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Advances in Retrofitting and Rehabilitation of Steel Structures Against Progressive Collapse and Seismic Hazards:
A Systematic Review

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Abstract

The structural resilience of steel buildings against progressive collapse and seismic hazards is a critical concern in modern engineering. This study presents a systematic review of recent advancements in retrofitting and rehabilitation techniques aimed at improving the robustness of steel structures under extreme loading conditions. The review synthesizes findings from experimental, numerical, and theoretical research, emphasizing key resistance mechanisms, structural vulnerabilities, and innovative mitigation strategies. Experimental investigations highlight that enhanced beam-column connections, composite floor systems, and energy-dissipating components significantly improve collapse resistance. Large-scale tests confirm that catenary action, flexural resistance, and compressive arch action play crucial roles in load redistribution following local failure. Numerical studies, utilizing Finite Element Analysis and Applied Element Method, have refined predictive modeling, optimizing progressive collapse-resistant designs. Advanced retrofitting solutions, including bolted-welded hybrid joints and energy-dissipating devices, enhance ductility, load redistribution, and energy absorption. However, challenges such as high implementation costs, material degradation, and regulatory inconsistencies persist. Addressing these issues requires an integrated approach incorporating multi-hazard performance assessments, AI-driven predictive modeling, and advanced material innovations. This review highlights the need for harmonized design guidelines, experimental validation of emerging retrofit techniques, and computational optimization to develop cost-effective, scalable solutions for seismic and progressive collapse mitigation. By bridging research advancements and practical applications, this study contributes to the development of next-generation steel structures with enhanced safety, economic feasibility, and long-term structural integrity.

Keywords: **Steel structures, progressive collapse, seismic hazards, retrofitting, rehabilitation, structural resilience.**

1. INTRODUCTION

1.1 General Concepts

Steel structures are a cornerstone of modern construction, celebrated for their high strength, ductility, and adaptability. Their ability to withstand significant loads while maintaining relatively low weight makes them indispensable in various applications such as high-rise buildings, industrial facilities, and bridges. Prefabrication enhances their efficiency by allowing components to be manufactured under controlled conditions, ensuring superior quality, reducing material waste, and expediting on-site assembly. This process aligns with global sustainability goals by minimizing environmental impacts, noise pollution, and resource consumption[1,2].

Despite their advantages, steel structures are susceptible to extreme loading conditions, such as earthquakes, explosions, and accidental impacts. These events can trigger progressive collapse—a catastrophic chain reaction where a localized failure propagates through the structural system, leading to partial or total collapse. This phenomenon is particularly concerning due to inadequate redundancy in load paths and deficiencies in connection detailing[3,4].

Historical events, such as the Ronan Point collapse in 1968, the World Trade Center disaster in 2001, and the Windsor Tower fire in 2005, have underscored the critical need to address these vulnerabilities. These incidents served as wake-up calls, prompting significant advancements in design codes and retrofitting practices aimed at enhancing structural resilience. Fig.1 outlines major milestones in the evolution of safety standards for steel structures, from early collapses like Ronan Point to the introduction of modern guidelines such as UFC 4-023-03. These events highlight how engineering practices have evolved to mitigate progressive collapse risks [5,6].

To mitigate progressive collapse risks, various retrofitting techniques have been developed. The Alternate Load Path (ALP) method is widely employed to redistribute loads and prevent failure propagation, while the Tie Force

Method ensures continuity and resilience. Advanced materials such as fiber-reinforced polymers (FRPs) have revolutionized retrofitting by providing lightweight, corrosion-resistant solutions that effectively strengthen structural components[7,8]. Additionally, post-tensioning techniques have been adopted to introduce compressive forces that counteract tensile stresses during extreme events, enhancing structural stability[9].

Numerical modeling tools, particularly Finite Element Analysis (FEA), have enabled engineers to simulate complex collapse scenarios and optimize retrofitting strategies. These tools provide detailed insights into structural behavior, allowing for precise identification of vulnerabilities and the evaluation of solutions. Artificial intelligence (AI) has further advanced structural health monitoring by offering predictive maintenance capabilities and enabling early detection of potential failures, which enhances the safety and longevity of steel structures[10,11].

Despite these advancements, challenges persist. High implementation costs, especially in resource-constrained settings, remain a barrier to widespread adoption. Additionally, inconsistencies in design codes and standards across regions complicate the development of universally applicable solutions. The interaction between structural and non-structural elements, such as cladding panels and floor systems, also remains underexplored, despite their significant impact on overall stability during extreme events[12,13].

Addressing these challenges requires a collaborative approach that integrates research, innovation, and practical applications. Partnerships among academic institutions, industry stakeholders, and regulatory bodies are essential to develop cost-effective, efficient, and globally adaptable solutions. As the construction industry evolves, ensuring the resilience and sustainability of steel structures against progressive collapse and seismic hazards remains a paramount objective.

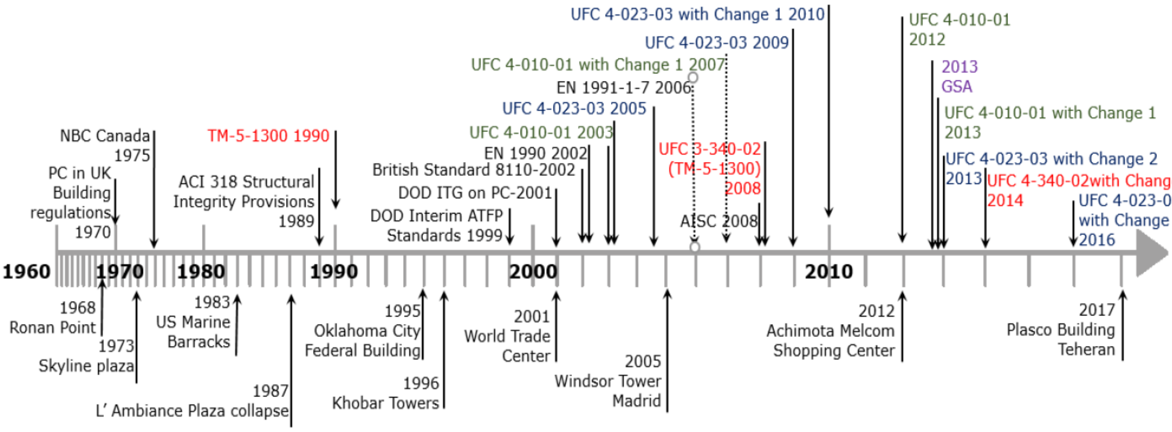


Fig. 1: Historical Timeline of Progressive Collapse Events and Design Code Developments [5,6].

1.2 Definition of Progressive Collapse

Progressive collapse is a catastrophic structural failure mechanism in which the failure of a single component or a localized area of a structure triggers a chain reaction, leading to the collapse of a disproportionately large portion or even the entire structure. This phenomenon often results from a combination of extreme loading conditions, structural vulnerabilities, and inadequate redundancy in load distribution systems. The American Society of Civil Engineers (ASCE 7-16) defines progressive collapse as “the spread of an initial local failure from element to element, resulting in the collapse of an entire structure or a disproportionately large part of it”[12].

This failure mode is characterized by the inability of a structure to redistribute loads effectively once a critical element fails (Fig.2). For example, the loss of a single column due to an explosion, impact, or seismic event can initiate a chain reaction where adjacent elements become overloaded, causing further failures and an eventual cascading collapse. Progressive collapse is particularly severe because it often leads to sudden and extensive damage, leaving little time for evacuation or intervention [13,14].

The phenomenon of progressive collapse can occur in different forms, including:

- Pancake Collapse: Typically seen in multi-story buildings, where floor systems collapse onto one another in a cascading manner.
- Zipper Collapse: Common in trusses and similar structures, where failure propagates sequentially along a weak axis.
- Domino Collapse: Often observed in tall and slender structures, where one element topples over and causes adjacent elements to collapse [15].

Historical examples of progressive collapse highlight its devastating consequences. The collapse of Ronan Point in London (1968) following a gas explosion and the World Trade Center collapse (2001) after the aircraft impact and subsequent fires are prominent cases that brought global attention to the importance of addressing progressive collapse in structural design. These incidents underscored the critical need for redundancy, robustness, and ductility in structural systems to prevent localized failures from escalating into widespread collapses[16,17].

Modern design practices aim to mitigate progressive collapse through various approaches, including:

- Alternate Load Path (ALP) Method: Ensuring that loads can be redistributed to other elements if one fails.
- Tie Force Method: Strengthening connections to provide continuous load transfer.
- Key Element Design: Reinforcing critical elements to withstand abnormal loads without failing[18,19].

Recent advancements in numerical modeling and simulation techniques, such as Finite Element Analysis (FEA), have allowed engineers to better understand the mechanisms of progressive collapse and evaluate the effectiveness of mitigation strategies. Moreover, the integration of innovative materials like fiber-reinforced polymers (FRPs) has further enhanced the resilience of structures by improving the strength and ductility of critical elements[20].

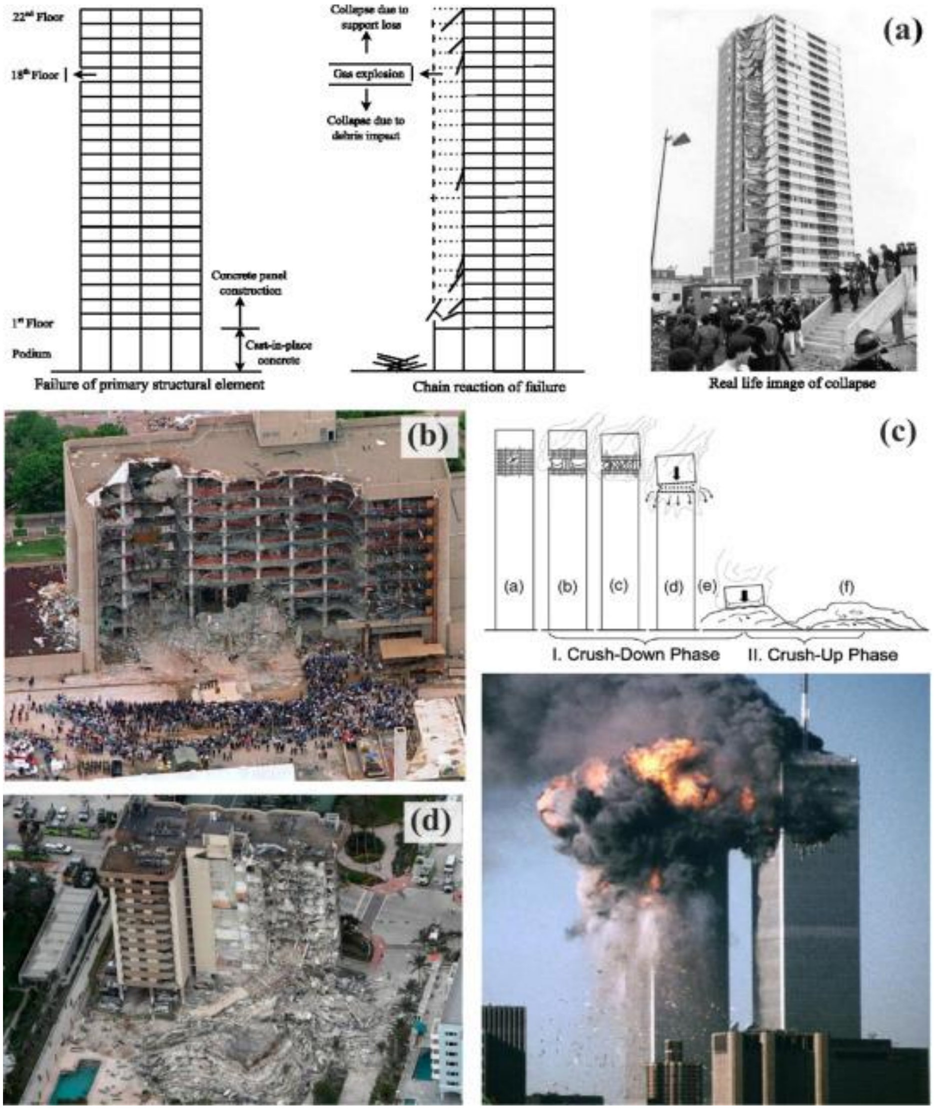


Fig. 2. Progressive collapse events: (a) Ronan point collapse sequence, adapted based on [21]; (b) Alfred P. Murrah Building after collapse [22]; (c) Predicted collapse scenario of WTC 1 and 2 [23] and Initial damage endured by WTC Twin Towers [24]; and (d) Champlain Towers South after partial collapse [25].

1.3 Resistance Mechanisms and Design Approaches Against Progressive Collapse and Seismic Hazards

The ability of steel structures to withstand progressive collapse and seismic hazards relies on a clear understanding of their structural behavior under extreme conditions. Progressive collapse is often mitigated using direct design approaches, such as the Alternate Load Path (ALP) Method, which ensures the redistribution of loads in case of localized failures, particularly the loss of a critical column. A detailed study of beam behavior reveals a sequence of resistance mechanisms: Flexural Action (FA), Compressive Arch Action (CAA), and Catenary Action (CTA). The initial Elastic Stage, illustrated in the figure, corresponds to the FA phase, where the beam resists applied loads through bending without permanent deformation. As the displacement increases, the beam transitions into the Flexural Stage, characterized by inelastic deformations. During this phase, the formation of plastic hinges enhances energy dissipation, ensuring structural stability while delaying failure.

In the CAA phase, the axial compressive forces generated in the beam lead to a significant increase in load-carrying capacity. This mechanism is particularly dependent on key factors such as cross-sectional dimensions, reinforcement detailing, and lateral restraints from beam-column connections. The effectiveness of this phase directly influences the overall stability of the structural system during extreme loading events.

The final CTA phase occurs when the beam experiences large vertical deflections, transforming it from a flexural element into a tensile one. At this stage, the beam resists loads primarily through tensile forces, effectively redistributing the applied loads and preventing progressive collapse. This phase, known as the Catenary Stage, provides an additional safety margin, ensuring that the structure remains stable even after significant damage.

Fig. 3 illustrates the progression of structural behavior in beams during extreme loading scenarios. The load-displacement curve highlights the performance of proposed steel connections compared to traditional ones, emphasizing the improved load-carrying capacity and ductility achieved through advanced design strategies. In the CTA phase, enhanced connections sustain additional tensile forces, preventing further collapse and improving resilience under extreme deflections.

The axial force-displacement curve in the figure further emphasizes the importance of connection detailing in achieving full Catenary Action. Proposed steel connections exhibit higher tensile capacity and better performance in resisting large displacements compared to traditional designs. These observations underline the critical role of innovative materials, such as high-strength steel and fiber-reinforced polymers (FRPs), in enhancing structural performance.

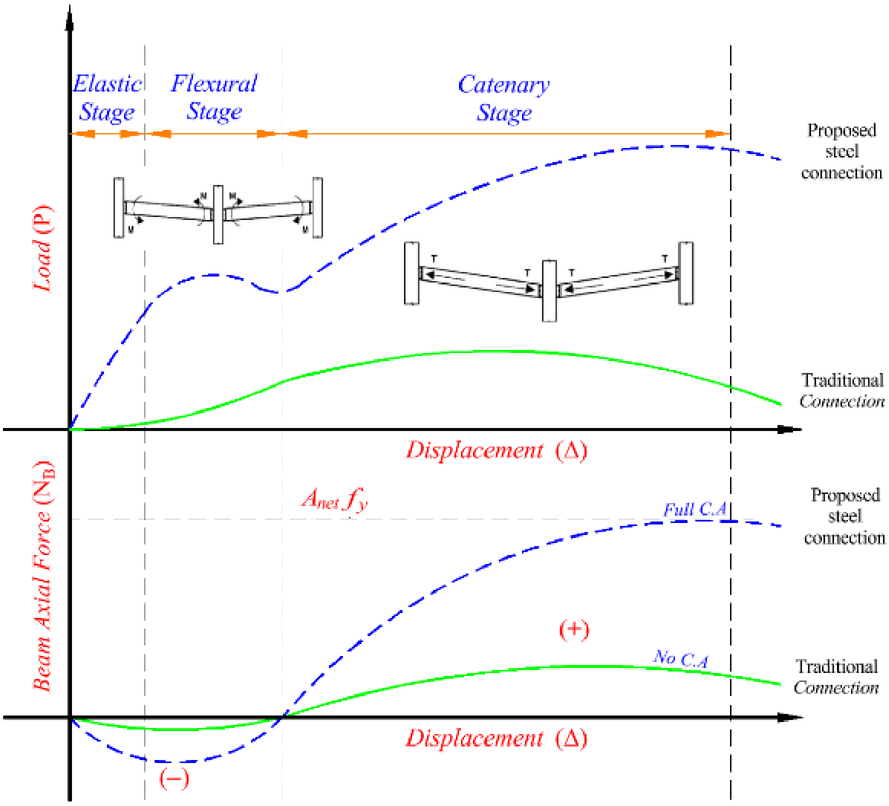


Fig. 3: Formation of catenary behavior in beams.

1.4 Impact on Infrastructure Safety and Economy

The resilience and safety of steel structures are critical in enhancing the stability of infrastructure and the economy. Modern design techniques, such as alternate load paths and moment-resisting systems, play a key role in reducing the risks of progressive collapse and seismic hazards, ensuring the protection of lives and minimizing physical damage [12,23. Economically, investing in performance-enhancing structural technologies, such as seismic isolation systems, energy dissipation devices, and advanced retrofitting methods, significantly reduces costs associated with repairs or catastrophic collapses. These technologies provide long-term stability and minimize indirect costs resulting from business disruptions or the failure of essential services [14,20].Additionally, advanced engineering solutions, such as optimizing connection designs and analyzing dynamic responses using precise simulation models, improve the structures' resistance to unforeseen impacts. These efforts not only enhance safety but also ensure the sustainable operation of critical infrastructure, such as hospitals and transportation systems, thereby supporting local economic stability and boosting investor confidence [26].

2. SIGNIFICANCE OF THE CURRENT LITERATURE REVIEW

This literature review holds significant value in advancing the understanding of resistance mechanisms and design strategies for mitigating progressive collapse in steel structures. By critically analyzing existing studies, this review bridges knowledge gaps and provides a comprehensive overview of the current advancements in the field. It evaluates the performance of steel structures under various failure scenarios, focusing on deformation capacity, load redistribution mechanisms, and the role of advanced connection designs in enhancing structural integrity.
The review is particularly significant as it consolidates findings on critical factors, such as the role of catenary action, moment-resisting connections, and innovative retrofitting techniques in preventing progressive collapse. These insights are not only valuable for academics but also for practicing engineers seeking to apply state-of-the-art methods in designing safer and more resilient steel structures. Furthermore, this review highlights the limitations of current research, offering a roadmap for future investigations into unaddressed areas, including the dynamic behavior of large-scale steel assemblies and the integration of advanced simulation tools in design validation. In addition to its academic contributions, this review provides a practical foundation for updating building codes and engineering guidelines. By addressing how steel structures can be designed and retrofitted to withstand abnormal loads, the findings of this review directly contribute to enhancing infrastructure safety and economic sustainability.

3. BIBLIOMETRIC DETAILS

3.1 Research Trends on Progressive Collapse Resistance in Steel Structures

A comprehensive bibliometric analysis was conducted to evaluate research trends in the field of progressive collapse resistance in steel structures. Utilizing databases such as Scopus, Web of Science, and Google Scholar, the analysis covered studies published up to January 2025. Search keywords included "progressive collapse," "alternate load paths," and "steel structures," combined with terms like "experimental studies," "numerical models," and "theoretical analysis."

Key Observations:

1. Growth in Research Output:
   As shown in Fig. 4, there has been a steady increase in research output over the past decade. Experimental studies dominate the field, reflecting a focus on validating theoretical models and improving empirical evidence. Numerical and theoretical studies have also seen consistent growth, driven by advancements in simulation tools and computational methodologies.

2. Focus on Experimental Studies:
   Experimental investigations focus predominantly on beam-column sub-assemblages, which are critical in redistributing loads during progressive collapse scenarios. These studies emphasize the role of advanced connection designs in enhancing structural resilience.

3. Advances in Numerical Modeling:
   Numerical studies, including finite element analyses, have grown substantially. They enable the exploration of various design parameters, such as connection details and material properties, under extreme loading conditions.

4. Integration of Theoretical Frameworks:
   Theoretical studies provide essential insights into load redistribution mechanisms, including catenary action and compressive arch action. These frameworks form the basis for developing effective design guidelines.

3.2 Focus of Studies on Structural Elements

The bibliometric analysis also highlights the distribution of studies across different structural elements, as shown in Fig. 5:

- Beam-Column Connections (50 studies): These serve as critical points for load redistribution, receiving the highest research focus.
- Beams (35 studies): The response of beams during column removal scenarios and their ability to develop arch and flexural action are key areas of investigation.

- Columns (25 studies): Columns are studied primarily in the context of cascading failures and their role in structural redundancy.

- Slabs (20 studies): Research emphasizes the ability of slabs to transfer loads across spans and their susceptibility to punching shear failures.
- Foundations (15 studies): Despite their importance, foundations remain underexplored, highlighting a gap in understanding their interaction with other structural elements during progressive collapse.

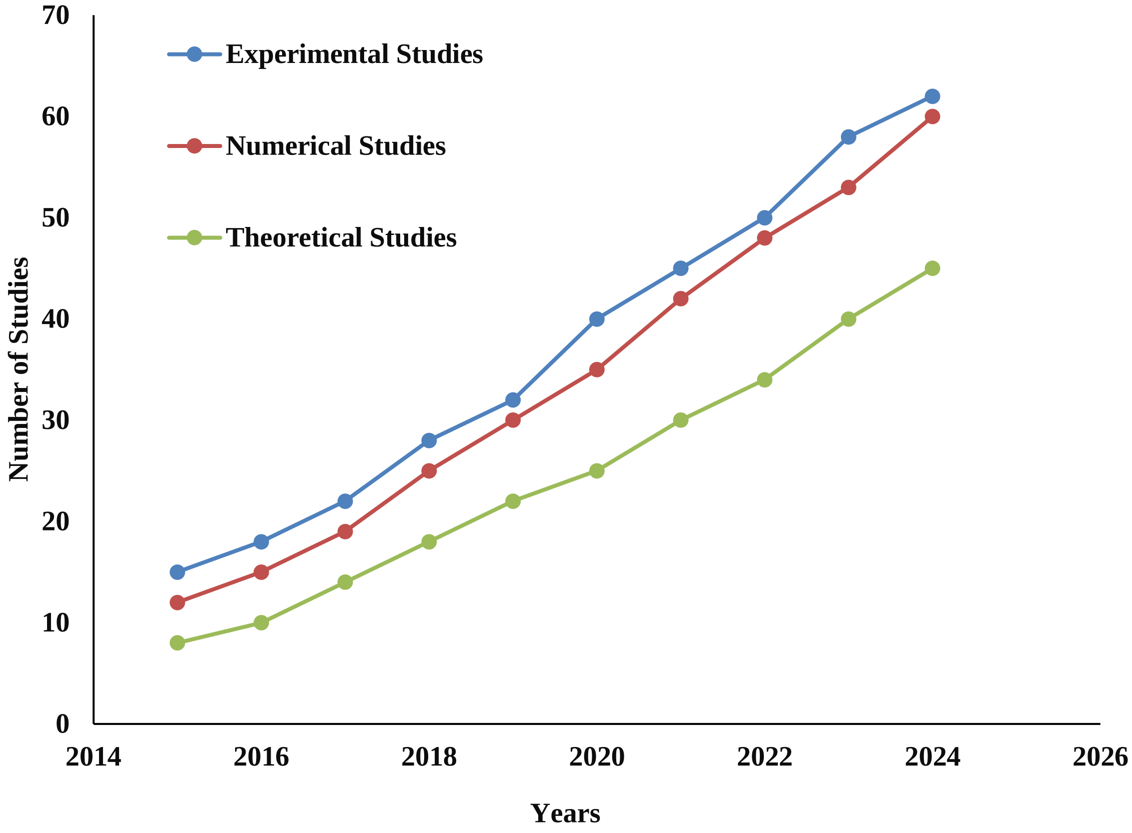


Fig. 4: Trends in research output for experimental, numerical, and theoretical studies, illustrating significant growth in all three categories.

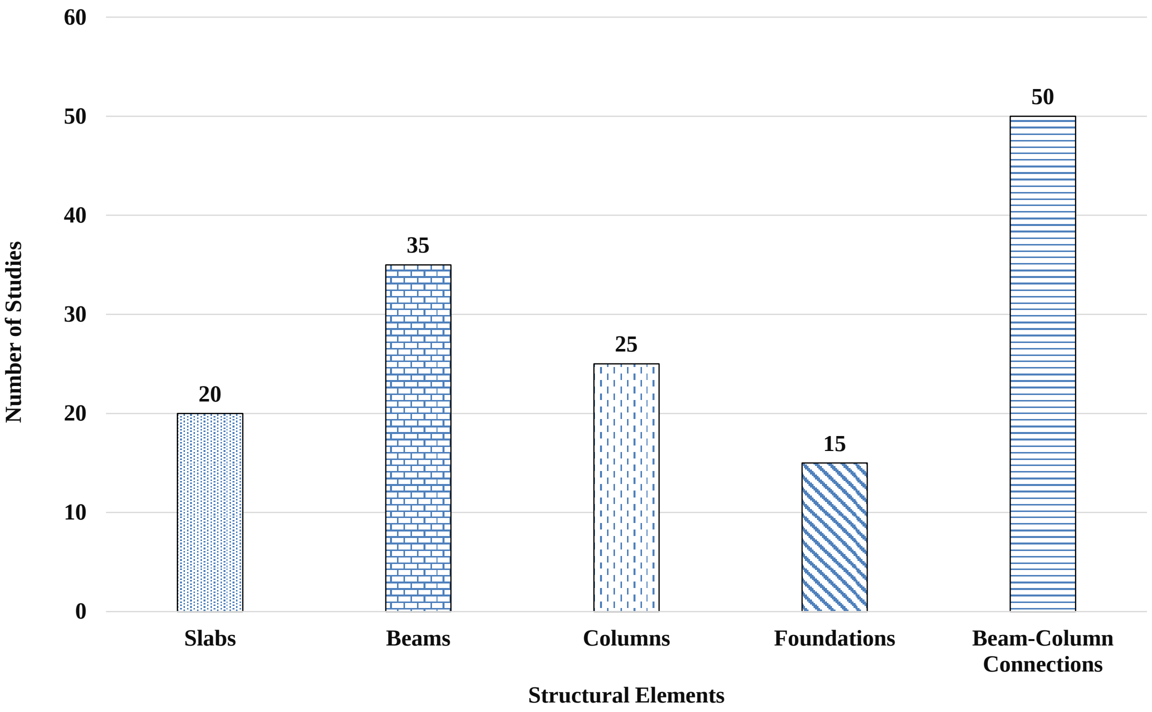


Fig. 5: Distribution of studies by structural elements, highlighting the dominance of beam-column connections and the need for further research on foundations and slabs.

4. INFLUENCE OF VARIOUS PARAMETERS ON STEEL STRUCTURES' PERFORMANCE UNDER PROGRESSIVE COLLAPSE AND SEISMIC HAZARDS

4.1 Experimental Studies

Experimental studies are fundamental to advancing retrofitting and rehabilitation strategies for steel structures, particularly in mitigating progressive collapse and seismic hazards. These investigations evaluate structural performance under extreme conditions, providing critical insights into the behavior of key components and guiding the development of innovative solutions to enhance resilience. Rigorous experimental setups help researchers analyze the influence of various factors, such as material properties, connection designs, and loading conditions, on the stability and integrity of steel structures.

Experimental research is categorized into two primary areas. The first focuses on assessing the structural performance of steel systems under progressive collapse and seismic loading scenarios. This involves simulating critical conditions, such as column removal or seismic excitation, to analyze load redistribution mechanisms, ductility, and failure patterns. Experimental methods include quasi-static and dynamic loading techniques, where quasi-static tests gradually remove key structural elements to evaluate redistribution capacity, while dynamic tests replicate sudden load applications, mimicking real-world seismic or impact events. These studies provide crucial data on how steel structures respond to abnormal loading conditions, identifying vulnerabilities and areas for improvement.

The second area focuses on retrofitting and strengthening techniques, aiming to improve the capacity of steel structures to withstand progressive collapse and seismic forces. Advanced retrofitting solutions, such as bolted-welded connections and damping systems, have demonstrated significant improvements in energy dissipation and deformation capacity. These strategies enhance load absorption and redistribution, preventing catastrophic failures. Additionally, floor systems have been extensively studied for their role in transferring loads and mitigating localized failures, such as punching shear, which can trigger progressive collapse mechanisms.

Despite significant advancements, challenges remain, including the lack of standardized testing protocols and the resource-intensive nature of large-scale experiments. However, integrating experimental findings with numerical and theoretical models has facilitated comprehensive frameworks that address complex interactions within steel structures under extreme conditions. These insights not only enhance the understanding of failure mechanisms but also inform the development of robust retrofitting and rehabilitation strategies, contributing to global efforts to improve the safety and resilience of steel structures. A summary of several experimental studies is provided in Table 1.

The following sections provide an in-depth review of previous studies related to retrofitting techniques and the structural performance of steel buildings under progressive collapse and seismic hazards. This review highlights key findings, methodologies, and their effectiveness in enhancing structural resistance against extreme loads and sudden collapse scenarios.

Table1 : Summary of Experimental Studies on Progressive Collapse and Seismic Resistance in Steel Structures

Study	**Focus Area**	**Experimental Approach**	**Key Findings**	**Limitations**
Jiang & Li [26]	Fire-induced progressive collapse	Literature review & theoretical analysis	Identified catenary and tensile membrane action as key resistance mechanisms	Lacked collapse behavior analysis during cooling phase
Chen et al. [27]	Progressive collapse resistance of steel frames	Column removal tests & computational modeling	Composite beam action mitigates collapse risk	Limited scope for high-rise structures
Parsaeifard & Nateghi [28]	Seismic progressive collapse	Analytical modeling	Identified failure propagation through steel frames	Lacked experimental validation
Uang & Bruneau [29]	Seismic design of steel structures	Review study	Summarized advancements in seismic resistance mechanisms	No experimental validation
Tan & Yang [30]	Steel beam-column connection behavior	Physical tests on bolted connections	Web cleat connections exhibited best catenary action	Did not analyze long-term durability
Kiakojouri et al. [31]	Dynamic column removal in progressive collapse	Review of experimental techniques	Summarized quick-release and explosion-based methods	No direct testing
Zhao et al. [32]	Dynamic progressive collapse of reinforced concrete frames	Experimental testing & energy-based assessment	Introduced dynamic amplification factor for collapse analysis	Limited to reinforced concrete structures
Alrubaidi et al. [33]	Strengthened beam-column joints	Experimental & numerical analysis	Welded side plates & steel rods improved collapse resistance	Limited dataset for large-scale buildings
Qian et al. [34]	Seismic-configured steel sub-frames	Scaled model testing	Reduced beam sections enhanced failure resistance	Did not address irregular seismic loading
Wang et al. [35]	Floor systems with various beam-column connections	Numerical modeling & testing	Welded haunch plates improved joint performance	Lacked full-scale validation
Elsanadedy et al. [36]	Precast concrete beam-column connections strengthened with steel plates	Finite element analysis	Strengthened joints improved collapse mitigation	Focused only on precast structures

Alrubaidi & Alhammadi [37]	Influence of masonry infill walls on steel frames	Experimental testing & modeling	Infill walls significantly enhanced structural strength	Lacked cyclic loading evaluation
Mirtaheri et al. [38]	Novel passive connection for progressive collapse mitigation	Half-scale frame tests	Increased load-bearing capacity by 75%	Economic feasibility not analyzed
Shao et al. [39]	Low-yield steel energy absorbers for seismic resistance	Shaking table tests	Absorbers effectively dissipated energy & improved seismic response	Cost implications not assessed
Dinu et al. [40]	Floor slab contribution to progressive collapse mitigation	Full-scale slab testing	Slabs improved resistance to collapse	Did not analyze high-rise applicability
Alrubaidi et al. [41]	Steel intermediate moment frame connections under column loss	Physical experiments & FE modeling	Different IMF connections showed varying resilience	No real-world validation
Tsitos et al. [42]	Multi-hazard progressive collapse in steel frames	Large-scale experimental tests	Identified key robustness strategies	Did not investigate long-term durability
Astaneh-Asl et al. [43]	Progressive collapse resistance of steel building floors	Full-scale structural testing	Floor catenary action prevented collapse	Did not incorporate effects of extreme seismic loads
Ribeiro et al. [44]	Seismic design of bolted connections	Review of experimental studies	Identified key failure mechanisms	Needs experimental calibration
Hadjioannou et al. [45]	Large-scale testing of composite floor systems	Structural load testing	Concrete slabs enhanced collapse resistance	Limited assessment of degradation effects
Xiuzhang et al. [46]	Energy-dissipating steel connections	Physical & numerical testing	Replaceable energy elements reduced repair costs	Needs real-world validation
Bahirai & Gerami [47]	Seismic retrofit of steel frames	Experimental studies	Heat induction improved stress distribution	Drilling weakened buckling resistance
Alrubaidi et al. [48]	Strengthening beam-column connections with welded plates	Experimental & numerical study	Strengthened joints improved energy dissipation and shifted failure modes to non-critical components	Limited scalability for high-rise buildings
Shao et al. [49]	Shaking table tests on retrofitted steel frames	Seismic performance evaluation	Low-yield steel absorbers enhanced seismic performance and allowed for high-intensity earthquake resistance	Lacks assessment of economic feasibility

Hadjioannou et al. [50]	Large-scale testing of steel floor slabs	Experimental study	Concrete and corrugated steel decking contributed to robustness and provided data for progressive collapse mitigation strategies	Limited assessment of long-term degradation effects
Xiuzhang et al. [51]	Experimental testing of energy-dissipating steel connections	Physical experiments & numerical modeling	Improved seismic and progressive collapse performance; replaceable energy dissipation elements reduced repair costs	Needs real-world performance validation
Alrubaidi et al. [52]	Strengthening beam-column connections with welded plates	Experimental tests & numerical validation	Strengthened joints improved energy dissipation and collapse resistance	Limited scalability for high-rise buildings
Bahirai & Gerami [53]	Seismic retrofit of steel moment frames	Experimental studies	Heat induction improved stress distribution, while drilling technique increased vulnerability to buckling	Drilling technique weakened out-of-plane buckling resistance

4.1.1 Large-Scale Testing

Large-scale experimental testing plays a critical role in comprehending the behavior of steel structures subjected to extreme loading conditions, including progressive collapse and seismic hazards. While small-scale tests provide valuable initial insights, they often fail to replicate the intricate interactions that occur in full-scale systems. The complexities associated with load redistribution, material behavior, connection responses, and structural integrity under dynamic and quasi-static loading conditions necessitate large-scale investigations to develop accurate predictive models and effective retrofitting strategies.

Several landmark studies have significantly advanced the understanding of progressive collapse mechanisms and mitigation strategies through large-scale experimental research, Jiang & Li [26] conducted an extensive review of progressive collapse mechanisms in steel-framed buildings exposed to fire. Their findings highlighted that high load ratios, fire-induced weakening, and inadequate bracing can lead to undesirable global failures. The study underscored the importance of catenary action in beams and tensile membrane action in slabs, both of which enhance the overall ductility and robustness of steel structures. The research also suggested that increasing the reinforcement ratio in the sagging and hogging regions of slabs can significantly improve tensile membrane action, thereby preventing beam-to-column connection failures. However, the authors emphasized the need for further investigations into the effects of cooling phases and traveling fires on structural collapse, as these conditions often exacerbate the degradation of steel members. Chen et al. [27] performed full-scale column removal tests on a two-story steel moment-resisting frame to examine its response under sudden load redistribution. Their study incorporated computational modeling to simulate the role of composite beam action in mitigating progressive collapse risks. The results confirmed that the shear connectors between concrete slabs and steel beams significantly enhanced structural integrity, reducing stress concentrations and limiting vertical displacements above the removed column (Fig. **6**). The experimental data provided critical validation for numerical models that predict progressive collapse resistance in multi-story steel buildings. Parsaeifard & Nateghi [28] focused on the seismic progressive collapse of steel frame buildings, investigating how local damage initiates and propagates through structural components. By analyzing failure sequences under seismic loading, the study demonstrated that beam-column connections play a crucial role in maintaining structural stability. The findings emphasized that semi-rigid and flexible connections exhibit greater ductility, which enhances energy dissipation and delays global collapse. However, the authors noted that fully rigid connections, despite their high strength, suffered from lower rotational capacities, making them more vulnerable to progressive collapse under seismic excitation. The study recommended the adoption of hybrid connection systems that balance stiffness and ductility for optimal seismic performance.

Fig. 6. Test setup of the two-story steel frame [27].

Uang & Bruneau [29] provided a state-of-the-art review on seismic design methodologies for steel structures, analyzing the evolution of seismic force-resisting systems (SFRS) such as moment frames, braced frames, and shear walls. Their research outlined key resistance mechanisms that govern structural behavior during seismic events, including plastic hinge formation, energy dissipation through yielding, and dynamic load redistribution. A major contribution of this review was the identification of gaps in current seismic design codes, particularly in accounting for post-elastic deformations and load redistribution pathways in progressive collapse scenarios. The study suggested that integrating nonlinear global analysis methods and performance-based design approaches would significantly enhance the seismic resilience of modern steel structures.

These studies collectively underscore the critical role of large-scale experimental research in advancing the understanding of progressive collapse resistance in steel structures. By integrating empirical data with computational modeling, these investigations have laid the foundation for improved design guidelines, robust retrofitting techniques, and enhanced regulatory frameworks aimed at mitigating collapse risks under extreme conditions.

Future research should focus on multi-hazard interaction effects, examining how progressive collapse mechanisms evolve under combined fire, seismic, and impact loading conditions. Additionally, the integration of high-fidelity numerical simulations with full-scale experimental validations will be instrumental in developing next-generation resilient steel structures that can withstand unexpected and extreme loading scenarios.

4.1.2 Steel Beam-Column Sub-Assemblage Behavior

Steel beam-column sub-assemblages are fundamental components in structural frames, directly influencing the overall stability and load redistribution capacity of steel structures. Their performance under extreme loading conditions, particularly in progressive collapse scenarios, determines a structure’s ability to withstand localized failures without leading to catastrophic collapse. Experimental and numerical studies have been instrumental in evaluating different connection designs, material properties, and energy dissipation mechanisms to enhance structural resilience. Understanding the progressive collapse resistance of steel beam-column connections requires a multi-faceted approach that integrates experimental validation with advanced numerical modeling. Recent investigations have provided critical insights into the effectiveness of various connection configurations and strengthening techniques: Tan & Yang [30] conducted an extensive experimental study on different bolted steel beam-column connections under progressive collapse scenarios. Their findings demonstrated that web cleat connections exhibited superior catenary action, significantly improving robustness against failure. The study confirmed that catenary action effectively redistributes loads following a column loss event, enhancing ductility and delaying structural collapse. Kiakojouri et al. [31] reviewed various experimental techniques for dynamic column removal, emphasizing explosion and quick-release mechanisms to assess progressive collapse resistance. Their study underscored the limitations of static removal techniques, as dynamic loading conditions more accurately replicate real-world failure scenarios. The research highlighted the necessity of incorporating dynamic amplification factors when designing steel sub-assemblages to withstand sudden load redistributions. Zhao et al. [32] conducted large-scale dynamic progressive collapse tests on reinforced concrete beam-column assemblies, simulating a middle-column removal scenario. Their study introduced an energy-based assessment methodology to quantify the residual strength of structures post-failure. Although their research primarily focused on reinforced concrete frames, the findings provided valuable insights into energy dissipation mechanisms that can be adapted for steel structures. Alrubaidi et al. [33] conducted a comprehensive experimental and numerical investigation to evaluate the progressive collapse resistance of steel intermediate moment frame (IMF) connections under a column-loss scenario. The study assessed the structural behavior of various IMF connection configurations, focusing on their ability to redistribute loads and sustain stability following the sudden removal of a supporting column (Fig. 7). Faridmehr & Baghban [34] conducted full-scale experimental tests on double-span steel beam-to-column assemblies to evaluate their performance under progressive collapse scenarios. Their research demonstrated that beam continuity plays a pivotal role in preventing localized failures from propagating throughout the structure. The study emphasized the need for continuous load paths in steel frames and suggested that strengthening connections at key locations could significantly mitigate progressive collapse risks. These studies collectively highlight the crucial role of beam-column sub-assemblages in ensuring the robustness of steel frames under extreme loading conditions. Future research should focus on integrating smart materials, such as high-performance steel alloys and self-healing coatings, to further enhance connection durability. Additionally, advanced numerical modeling techniques, including machine learning-based predictive analytics, can optimize connection detailing for enhanced progressive collapse resistance. The continued evolution of experimental and computational methodologies will be instrumental in refining design codes and retrofitting strategies, ensuring that steel structures remain resilient against unforeseen structural failures (Fig. 8).

Fig. 7. Different Steel Intermediate Moment Frame Connections Under Column-Loss Scenario [33].

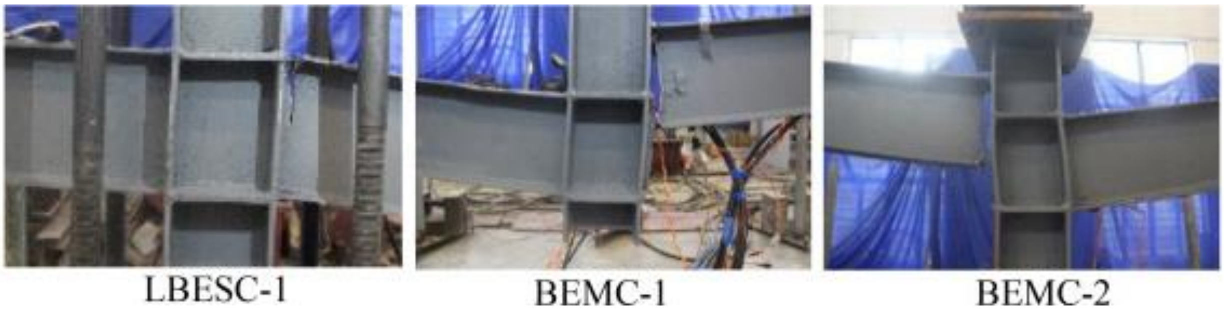


Fig.8. Moment Frame Connections Under Column-Loss Scenario [34].

Wang et al. [35] Floor systems with various beam-column connections Numerical modeling & testing Welded haunch plates improved joint performance Lacked full-scale validation. Kukla et al. [36] conducted experimental impact tests on two steel beam-column-beam substructures to assess their performance under accidental loading scenarios. The study compared a conventional bolted flush end-plate joint with an innovative joint design, both subjected to identical impact energy levels using a free-falling steel-concrete package. Advanced dynamic measurement equipment was employed to capture strain and deformation in steel members and bolts, allowing for the calculation of strain rate and the Dynamic Impact Factor (DIF) using the Johnson-Cook, Cowper-Symonds, and Malvar-Crawford models. The results demonstrated that both joint types exhibited high ductility, effectively dissipating impact energy; however, the flush end-plate joint was limited by bolt fractures, whereas the innovative joint retained significant load capacity reserves throughout the tests. These findings emphasize the necessity of enhanced bolted connection designs to mitigate progressive collapse risks under impact loads. Future research should explore hybrid steel connections with energy-dissipating elements and employ high-fidelity numerical modeling, such as finite element-based impact simulations, to further optimize joint behavior under extreme loading conditions. The development of next-generation bolted joints with adaptive and self-reinforcing mechanisms could play a crucial role in enhancing the resilience of steel structures in high-risk environments. Alrubaidi & Alhammadi [37] Influence of masonry infill walls on steel frames Experimental testing & modeling Infill walls significantly enhanced structural strength Lacked cyclic loading evaluation

4.1.3 Steel Floor Systems and Their Seismic Response

Steel floor systems are critical components in structural stability, serving as integral load transfer elements in both seismic events and progressive collapse scenarios. Their role extends beyond merely providing a horizontal diaphragm; they contribute to overall structural integrity by enhancing load redistribution, reducing stress concentrations, and mitigating localized failures. The interaction between floor slabs, beam-column connections, and lateral force-resisting systems is pivotal in preventing disproportionate collapse following extreme loading events.

A comprehensive understanding of steel floor systems' response to seismic and progressive collapse conditions has been the focus of several experimental and numerical studies, with key findings advancing structural engineering design and retrofitting methodologies: Mirtaheri et al. [38] investigated the effectiveness of a new passive connection system for mitigating progressive collapse in steel structures. Their study demonstrated that the proposed connection significantly enhanced load redistribution capabilities, increasing the structural redundancy by 75% compared to traditional designs. The experimental results highlighted that the passive connection system improved ductility and energy absorption, preventing sudden failure propagation. However, the study emphasized the need for further research on long-term durability and economic feasibility before large-scale implementation. Shao et al. [39] explored the seismic resilience of steel frames retrofitted with low-yield-point (LYP) steel energy absorbers. Through extensive shaking table tests, the study demonstrated that LYP steel components effectively dissipated seismic energy, significantly reducing structural deformations under earthquake loading. The research highlighted that incorporating LYP absorbers in beam-column connections improved the elastic-plastic transition behavior of steel frames, enhancing their ability to withstand progressive collapse. The findings suggested that LYP-based retrofitting solutions could provide a cost-effective alternative to conventional seismic reinforcement techniques (Fig. 9).

(a) (b) (c) (d)

Fig. 9. Measuring devices of the specimen. (**a**) Connection of strain gauges; (**b**) YHD sensors; (**c**) TST sensors; (**d**) data acquisition instrument [39].

Dinu et al. [40] conducted full-scale experimental tests to assess the impact of floor system reinforcement on the robustness of multi-story steel-frame buildings. Their findings indicated that composite steel-concrete floor slabs played a crucial role in mitigating progressive collapse, as they significantly enhanced load path redundancy and stress redistribution mechanisms. The study underscored the importance of strong diaphragm action in floor systems, preventing localized failures from escalating into catastrophic structural collapses. Hadjioannou et al. [41] provided a comprehensive experimental evaluation of the role of floor slabs in preventing progressive collapse in steel structures. Their research demonstrated that properly designed floor diaphragms could sustain substantial alternative load paths following the loss of a critical column. The results emphasized that well-connected slab systems significantly improved progressive collapse resistance, ensuring enhanced structural continuity under extreme loading conditions. The study recommended post-tensioned reinforcements in floor slabs to further improve their seismic resilience and collapse mitigation capacity. Xiuzhang et al. [42] examined the performance of replaceable energy-dissipating connections in moment-resisting composite steel frames through large-scale dynamic testing. Their study introduced a novel energy-dissipating steel component, which allowed damaged connections to be easily replaced after extreme events such as earthquakes or impact loads. The findings revealed that modular replaceable connections significantly enhanced seismic performance, reducing repair costs and improving the long-term sustainability of steel structures. The study highlighted the practical advantages of replaceable damping elements, particularly in seismic-prone regions where frequent structural repairs are necessary.

These studies collectively emphasize the importance of advanced connection designs, reinforced floor slabs, and energy-dissipating components in mitigating progressive collapse and seismic hazards. Future research should focus on integrating adaptive retrofitting techniques, such as self-healing materials, smart monitoring technologies, and hybrid modular reinforcements, to further enhance the safety, sustainability, and resilience of modern steel structures.

4.1.4 Retrofitting Steel Connections

Retrofitting steel connections is a crucial strategy for enhancing the resilience of existing structures against progressive collapse and seismic hazards. Recent research has focused on advanced materials and connection designs to address structural vulnerabilities, emphasizing the importance of energy dissipation, load redistribution, and reinforcement of critical structural components. Alrubaidi et al. [43] conducted an experimental and finite element (FE) study on strengthened steel beam-column joints under column-loss scenarios, revealing that welded side plates and stiffening elements significantly improved joint ductility and load-bearing capacity, reducing the risk of disproportionate collapse. The findings emphasized that properly designed reinforced connections can mitigate progressive collapse in steel-framed structures.

Fig. 10. Strengthened steel beam-column joints [43].

Bahirai & Gerami [44] performed an experimental and numerical investigation on the seismic retrofitting of steel moment frame connections, analyzing the effects of reinforcement techniques, such as external bolted plates and stiffeners, on structural behavior. Their results demonstrated that retrofitted moment connections exhibited enhanced energy dissipation and increased ductility, making them more resilient to seismic and progressive collapse scenarios.

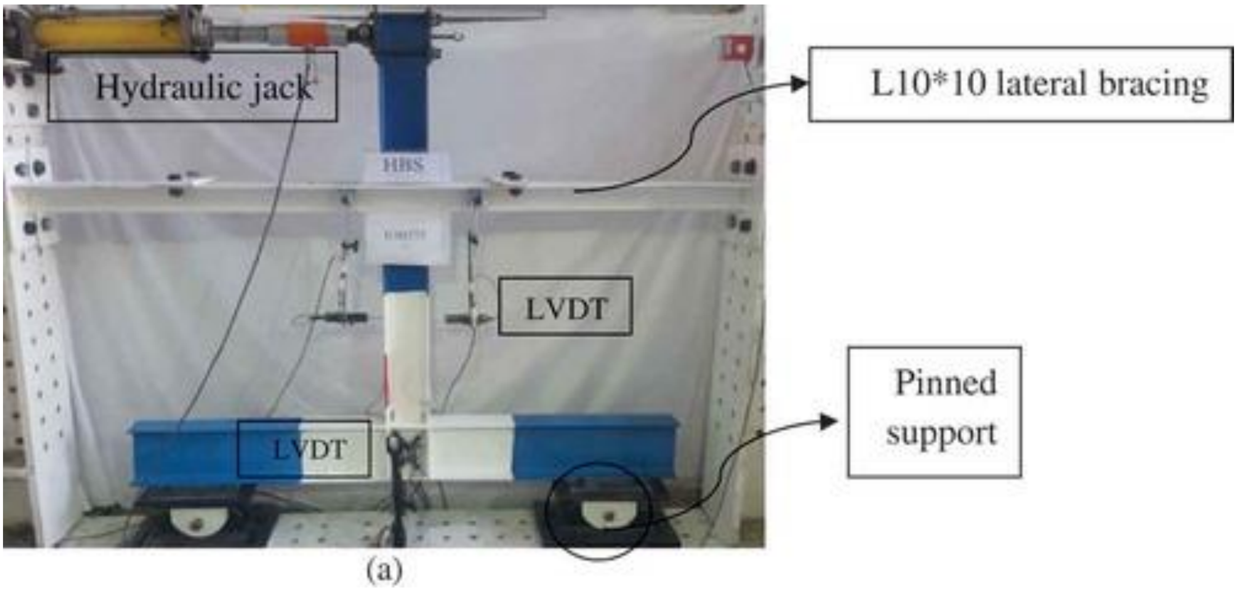


Fig. 11. Retrofitting of steel moment frame connections [44].

Tsitos et al. [45] explored the progressive collapse resistance of steel frames under multi-hazard extreme loading conditions. Their large-scale experimental study demonstrated that moment-resisting connections and reinforced beam-column joints could significantly improve the structural integrity of steel frames when exposed to seismic and impact loads, underscoring the importance of integrated retrofitting strategies. Astaneh-Asl et al. [46] focused on progressive collapse resistance in steel building floors, particularly composite floor systems. Their findings confirmed that floor slab continuity and reinforced connections play a pivotal role in preventing collapse propagation, particularly in buildings vulnerable to sudden load redistribution.

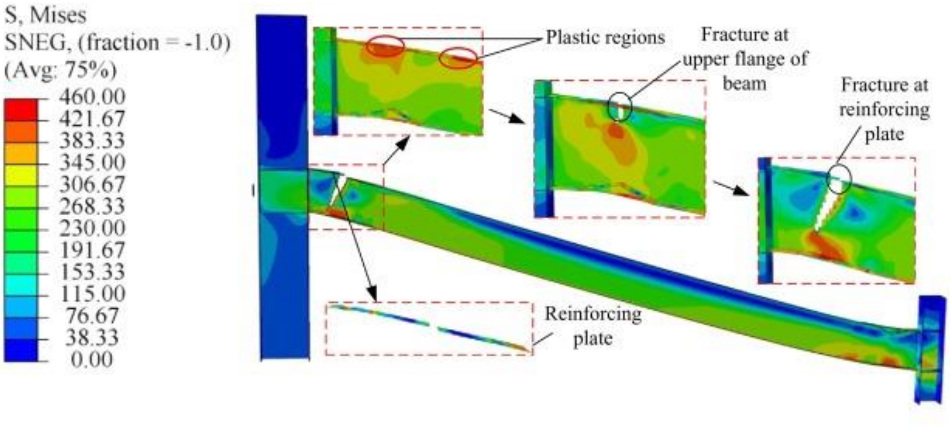
Ribeiro et al. [47] provided a critical assessment of bolted connections in seismic design, evaluating their performance under progressive collapse and cyclic loading conditions. Their research identified key failure mechanisms in bolted connections, highlighting the need for reinforcement strategies to enhance ductility and load-carrying capacity. Hadjioannou et al. [48] performed large-scale experimental tests on composite steel floor systems subjected to column-loss scenarios. Their study demonstrated that composite slabs with robust steel connections exhibited enhanced collapse resistance, effectively redistributing loads to adjacent structural elements. Xiuzhang et al. [49] investigated replaceable energy dissipation connections for moment-resisting composite steel frames, proposing an innovative replaceable connection system that improved seismic resilience and post-earthquake reparability. Their findings suggested that modular, replaceable connections could provide cost-effective retrofitting solutions for steel structures vulnerable to seismic-induced collapse. Bahirai & Gerami [50] examined seismic retrofit techniques using drilling and heat induction methods, analyzing their effects on the stress distribution and failure mechanisms of steel frames. Their study confirmed that heat induction techniques improved stress distribution, while drilling methods weakened the buckling resistance of connections, emphasizing the need for optimized reinforcement strategies. Alrubaidi et al. [51] conducted an experimental study on strengthening beam-column connections using welded plates, revealing that reinforced joints significantly enhanced energy dissipation and collapse resistance under progressive collapse scenarios. Their results reinforced the necessity of rigid joint reinforcement to prevent failure propagation. Shao et al. [52] performed shaking table tests on retrofitted steel frames with low-yield-point energy absorbers, demonstrating that energy-dissipating elements effectively reduced seismic-induced deformations, enhancing the overall seismic performance of steel structures. Hadjioannou et al. [53] conducted experimental testing of composite floor systems under progressive collapse conditions, confirming that structural continuity in composite slabs significantly improved their resistance to collapse propagation. Their findings suggested that properly reinforced composite floor systems could serve as effective retrofitting solutions for steel-framed structures.

4.2 Numerical Studies

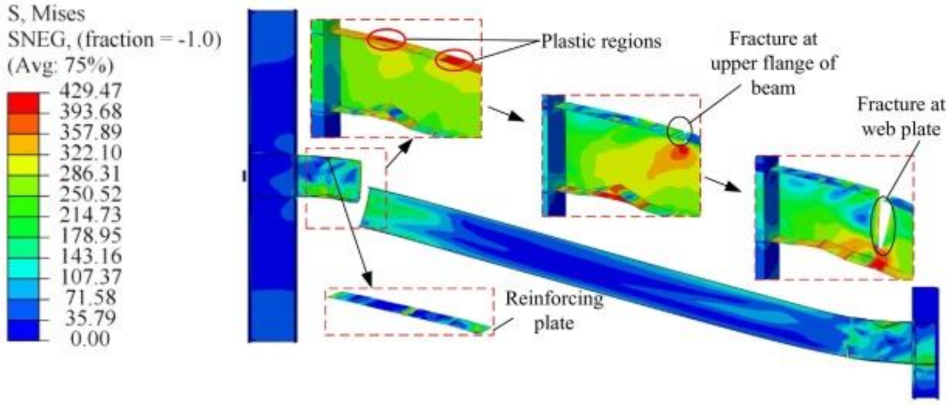
Numerical modeling has played a crucial role in advancing the understanding of progressive collapse resistance in steel structures. Various studies have employed finite element analysis (FEA) techniques to evaluate retrofitting strategies, failure mechanisms, and structural robustness under extreme loading scenarios. The following section presents a comparative analysis of recent numerical investigations, emphasizing methodology, findings, and key differences (Table 2).

4.2.1 Finite Element Modeling (FEM) for Enhanced Structural Robustness

Meng et al. [54] employed advanced finite element modeling (FEM) techniques to analyze the anti-collapse performance of steel frames with novel Reduced Beam Section (RBS) connections. The study introduced "V"-type reinforcing plates into the beam flanges to enhance load redistribution and structural robustness. The numerical model was validated against experimental results, ensuring accuracy and reliability. The key findings demonstrated that the reinforcing plates increased the bearing capacity by 180.9% and the displacement capacity by 85.8% under simulated collapse scenarios, significantly improving the structure's ability to withstand progressive collapse (Fig.11).



(a) Failure process of model specimens with $t \leq t_0$



(b) Failure process of model specimens with $t > t_0$

Fig.11. Improving anti-collapse performance of steel frame with RBS connection [54].

4.2.2 Evaluation of Retrofitted Beam-Column Connections

Alrubaidi and Abadel [55] conducted a numerical investigation using ABAQUS software to assess the effectiveness of upgraded beam-column connections in steel-framed buildings. The study explored multiple connection configurations, including: Shear joints, Bolted connections, Welded side-plate connections (Fig.12). The parametric analysis considered factors such as plate thickness and steel grade, demonstrating that retrofitted connections significantly improved load-carrying capacity and energy dissipation. One of the critical observations was that failure modes shifted from brittle connection failures to ductile beam failures, thereby enhancing the structural redundancy against progressive collapse.

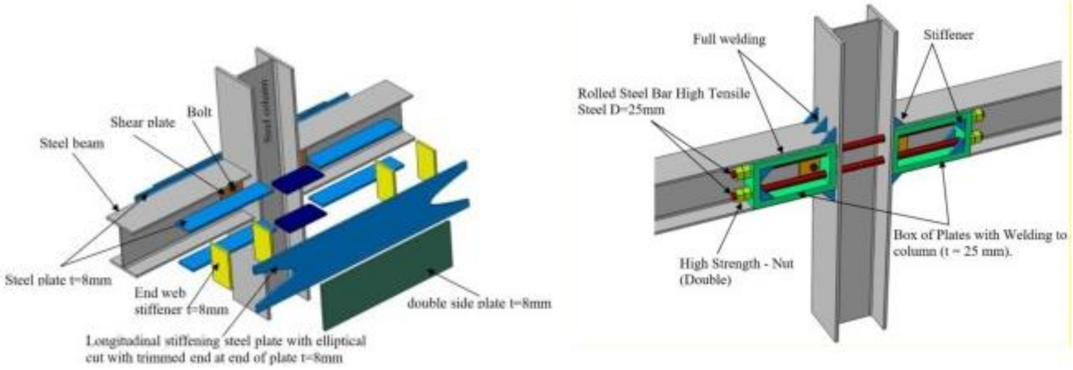
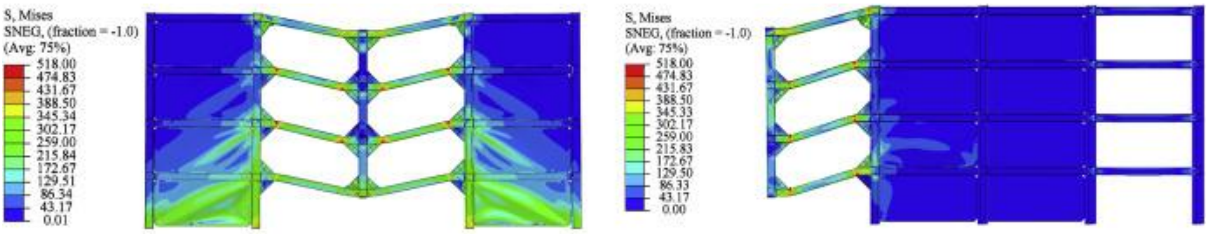


Fig.12. technical upgrading beam-column connections [55].

4.2.3 Integration of Shear Wall Systems for Collapse Mitigation

Feng et al. [56] developed a detailed numerical model in OpenSEES software to evaluate the progressive collapse behavior of steel frame-steel plate shear wall (SF-SPSW) systems. The study analyzed various resistance mechanisms, including: Flexure, Catenary action, and Tensile behavior. Results indicated that stiffened triangular steel plates significantly improved the collapse-resistant capacity, providing valuable insights into the optimal design of SF-SPSW structures. Compared to conventional systems, the integration of shear walls enhanced the lateral load resistance, which is crucial for improving seismic resilience and preventing progressive failure in steel structures.



(a) SF-SPSW-I-1 with triangular steel plate adding stiffeners

(b) SF-SPSW-II-3 with triangular steel plate adding stiffeners

Fig.13. Significantly improved the collapse-resistant capacity using plate shear wall [56].

4.2.4 Retrofit Strategies for Beam-to-Column Connections

Zhang et al. [57] focused on retrofit strategies for simple beam-to-column connections in steel gravity frames. Using a refined finite element mesh technique, the study simulated various enhanced connection types, including: Seat angles and Long-slotted steel plates. The results showed that retrofitted frames experienced a 55.7% increase in static collapse resistance and a 45.8% improvement in dynamic robustness, without compromising seismic performance. The findings highlighted the importance of connection detailing in resisting progressive collapse, particularly in structures with simple beam-to-column connections.

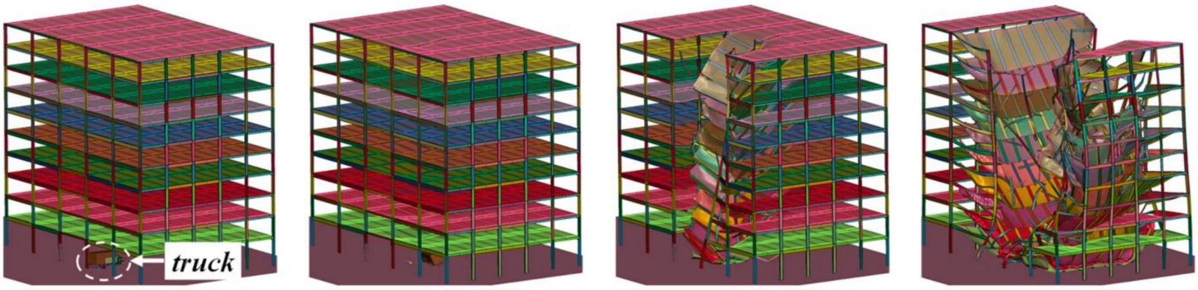
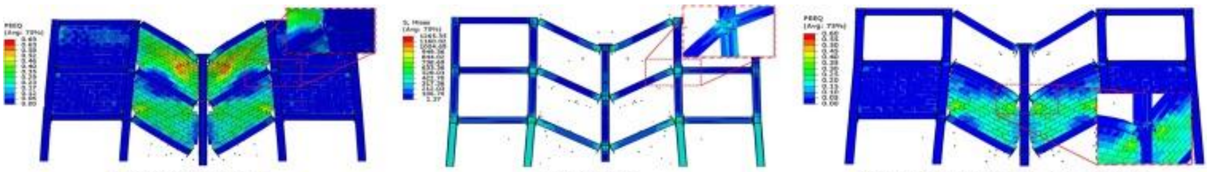


Fig. 13. Response of bulding subjected to sudden loss of column [57].

4.2.5 Strengthening Beam-Column Joints with Double-Sided Plates

Alrubaidi et al. [58] performed an extensive numerical study using ABAQUS software to assess the effectiveness of strengthened beam-column joints with double-sided steel plates. The investigation examined key parameters, including: Plate thickness, Steel grade, and Joint configurations. Results demonstrated a significant improvement in load-bearing capacity and energy dissipation, proving that double-sided welded connections effectively mitigate progressive collapse risks. The study also emphasized the benefits of reinforced joints in redistributing loads under column removal scenarios, ensuring enhanced structural stability.

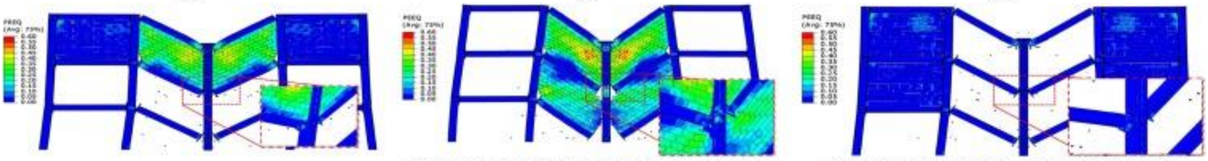
Roof-Truss Retrofitting for Enhanced Structural Redundancy



Full infilled frame
P-T-1-B
(a)

Bare frame
P-T-2-B
(b)

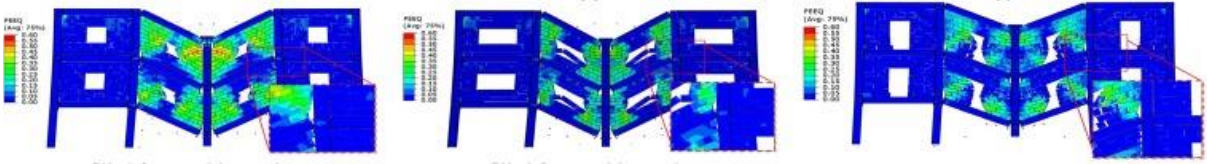
Partial infilled frame - Lower story
P-T-3-B
(c)



Partial infilled frame - Upper story
P-T-4-B
(d)

Partial infilled frame - Next to the removed column
P-T-5-B
(e)

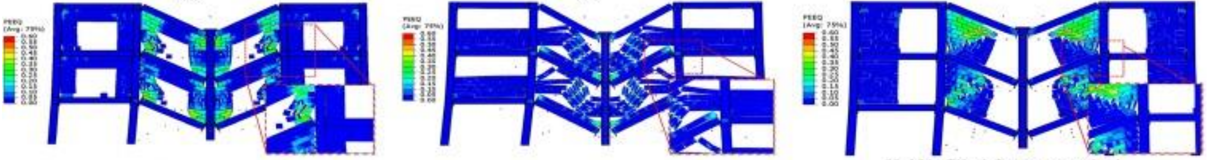
Partial infilled frame - Far to the removed column
P-T-6-B
(f)



Infilled frame with openings
(Lo= ho)
P-T-7-B
(g)

Infilled frame with openings
(Lo = 2ho)
P-T-8-B
(h)

Infilled frame with openings (2Lo = ho)
P-T-9B
(i)



Infilled frame with openings (2Lo = 2ho)
P-T-10-B
(j)

Half infilled frame - Horizontal
P-T-11-B
(k)

Half infilled frame - vertical
P-T-12-B
(l)

Fig. 13. Mitigation of steel beam-column joint[57].

Freddi et al. [59] explored the application of roof-truss retrofitting systems to enhance the robustness of steel moment-resisting frames against progressive collapse. Using non-linear dynamic analysis, the study revealed that the retrofit system effectively redistributed loads after column removal. However, one of the critical challenges was optimizing the design stiffness of the roof-truss system, as excessive stiffness could induce undesirable force concentrations in adjacent columns, potentially leading to secondary failures.

Table 2: Comparative Analysis and Key Takeaways

Study	Methodology	Key Findings	Strengths	Limitations
Meng et al. [54]	FEM analysis with RBS connections	Reinforcing plates increased bearing capacity by 180.9%	Improved robustness via reinforcing plates	Requires experimental validation for different structural configurations
Alrubaidi & Abadel [55]	ABAQUS analysis of beam-column connections	Retrofitting shifted failure from brittle to ductile	Enhanced redundancy and energy dissipation	High retrofitting costs
Feng et al. [56]	OpenSEES modeling of SF-SPSW systems	Shear walls improved collapse resistance	Strong seismic resilience	Shear wall integration increases construction complexity
Zhang et al. [57]	FEM with enhanced beam-column connections	Retrofit increased static collapse resistance by 55.7%	Effective for simple connections	Limited application to high-rise structures
Alrubaidi et al. [58]	ABAQUS analysis of strengthened joints	Double-sided plates enhanced energy dissipation	Strong load redistribution	Additional weight considerations
Freddi et al. [59]	Non-linear dynamic analysis of roof-truss systems	Retrofit improved structural redundancy	Effective for roof systems	Potential force redistribution issues

4.2.6 Summary & Future Research Directions

- Load Redistribution Mechanisms: Several studies have confirmed that advanced connection designs and shear wall integrations significantly enhance load redistribution capacity, reducing the risk of progressive collapse.
- Retrofit Optimization: Although retrofitting techniques such as reinforcing plates, double-sided plates, and roof-truss systems have shown promise, further research is required to optimize cost-effectiveness while maintaining structural integrity.
- Numerical Model Refinement: While FEM-based studies provide valuable insights, hybrid experimental-numerical validation is needed to enhance the real-world applicability of numerical findings.
- Seismic Performance Considerations: Most studies focused on progressive collapse mitigation, but the interaction between seismic hazards and progressive collapse resistance requires further exploration, particularly in high-seismic regions.

4.3 Theoretical Studies

Theoretical research has significantly contributed to advancing the resilience of steel structures against progressive collapse and seismic hazards. These studies primarily focus on load redistribution mechanisms, structural robustness quantification, and advanced retrofitting strategies. This section presents key theoretical advancements, highlighting their contributions and limitations (Table 3).

4.3.1 Structural Robustness Quantification

To assess structural resilience, researchers have introduced capacity-based indices and energy-based models that quantify the ability of steel structures to withstand localized failures.

- Li et al. [60] proposed a capacity-based robustness index, which considers redundancy, ductility, and load redistribution capacity as key metrics.
- Energy-based models have been formulated to quantify the total energy dissipation under extreme events, aiding in performance-based seismic design.

These models provide a systematic framework for assessing progressive collapse resistance, but their practical application requires experimental validation to refine the proposed indices.

4.3.2 Finite Element-Based Theoretical Approaches

Finite Element Analysis (FEA) plays a crucial role in theoretical modeling, enabling researchers to predict failure mechanisms and optimize structural detailing.

- Kandil et al. [61] employed nonlinear FEA to investigate force redistribution in steel frames subjected to column loss scenarios.
- Their findings demonstrated that moment-resisting connections significantly enhance robustness compared to traditional bolted connections.
- However, the computational complexity of detailed FEA models limits their widespread use in real-time assessments.

4.3.3 Material Innovations and Structural Optimization

Advancements in high-strength steel, fiber-reinforced polymers (FRPs), and composite materials have played a vital role in improving the seismic resilience of steel structures.

- Fang et al. [62] explored lightweight steel alloys and composite members, showing improved energy dissipation and load redistribution capabilities.

- Theoretical studies suggest that incorporating hybrid materials enhances the ductility and overall collapse resistance, making them promising candidates for future seismic retrofitting.

- However, the cost implications and long-term durability of these materials require further investigation.

4.3.4 Advanced Computational Methods for Collapse Prediction

- Elkholy & Meguro [63] developed the Improved Applied Element Method (AEM) for simulating progressive collapse in large-scale steel structures.
- Unlike traditional FEA, AEM accounts for the complete collapse process, from initial damage propagation to total failure, making it a more comprehensive tool for evaluating structural integrity.
- The primary limitation is the high computational demand, which restricts its application to high-performance computing environments.

4.3.5 Retrofitting Strategies and Theoretical Frameworks

Theoretical studies have examined innovative retrofitting solutions to mitigate progressive collapse and seismic hazards.

- Ciman et al. [64] proposed rooftop truss systems as an effective retrofit method, redistributing loads and preventing sudden collapses.
- Qian & Li [65] identified deficiencies in existing design codes, proposing modifications to improve structural integrity and load path redundancy.
- These studies highlight the importance of integrating retrofitting strategies into existing steel structures, ensuring compliance with modern safety standards.

4.3.6 Alternate Load Path Method and Seismic Collapse Mechanisms

- Dinu et al. [66] analyzed the Alternate Load Path (ALP) Method, confirming its effectiveness in enhancing structural redundancy during column removal scenarios.
- Parsaeifard & Nateghi Alahi [67] conducted seismic progressive collapse studies, revealing that multi-hazard design approaches are necessary to address simultaneous seismic and progressive collapse risks.
- These findings underscore the necessity of developing integrated design guidelines that consider both seismic resilience and progressive collapse prevention.

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Table 3: Comparative Analysis of Theoretical Studies

Study	Focus Area	Key Contributions	Limitations
Li et al. [60]	Capacity-based indices	Introduced a quantitative robustness index	Requires experimental validation
Kandil et al. [61]	FEA-based redistribution analysis	Showed moment-resisting connections enhance robustness	Computationally expensive
Fang et al. [62]	Material innovation	Proposed lightweight alloys & hybrid materials for improved ductility	Cost implications & long-term durability concerns
Elkholy & Meguro [63]	AEM for collapse prediction	Simulated total failure mechanisms	Requires high computational power
Ciman et al. [64]	Retrofitting strategies	Proposed rooftop truss systems for collapse mitigation	Practical application needs validation
Qian & Li [65]	Design code improvements	Identified gaps in current guidelines	Implementation challenges
Dinu et al. [66]	Alternate Path Method	Demonstrated load redistribution effectiveness	Limited to specific structural typologies
Parsaeifard & Nateghi Alahi [67]	Seismic collapse studies	Highlighted multi-hazard design challenges	Requires integrated seismic-progressive collapse framework

4.3.7 Summary & Future Research Directions

1. Integration of Theoretical Models with Experimental Validation: Future research should bridge the gap between theoretical frameworks and real-world applications by conducting large-scale experimental validation of proposed indices and design improvements.
2. Computational Optimization: There is a need to develop computationally efficient yet highly accurate predictive models for progressive collapse assessment, particularly for use in real-time structural monitoring systems.
3. Multi-Hazard Considerations: The interaction between seismic loading and progressive collapse resistance remains underexplored; integrated design methodologies should be developed.
4. Refinement of Design Guidelines: Existing progressive collapse prevention strategies require modifications to align with new material innovations and advanced structural solutions.

5. CHALLENGES AND LIMITATIONS

Despite significant advancements in retrofitting and rehabilitation strategies for steel structures against progressive collapse and seismic hazards, several challenges and limitations persist. These constraints can be categorized into technical, economic, computational, and regulatory aspects, all of which hinder the widespread implementation and optimization of progressive collapse mitigation strategies.

5.1 Technical Challenges

- Inadequate Experimental Validation: While numerical simulations and finite element modeling (FEM) have greatly enhanced our understanding of progressive collapse mechanisms, large-scale experimental validation remains limited. The lack of full-scale testing restricts the ability to accurately predict structural performance under extreme loading conditions.
- Material Behavior Under Multi-Hazard Scenarios: The complex interaction between seismic events and progressive collapse mechanisms is not fully understood, particularly in high-rise steel structures subjected to both vertical and lateral forces. The coupled effects of dynamic loading, fire exposure, and impact forces require further investigation.
- Limitations of Existing Connection Designs: Current retrofitting strategies primarily focus on enhancing beam-column connections. However, there is limited research on the behavior of floor diaphragms, lateral load-resisting systems, and secondary structural elements, which also play a critical role in preventing progressive collapse.
- Performance Degradation Over Time: Structural elements subjected to cyclic loading, corrosion, and long-term creep deformation exhibit gradual deterioration. Existing retrofitting techniques lack comprehensive long-term performance evaluations, making it difficult to predict service life under real-world conditions.

5.2 Economic and Implementation Challenges

- High Costs of Retrofitting and Rehabilitation: Advanced retrofitting techniques, such as fiber-reinforced polymers (FRPs), high-strength steel alloys, and damping systems, significantly improve structural resilience but at substantial financial costs. Many developing regions struggle to allocate budgets for these high-cost interventions.
- Disruptions to Existing Infrastructure: Retrofitting steel structures often requires partial or complete operational shutdowns, particularly in critical infrastructure such as hospitals, airports, and transportation hubs. This presents logistical challenges and limits the feasibility of large-scale implementation.

5.3 Computational and Modeling Limitations

- Computational Intensity of High-Fidelity Models: Advanced numerical simulations, such as Applied Element Method (AEM) and Large-Scale Nonlinear Finite Element Models, require high computational resources, making them impractical for routine engineering design applications.
- Lack of Unified Validation Criteria: Different numerical models often produce varying results due to differences in boundary conditions, material properties, and meshing techniques. The absence of standardized validation protocols for progressive collapse simulations hinders model reliability and comparability.

5.4 Regulatory and Standardization Issues

- Inconsistent Design Guidelines: Progressive collapse prevention measures vary significantly across international building codes, including Eurocode, AISC 341, UFC 4-023-03, and ASCE 7. The lack of globally harmonized design methodologies creates challenges in developing universally accepted retrofitting strategies.
- Regulatory Constraints on Material Usage: The adoption of new materials and retrofitting technologies is often limited by regulatory restrictions. Many national standards have not yet incorporated emerging innovations, delaying the implementation of advanced resilience strategies.

6. FUTURE RESEARCH DIRECTIONS

To address the challenges and limitations identified in this review, future research efforts should focus on integrating multi-disciplinary approaches, enhancing numerical-experimental validation, and developing cost-effective, scalable solutions for mitigating progressive collapse and seismic hazards in steel structures.

6.1 Advanced Multi-Hazard Performance Assessment

Future studies should explore integrated multi-hazard assessment frameworks that evaluate the simultaneous effects of:

- Seismic loading combined with progressive collapse scenarios, ensuring that structures can withstand extreme lateral and vertical forces.
- Fire-induced collapse mechanisms, particularly in high-rise steel buildings with exposed connections.
- Blast and impact resistance of retrofitted structures, incorporating shock wave dissipation techniques.

6.2 Innovative Retrofitting Strategies

- Self-Healing and Smart Materials: Research into self-healing polymer composites, shape-memory alloys, and advanced nano-coatings could revolutionize steel structure rehabilitation by improving fatigue resistance and crack healing capabilities.
- Hybrid Retrofitting Techniques: Combining steel plate strengthening, high-performance fiber-reinforced concrete (HPFRC), and friction-damping connections may provide superior energy dissipation and load redistribution properties.

6.3 Computational Advancements in Collapse Simulations

- AI-Powered Predictive Modeling: Machine learning (ML) and artificial intelligence (AI) can optimize progressive collapse analysis by predicting failure patterns based on historical data and real-time structural monitoring.
- Development of High-Fidelity Digital Twins: Digital twin technology allows real-time monitoring and predictive maintenance of steel structures by simulating their actual performance under progressive collapse scenarios.
- Refinement of Applied Element Method (AEM) for Large-Scale Simulations: AEM has shown promise in progressive collapse modeling, but further refinements are needed to reduce computational time while maintaining accuracy.

6.4 Standardization and Code Development

- Establishing Unified Design Guidelines: Future research should contribute to the harmonization of global progressive collapse prevention codes, ensuring that newly developed methodologies are adopted in international regulatory frameworks.
- Performance-Based Seismic Design for Progressive Collapse Mitigation: Incorporating robustness indices and energy-based failure criteria into seismic design guidelines can help prevent disproportionate structural failure.

7. CONCLUSION

The increasing vulnerability of steel structures to progressive collapse and seismic hazards has driven extensive research into retrofitting and rehabilitation techniques. This systematic review has provided a comprehensive evaluation of existing methodologies, highlighting both their strengths and limitations.

Key findings from this study include:

1. Advancements in Retrofitting Techniques:
    - The Alternate Load Path Method (ALP) and Catenary Action Mechanisms have proven highly effective in load redistribution strategies.
    - Innovative steel connections, including bolted-welded hybrid joints and energy dissipation devices, significantly enhance structural resilience.
    - Material innovations, such as high-strength steels and FRP composites, provide enhanced ductility and energy absorption.

2. Role of Numerical Modeling:
    - Finite Element Analysis (FEA) and Applied Element Method (AEM) have enabled detailed collapse prediction, though computational limitations remain a challenge.
    - Hybrid experimental-numerical approaches offer the most accurate representation of real-world collapse mechanisms.

3. Challenges and Future Directions:
    - Economic feasibility and retrofitting costs remain a primary barrier to large-scale implementation.
    - Multi-hazard assessment is essential to ensure the resilience of steel structures against combined seismic, impact, and fire loads.
    - The need for standardized global design codes is crucial to unify progressive collapse mitigation strategies.

Looking ahead, emerging technologies such as AI-driven structural monitoring, digital twin modeling, and self-healing materials hold great potential for transforming the field of steel structure resilience. Further integration between numerical simulations, experimental validation, and practical implementation is essential to develop cost-effective, scalable solutions for future infrastructure safety.

By bridging the gap between research innovations and real-world applications, engineers and policymakers can ensure the long-term stability and safety of critical steel infrastructure, safeguarding lives and minimizing economic losses from catastrophic collapses.

Declaration of Competing Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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