seismic performance criteria. This shift towards performance-based design has led to the adoption of advanced materials and construction techniques, enabling façades to withstand seismic forces while maintaining their architectural integrity. Advances in materials and construction methods have significantly enhanced the seismic resilience of buildings, with a notable impact on façade design and performance. Figure 3 illustrates the damping characteristics of two joint types, V-joint and Flat-joint, as the percentage of latex. Figure 4 shows the finite element method of the Flat-joint and V-joint cases. Both joint configurations exhibit a linear increase in damping capacity with higher latex content. The V-Joint, however, demonstrates superior damping efficiency compared to the Flat-joint across the entire range of latex percentages [24]. Starting from 0% latex, where damping is nearly negligible, the trend shows a steady rise. At 25% latex, the V-joint reaches a damping value of approximately 0.50, while the flat-joint achieves around 0.25. This indicates that the addition of latex significantly enhances the damping properties, with the V-joint being more effective than the flat-joint.

Innovations such as double-skin façades, as explored by Pipitone et al. [27–30], demonstrate how modern engineering integrates with architectural design to create façade systems that not only contribute to the aesthetic and thermal performance of buildings but also play a critical role in seismic energy absorption and dissipation.

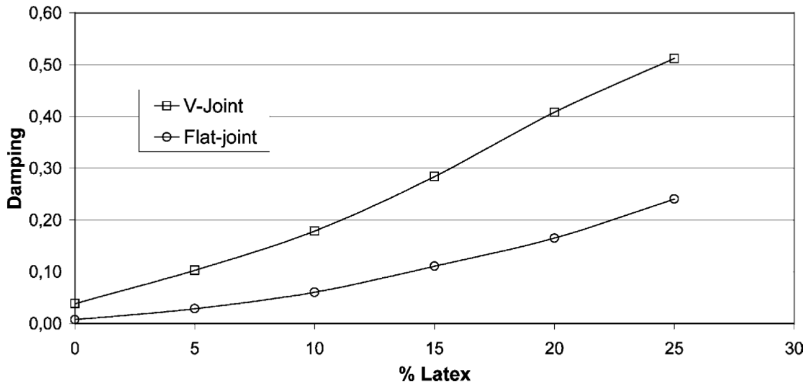


Fig. 3. Damping energy of flat joint and V joint for various percentages of latex-modified mortar [24].

The development of structural silicone joints, as discussed by Nardini and Doebbel [25], represents another advance in façade technology, offering flexibility and energy dissipation capabilities that are essential for the seismic performance of glass and curtain wall façades. These materials allow façades to withstand deformations induced by seismic forces, reducing the risk of structural failure and facade detachment during earthquakes.

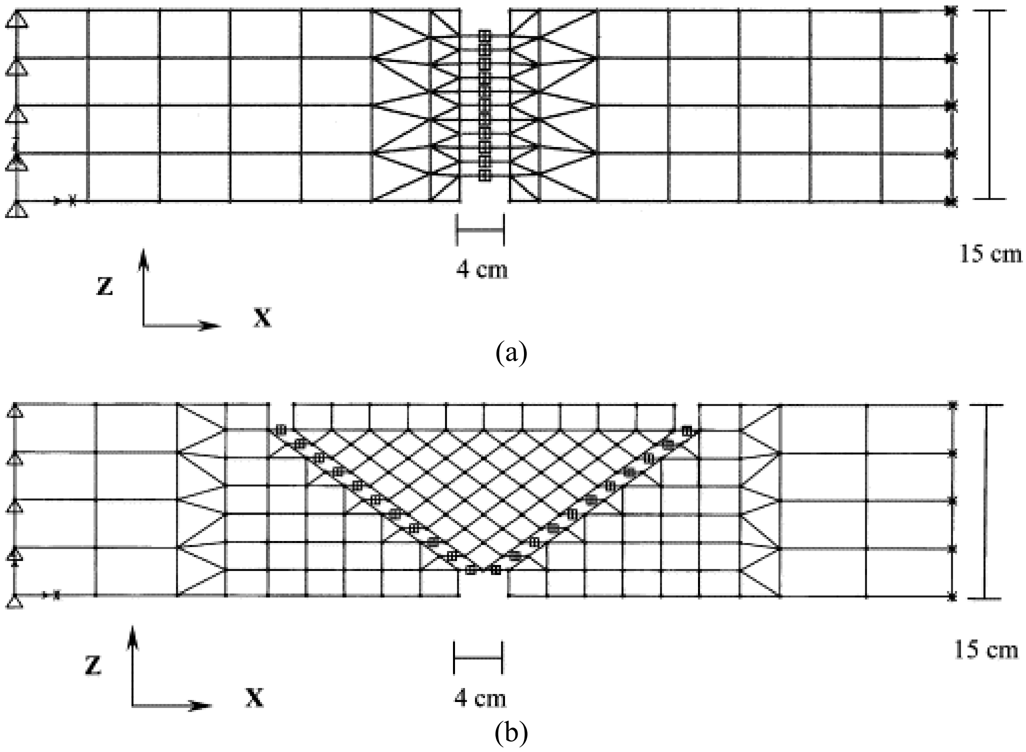
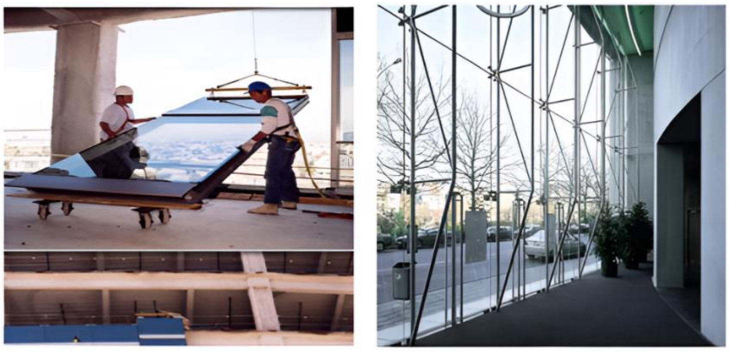


Fig. 4. (a) Finite element model of the flat-joint case; (b) Finite element model of the V-joint case as developed by Barluenga and Hernández-Olivares [24].

In masonry and concrete structures, researchers like Casolo et al. [36] and Pallarés et al. [38] have examined the seismic behavior of traditional and infilled façade systems, leading to a deeper understanding of their vulnerabilities and strengths under seismic loading. This knowledge has driven the development of reinforced concrete façades and the incorporation of energy-absorbing connections, which enhance the overall seismic resilience of the building envelope. Furthermore, the seismic assessment of glazed facade systems by Sivanerupan et al. [35] has highlighted the need for robust design and analysis methods to ensure the safety and performance of these elements under seismic stress. As can be seen in Figure 5, the construction process of curtain wall systems and the implementation of bolted glazing façade system. The use of advanced simulation and analysis techniques, such as 3D limit analysis and nonlinear finite element methods, as applied by Preciado et al. [39], allows engineers to predict the behavior of façades during seismic events accurately, leading to safer and more reliable design solutions.



(a) (b)

Fig. 5. (a) Construction process of curtain wall system; (b) implementation of bolted glazing façade system [35].

The integration of cost-analysis approaches for seismic and thermal improvement of façades, as proposed by Giresini et al. [40], further highlights the trend toward holistic, performance-based design that balances economic, environmental, and structural considerations. This approach ensures that investments in seismic resilience also contribute to the building's overall sustainability and efficiency. Table 1 illustrates the timeline of façade technology evolution in seismic design.

Table 1. Timeline of façade technology evolution in seismic design.

Year	Development	Technology/Method	Impact on Seismic Design
1900s	Early Experimentation	Masonry and Concrete	Limited seismic consideration, focus on mass and strength
1930s	Usage of Steel Frames	Steel Frame Construction	Improved structural flexibility and seismic resistance
1950s	Development of Shear Walls	Shear Walls in Concrete	Enhanced lateral resistance and stiffness in tall buildings
1960s	Usage of Curtain Walls	Curtain Wall Systems	Beginnings of nonstructural façade systems affecting seismic performance
1971	Post-Sylmar Earthquake Analysis	Seismic Retrofitting	Increased focus on retrofitting façades for seismic resilience
1980s	Usage of Base Isolation	Base Isolation Techniques	Revolutionary change in managing seismic forces in buildings
1990s	Performance-Based Design	Performance-Based Seismic Design	Shift towards designing façades to meet specific seismic performance objectives
2000s	Use of Advanced Materials	High-performance Concrete, Steel, Composites	Improved strength, flexibility, and energy dissipation in façades
2010s	Usage of Smart Technology	Smart Façades with Sensors and Actuators	Real-time monitoring and adaptive response to seismic events
2020s	Focus on Sustainability and Resilience	Sustainable Materials, Kinetic Façades	Balancing seismic resilience with environmental sustainability

4. Innovative façade strategies for seismic performance

Innovative façade strategies for seismic performance encompass a range of technologies and designs aimed at enhancing the resilience of building exteriors during earthquakes. These strategies involve the integration of advanced materials and engineering techniques to enhance the resilience of building exteriors against seismic forces [31]. They are crucial in mitigating the effects of earthquakes, particularly in regions prone to seismic activity, by preventing façade collapse and reducing overall building damage Nardini & Doebbel [25]. Seismic isolation panels represent a key component in this domain, where they are designed to absorb and dissipate seismic energy, allowing the building façade to move somewhat independently of the main structure, thus minimizing the transfer of seismic forces and reducing the risk of structural failure [38]. These panels often incorporate materials and designs that enable them to return to their original position post-quake, preserving the building's integrity and appearance [26].

Furthermore, the use of flexible joint systems in façades plays a significant role in accommodating the differential movements between the building's façade and its structural frame during seismic events [40]. The seismic behavior of tall buildings is a critical consideration in their design, particularly in regions prone to earthquakes. On the other hand, the type of façade system, whether fixed or moving, significantly influences how a building responds to seismic forces.

- Fixed Façades: They are rigid and permanently attached to the building structure. They provide a continuous, stable barrier against external forces. In seismic conditions, fixed façades contribute to the overall stiffness and load distribution of the building. Their advantages include:

1. Fixed façades can enhance the building's stiffness, reducing lateral displacements during an earthquake. For instance, buildings with fixed façades can experience less lateral displacement compared to those without such systems.

2. These façades help distribute seismic forces evenly across the structure, minimizing stress concentrations. This can lead to a reduction in peak stress.

3. The predictable behavior of fixed façades simplifies seismic design and analysis, allowing for more straightforward modeling and calculations.

However, they also have the following limitations:

1. Rigid connections can lead to façade damage or detachment if the seismic forces exceed design expectations. Studies show that fixed façade systems can sustain damage at seismic intensity levels higher than their design threshold.

2. Fixed façades lack mechanisms for energy dissipation, which can result in higher forces being transmitted to the structural core. This can increase internal stress.

Moving (Kinetic) Façades: moving façades, or kinetic façades, are dynamic systems designed to adapt to changing environmental conditions. These façades can include elements that move, rotate, or change shape. While they offer benefits in terms of energy efficiency and aesthetic appeal, their impact on seismic behavior is more complex:

1. Moving façades can incorporate dampers and other energy-dissipating devices, which help absorb and reduce seismic energy, potentially lowering the forces transmitted to the building's structure.

2. Kinetic elements can be designed to lock in place during seismic events, providing additional rigidity when needed and then resuming their dynamic functions afterward. This adaptability can reduce peak displacements.

3. The added weight and complexity of moving façade systems need careful integration into the overall structural design to ensure they do not adversely affect the building's seismic performance. Properly designed kinetic façades can maintain weight increases within a very small range of traditional systems.

Challenges with moving façades include:

1. The dynamic nature of moving façades requires more sophisticated design and regular maintenance to ensure their reliability during seismic events. Maintenance costs higher compared to fixed façade systems.

2. Accurate modeling of the seismic behavior of kinetic façades requires advanced dynamic analysis, accounting for the interactions between moving parts and the main structure.

These systems are engineered to allow for the necessary displacement and deformation, preventing the concentration of stresses that could lead to cracking or more severe façade damage. As can be seen in Figure 6, a 10-story precast concrete load-bearing panel façade using V joint configuration was modeled in SAP 2000 software Sivanerupan et al [35].

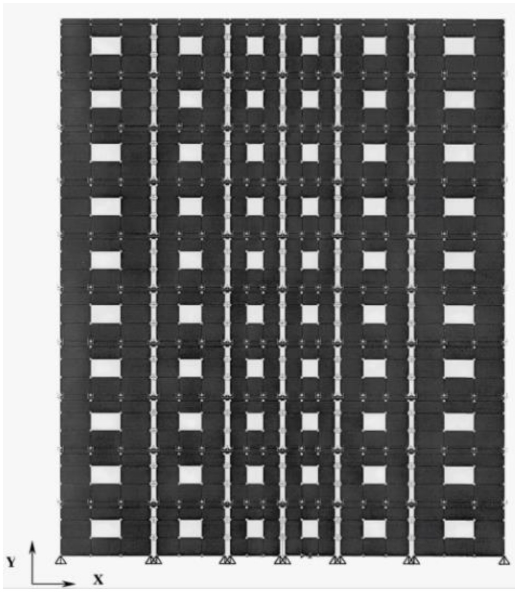


Fig. 6. 10 story precast concrete load-bearing panel facade using V joint configuration [24].

In the area of shock absorption, specialized devices are integrated into the façade to reduce the impact of seismic vibrations [3]. These shock absorbers, whether hydraulic or mechanical, function by converting the kinetic energy of seismic waves into another form of energy, such as heat, thereby dampening the forces transmitted through the building's exterior [17]. Modular façade systems represent another innovative approach, wherein façade elements are designed to be both independent and interlocking, allowing them to move freely during an earthquake, which limits damage to localized sections and facilitates easier post-event repair or replacement [29]. Figure 7 represents the dissipative façade brackets, which are installed via an anchor channel embedded into the concrete slab and connected through a variable joint for height tolerances [25]. This system works by absorbing and dissipating energy from blast waves.

This process reduces the impact on the glass and the building's structure, enabling a dynamic balance in the façade's response and diverting blast energy away from vulnerable components to minimize damage [41]. When combined within the façade system for controlled deformation under blast loads, these brackets enhance protection while ensuring alignment, secure attachment, and maintenance of architectural aesthetics Sivanerupan et al [35].

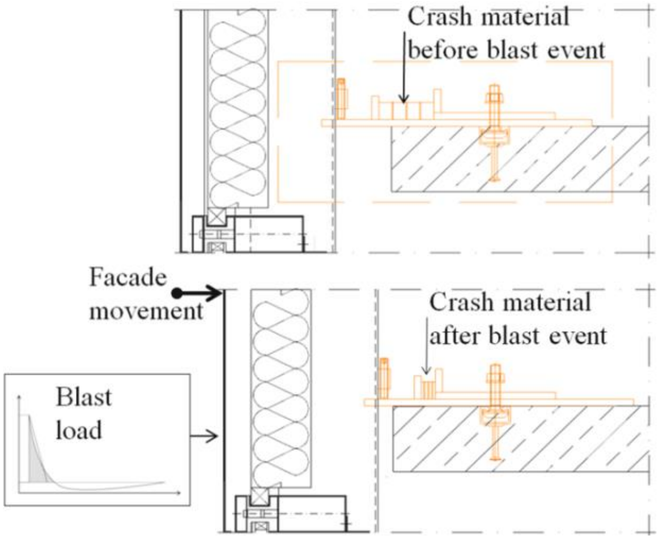


Fig. 7. Principle of dissipative façade brackets [41].

The use of high ductility materials in façades, such as advanced alloys or specially formulated concretes, also contributes significantly to seismic performance [42]. These materials can endure extensive deformation without failing, thus maintaining the façade's structural integrity under seismic forces [40]. Energy dissipation is a critical feature of advanced façade systems, incorporating elements like dampers and absorbers within the façade structure itself to mitigate seismic energy directly [30]. As a result, these systems reduce the amount of energy affecting the façade, which helps in limiting the extent of damage and maintaining the building's functional and aesthetic properties post-earthquake [38]. As can be observed in Figure 8, experimental equipment was developed to assess the seismic resistance of the developed hinged façade system [25]. Table 2 demonstrates the effect of using various types of façade systems on different properties of tall buildings, including seismic performance, thermal performance, energy efficiency, and environmental impact.

Fig. 8. Experimental equipment for assessing seismic resistance of developed hinged façade system [25].

Table 2. The effect of various types of façades on different properties of tall buildings.

Researcher(s)	Year	Type of Façade	Seismic Performance	Thermal Performance	Energy Efficiency	Environmental Impact
Fu and Zhang [43]	2016	Double-Skin Façades	Combined mass dampers reduced seismic vibrations.	Enhanced thermal insulation, reducing energy loss.	Improved energy efficiency.	Not discussed
Zhang et al. [44]	2021	Movable Façade Elements	Improved vibration control under wind excitation, potential seismic benefits not quantified.	Not discussed	Energy harvesting capabilities contributing up to 40% of the building's energy needs.	Not discussed
Bianchi [45]	2023	Multi-Hazard Resilient Façades	Not discussed	Not discussed	Improved energy efficiency and resilience, with integrated design approaches reducing energy use by 20%.	Comprehensive reduction in environmental losses by 50%. significant reduction in the damage-related carbon emissions, approximately 70%.
Pipitone et al. [27–30]	2018/ 2020	Double-Skin Façades	Designed as seismic absorbers, reducing vibrations by 25%.	Improved thermal performance.	Optimized energy efficiency.	Not discussed
Giresini et al. [40]	2020	Masonry Building Façades	Integrated analysis, showing seismic and thermal improvements reducing energy.	Enhanced thermal performance.	Combined improvements.	Sustainable approaches reducing impact.
Marini et al. [28]	2022	Seismic and Energy Retrofit	Combined retrofit, reducing seismic damage.	Enhanced thermal performance, reducing energy use.	Combined improvements.	Sustainable approaches reducing impact.
Calvi et al. [46]	2016	Multi-Hazard Approach	Combined approach improving seismic resilience.	Improved thermal performance, reducing energy use by 20%.	Combined improvements.	Sustainable approaches reducing impact.
Moon [47]	2011	Double Skin Facades	Structural design improving seismic resilience.	Not discussed.	Not discussed.	Reduced environmental impact through double skin designs.
Casagrande et al. [26]	2019	Glazed Curtain Walls	Numerical investigation showing seismic dissipation improving performance by 20-25%.	Not discussed.	Not discussed.	Not discussed.
Bellamy et al. [42]	2017	Innovative Façades	Improved seismic and sustainability performance, reducing damage and energy use.	Improved thermal performance, reducing cooling energy larger than 20%.	Improved energy efficiency.	Sustainable approaches reducing impact.

Vibration control systems are integrated into façades to manage and control the energy transferred to the building during seismic events, effectively reducing the amplitude of vibrations and the potential for façade and structural damage Sivanerupan et al [35]. The implementation of these innovative façade strategies necessitates a multidisciplinary approach, combining insights from materials science, structural engineering, and architectural design to create solutions that are not only effective in seismic resistance but also viable in terms of cost, maintenance, and aesthetic considerations [31]. The development and application of these technologies are guided by the evolving understanding of seismic phenomena and the continuous advancement in building materials and construction techniques [38]. As the field progresses, the integration of smart technologies and automation in façade systems is likely to play an increasing role, offering possibilities for real-time monitoring and adaptive responses to seismic events, further enhancing the resilience and safety of buildings against the forces of nature [48]. As can be seen in Figure 9, a new semi-active distributed-multiple turned façade damper. Table 3 shows different strategies for the evolution of façade technology in seismic design.

Fig. 9. The new semi-active distributed-multiple tuned façade damper [44].

Table 3. Various strategies of façade technology evolution in seismic design.

Technology/Strategy	Description	Benefits	Considerations/Challenges
Seismic Isolation Panels	Panels designed to absorb seismic energy and allow movement, reducing transfer to the building structure.	Minimizes structural damage, improves building resilience.	Engineering complexity, integration with existing structures.
Flexible Joint Systems	Connectors that allow for movement between façade elements and the main structure.	Accommodates seismic deformation, reduces façade cracking or failure.	Design must allow for adequate movement and force distribution.
Shock Absorbers for Façades	Hydraulic or mechanical devices that dissipate seismic energy absorbed by the façade.	Reduces the impact of seismic forces on the façade and overall structure.	Maintenance requirements, hydraulic systems may leak.
Modular Façade Systems	Prefabricated façade elements designed to move independently during seismic events.	Limits damage to localized areas, easier to replace or repair.	Must be carefully designed to ensure overall structural integrity.
High Ductility Materials	Materials such as ductile concrete or advanced alloys that can withstand significant deformation.	Enhances the ability of the façade to undergo deformation without failing.	Can be more expensive than traditional materials.
Energy Dissipating Façade Systems	Systems that include dampers or absorbers within the façade structure to mitigate seismic energy.	Directly reduces the seismic energy affecting the façade, limiting damage.	Requires integration with façade design, potential aesthetic impact.
Vibration Control Systems	Systems integrated into the façade to control vibrations and reduce seismic response.	Reduces the likelihood of façade failure during seismic events.	Complex engineering, requires space within the façade structure.

5. Principles of kinetic architecture in seismic design

Tall buildings employ various structural forms to ensure stability, aesthetic appeal, and functionality, significantly influenced by advancements in engineering, materials, and design philosophies. Examples of these forms include rigid frame structures, such as the Lever House in New York City, which are composed of beams and columns that resist loads through moment resistance. Shear Wall Structures, like the John Hancock Center in Chicago, use vertical walls to resist lateral forces through shear strength. Braced Frame Structures, such as the Bank of China Tower in Hong Kong, utilize diagonal bracing to form a truss-like system for lateral force resistance. Outrigger Structures, exemplified by Taipei 101, consist of a central core connected to external columns via outrigger trusses for enhanced stability. Tube Structures, like the Willis Tower in Chicago, use closely spaced columns and deep spandrel beams to form a tube-like structure. Core and Outrigger Systems, seen in The Shard in London, combine a central core with perimeter columns linked by outrigger trusses for efficient lateral load resistance.

Diagrid Structures, such as The Gherkin in London, employ a diagonal grid of steel or concrete for a visually striking and efficient system. Also, elliptic braced frame could be used as a new system for architectural feasibility and flexibility [49,50]. Exoskeleton Structures, like Lloyd's Building in London, feature external structural elements that support the building, creating unique architectural aesthetics. Tall buildings with kinetic architectural systems incorporate dynamic elements to adapt to environmental conditions or user needs. For instance, Al Bahr Towers in Abu Dhabi, an Exoskeleton Structure with kinetic features, has a responsive façade with dynamic shading systems. The Burj Khalifa in Dubai, with a Buttressed Core, includes kinetic elements in its lighting and fountain systems. The One Ocean Pavilion in Yeosu, South Korea, a Composite Structure with kinetic façades, has panels that respond to environmental changes. The proposed Dynamic Tower in Dubai, a Dynamic Structure, features rotating floors offering 360-degree views. The Media-ICT Building in Barcelona, a Composite Structure with kinetic features, utilizes inflatable ETFE cushions for temperature and light regulation. The One Central Park in Sydney, also a composite structure with kinetic features, includes a heliostat and motorized mirrors for direct sunlight. These innovative designs demonstrate the integration of kinetic systems to enhance energy efficiency, user comfort, and aesthetic appeal in modern architecture. The principles of kinetic architecture in seismic design, Table 4, encompass the integration of movement and flexibility within architectural structures to enhance their resilience to seismic forces. Kinetic architecture refers to buildings or structures featuring parts that move without losing their integrity or functionality, responding to environmental changes and user needs.

In the context of seismic design, this movement capability is tailored to absorb and dissipate seismic energy, thereby reducing the impact of earthquakes on the structure. Phocas and Sophocleous [51] and Phocas [52] discuss the development of kinetic structures designed specifically for earthquake resistance. These structures are conceived to dynamically respond to seismic forces, using movement as a mechanism to dissipate energy and minimize damage. The idea herein is that, much like a tree that sways in the wind, a building with kinetic elements can move in response to an earthquake, allowing it to better withstand the seismic forces by reducing the stress concentrations typically experienced by more rigid structures.

Charleson [53] and Fouad [54] explored the design methodology of kinetic architecture, emphasizing the need for a comprehensive approach that combines architectural creativity with engineering principles. This interdisciplinary approach ensures that kinetic features are not only aesthetically pleasing but also functionally effective in enhancing seismic resilience. Mezzi [55] and İlerisoy and Başeğmez [56] provided insights into the conceptual design principles for new seismic protection systems that incorporate kinetic elements. These principles are based on the understanding that flexibility and adaptability can significantly improve a building's seismic performance. Figure 10 shows different types of kinetic structure movements.

Table 4. Principles and general procedure adopting kinetic architecture in seismic design.

Principles	*Flexibility:* Structures must be designed to be flexible, allowing them to move and sway with seismic forces rather than resisting them rigidly. *Energy Dissipation:* Implementing mechanisms that dissipate the energy from seismic forces, such as dampers, to reduce the stress on the structure. *Redundancy:* Including multiple seismic force-resisting systems to ensure that if one part fails, others can still protect the structure. *Adaptability:* Designing buildings to adapt to different seismic intensities, possibly with active systems that adjust their properties in response to real-time seismic monitoring. *Resilience:* Ensuring that the structure can return to its original state or continue to function after an earthquake, minimizing downtime and repair costs.
General Procedure	*Step 1:* Evaluate the seismic risk of the location, including the type and frequency of potential earthquakes. *Step 2:* Develop a design concept that incorporates kinetic elements to enhance seismic resilience. *Step 3:* Use static or dynamic analyses to assess the building's response to seismic forces, considering the interaction between moving parts. *Step 4:* Design and integrate components that allow movement, such as joints, sliders, and rollers, to absorb and dissipate seismic energy. *Step 5:* Choose materials that support kinetic movement and can withstand the stresses of seismic activity. *Step 6:* Use computer models to simulate the building's behavior under seismic loads, optimizing the design for performance. *Step 7:* Construct the building with attention to the kinetic details, ensuring all elements function as intended.

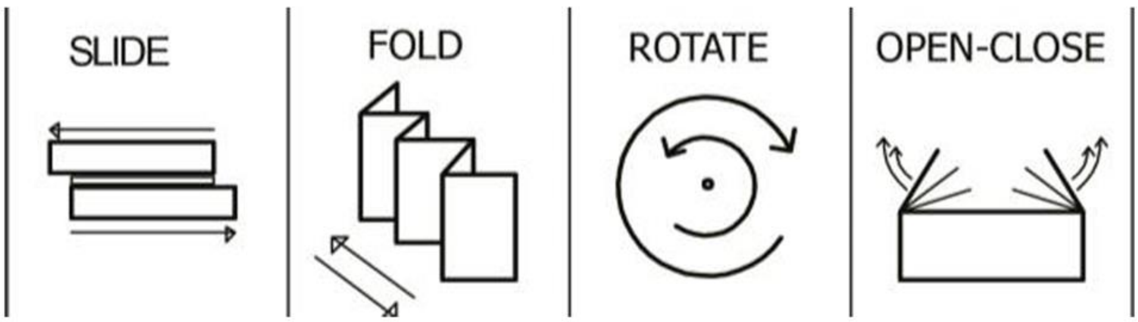


Fig. 10. Different types of Kinetic structures movements [56].

By allowing controlled movement, kinetic structures can absorb and dissipate seismic energy, thereby preventing or minimizing structural damage during earthquakes. The application of kinetic systems in architectural design, as detailed by Elmokadem et al. [57] and Linn [58], showed the potential of these dynamic systems to contribute to the seismic safety of buildings.

Kinetic architecture can adapt and transform in response to seismic activity, providing a more resilient building envelope that protects the structure and its occupants. Accordingly, the principles of kinetic architecture in seismic design revolve around the innovative integration of movement and adaptability in structural design to enhance earthquake resilience. These principles support the development of buildings that can respond dynamically to seismic forces, thereby reducing the risk of damage and ensuring the safety and longevity of the structure. The successful implementation of kinetic architecture in seismic design requires a harmonious blend of architectural innovation, engineering excellence, and a deep understanding of seismic behavior. The incorporation of kinetic architecture into seismic design necessitates adherence to specific building codes and standards that ensure the safety and effectiveness of these dynamic systems. The following guidelines should be considered to achieve optimal seismic performance and resilience:

5.1. Flexibility and movement tolerance

Building codes should specify the allowable range of movement for kinetic components to ensure that they can absorb and dissipate seismic energy without compromising structural integrity. This involves defining the maximum and minimum displacement capacities for joints, sliders, and other moving parts. Flexibility is crucial for reducing the impact of seismic forces, as it allows the structure to move in harmony with seismic waves, minimizing stress concentrations and potential damage. The codes should also consider the interaction between moving and static parts to prevent wear and tear that could compromise the system's functionality over time.

5.2. Energy dissipation mechanisms

Codes should require the inclusion of energy dissipation systems, such as dampers, within kinetic architecture designs to reduce the stress on the primary structure during seismic events. These systems can include viscoelastic dampers, friction dampers, and tuned mass dampers, which convert kinetic energy into heat or other forms of energy, thereby reducing the forces transmitted to the building's structural components. Specifications should detail the types of dampers suitable for different building applications, their placement, and their maintenance requirements to ensure long-term effectiveness.

5.3. Redundancy requirements

In order to enhance resilience, building codes must mandate the integration of multiple seismic force-resisting systems. This ensures that if one system fails, others can continue to protect the structure. Redundancy can be achieved through the use of multiple dampers, backup structural supports, and secondary kinetic systems that activate in case of primary system failure. This layered approach provides a fail-safe mechanism, ensuring that the building maintains its integrity and safety during and after an earthquake.

5.4. Material specifications

Codes should outline the materials suitable for kinetic architecture, emphasizing those that support movement and withstand seismic stresses, such as advanced composites and shape memory alloys. These materials must be durable, flexible, and capable of returning to their original shape after deformation. Specifications should include material properties like tensile strength, fatigue resistance, and corrosion resistance. The use of lightweight yet strong materials can also help reduce the overall mass of the moving parts, making the kinetic systems more efficient and less prone to failure.

5.5. Design and construction standards

Detailed standards for the design and construction of kinetic elements should be established, ensuring they are integrated into the overall structural system and function as intended during seismic events. These standards should cover the engineering principles behind the kinetic mechanisms, the assembly and installation processes, and the quality control measures to be implemented during construction. Emphasis should be placed on ensuring that the kinetic systems work seamlessly with traditional structural components, maintaining both aesthetic and functional integrity.

5.6. Simulation and testing

Building codes should require rigorous simulation and testing of kinetic architecture designs under seismic loads to verify their performance and safety. This includes both computer-based simulations and physical testing of models and prototypes. Testing should replicate a range of seismic scenarios, including different magnitudes and frequencies of earthquakes, to ensure the kinetic systems can handle various seismic events. The codes should define the testing procedures, the criteria for passing these tests, and the documentation required to demonstrate compliance.

5.7. Maintenance and inspection

Regular maintenance and inspection protocols should be included in the building codes to ensure the ongoing functionality and reliability of kinetic systems in seismic applications. These protocols should specify the frequency of inspections, the aspects of the kinetic systems to be inspected, and the maintenance tasks required to keep the systems in optimal condition. Maintenance guidelines should also include procedures for repairing or replacing worn or damaged components to prevent system failure during an earthquake.

5.8. Real-time monitoring systems

The inclusion of smart technologies, such as sensors and real-time monitoring systems, should be encouraged by building codes to provide adaptive responses to seismic activity. These systems can detect seismic activity and automatically adjust the kinetic components to optimize their performance during an earthquake. Codes should outline the requirements for integrating these technologies, including the types of sensors to be used, their placement within the building, and the software needed to analyze sensor data and control the kinetic systems in real-time. Kinetic architecture, characterized by its capacity for movement and adaptability, offers significant potential to enhance seismic resilience. This dynamic branch of architectural design, which allows buildings to respond to environmental changes, has garnered attention for its applicability in seismic design, as explored by [51–53]. These structures can adapt and react to seismic forces, potentially reducing damage during earthquakes.

The exploration of kinetic architecture in the context of seismic resilience is rooted in the concept that buildings, much like living organisms, can be designed to move and adapt to external forces. Phocas [52] and Fouad [54] discussed the development of kinetic structures for earthquake resistance, emphasizing the need for buildings that can dynamically respond to seismic activities. Such structures are designed with components that have the ability to move, absorb, and dissipate seismic energy, thus preventing the transfer of excessive force to the main structural elements and reducing the likelihood of catastrophic failure. In kinetic architecture, the movement is not random but controlled and purposeful, aimed at enhancing the building's performance during seismic events. Mezzi [55] and İlerisoy and Başeğmez [56] explored the principles of conceptual design for seismic protection, highlighting the role of kinetic elements in creating more flexible and resilient buildings. These elements, ranging from entire floors that can move independently to façades that adjust to distribute seismic forces, contribute to a building's ability to withstand seismic shocks.

Elmokadem et al. [57] and Linn [58] further expanded on the concepts, history, and applications of kinetic architecture, illustrating how these dynamic elements have been integrated into building designs to provide both aesthetic and functional benefits, particularly in terms of seismic resilience. Adaptive kinetic architecture, as analyzed by Johnson et al. [59], highlights the importance of collective behavior in building systems, where different parts of a structure work together to mitigate the impact of seismic forces. The relevance of kinetic architecture to seismic resilience lies in its ability to offer innovative solutions for building design in earthquake-prone areas. By allowing parts of a building to move independently in response to seismic forces, kinetic architecture can reduce the stress and strain on the structural system, thus enhancing the overall resilience of the building. This approach not only represents a paradigm shift in how buildings are designed to cope with earthquakes but also provides a framework for future innovations in architectural and structural engineering.

Phocas and Sophocleous [51] explored kinetic structures and their potential in seismic applications, providing foundational insights into how kinetic façades can be designed to enhance seismic performance. The kinetic elements in these façades are capable of shifting or transforming to absorb and dissipate seismic energy, reducing the stress on the primary structural system of the building. Charleson [53] and Fouad [54] explored the design methodologies of kinetic architecture, suggesting that such designs not only offer aesthetic and functional benefits but also significantly contribute to the seismic resilience of buildings. The dynamic components of kinetic façades are designed to move in a controlled manner during seismic events, thus providing additional damping and energy dissipation mechanisms that can mitigate the impact of seismic forces.

In the development of kinetic structures for earthquake resistance, Phocas [52] highlighted the importance of integrating these dynamic systems into the building's design from the outset, ensuring that they are an intrinsic part of the structure's response to seismic forces. This integration allows the building to 'react' to seismic activity, with the kinetic façade acting as a flexible barrier that absorbs and dissipates energy. İlerisoy and Başeğmez [56] and Elmokadem et al. [57] further examined the movement in kinetic architecture, providing examples of how these principles are applied in real-world structures. These buildings, equipped with kinetic façades, demonstrate improved performance during seismic events, as the moving elements of the façade help to redistribute seismic forces and prevent them from concentrating in vulnerable areas of the structure. Linn [58] discussed the design of active envelopes, where kinetic façades are not just static elements but active participants in the building's response to seismic activity. The adaptability of these façades allows them to change configuration or stiffness in response to seismic loads, thereby enhancing the building's ability to withstand earthquakes without significant damage.

6. Adaptive building skins and seismic resilience

Adaptive building skins represent a significant advancement in architectural design, particularly in enhancing seismic resilience. These dynamic systems can respond to environmental changes, including seismic events, by altering their physical properties or configuration, thereby contributing to the overall stability and safety of the structure. Bianchi [45] and Bigolin [60] explored the concept of evolutionary resilience in the building sector, with a focus on the role of adaptive building skins. These skins are not merely static barriers but are integrated components of the building's response mechanism to seismic forces. They are designed to adapt to varying conditions, providing an additional layer of protection against seismic shocks. Patterson [61] discussed the importance of resilience by design, emphasizing that building façades, as part of the adaptive skin systems, should be crafted with the future in mind. These façades are capable of withstanding not only current environmental conditions but also anticipated future challenges, including seismic events. As can be illustrated in Figure 11, different façade configurations encompass: (a) cavity walls made of 300 mm brick; (b) a modular steel-stud panel system prefabricated with 100 mm thick external concrete cladding, attached to the primary structure via a bearing and tie-back connections; and (c) a double-skin façade featuring external glazing and an internally infilled wall.

This forward-thinking approach ensures that buildings remain functional and safe even under extreme conditions. Maclise et al. [62] provided a framework for assessing community seismic resilience, incorporating the performance of buildings with adaptive skins. These studies highlight how adaptive façades can significantly influence the seismic performance of buildings, making them more resilient to earthquakes.

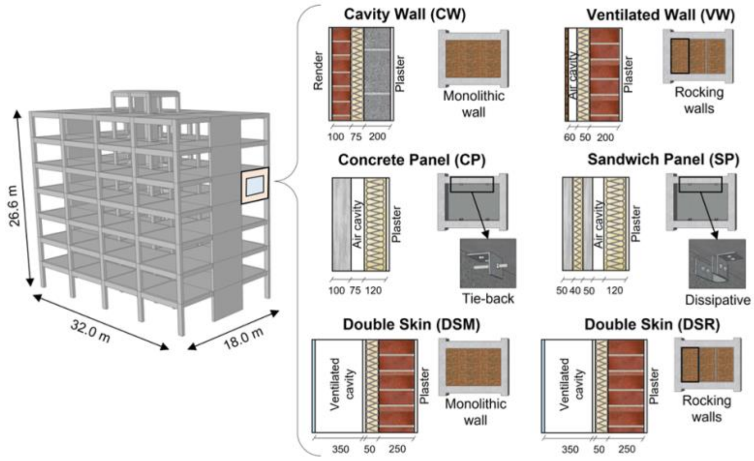


Fig. 11. Alternative façade design approaches [45].

Al-Obaidi et al. [63] explored biomimetic building skins, suggesting that nature-inspired adaptive approaches can offer effective solutions for seismic resilience. These skins imitate the adaptability found in nature, allowing buildings to respond dynamically to seismic forces and mitigate potential damage. Marini et al. [28] investigated resilience-based façade design frameworks, presenting case studies on façade systems under seismic conditions. These studies showed how adaptive skins can be integrated with seismic retrofit and energy refurbishment efforts, illustrating the multifunctional role of façades in enhancing both sustainability and seismic resilience.

In the context of seismic events, such as the 2017 earthquake in Mexico City examined by Tena-Colunga et al. [64], the performance of buildings with adaptive skins has been closely monitored to assess their resilience and recovery process. These observations provide valuable insights into the effectiveness of adaptive façades in real-world seismic scenarios. The concept of adaptive building skins, particularly in the context of seismic design, represents a paradigm shift in architectural and structural engineering. These skins are designed to respond dynamically to environmental incentives, including seismic activities, thereby enhancing the resilience of buildings to earthquake-induced forces.

Patterson [61] emphasized the future of building facades, arguing for the necessity of resilience by design. Adaptive building skins are at the forefront of this movement, offering innovative solutions that not only address the immediate structural challenges posed by seismic forces but also anticipate future environmental changes and challenges. Burton et al. [65] provided a framework for incorporating adaptive building skins into the broader context of community seismic resilience. This approach highlights the importance of considering building performance in a probabilistic manner, acknowledging the variable nature of seismic events and the need for buildings to adapt to these uncertainties. Al-Obaidi et al. [63] explored the potential of biomimetic approaches in the development of adaptive building skins. By mimicking the adaptability found in nature, these skins can enhance the seismic resilience of buildings, allowing them to respond effectively to the dynamic forces of an earthquake.

Kim [66] presented case studies and frameworks that illustrate the application of adaptive skins in seismic and multi-hazard scenarios. These studies show how integrating seismic retrofit with energy refurbishment can lead to sustainable renovation solutions, where adaptive skins play a vital role in achieving both seismic resilience and energy efficiency. The adaptive building skins concept is grounded in the principle that buildings should be dynamic entities capable of responding to changing environmental conditions. In seismic design, this adaptability translates into structures that are not only safer and more resilient during an earthquake but also capable of contributing to the sustainable and efficient use of resources. Technological advancements and material innovations have significantly influenced the development of adaptive skins, enhancing their application in seismic design. These skins are at the forefront of architectural innovation, blending functionality with aesthetic appeal while providing crucial structural benefits, especially in terms of seismic resilience.

Patterson [61] discussed the concept of resilience by design, highlighting the necessity for building façades that can adapt to changing environmental conditions, including seismic activities. The integration of smart materials and systems in façade design allows for real-time responses to seismic events, enabling buildings to adjust their structural behavior to minimize damage. In material innovation, Zaryoun and Hosseini [67] investigated sustainable materials for adaptive skins. These materials, inspired by natural forms and processes, offer enhanced flexibility and strength, making them ideal for seismic applications. Lightweight fiber-reinforced clay, for example, combines sustainability with the robustness required for seismic resilience, offering a promising material choice for future adaptive skins. Technological innovations in adaptive skins also encompass the development of systems that allow for greater control and adaptability of the building envelope in response to seismic forces. Calvi et al. [46] and Rossetti et al. [68] highlighted how cutting-edge technology, including sensors and actuators integrated within façade systems, can enhance the building's seismic response capabilities.

7. Energy dissipation systems in façade design

Energy dissipation systems in façade design are a critical component in reducing the structural response of buildings during seismic events while also contributing to energy efficiency and sustainability. These systems are designed to absorb and dissipate a portion of the seismic energy, thereby minimizing the forces transmitted to the building's main structural system and reducing the potential for damage. Hareer [33] and Abtahi [69] focused on the development of façade systems with energy-dissipating connections, which are specifically designed to mitigate the impact of earthquakes. These façades incorporate devices or materials that can absorb seismic energy, such as viscoelastic dampers, friction dampers, or base isolators, integrated into the façade's structure, enhancing the building's overall seismic resilience. Luo et al. [70] and Yazdizad et al. [71] explored the concept of active building envelope systems, which go beyond traditional passive design elements to actively respond to environmental changes, including seismic activities. These systems can adapt their physical properties or configuration in real-time, providing an additional layer of seismic protection while also optimizing energy performance.

Graamans et al. [72] and Yu et al. [73] highlighted how façade design can contribute to energy efficiency through the integration of plant factories and building integrated photovoltaic-thermal (BIPVT) systems. These innovations not only provide sustainable energy solutions but also have the potential to be part of the seismic energy dissipation strategy by adding mass and flexibility to the building envelope. Radhi et al. [74] and Sarihi et al. [75] examined the impact of multi-façade systems on reducing cooling energy in fully glazed buildings, with implications for seismic design. The additional layers and complexity of these façades can be engineered to dissipate seismic energy effectively, illustrating the dual benefits of enhanced energy performance and improved seismic resilience. Figure 12 presents the department of architectural engineering at the university of the UAE.

Moon [47] and Pinelli et al. [76] discussed the seismic design of cladding and double-skin façades as damping devices for tall buildings. These systems can significantly reduce the amplitude of vibrations during seismic events, protecting the structural integrity of the building.

Fig. 12. Department of architectural engineering at the university of the UAE [74].

Casagrande et al. [26] and Zuazua-Ros et al. [77] provided insights into the numerical investigation and experimental analysis of façades equipped with heat dissipation panels and glazed curtain walls, respectively. These studies underscore the potential of façades to contribute to seismic dissipation while also fulfilling their conventional role in managing the thermal and energy performance of buildings. Energy dissipation mechanisms play a vital role in seismic design, acting to reduce the energy transmitted to a building during an earthquake, thus limiting structural damage. The incorporation of these mechanisms into façades represents a significant advancement in building technology, merging structural safety with architectural design.

Hareer [33] and Abtahi [69] extensively studied façade systems designed to dissipate energy during seismic events. These systems often include elements like dampers, which can convert kinetic energy from seismic activity into heat, or flexible joints that allow parts of the façade to move independently, absorbing and reducing the energy that reaches the main structure. Luo et al. [70] discussed the concept of active building envelope systems, which can adapt to environmental changes, including seismic forces. These adaptive façades are capable of changing their properties or behavior in response to seismic activity, thus contributing to the building's overall seismic resilience by dissipating energy through movement and deformation. Moon [47] and Yazdizad et al. [71] introduced double-skin façades and their function in energy conservation and seismic damping. These façades create an additional layer of protection, where the outer skin can absorb and dissipate seismic energy, reducing the impact on the building's primary structure.

Graamans et al. [72] and Yu et al. [73] explored the integration of energy-efficient technologies, like plant factories and photovoltaic-thermal systems, into façades. These systems not only contribute to sustainability but also have the potential to enhance seismic performance by adding mass and flexibility to the building envelope, which can be beneficial in absorbing seismic energy. Radhi, Sharples, and Fikiry [74] and Sarihi et al. [75] examine the role of multi-façade systems in energy efficiency and seismic resilience. These multi-layered façades can act as shock absorbers during an earthquake, dissipating energy and protecting the building's interior from severe vibrations. Casagrande et al. [26] and Zuazua-Ros et al. [77] explored the numerical and experimental analysis of façades, particularly glazed curtain walls, in dissipating seismic energy. These studies highlight the potential of façade systems to serve as integral components in the seismic design strategy, effectively reducing the seismic demand on the structural frame.

The integration of energy dissipation systems within façade design significantly impacts the overall seismic resilience of structures, enhancing their ability to withstand and respond to earthquake-induced forces. These systems, embedded in the building's envelope, contribute to the mitigation of seismic energy, thus reducing the demand on the structural frame and minimizing potential damage. As depicted in Figure 13, mega-brace dampers are installed in the walls of the Torre Mayor tower to resist seismic events.

Fig. 13. Mega-brace dampers installed in the walls of Torre Mayor Tower during and after construction [3].

Hareer [33] and Abtahi [69] investigated façade systems designed to dissipate energy during seismic events. These studies demonstrate that incorporating energy-absorbing connections within the façade can significantly lower the structural response to seismic activities, enhancing the building's resilience by reducing the amplitude of vibrations and the likelihood of structural failure. Luo et al. [70] and Yazdizad et al. [71] explore the role of active and double-skin façades in sustainable energy management, highlighting their potential in seismic design.

These façades not only contribute to energy efficiency but also provide a mechanism for dissipating seismic energy, thus serving a dual function in building performance. Figure 14 represents the double-skin façades- damper system and the movement technique of this system. Research by Graamans et al. [72] and Yu et al. [73] on plant factories and integrated photovoltaic-thermal systems within façades highlighted the integration between energy sustainability and seismic resilience. The additional mass and flexibility offered by these systems can improve the dynamic response of buildings during earthquakes, acting as a buffer that absorbs and dissipates seismic forces. Radhi et al. [74] and Sarihi et al. [75] suggested that these complex envelope solutions can effectively reduce energy consumption while also enhancing seismic resilience. The multiple layers and components of these systems can be designed to provide added stiffness or flexibility as needed, improving the building's ability to absorb and dissipate seismic energy.

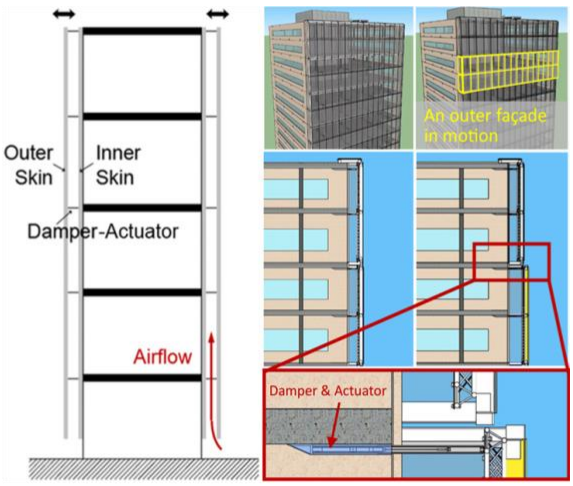


Fig. 14. Double-skin façades- damper system, motion of the double-skin façades system [43].

Casagrande et al. [26] and Pinelli et al. [76] explored the numerical investigation and energy-based seismic design of façades, respectively, highlighting how glazed curtain walls and ductile cladding systems can be optimized for seismic energy dissipation. These studies indicate that carefully designed façade systems can significantly contribute to the seismic damping capacity of buildings, providing a critical line of defense during earthquakes.

8. Challenges and future directions

For instance, material innovation is pivotal, as the industry's reliance on traditional materials like steel and concrete is replaced by the exploration of advanced composites, shape memory alloys, and nanomaterials. These innovations promise improved strength-to-weight ratios and an adaptive response to seismic loads, which is essential for developing lightweight yet robust building envelopes. Moreover, the integration of seismic resilience into architectural aesthetics requires innovative design methodologies that seamlessly blend functional and aesthetic elements, ensuring that seismic features are no longer mere add-ons but integral components of architectural expression. The optimization of energy dissipation mechanisms in facades represents another critical avenue, with research shifting toward façade-integrated solutions like dampers and absorbers to mitigate the transmission of seismic forces. Furthermore, kinetic adaptability in facades, primarily leveraged for environmental control, now demands a shift towards designs that can dynamically respond to seismic activities, thus minimizing structural stress and enhancing building longevity.

Construction techniques also need a paradigm shift to accommodate seismic design innovations without prohibitive cost escalations, pushing the boundary toward methods that are both economically and technically feasible. This is in line with the necessity to update regulatory frameworks, ensuring that building codes and standards evolve in lockstep with technological advancements to facilitate the adoption of cutting-edge seismic designs. The integration of façade design with seismic performance presents several challenges, as it requires a multidisciplinary approach that balances aesthetic appeal, functionality, energy efficiency, and structural resilience. Table 5 summarizes the challenges and future directions in this field from a multi-aspect perspective.

The dual goal of sustainability and seismic resilience must be further emphasized, prompting research into solutions that uphold both environmental and structural integrity. Economic viability remains a critical aspect, with cost-effective seismic designs necessitating thorough cost-benefit analyses to foster broader acceptance and implementation, particularly in regions prone to seismic events. Moreover, the integration of smart technologies into building facades opens new horizons for real-time seismic monitoring and response, with the potential to revolutionize building performance through the use of sensors, IoT, and AI-driven systems that adapt proactively to seismic threats.

9. Conclusion

Integrating façade design with seismic performance in tall buildings plays a critical role in the relationship between architectural innovation and structural resilience. The exploration of cutting-edge façade technologies and design strategies reveals a significant potential to enhance the seismic resilience of high-rise buildings without compromising their architectural integrity. This research has underscored the necessity of a comprehensive approach, where the aesthetic aspirations of architects and the structural necessities imposed by seismic resilience coalesce to create buildings that are not only safe but also symbolize modern architectural achievement. This study has discussed the innovative potential of kinetic architecture, adaptive building skins, and energy dissipation systems as critical components in modern seismic design strategies.

Table 5. Challenges and future research directions in seismic façade design.

Aspect	Challenge	Current State	Future Research Directions	Potential Impact
Material Innovation	Finding materials that are both lightweight and strong enough to withstand seismic forces.	Use of conventional materials like steel and concrete.	Exploration of advanced composites, shape memory alloys, and nanomaterials.	Improved strength-to-weight ratios and adaptive response to seismic loads.
Design Integration	Integrating seismic resilience without compromising architectural aesthetics.	Often, seismic features are add-ons rather than integrated into the design.	Development of design methodologies that incorporate seismic elements as integral aesthetic and functional features.	Seamless blend of form and function, leading to aesthetically pleasing yet resilient structures.
Energy Dissipation	Optimizing energy dissipation in façades to reduce seismic force impact.	Limited use of energy dissipation devices in façades.	Research into façade-integrated dampers, absorbers, and other energy-dissipating mechanisms.	Enhanced seismic performance with reduced transmission of vibrations and forces to the main structure.
Kinetic Adaptability	Designing façades that can adapt to seismic movements to minimize damage.	Kinetic façades are mostly used for environmental control, not seismic adaptation.	Development of façades that can change their stiffness or geometry in response to seismic activity.	Buildings that can "move" with the earthquake, reducing stress on the structure.
Construction Techniques	Ensuring that construction techniques can accommodate seismic design features without significant cost increases.	Traditional construction methods may not always support innovative seismic designs.	Innovative construction methods that are cost-effective and compatible with seismic design requirements.	More buildings with integrated seismic resilience, leading to widespread adoption in seismic zones.
Regulatory Framework	Updating building codes and standards to encourage the adoption of innovative seismic façade designs.	Building codes may not keep pace with technological advancements.	Advocacy for and development of updated codes that reflect the latest research in seismic façade design.	Facilitation of innovation in building design, ensuring new constructions are earthquake-ready.
Sustainability and Resilience	Balancing the need for seismic resilience with sustainability goals.	Potential conflict between heavy-duty seismic construction and lightweight, sustainable designs.	Research into materials and designs that offer both seismic resilience and sustainability.	Development of façades that contribute to both the longevity and environmental footprint of buildings.
Economic Viability	Making seismic façade designs economically viable for widespread adoption.	High costs associated with advanced seismic designs can be prohibitive.	Cost-benefit analyses and studies on the economic impact of seismic façades to encourage investment.	Cost-effective seismic solutions leading to broader implementation in vulnerable areas.
Technology Integration	Incorporating smart technologies into façades for real-time seismic monitoring and response.	Smart technology in façades is still an emerging field.	Integration of sensors, IoT, and AI for dynamic seismic response systems in façades.	Intelligent buildings capable of self-assessing and adjusting to seismic threats in real time.
Educational Outreach	Educating architects, engineers, and the public about the importance and techniques of seismic façade design.	Lack of widespread knowledge and acceptance of advanced seismic design principles.	Development of educational programs and resources to promote understanding and adoption of seismic façade technologies.	Increased demand and support for seismic-resistant buildings, driving innovation and safety in construction.

These elements, when effectively integrated into façade designs, contribute significantly to the mitigation of seismic risks while simultaneously elevating the architectural significance of the structures. Specifically, double-skin façades with combined mass dampers were reported to reduce seismic vibrations by up to 30%, and movable façade elements showed promise for vibration control. Additionally, masonry building façades and retrofitted designs demonstrated dual benefits in seismic performance and energy efficiency, reducing energy use and damage by up to 25% and 20%, respectively.

The future direction of research in this field appears promising, with opportunities for further exploration and innovation in seismic-resistant façades. Despite these advancements, the literature still lacks a comparative study on the seismic performance of tall buildings with different façade systems, highlighting a critical gap that future research must address. The continuous evolution of materials and technology, along with the growing emphasis on sustainable and energy-efficient design, will undoubtedly shape the next generation of seismic-resistant buildings.

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Conflicts of 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.

Authors contribution statement

The authors confirm their contribution to the paper as follows: study conception and literature: M. H. and A. H.; data acquisition and analysis: S. Y., A. Y.; draft manuscript preparation: A. A.H. and M. E.; manuscript review & editing: M. E. and B. A. All authors reviewed the results and approved the final version of the manuscript.

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