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Review

Post-Earthquake Fire Resistance in Structures: A Review of Current Research and Future Directions

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Abstract: Post-earthquake fires (PEFs) pose a significant secondary hazard in earthquake-prone regions, compounding the destruction caused by seismic events and threatening structural safety. This review explores the interplay between seismic damage and fire resistance, focusing on ignition sources such as damaged utility systems and overturned appliances, and their cascading effects on structural integrity. Advanced performance-based design approaches are evaluated, emphasizing the integration of probabilistic risk assessments, sequential analysis, and hybrid fire simulations to address multi-hazard scenarios. Key findings of current studies reveal that seismic damage, including spalling, cracking, and loss of fireproofing, substantially reduces the fire resistance of materials like steel and reinforced concrete, exacerbating structural vulnerabilities. Despite advancements, critical gaps persist in experimental data, probabilistic modeling, and comprehensive performance-based design guidelines for PEF scenarios. Addressing these deficiencies requires enhanced data collection, improved modeling techniques, and the integration of PEF considerations into building codes. This study provides a comprehensive review of PEF damage assessment and underscores the need for a holistic, multi-hazard design paradigm to enhance structural resilience and ensure safety in regions subject to seismic and fire risks. These insights provide a foundation for future research and practical applications aimed at mitigating the compounded effects of earthquakes and fires.

Keywords: post-earthquake fire (PEF); multi-hazard structural design; fire resistance; structural resilience; seismic damage; performance-based design

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1. Introduction

Post-earthquake fire (PEF) presents a significant secondary hazard following seismic events, often leading to extensive damage and casualties. Characterized as a widespread and imminent threat, PEF ignition probability surges immediately after an earthquake, with approximately 70% of ignitions occurring within one day of the main event [1]. This cascading hazard exacerbates existing earthquake damage, increasing community vulnerability. PEF ignition stems from both external and internal sources. External causes primarily involve damage to utility systems, such as gas pipelines and electrical networks, resulting in gas leaks and electrical sparks. Internal ignition sources include overturned flammable contents, damaged electrical appliances, and compromised internal gas piping within structurally damaged buildings [2]. Historical accounts, particularly from Japan and the United States, underscore the significant role of PEF in post-earthquake damage, as exemplified by the 1995 Kobe earthquake. While early research focused on community-level impacts and fire spread modeling, recent studies have shifted towards building-level analysis and the mechanical aspects of PEF [3]. This evolving research landscape emphasizes the need for a probabilistic understanding of earthquake–fire sequences to facilitate a comprehensive assessment of hazard risk. The cascading progression of earthquake-induced fire ignition, structural damage, and economic loss is effectively depicted in Figure 1, which illustrates the interconnected nature of these hazards in post-earthquake scenarios. Despite this progress, significant challenges remain. Knowledge gaps persist regarding performance-based assessment procedures and evaluation methods specific to PEF scenarios, hindering effective structural design and performance evaluation. Furthermore, limitations in data availability necessitate reliance on expert opinions for structural fragility assessment and impede accurate quantification of PEF ignition probability, particularly for internal causes. Current methodologies often oversimplify fire intensity, neglecting crucial aspects like uneven fire distribution. Addressing these challenges necessitates a multi-hazard design approach, incorporating advanced analytical tools, expanded experimental research, and the integration of PEF considerations into building codes. Future research priorities include investigating the complex interplay between earthquake damage and fire behavior, and developing sophisticated risk prediction models to enhance structural resilience and inform decision-making in multi-hazard scenarios.

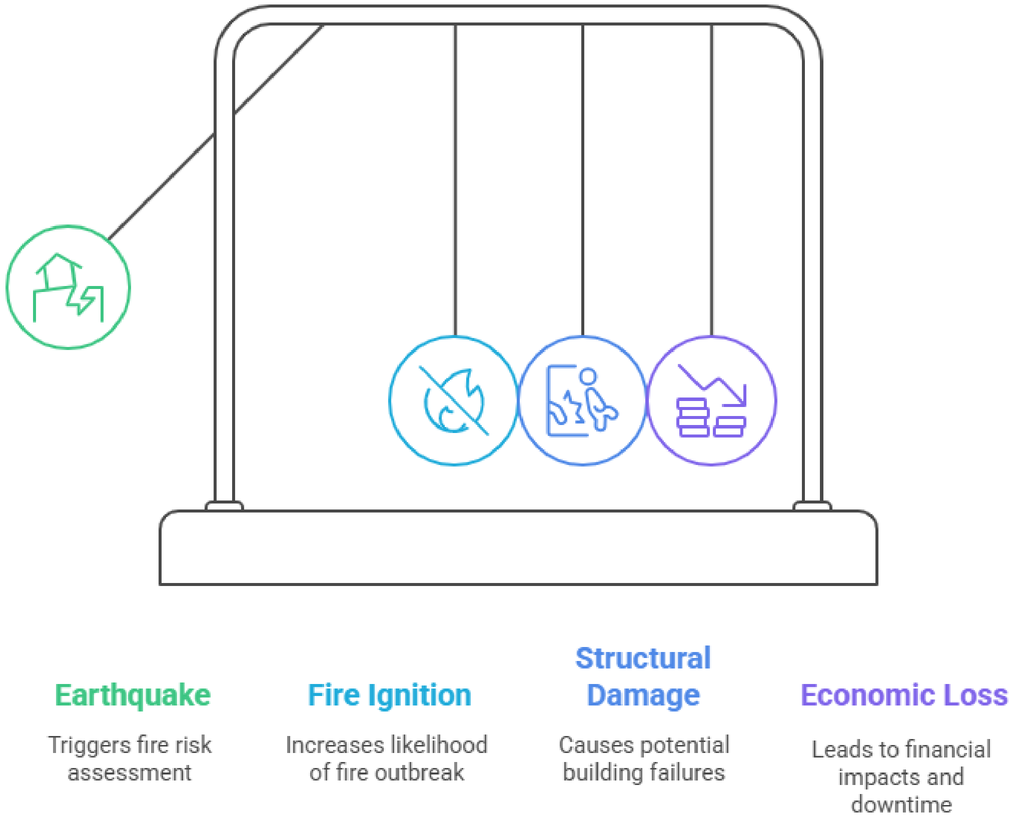

Figure 1. Post-earthquake fire impact.

Research indicates that traditional design methodologies often treat seismic and fire hazards independently. This compartmentalized approach overlooks the synergistic effects of fire following an earthquake, posing a significant risk to structures in earthquake-prone regions. Performance-based design, which integrates both seismic and fire loads, is essential to ensure structural resilience in the context of PEF scenarios.

2. Historical Overview of Post-Earthquake Fire (PEF) Events

Historically, post-earthquake fire (PEF) events have presented significant challenges to disaster response and risk mitigation, particularly in urban areas where damaged infrastructure and disrupted emergency services intensify fire hazards. Several major PEF incidents have been documented, highlighting the catastrophic interplay between seismic activity and fire outbreaks. Below is a historical overview of notable PEF events, outlining their seismic characteristics, causes, and consequences.

2.1. 1906 San Francisco PEF

On 18 April 1906, a magnitude 8.3 earthquake struck San Francisco, originating from the San Andreas Fault, a fault system extending over 960 km [4]. The earthquake caused severe structural damage, but the most devastating impact came from over 50 fire ignitions that erupted shortly after the shock, leading to a four-day conflagration. Fire accounted for approximately 80% of the total destruction, with an economic loss exceeding USD 350 million (in 1906 dollars).

The fires destroyed over 28,000 buildings and resulted in more than 3000 deaths. Key fire sources included ruptured gas pipes, broken chimneys, and electrical short circuits. The failure of the water supply system left firefighters unable to contain the flames [5], while misuse of dynamite by inexperienced responders further spread the fire. Some property owners also intentionally set fires to claim insurance, as policies did not cover earthquake damage.

Compounding the crisis, disruptions to fire alarm systems and communication networks delayed firefighting efforts. Additionally, low humidity and shifting winds accelerated the fire's spread. This disaster underscored the vulnerability of urban areas to post-earthquake fires and emphasized the need for improved emergency response and fire mitigation strategies.

2.2. 1923 Kantō, Japan PEF

Following a magnitude 8.3 earthquake in the Kantō region, a large-scale fire erupted and lasted for two days. This disaster resulted in over 140,000 fatalities and numerous injuries, with approximately 694,000 houses partially or entirely destroyed—mainly due to fire. The fire accounted for about 78% of the total economic loss, estimated at around USD 1 billion (in 1923 dollars). Escape efforts were hindered by destroyed bridges, damaged railway tracks, and heavy traffic congestion, while a sudden shift in wind direction tragically engulfed groups of refugees [6].

2.3. 1931 Hawkes Bay, New Zealand PEF

A magnitude 7.8 earthquake struck the Hawkes Bay region, leading to a significant fire outbreak despite the gas supply being shut off and electrical short-circuit risks being minimized. Three fires ignited in chemist shops storing flammable materials, and strong winds facilitated their rapid spread. Over 400 buildings were destroyed, and more than 260 lives were lost. Firefighting efforts were severely hampered by damage to the central fire station, which left fire engines buried under debris, and a compromised water supply. Firefighters resorted to using dynamite to create firebreaks, while damaged communication systems necessitated wireless technology to request assistance. This event remains the deadliest fire-related disaster in New Zealand's history [7].

2.4. 1933 Long Beach, California PEF

An earthquake with a magnitude of 6.3 resulted in more than 140 deaths and 2000 injuries due to structural failures in weak buildings. Approximately 15 PEFs occurred, but none escalated into a conflagration. The sources attribute this to well-engineered automatic cut-offs for gas and electricity supplies. Notably, over 60% of indoor sprinkler systems sustained damage, though the operational ones functioned correctly, preventing major fire spread [8].

2.5. 1964 Niigata, Japan PEF

A magnitude 7.5 earthquake in Niigata caused extensive damage to buildings and infrastructure, including the water supply system. The earthquake also triggered a tsunami, leading to oil leaks from damaged industrial facilities that spread fire throughout the city. A total of nine PEFs occurred; four were extinguished quickly, while the remaining fires escalated into a conflagration, destroying over 2200 buildings, with approximately 350 directly attributed to the PEFs [9]. Fire suppression efforts were severely hindered by road closures and restricted access to affected areas. This incident is regarded as one of Japan's most complex industrial fire disasters.

2.6. 1985 Mexico City PEF

On 19 September 1985, Mexico City was severely shaken by a magnitude 8.1 earthquake, lasting for approximately one minute. This event is regarded as the most devastating earthquake to have occurred in Mexico and North America in the 20th century. A magnitude 7.5 aftershock followed the next day, intensifying the destruction. The combined shocks resulted in over 10,000 fatalities, 30,000 injuries, and more than 50,000 people left homeless. Hundreds of low- and high-rise buildings collapsed, blocking numerous streets and severely damaging water distribution systems, leading to a complete loss of water supply in many districts. Additionally, electricity networks failed, causing a severe power outage in the city center, while telephone lines were extensively damaged, disrupting communication and preventing updates about the city's condition from reaching rescue teams.

The earthquake triggered approximately 200 PEFs, but none developed into a major conflagration. The source attributes this to the widespread use of non-combustible building materials and the absence of gas supply systems, which limited fire spread [10].

2.7. 1987 Whittier Narrows, Los Angeles PEF

Following a magnitude 5.7 earthquake, fire departments in Los Angeles responded to 112 fire incidents in residential and commercial buildings. Despite the number of fire outbreaks, none escalated into large-scale conflagrations [11].

2.8. 1995 Kobe, Japan PEF

The Great Hanshin-Awaji earthquake on 17 January 1995, with a magnitude of 7.2, triggered 53 fires within 15 min of the initial shock. These fires rapidly spread, with some burning for over 24 h and others lasting more than two days. Approximately 5000 buildings were destroyed across an area of 660,000 m^2. The fires were fueled by broken gas pipes, electrical short circuits, the collapse of buildings with combustible debris, and the uncontrolled use of heating sources. Additionally, narrow alleys filled with burning vehicles contributed to the spread of fire through thermal radiation. The rapid escalation of fires, combined with damage to infrastructure and firefighting systems, led to one of the most severe fire-related disasters in Japan's history [12].

2.9. 1999 İzmit, Turkey PEF

A magnitude 7.6 earthquake caused widespread devastation, leading to over 17,100 deaths and displacing at least 500,000 people. More than 120,000 buildings sustained severe damage, with over 2000 collapsing entirely [13]. The most significant PEF event occurred at the TUPRAS İzmit refinery, where a fire raged for more than five days and required international assistance to be extinguished. Damage to electricity and water supply systems severely hindered firefighting efforts, while an inadequate sprinkler system contributed to the fire's escalation.

2.10. 2003 Hokkaido, Japan PEF

On 26 September 2003, a magnitude 8.0 earthquake struck Hokkaido, Japan, causing significant damage to industrial facilities. A fire broke out at the Hokkaido Refinery in Tomakomai, originating from a tank containing raw oil. The fire spread through the refinery's piping systems, creating a large-scale blaze that took approximately eight hours to control and extinguish. Two days later, another fire ignited from a different tank, but it was swiftly contained. The event highlighted the vulnerability of industrial sites to post-earthquake fires and the challenges associated with fire suppression in such environments [14].

The historical record of PEF events underscores the devastating impact that fires can have following seismic activity, particularly in densely populated urban areas. These incidents underscore the importance of resilient infrastructure, efficient firefighting systems, and comprehensive disaster response strategies to mitigate fire risks following seismic events. Key factors influencing fire spread include damaged water supply systems, disrupted communication networks, the presence of combustible materials, and adverse weather conditions. The economic losses associated with these events, including the USD 1 billion economic loss from the 1923 Kantō PEF and the USD 350 million loss from the 1906 San Francisco PEF, further illustrate the significant financial burden that PEFs can impose. Insights gained from historical PEFs contribute to advancing emergency preparedness and enhancing urban resilience against future seismic disasters.

3. Background

Existing research on post-earthquake fire (PEF) has explored a wide range of aspects, from community-level impacts to the behavior of specific structural components under the combined effects of seismic damage and fire [15]. Authors in [16–19] highlight the complex interplay between these hazards and reveals critical vulnerabilities in the built environment.

Early PEF research focused on community-level analysis, developing models to simulate fire ignition, spread, and suppression [20] within an urban context [21]. These models often incorporate physics-based fire safety principles and have the potential to integrate earthquake damage models for a more comprehensive evaluation [22,23]. Some models account for various uncertainties, including earthquake-induced structural damage, to create realistic PEF scenarios [24,25]. In contrast to building-level analysis, which emphasizes mechanical aspects, community-level analysis relies more heavily on principles of thermal and fluid dynamics.

Building-level PEF analysis investigates the mechanical response of materials, components, connections, and entire structural systems. Studies on materials have examined the combined effects of earthquake damage and high temperatures on the properties of materials like steel [26–28]. Research on components has focused on elements such as concrete-filled steel tube (CFST) columns and load-bearing walls [29], assessing their fire resistance after cyclic loading [30–32]. Investigations into connections have explored the behavior of common configurations like moment-resisting beam–column connections under PEF conditions [33–35]. System-level studies have analyzed the response of entire structures [36,37], including novel seismic-resilient systems [38,39], to determine whether their PEF resistance benefits from reduced seismic damage.

A critical area of research involves establishing the probabilistic relationship between earthquakes and subsequent fires [17]. Quantifying this risk is crucial for developing effective design and mitigation strategies [18]. This necessitates probabilistic models for PEF ignition, considering both external causes, such as damage to utility systems, and internal causes, like the overturning of flammable contents [4]. While hazard analysis often considers both internal and external ignition sources, it is often qualitative due to a lack of data for quantitative assessment [19].

Despite growing interest in performance-based assessment for PEF, significant knowledge gaps remain. Existing studies have explored PEF risk evaluation in urban areas [24], considering fire spread and evacuation, as well as the residual capacity of earthquake-damaged structures exposed to fire [22,40,41]. However, a comprehensive approach integrating probabilistic risk assessment, structural behavior analysis, and performance metrics is needed. Furthermore, the development of PEF fragility data [2], which relates structural demands to damage and loss, is crucial but currently limited.

Specific research on structural elements and systems has focused on steel and reinforced concrete (RC) structures. Studies on steel structures have highlighted the importance of fireproofing materials and the detrimental effects of even minor losses in fire protection [3,42,43]. Research on RC structures has examined the impact of earthquakes on passive fire protection and the behavior of connections under PEF [44,45]. Numerical and experimental methods have been employed to analyze the effects of PEF on various RC elements and full-scale frames [15].

Key findings from these investigations emphasize the importance of fire protection, the influence of drift ratio on fire resistance, and the dependence of failure mechanisms and PEF resistance on fire scenarios and gravity loads. Pre-existing earthquake damage significantly reduces fire resistance, and earthquake-induced deformations further increase vulnerability [46]. Sequential analysis has emerged as a valuable tool for evaluating the combined effects of earthquakes and fire [47].

Despite considerable progress, research gaps persist. These include limited data for quantitative analysis of PEF ignition, particularly for internal causes; a scarcity of full-scale studies; and a lack of consideration for long-term effects of concrete in PEF evaluations. Future research should prioritize expanding PEF ignition models, conducting more experimental research on various structural systems, and further developing numerical and experimental studies with diverse typologies and fire scenarios. Addressing these gaps will contribute to a more comprehensive understanding of PEF and facilitate the development of effective mitigation strategies.

4. Post-Earthquake Fire (PEF) Damage Assessment

Structures affected by earthquakes are particularly vulnerable to fire for several reasons. First, physical deterioration of the structure increases its susceptibility to fire. Second, earthquakes can affect fire protection systems, rendering them less effective or completely inoperable during a fire event. Third, earthquake-induced damage can obstruct access for firefighters, facilitating the unchecked spread of fire.

The assessment of damage to structural components is a pivotal aspect of evaluating a building's resistance to post-earthquake fire (PEF) [48]. Prior to an earthquake, buildings are primarily subjected to gravity loads, comprising both dead and live loads. During seismic events, lateral vibrations inflict damage and cause permanent lateral deformation, impacting the structural integrity of the components.

In this compromised state, the structure, now burdened with residual stress from the earthquake, must withstand additional stresses imposed by any ensuing post-earthquake fire. The severity of seismic damage is contingent upon the earthquake's duration and intensity, which subsequently dictates the building's drift, acceleration, peak structural temperatures, and deflections [3]. These factors are crucial for assessing the extent of damage to structural components and for identifying necessary modifications to maintain safety.

5. Methodology

A structured methodology for conducting post-earthquake fire (PEF) analyses can be established using a performance-based framework, integrating hazard risk assessment, structural response evaluation, damage quantification, and loss estimation. Existing methodologies are largely derived from the performance-based earthquake engineering (PBEE) paradigm, which provides a systematic approach for evaluating structural behavior under sequential and compounding hazards (e.g., earthquake-induced damage followed by fire exposure) [2]. As illustrated in Figure 2, this framework follows a step-by-step process that begins with defining performance objectives and progresses through hazard evaluation, scenario development, and structural response analysis, ultimately concluding with damage assessment and loss quantification.

The general methodology consists of the following key steps:

1. Defining performance objectives;
2. Assessing seismic hazards and structural damage resulting from the earthquake;
3. Evaluating the probability of post-earthquake fire (PEF) ignition and subsequent fire spread dynamics;
4. Analyzing the structural response under combined earthquake and fire loading conditions;
5. Assessing damage and quantifying associated losses.

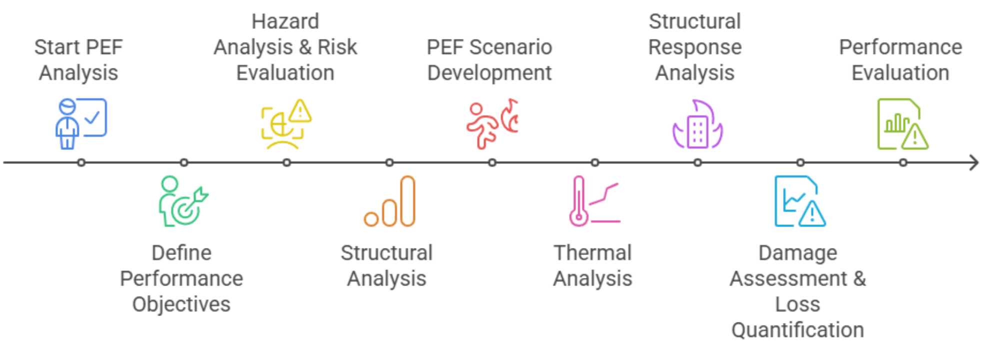

Figure 2. Post-earthquake fire analysis process.

5.1. Hazard Analysis and Risk Evaluation

A detailed breakdown of the methodology is provided below.

5.1.1. Seismic Hazard Assessment

The first stage involves evaluating the seismic hazard level for the given site using seismic hazard spectra. Appropriate ground motion records must be selected to ensure accurate representation of seismic demand during structural analysis [3]. A seismic hazard curve is employed to establish the probability distribution of various intensity measures (IMs) based on the site's geotechnical characteristics and seismic design parameters [2].

5.1.2. PEF Ignition Modeling

The probability of PEF ignition is assessed by considering both internal and external ignition sources. A dual-cause ignition model is commonly used to capture the probabilistic nature of fire ignition in cascading earthquake–fire events [2]:

- External ignition sources typically arise due to ground-shaking-induced failures, such as ruptured gas pipelines, damaged electrical substations, or compromised industrial storage facilities;
- Internal ignition sources are linked to structural response mechanisms, such as electrical short circuits, sparking due to mechanical deformations, or ignition from heated surfaces in damaged infrastructure.

A Fault Tree Analysis (FTA) approach is often employed to quantify the likelihood of ignition, considering both direct damage mechanisms and secondary effects (e.g., gas accumulation leading to delayed fire outbreaks) [2].

5.1.3. Fire Hazard Analysis

This step involves determining fire growth patterns and spread dynamics under post-earthquake conditions. Design fire scenarios are developed based on parametric fire models (e.g., time–temperature curves) or fire load and ventilation-based calculations. Key influencing parameters include the following:

- Fuel load density;
- Ventilation conditions;
- Thermal properties of interior linings;
- Compartmentation failure due to earthquake damage.

The interaction between seismic damage and fire spread is crucial, as breached fire barriers, compromised fireproofing systems, and damaged suppression mechanisms significantly alter conventional fire behavior.

5.2. Structural Analysis

5.2.1. Initial Static Analysis

Structural analysis begins with an initial static equilibrium assessment, where gravity loads are applied to establish the baseline stress state before seismic excitation [49].

5.2.2. Seismic Analysis

Seismic performance evaluation is conducted using static or dynamic analysis methodologies, depending on the complexity of the structural system:

- Nonlinear static pushover analysis is frequently utilized to estimate structural capacity under increasing lateral loads until a predefined target displacement is reached [50];
- Advanced pushover techniques, such as adaptive pushover analysis and modal pushover analysis, are employed to capture higher-mode effects and progressive damage patterns more accurately [49];
- Time-history analysis may be implemented for structures requiring a more precise representation of inelastic seismic behavior [3].

5.2.3. PEF Scenario Development

To evaluate the structural response under combined earthquake–fire scenarios, numerical models are subjected to a series of sequential hazard loadings. These include the following:

- Varying Peak Ground Accelerations (PGAs) to represent different seismic intensities;

- Fire simulations incorporating diverse thermal profiles, including localized fires, compartmentalized fires, and fully developed post-flashover conditions;
- Control scenarios involving fire-only cases, which isolate the effects of fire without prior seismic damage for comparative assessment.

5.2.4. Thermal Analysis

A thermal analysis is conducted to evaluate temperature distributions across structural components, considering heat transfer mechanisms such as conduction, convection, and radiation. Finite element software, such as SAFIR, is commonly employed to simulate thermal and mechanical behavior under elevated temperatures [49,51,52].

5.2.5. Structural Response Analysis

The structural response under fire loading is analyzed with emphasis on displacement profiles, fire resistance time, and critical temperature thresholds. Nonlinear geometric effects are incorporated using large-displacement formulations to capture progressive loss of load-bearing capacity under extreme thermal conditions [37,53,54].

5.3. Damage Assessment and Loss Quantification

5.3.1. PEF Fragility Development

To quantify structural vulnerability, PEF fragility functions are developed to establish relationships between engineering demand parameters (EDPs) and damage states. In cases where empirical post-earthquake fire data are unavailable, expert judgment and probabilistic models are used to approximate fragility relationships [2].

5.3.2. Damage Measures (DMs)

Structural damage assessment is performed using demand parameters, such as inter-story drifts, residual deformations, and material degradation metrics. These indicators define the performance thresholds of fire-exposed structures [2].

5.3.3. Loss Estimation

Estimated damage measures (DMs) are translated into decision variables (DVs) to facilitate risk-informed decision-making [2]. These include the following:

- Repair costs (direct economic losses);
- Downtime estimations (functional recovery periods);
- Occupant safety risks (probability of injury or fatality).

Loss estimation frameworks integrate cost–benefit analyses to support performance-based decision-making in seismic and fire-prone regions.

5.3.4. Performance Evaluation

Structural performance is evaluated under PEF scenarios using quantitative metrics [2], including the following:

- Failure probabilities;
- Serviceability loss;
- Occupant safety risks.

5.4. Software and Computational Tools

Various computational tools are utilized to conduct PEF analyses efficiently:

- SAFIR—Finite element software for thermal–structural fire analysis [55];
- OpenSees—Open-source platform for seismic and fire-following-earthquake (FFE) simulations [56];

- Ozone—A zone model software for predicting fire development and smoke propagation [57];
- MATLAB—Utilized for heat transfer modeling and custom computational scripting [58];
- ABAQUS—Advanced finite element analysis (FEA) software for coupled fire–seismic response studies [59];
- SAP2000—Commonly used for pushover analysis and seismic performance evaluation [60].

Each of these dimensions is integral to the comprehensive assessment of a building's PEF resistance, underscoring the need for a multi-faceted approach to ensure structural safety and resilience in the face of compounded hazards. Simulating seismic damage in reinforced concrete (RC) elements often involves modifying numerical models to reflect the expected degradation. One common approach is the reduction of concrete cover in plastic hinge regions, where damage concentrates during seismic events [1]. This reduction simulates cracking and spalling, with varying degrees of removal representing different damage levels [51,52]. Minor damage (D0/D1), characterized by minimal cracking, assumes an intact section with negligible impact on thermal properties, aligning with the Immediate Occupancy (IO) performance level [51,52]. Slight damage (D2), typically simulated by removing 50% of the concrete cover, represents spalling and exposure of reinforcement, corresponding to the Life Safety (LS) performance level [51,52]. Severe damage (D3) involves complete removal of the cover, exposing the reinforcement and reflecting the Collapse Prevention (CP) performance level [51,52]. To streamline complex post-earthquake fire (PEF) analyses, simplified criteria are employed to represent these damage levels [51]. Additionally, some studies utilize geometric damage parameters, such as relative crack depth and spalling extent, to quantify damage and its influence on the thermal behavior of RC elements [61].

In steel structures, earthquake-induced damage to components can be modeled as a combination of geometric damage and mechanical damage, such as residual deformation, including stiffness and strength degradation. For example, in one study, the inter-story drift angle was used as the primary indicator of structural damage, with residual values of the inter-story drift angles representing the seismic damage in a structure with non-degrading components [62].Another study introduced a comprehensive damage index (damage variable) to quantify the extent of damage in welded–bolted hybrid connection joints under seismic loading [63].

Researchers have also utilized the Johnson–Cook ductile damage model to capture the degradation of steel elements in damage models [36]. This model defines the damage initiation point as the equivalent plastic strain (ϵ_d), which is a function of stress triaxiality (σ^*), strain rate ($\dot{\epsilon}$), and homologous temperature (T^*):

$$\epsilon_d = D1 + D2\exp(D3\sigma^*)(1 + D4\ln(\dot{\epsilon}))(1 + D5T^*) \tag{1}$$

The five constants D1–D5 are specified in Johnson and Cook [64]. The model assumes that the damage variable evolves linearly, allowing the equivalent plastic displacement to be defined at the point of full material degradation (ϵ_f).

Some studies note that damage to non-structural elements, such as walls, partitions, and external glazing, can significantly impact a building's fire performance [65]. For example, damage to non-structural fire protection systems can accelerate fire spread and lead to quicker temperature increases in structural elements. Another reference describes tests conducted to evaluate the performance of fire door sets after simulated earthquake damage. The earthquake effects were replicated using quasi-static cyclic loading tests, which revealed severe distortion of the fire door frames [66].

6. Behavior of Materials at Elevated Temperatures

Investigating the behavior of steel and concrete under high temperatures is crucial for understanding the performance of structures during post-earthquake fires (PEF). Elevated temperatures have a profound impact on the mechanical properties of these materials, including compressive strength, Young's modulus, yield strength, and ultimate strength [15,63,67,68].

While concrete, being a heat-inert material, can provide some degree of fire resistance, high temperatures can lead to spalling, which reduces the cross-sectional area of concrete elements and exposes the reinforcing steel to further damage. The presence of cracks, whether induced by seismic activity or fire, can significantly affect heat propagation, thereby compromising the structural integrity [50,69]. This issue becomes even more critical when the concrete cover that protects the reinforcing steel is damaged [70]. The localization of maximum temperatures within a fire underscores the importance of precise thermal analysis [15].

Furthermore, the residual strength and ductility of steel are significantly affected by the cooling methods applied after a fire, such as air and water cooling [67]. Ongoing research into the behavior of steel and concrete at elevated temperatures has led to the development of predictive formulae and constitutive models, which are essential for estimating material properties under these extreme conditions [15,69].

Under an air cooling condition, the behaviour of both CFS-F (flat region of cold-formed steel specimens) and CFS-C (corner region of cold-formed steel specimens) can be understood as follows:

$$20\ ^\circ\mathrm{C} \le T \le 1000\ ^\circ\mathrm{C}, \quad \frac{f_{uPT}}{f_u} = 0.992 + 3.97 \times 10^{-4}T - 1.76 \times 10^{-6}T^2 + 1.37 \times 10^{-9}T^3 \qquad (2)$$

Under a water cooling condition, the behaviour of both CFS-F (flat region of cold-formed steel specimens) and CFS-C (corner region of cold-formed steel specimens) can be represented as:

$$20\ ^\circ\mathrm{C} \le T \le 1000\ ^\circ\mathrm{C}, \quad \frac{f_{uPT}}{f_u} = 0.995 + 2.55 \times 10^{-4}T - 9.89 \times 10^{-7}T^2 + 7.19 \times 10^{-10}T^3 \qquad (3)$$

In the given equation, f_{uPT} denotes the ultimate tensile strength of steel following exposure to a specified elevated temperature. This parameter reflects the potential degradation in mechanical properties due to thermal effects. Conversely, f_u represents the ultimate tensile strength of steel under ambient conditions, where the material has not been subjected to fire or elevated temperatures. The variable T corresponds to the maximum temperature to which the steel has been exposed, serving as a critical factor in assessing the thermal degradation of its structural integrity.

Advanced methodologies, such as hybrid fire simulation (HFS), are being developed to better understand the complex interactions between thermal and mechanical behaviors in PEF scenarios [15].

In conclusion, a thorough understanding of the thermal and mechanical behavior of steel and concrete at elevated temperatures is essential for developing accurate PEF assessment techniques, designing resilient structures, and ensuring the safety of buildings and their occupants during post-earthquake fire incidents.

Steel's mechanical properties are highly sensitive to changes under elevated temperatures, which significantly affect its structural performance during fire events. Due to its high thermal conductivity, steel rapidly loses strength and stiffness as temperatures increase. This reduction in mechanical properties is particularly critical in fire scenarios, where maintaining structural integrity is essential. Beyond 500 °C, the ultimate strength of steel decreases by approximately 50% [71]. Additionally, the modulus of elasticity and yield strength substantially decline with rising temperatures, primarily due to the weakening of atomic bonds within the material. As a result, accurate fire simulations must incorporate temperature-dependent values for these properties to predict structural behavior effectively [68]. The thermal conductivity of steel, which dictates the rate at which heat is transferred through the material, decreases as temperatures rise. Specific heat—the amount of heat required to increase the temperature of a unit mass of steel by one degree Celsius—increases with temperature, particularly up to 700 °C. Moreover, steel's thermal expansion slightly increases with temperature, necessitating the inclusion of these values in thermal analyses to accurately model fire conditions [68]. The stress–strain relationship of steel also undergoes significant alterations at elevated temperatures, which is crucial for understanding the performance of steel structures during fires. For example, hot-rolled steel exhibits distinct changes in its stress–strain behavior as temperatures escalate [72].

The cooling process following exposure to high temperatures plays a critical role in determining the residual mechanical properties of steel, especially its residual strength and ductility. Studies have shown that different cooling methods, such as air cooling and water cooling, can lead to varying degrees of residual strength and ductility, influencing the post-fire performance of steel structures [67]. Interestingly, research suggests that multiple heating–cooling cycles have a negligible impact on the mechanical properties of certain hot-rolled steels, such as Q345, which is a high-strength (minimum yield strength of 345 MPa and minimum tensile strength of 470 MPa), low-alloy structural steel that is widely utilized in various industries due to its excellent mechanical properties and cost-effectiveness. Q345 steel primarily comprises iron (98–99%) with a small percentage (1–2%) of alloying elements such as carbon, manganese, silicon, phosphorus, and sulfur.

This finding implies that the effects of cyclic heating and cooling on these steels are minimal and can be largely disregarded in some scenarios [67]. While current literature provides valuable insights into the macroscopic behavior of steel at elevated temperatures, it often lacks a detailed exploration of the microstructural changes that underpin these alterations in properties. Understanding these microstructural transformations could further enhance the predictive models used in fire simulations and the design of steel structures for fire resilience.

Concrete undergoes complex transformations when exposed to high temperatures, significantly affecting its structural performance. These transformations encompass both physical changes, such as expansion, and a series of chemical reactions among its components—cement, aggregate, and moisture—each responding differently to heat [15]. Due to its low thermal conductivity, concrete transmits heat slowly within its cross-section, which can provide some protection to the embedded steel reinforcement against rapid temperature increases. However, damage caused by earthquakes, such as cracks or spalling, can accelerate heat penetration, thereby compromising the reinforcement's integrity [50]. As the temperature in concrete rises, its crushing and yield strengths decrease, making it less effective as a structural material, especially at temperatures exceeding 500 °C [50]. This deterioration is even more pronounced in concrete that has been previously damaged, such as from seismic events [50]. A critical issue is the potential for thermal spalling—a sudden and violent chipping or explosion of the concrete surface—which can significantly reduce the structure's load-bearing capacity. Several factors influence spalling, including the thickness of the concrete cover, with spalling being more common in beams and columns where the cover exceeds 4–5 cm. Additionally, the type of concrete plays a role; high-strength concrete (HSC), particularly that with moisture content exceeding 3–4%, is more prone to spalling. Fire intensity is another critical factor, with the time to spalling being heavily dependent on how intense the fire is. For instance, under a high-intensity fire scenario, spalling in slabs can occur in as little as 2 min [70]. Cracks in concrete, often resulting from seismic activity, significantly alter the material's behavior at elevated temperatures. Larger crack widths, which indicate severe initial damage, are associated with higher temperatures within the concrete member during a fire. While normal-strength concrete may resist spalling, cracked and damaged concrete members are much more vulnerable. The presence of cracks can lead to localized temperature variations within the concrete when exposed to fire. Numerical simulations have shown that as the projected length of a crack increases, higher temperatures tend to concentrate near the crack's surface [15]. This uneven temperature distribution complicates the analysis and prediction of concrete's behavior in post-earthquake fire scenarios. In summary, the intricate interplay of physical and chemical changes in concrete at elevated temperatures, exacerbated by pre-existing damage from seismic events, necessitates a nuanced understanding of its behavior. This understanding is crucial for accurately predicting structural performance in post-earthquake fire conditions and ensuring the safety and resilience of structures subjected to such extreme events.

7. Influence of Different Structural Systems

Studying the behavior of various structural systems under post-earthquake fire (PEF) conditions is vital due to the distinct vulnerabilities and damage patterns associated with each system. This knowledge is crucial for developing effective design strategies that enable engineers to create targeted solutions, enhancing fire resistance and preventing collapse under such extreme conditions [3,65,73,74]. For instance, understanding that irregular buildings are more prone to earthquake damage and, consequently, have reduced fire resistance can guide design choices to improve PEF performance [50,68]. Incorporating PEF considerations into performance-based design paradigms is also essential. This approach transcends traditional design methods that address individual hazards like fires or earthquakes separately and instead focuses on their combined effects, ensuring a comprehensive assessment of structural integrity under multiple hazards [68]. Evaluating how earthquake-induced damage impacts fire resistance is fundamental to this holistic design approach [3].

Enhancing post-disaster safety is another critical aspect of this research. Understanding how different structural systems behave in PEF scenarios helps predict potential damage patterns and collapse modes, which is invaluable for informing post-disaster response and recovery efforts [54]. Such insights are particularly beneficial for fire and rescue services, as they improve preparedness and response strategies. Furthermore, a deep understanding of the influence of different structural systems on PEF response is crucial for developing accurate risk assessment models and informing effective mitigation strategies [51].

Various studies have examined the PEF performance of different structural systems, including steel structures, reinforced concrete structures, and concrete-filled steel tube (CFST) structures. Research on steel structures, for example, has explored the PEF behavior of steel moment-resisting frames, taking into account factors such as fire scenarios, gravity loads, connection damage, and the effectiveness of fireproofing materials [62,73,75]. These studies highlight the vulnerability of steel structures to PEF and emphasize the critical role of effective fireproofing in enhancing fire resistance [74]. For reinforced concrete structures, research has focused on the impact of earthquake-induced damage on fire resistance, considering factors such as concrete spalling, reinforcement exposure, and varying levels of damage [15,51,76]. Similarly, studies on CFST structures have investigated the PEF performance of CFST columns and connections, analyzing aspects like residual stress, deformation, and temperature gradients [31,77].

However, there are still significant gaps in the research that need to be addressed. Most existing studies have concentrated on individual structural elements or 2D frame analyses, highlighting the need for more research on full-scale structures and the interactions between different structural systems under PEF conditions [15,78]. Developing more advanced modeling techniques is also necessary. This includes incorporating more realistic damage representations, accounting for uncertainties in structural analysis—such as variations in geometric parameters, fire location, and spread—and considering the dynamic nature of fire spread to enhance the accuracy of PEF simulations [2,31,79]. Additionally, addressing gaps related to the long-term effects of PEF on structural performance is crucial. Further investigation is needed into the long-term effects of concrete properties, such as creep and shrinkage, on PEF response, which will improve the realism of sequential analysis [65]. By addressing these research gaps and deepening the understanding of how different structural systems behave under PEF conditions, the structural engineering community can make significant strides toward developing more resilient and safer buildings in earthquake-prone regions. This enhanced knowledge will not only improve the design of new structures but also inform retrofitting strategies for existing buildings, ultimately contributing to greater safety and resilience in the face of complex, multi-hazard scenarios. The following chapters will discuss the effect of post-earthquake fires on specific structural systems.

7.1. Moment-Resisting Steel Frames

The behavior of moment-resisting steel frames under post-earthquake fire (PEF) conditions is a complex issue, influenced by the interplay of multiple factors, including the severity of the preceding earthquake, the extent of damage to structural and non-structural components, and the characteristics of the fire itself. These interactions significantly affect the overall performance of the structure during PEF events. Earthquakes induce various forms of damage to steel structures, broadly categorized into mechanical and geometrical damage. Mechanical damage refers to the deterioration of material properties, such as the reduction in the strength and stiffness of steel due to the extreme stresses and strains encountered during seismic activity [80]. This degradation can severely compromise the structural integrity of the building, making it more vulnerable to subsequent fire. Geometrical damage, on the other hand, involves alterations to the building's original shape, including residual drift and member buckling, which disrupt load paths and compromise structural stability [36]. Connections are particularly susceptible to seismic forces, often experiencing spalling of fireproofing materials—exposing the underlying steel—and the formation of fractures and cracks due to cyclic loading [81]. The damage inflicted by an earthquake typically leads to a significant reduction in the fire resistance of steel frames [80].

This reduction is especially pronounced in the presence of residual drift, which increases the structure's vulnerability to fire [49]. Loss of fire protection through spalling or other forms of damage accelerates heat transfer to the structural steel, hastening the temperature-induced degradation of its strength. As a result, earthquake-damaged frames are at a higher risk of failure when subjected to post-earthquake fires compared to undamaged structures [82].

Gravity columns are crucial to the performance of moment-resisting frames during PEF scenarios [83]. These columns often bear high axial loads, which are exacerbated by additional stresses from earthquake-induced deformations. Failure of gravity columns can trigger catastrophic collapse, often acting as the initiating event in such scenarios, regardless of the performance of plastic hinges within the moment-resisting frame system [49]. This underscores the importance of ensuring the integrity of gravity columns following an earthquake.

The seismic design philosophy adopted for a structure significantly influences its behavior during a PEF event [36]. Structures designed with enhanced seismic performance levels, characterized by greater ductility and energy dissipation capacity, may exhibit improved fire resistance even after an earthquake. However, it is important to recognize that PEF conditions can still exceed the intended performance levels, even in seismically designed structures. This highlights the necessity of incorporating PEF scenarios into the design process to ensure that buildings can effectively withstand both seismic and fire events [84].

The specific behavior of moment-resisting frames under PEF conditions can vary widely depending on several factors, including the characteristics of the earthquake (e.g., intensity, frequency content, and duration), the nature of the fire (e.g., fire curve, compartment size, and ventilation conditions) [3,36,49,85], the characteristics of the building (e.g., height, number of stories, and framing configuration) [36,78], and the state of fireproofing materials. The interplay of these factors determines the overall performance of the structure during a PEF event [75,82]. To evaluate the performance of steel structures under PEF conditions, various analytical approaches are employed [75]. Nonlinear static pushover analyses and coupled thermal–mechanical analyses are widely used to assess PEF performance, with sophisticated finite element models playing a crucial role in accurately capturing the complex behavior of structures under these conditions [80]. These models incorporate material and geometric nonlinearity as well as temperature-dependent properties. For preliminary assessments, simplified methods such as the story-based stability approach provide computationally efficient alternatives, although they may not fully capture the complexity of PEF behavior [78]. The vulnerability of moment-resisting steel frames to PEF is underscored by the extensive damage that earthquakes can inflict, particularly on connections and fireproofing. Gravity columns are critical elements, often determining the overall structural stability during PEF events. Understanding the complex interactions among these factors and employing robust analytical techniques are essential for accurately evaluating and mitigating the risks associated with PEF in steel structures. This comprehensive approach is vital for developing resilient designs that can withstand the combined effects of seismic and fire hazards.

7.2. Moment-Resisting Reinforced Concrete Frames

The behavior of moment-resisting reinforced concrete (RC) frames under post-earthquake fire (PEF) conditions is influenced by the complex interaction between the damage caused by an earthquake and the subsequent exposure to fire. Earthquake-induced damage in RC frames can manifest in various forms, including tensile cracking, removal of rebar cover, compressive crushing, and residual deformations, all of which significantly compromise the fire resistance of RC elements [86]. While minor tensile cracking may have a limited impact on PEF resistance, severe damage—such as extensive cracking, removal of rebar cover, and concrete crushing—can drastically reduce the structure's ability to withstand fire [47]. The extent of this damage often correlates with the performance level the structure was designed to achieve during an earthquake, such as Immediate Occupancy (IO), Life Safety (LS), or Collapse Prevention (CP) [87]. Structures designed for higher performance levels, like CP, tend to sustain more significant damage compared to those designed for lower levels like IO [88]. The deformed geometry and degraded stiffness resulting from an earthquake significantly affect how an RC structure responds to fire [86]. Residual deformations and reduced load-carrying capacity increase the structure's vulnerability to fire damage. Damaged RC elements, particularly those with cracks and spalling, experience faster temperature increases in exposed areas compared to undamaged elements [87]. Cracks and spalling in the concrete facilitate quicker heat penetration, and the exposed rebar heats up more rapidly due to its high thermal conductivity [15,86]. Consequently, the ability of these damaged components to sustain gravity loads under fire conditions is significantly diminished, increasing the risk of structural failure [47]. Several factors influence the PEF resistance of RC frames. Structures designed for higher performance levels, such as LS or CP, generally exhibit lower fire resistance than those designed for lower levels like IO. This is because higher performance levels allow for greater plastic deformation during an earthquake, leading to more severe damage [88]. The extent of damage, particularly the depth of spalling and the degree of residual deformation, plays a critical role in determining fire resistance. Increased spalling depth and larger residual deformations further reduce fire resistance. The thickness of the concrete cover is another crucial factor; a thicker cover provides better protection for the rebar, delaying its exposure to high temperatures. However, spalling caused by earthquake damage or thermal effects can compromise this protection, accelerating the heating of the rebar and reducing the load-carrying capacity. Additionally, higher axial compression ratios in columns generally result in higher fire resistance, although they also make the fire resistance more sensitive to variations in other factors [69]. Accurately evaluating the PEF resistance of RC frames often requires a sequential analysis approach that considers the combined effects of gravity loads, earthquake loads, and fire loads [15,47]. This approach captures the progressive damage accumulation and its influence on the overall structural behavior. Advanced numerical models, such as fiber element models, are essential for capturing the nonlinear behavior of concrete and steel at elevated temperatures [88]. These models account for the degradation of material properties and the spread of plasticity within structural elements. Accurate thermal analysis is also crucial for determining the temperature distribution within RC elements under fire conditions [87]. Factors such as concrete moisture content, thermal expansion coefficients of concrete and steel, and fire exposure conditions (e.g., standard fire curves or compartment fire simulations) require careful consideration to ensure a realistic assessment. General observations from studies indicate that PEF can lead to the rapid collapse of structures already weakened by an earthquake. The fire resistance of RC frames exposed to PEF is substantially lower than that of undamaged frames [47]. Experimental tests on RC frames subjected to PEF have shown that damage patterns and failure modes are influenced by factors such as earthquake intensity, axial load levels, and detailing for ductility [15]. These findings consistently highlight that PEF poses a significant threat to the integrity of RC structures. They emphasize the need for comprehensive analysis and design approaches that explicitly address the combined effects of earthquake damage and fire exposure. While existing studies provide valuable insights into the behavior of moment-resisting RC frames under PEF conditions, further research—particularly through full-scale experimental investigations—is essential to deepen our understanding of this complex phenomenon. Such research will be critical in developing more robust design guidelines and mitigation strategies to enhance the resilience of RC structures in earthquake-prone regions.

7.3. Braced Frames

The behavior of steel braced frames under post-earthquake fire (PEF) conditions is a significant concern in structural engineering, particularly for buildings in seismically active regions. The performance of these structures when subjected to the combined effects of earthquake-induced damage and subsequent fire exposure presents unique challenges that demand careful consideration. Steel braced frames subjected to PEF conditions consistently exhibit reduced fire resistance compared to their undamaged counterparts. This reduction in fire resistance is primarily due to several interrelated factors:

1. Residual Deformations: Earthquake-induced residual deformations, such as drifts and the formation of plastic hinges in braces and beams, create weak points in the structure. Although these deformations may not immediately cause collapse, they significantly increase the structure's vulnerability to fire damage [89].

2. Material Degradation: Steel's strength and stiffness degrade considerably at elevated temperatures. When the frame is already compromised due to residual deformations, the high temperatures encountered during a fire further weaken the structure, exacerbating the risk of collapse.
3. Reduced Load-Carrying Capacity: The combination of residual deformations and material degradation reduces the structure's load-carrying capacity, making it more prone to failure when exposed to fire.

Within steel braced frames, braces are identified as the most vulnerable components under PEF conditions. Designed to yield or buckle under seismic loads, braces experience significant damage during an earthquake. This damage makes them particularly susceptible to early buckling and failure during subsequent fire exposure. This vulnerability underscores the need for targeted design considerations and protective measures specifically for braces in regions prone to both seismic activity and fire [89]. The damage sustained by a steel braced frame during an earthquake and its subsequent fire resistance are influenced by several factors:

- Earthquake Intensity and Characteristics: The intensity, duration, and frequency content of seismic events play a critical role in determining the level of structural damage. More severe earthquakes typically result in greater residual deformations, increasing the frame's vulnerability to fire [89].
- Fire Location and Intensity: The location and intensity of the fire within the structure critically affect the load distribution and performance of different structural elements. Fires occurring in unbraced bays are particularly concerning, as braces in braced bays contribute to load redistribution even when exposed to fire [90].
- Bracing System Type: The type of bracing system used—whether concentrically braced frames, eccentrically braced frames, or strongback braced frames—affects the structure's response to seismic loads and its overall PEF performance. Each system has different failure modes and vulnerabilities under combined seismic and fire loads [65,91].

To enhance the PEF performance of steel braced frames, several design strategies can be implemented:

- Protective Measures for Braces: Applying fireproofing materials to braces can significantly increase the fire resistance time, reducing the likelihood of early failure during a fire [89].
- Strengthening Connections: Enhancing the robustness of connections, particularly at critical points such as beam–column joints, can improve the structure's overall resilience to PEF conditions [73].
- Incorporating PEF Scenarios into Design Codes: To ensure fire safety in seismically active areas, it is crucial to integrate PEF considerations into building codes and standards. This approach will help in developing structures that can better withstand the combined effects of seismic and fire hazards [89].

Accurately predicting the behavior of steel braced frames under PEF conditions necessitates the use of advanced analytical tools that can capture the complex interactions between seismic and thermal loads, as well as material and geometric nonlinearities. Numerical simulations conducted using software like OpenSees and ABAQUS are essential for understanding the performance of these structures under PEF scenarios and for developing effective design solutions [92,93]. These simulations provide a comprehensive analysis that is crucial for designing steel braced frames capable of withstanding the dual challenges of seismic activity and fire exposure. The vulnerability of steel braced frames to PEF conditions is a significant concern, particularly in regions prone to both seismic and fire hazards.

The reduced fire resistance resulting from residual deformations, material degradation, and weakened braces underscores the importance of targeted design strategies. By employing advanced analytical techniques and incorporating PEF scenarios into design standards, structural engineers can develop safer and more resilient buildings capable of withstanding the combined impacts of earthquakes and fire.

7.4. Shear Walls

The research literature offers crucial insights into the performance of both steel and reinforced concrete shear walls under the combined impact of seismic activity and fire. An in-depth analysis of these behaviors highlights substantial challenges and considerations that must be addressed in the design and evaluation of such structures.

7.4.1. Steel Shear Walls

The performance of steel shear walls under post-earthquake fire (PEF) conditions is notably influenced by fire-induced degradation. A significant finding from an ABAQUS model analysis of a steel plate shear wall (SPSW) was the rapid reduction in lateral stiffness as the fire duration increased. This degradation is primarily attributed to the weakening of steel at high temperatures, with the model indicating a 50% reduction in stiffness after 35 min of fire exposure and a near-total loss of rigidity after 40 min [94]. Additionally, the study highlighted the dynamics of out-of-plane displacement (OOPD) in the infill plate, a critical component of SPSWs. Initially, the OOPD increased due to the thermal expansion of the steel plate, but as the fire continued, the OOPD decreased, likely due to the degradation of steel's mechanical properties at elevated temperatures, rendering the plate more susceptible to deformation under its own weight and any applied loads. The study also underscored the importance of material selection in enhancing fire resistance. Specifically, the use of higher-grade steel, such as S275, in SPSWs significantly delayed the loss of rigidity compared to lower-grade steel. This finding highlights the potential benefits of selecting high-performance materials to improve the resilience of steel shear walls in PEF scenarios.

7.4.2. Reinforced Concrete Shear Walls

The performance of reinforced concrete (RC) shear walls under post-earthquake fire (PEF) conditions is severely compromised by the degradation of both concrete and steel reinforcement. High temperatures drastically reduce the compressive strength of concrete, a particularly concerning issue in the context of PEF scenarios. Research involving a six-story RC building subjected to shaking table tests starkly demonstrated this effect [95], where the short columns on the ground floor—already heavily damaged during the earthquake simulation—experienced a reduction in concrete compressive strength to merely 20% of their original capacity. While steel reinforcement also experiences a reduction in yielding strength when exposed to fire, this effect is less pronounced than the degradation of the surrounding concrete, making the weakened concrete the predominant factor in the overall reduction of the shear wall's capacity under PEF conditions. Earthquake-induced cracks and spalling in the concrete create pathways for more rapid and deeper heat penetration into structural elements, exacerbating the degradation of both concrete and steel. This accelerated heat transfer initiates a dangerous cycle of weakening, further compromising the structural integrity of RC shear walls under fire conditions [95]. Residual drift and P-delta effects—additional forces and moments imposed on a structure due to its deformed shape—are critical considerations in the design of RC shear walls for PEF scenarios. Although a particular study on a six-story RC building found negligible residual lateral deformation after an earthquake simulation, the research emphasizes that these effects must be carefully evaluated to avoid underestimating potential risks [95]. A recurring theme across the findings is the necessity for a comprehensive approach to the analysis and design of structures for PEF events. Such an approach must consider the combined effects of both earthquake and fire hazards, as the interaction between these events can significantly impact structural performance. Ignoring this interplay could lead to dangerous design underestimations. The current scarcity of research focused specifically on PEF behavior is a significant concern. The findings consistently underscore the need for more experimental and analytical investigations to deepen our understanding of the complex interactions between earthquake damage and fire response in both steel and reinforced concrete structures. Advancing this knowledge is essential for developing accurate predictive models, improving design guidelines, and ultimately ensuring the safety and resilience of buildings in earthquake-prone regions.

7.5. Self-Centring Systems

Self-centering systems are renowned for their superior seismic performance, often exhibiting minimal residual deformation after significant earthquakes. However, their behavior in subsequent post-earthquake fire (PEF) scenarios remains underexplored, necessitating further investigation to ensure these systems can withstand the compounded effects of multiple hazards [39]. One of the primary impacts of PEF on self-centering systems is the alteration of material properties at elevated temperatures. Earthquake-induced damage can influence the strength and ductility of steel when it is later subjected to high temperatures. Research indicates that the history of cyclic loading significantly affects the mechanical properties of mild steel—such as fracture elongation, elastic modulus, and ultimate strain—under these conditions. Although the number of loading cycles has a minimal effect, the amplitude of pre-strain substantially influences the high-temperature behavior of the material [38]. This finding underscores the importance of considering pre-damage effects when assessing the fire performance of self-centering systems [39].

Another critical effect of PEF on self-centering systems is the geometric changes resulting from residual deformations caused by earthquakes. These deformations can lead to altered load paths and stress concentrations during fire exposure. For instance, studies have demonstrated that seismic events can significantly modify the geometric conditions of structures during subsequent fires [38], potentially reducing their fire resistance. The combined effects of these geometric alterations and changes in material properties due to PEF can lead to structural responses that differ markedly from those observed under fire-only conditions. Numerical simulations of steel self-centering moment-resisting frames (SC-MRFs) exposed to PEF have revealed larger inter-story drift ratios compared to those under fire-only scenarios [39]. This finding highlights the critical need to account for the combined effects of earthquakes and fire in the design of self-centering systems. The extent of pre-earthquake damage and the severity of the fire are crucial factors influencing the PEF behavior of self-centering systems. Generally, higher levels of pre-earthquake damage and more intense fire exposures result in more pronounced structural responses and an increased likelihood of failure. Moreover, various factors, including the type and arrangement of self-centering and energy-dissipating components, can significantly affect the PEF behavior of these systems. For example, SC-MRFs with different connection details—such as top-and-seat angles, post-tensioning strands, buckling-restrained plates, and pre-stressed bars—may exhibit varied responses under PEF conditions [38,96]. Consequently, the specific configuration of the self-centering system must be carefully considered in the analysis to ensure optimal performance.

7.6. Concrete-Filled Steel Tube (CFST) Columns

Concrete-filled steel tube (CFST) columns are widely recognized for their strength, seismic performance, and ease of construction. However, their load-bearing capacity can be significantly reduced when subjected to earthquakes followed by subsequent fires (PEF). Below are key insights into the behavior of CFST columns under PEF conditions. Researchers often utilize quasi-static tests and fire tests to examine CFST columns under PEF conditions. In quasi-static tests, columns are subjected to a constant compressive force and cyclic horizontal force to simulate earthquake-induced damage. This is followed by fire tests, where the pre-damaged columns are exposed to high temperatures while maintaining a constant axial load. These tests allow researchers to observe fire resistance time, failure modes, and temperature distribution within the columns. CFST columns exposed to PEF typically exhibit local buckling at the base, along with softening and buckling at mid-height. Additionally, concrete crushing and cracking may occur [77]. Several factors affect CFST column performance under PEF:

- Thickness of Steel Tube: Thicker steel tubes enhance a CFST column's load-bearing capacity, generally leading to increased fire resistance under normal conditions. However, in PEF scenarios, thicker tubes can result in more rapid concrete core failure. The deteriorated steel tube transfers more load to the concrete core, causing it to fail sooner, a pattern that persists regardless of the degree of pre-earthquake damage [77].
- Yield Strength of Steel Tube: Higher yield strength in steel tubes improves the initial load-bearing capacity of CFST columns. However, the fire resistance time decreases with increased yield strength. This is because high-strength steel, when exposed to PEF, undergoes accelerated material property degradation, which has a more pronounced impact on the column's overall behavior [77].
- Axial Compression Ratio: A higher axial compression ratio reduces the fire resistance time of a CFST column. The increased axial load diminishes the steel tube's ability to confine the concrete core, making the concrete more vulnerable to crushing under high temperatures [77].
- Height and Wall Thickness of the Column: The height and wall thickness of the CFST column significantly affect its fire resistance. Columns with insufficient wall thickness are more prone to local buckling, particularly at the top and bottom. To enhance fire resistance, it is recommended to maintain a wall thickness of 8.5–10.5 mm and a column height of 3250–3550 mm, which can help optimize steel content and mitigate excessive bending moments [78].

Understanding the behavior of CFST columns under PEF conditions is essential for developing robust design strategies that enhance their resilience. Future research should focus on these factors to improve the performance and safety of CFST columns in seismic regions.

8. Performance-Based Design for PEF

Performance-based design is a critical component of structural engineering, especially in regions susceptible to earthquakes, where post-earthquake fires (PEFs) pose a substantial threat. This approach aims to ensure that buildings can withstand both seismic events and subsequent fires, achieving specific performance objectives that prioritize occupant safety and structural integrity [15]. In contrast to traditional design methods, which may inadequately consider the combined effects of earthquakes and fires, performance-based design provides a more holistic framework for assessing and mitigating risks [75]. The philosophy behind performance-based seismic design focuses on engineering structural elements to meet various performance levels, such as Operational (O), Immediate Occupancy (IO), Life

Safety (LS), and Collapse Prevention (CP), depending on the building's occupancy and importance [68]. For instance, buildings designed to the LS level—like certain residential and educational structures—should maintain stability sufficient for safe evacuation during a design-level earthquake, even if significant damage occurs [66]. Performance-based fire design primarily aims to contain fires within compartments, preventing their spread to other building areas. This is achieved through active measures, such as sprinkler systems, and passive measures, such as using non-combustible materials. The key objective is to ensure building stability for a sufficient duration, allowing for occupant evacuation and fire suppression efforts, even after earthquake damage. This duration, known as fire resistance, is typically expressed in minutes and is influenced by factors such as compartment size, opening dimensions, and specific fire scenarios [66]. One of the key challenges in performance-based design for PEF scenarios is accounting for the complex interaction between seismic and fire loads. Earthquakes can inflict damage that significantly reduces a building's fire resistance by compromising the integrity of fire-resistant components or impairing the functionality of active fire protection systems [48]. Thus, a comprehensive approach requires consideration of the following:

- Potential damage to fire protection systems: Earthquakes can damage water supply lines, rendering sprinkler systems ineffective. Additionally, damage to passive fire protection, such as fire-resistant coatings on structural components, can expose these elements directly to flames, thereby reducing their fire resistance [72].
- Degradation of structural fire resistance: Earthquake-induced damage, such as concrete spalling or steel yielding, can significantly diminish the fire resistance of structural elements. Residual deformations from the earthquake can further exacerbate this degradation [65,66].
- Changes in fire dynamics: Earthquake damage can alter fire spread patterns within a building. For example, the collapse of a floor can facilitate vertical fire spread, while damage to partitions can create openings that allow for faster propagation of fire and smoke [66,75].

To address these complexities, a sequential analysis approach is commonly employed in performance-based PEF design, which involves the following elements:

1. Applying gravity loads: Simulating the dead and live loads the structure typically supports under normal conditions [69,75].
2. Simulating earthquake loading: Using techniques such as pushover analysis, which subjects the structure to incrementally increasing lateral loads to simulate seismic effects and assess damage levels. The target displacement for this analysis is determined based on the desired performance level, such as LS, as outlined in guidelines like FEMA 356 [66].
3. Applying fire loads: After simulating the earthquake, fire loads—often modeled using standard fire curves like ISO 834 [97] or natural fire models [69]—are applied to the damaged structure. This step determines the time to failure, known as fire resistance, while accounting for the impact of earthquake-induced damage.

Evaluating PEF resistance—defined as the time the structure can resist collapse under fire after an earthquake—is crucial. Research indicates that PEF resistance significantly declines as the structure experiences earthquakes that push it to higher performance levels, such as LS or CP [66].

Several studies highlight the importance of considering the following factors:

- Fire scenarios: Different fire scenarios, including those involving fire spread between compartments or across floors, can significantly affect PEF resistance [66,72,75]. For instance, research shows that fire resistance decreases when fire spreads rapidly between floors compared to scenarios with slower spread rates [75].
- Structural irregularities: Buildings with vertical irregularities, such as variations in stiffness or mass distribution across floors, are more vulnerable to both earthquakes and PEFs. For example, studies on steel frames have shown that irregular frames often experience a more significant reduction in fire resistance under PEF conditions than regular frames [71].
- Performance level: The fire resistance of a structure is influenced by its design performance level. Structures designed for higher performance levels, such as LS or CP, may experience more pronounced reductions in fire resistance after an earthquake compared to those designed for lower levels like IO [66].

Despite significant progress in understanding and modeling PEF behavior, further research is crucial for developing more accurate and reliable performance-based design methods. Key areas for future research include the following:

- Expanding the PEF ignition model: Current models often focus on a limited number of ignition causes, such as gas pipeline failures. A more comprehensive understanding of ignition sources and their likelihood following earthquakes is essential [15].
- Enhancing PEF fragility databases: Fragility curves, which describe the probability of exceeding a certain damage state for a given hazard level, are essential for performance assessment. However, data on PEF fragility, particularly at the structural system level, are currently limited. Expanding this database is critical for improving the accuracy of performance evaluations and facilitating more informed decision-making in PEF-prone areas [15].
- Investigating the impact of earthquake damage on concrete behavior at high temperatures: Concrete, a commonly used building material, exhibits complex behavior at elevated temperatures. Understanding how earthquake-induced damage, such as cracking or spalling, influences concrete's thermal and mechanical properties is crucial for accurately predicting PEF resistance [65].
- Developing practical design tools: The complexity of PEF analysis often requires specialized software and expertise. Developing more user-friendly tools that integrate PEF considerations into the design process would facilitate broader adoption of performance-based PEF design principles [15].

By addressing these research gaps and incorporating the findings into performance-based design guidelines and codes, the resilience of buildings in earthquake-prone regions can be significantly enhanced, reducing the risk of post-earthquake fires and improving overall community safety.

8.1. Performance Levels and Design Considerations

Performance-based design for structures subjected to post-earthquake fire (PEF) considers both seismic and fire events, aiming to ensure adequate safety for occupants even under chaotic post-earthquake conditions [66]. Rather than addressing fire and seismic events in isolation, performance-based design integrates these requirements to achieve a predetermined performance level across various hazards [48]. Structures are typically designed to meet different performance levels such as Operational (O), Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP), which correspond to increasing levels of damage, from minor (O) to severe (CP). For instance, at the LS level, buildings are designed to sustain significant damage to both structural and non-structural elements while ensuring the life safety of occupants by limiting drift values to around 2% [68]. The primary objective in fire design is to confine the fire within a compartment and prevent its spread. If containment fails, the design aims to ensure that the building remains stable long enough to allow for safe evacuation or fire suppression. Fire resistance, defined as the duration for which a structural member exposed to fire can maintain its integrity, is typically measured in minutes. Performance-based fire design considers various parameters such as compartment size, opening dimensions, and potential fire scenarios [66]. Performance-based PEF design must account for several critical factors:

- Reduced Fire Resistance Due to Seismic Damage: Earthquake damage can significantly diminish a structure's fire resistance. For example, a reinforced concrete frame designed for LS performance exhibited a 400% reduction in fire resistance when subjected to fire following an earthquake, compared to its resistance in an undamaged state [68].
- Impact of Performance Levels on PEF Resistance: The seismic performance level for which a structure is designed influences its PEF resistance. Structures designed for higher seismic performance levels (e.g., IO) generally demonstrate better fire resistance post-earthquake than those designed for lower levels (e.g., LS) [68].
- Fire Scenarios: Different fire scenarios (e.g., fuel-controlled vs. ventilation-controlled) can significantly affect structural response. Employing natural fire curves, which consider factors such as ventilation and fire load, aligns more closely with the concept of performance-based design than standard time–temperature curve [66].
- Damage to Fire Protection Systems: Earthquakes can compromise fire protection systems such as sprinklers and fire-resistant coatings, thereby reducing their effectiveness during a PEF event [72].
- Impact of Connection Details: The performance of connections between structural members is crucial during both seismic and fire events. For instance, research on gusset plate moment connections indicated that connection rotation increased at temperatures above 400 °C, and the connection completely lost efficiency beyond 500 °C [98].

The specific design considerations and performance levels will vary depending on factors such as:

- Building Occupancy and Use: Different occupancies have varying safety requirements. For example, a school necessitates a higher performance level (e.g., IO) than a residential building (e.g., LS) due to the need for immediate evacuation following an earthquake [68].
- Building Height: Taller buildings are generally more susceptible to seismic forces and fire spread, requiring more stringent design considerations [63].
- Structural System: Various structural systems (e.g., moment-resisting frames, braced frames) exhibit different levels of performance under seismic and fire loads [48,62].

Further research is needed to develop comprehensive performance-based design guidelines for PEF that account for these complexities and offer reliable methods for predicting and mitigating the impact of this cascading hazard.

8.2. Need for PEF Incorporation in Codes and Analysis

Most current building codes and standards do not adequately address the potential for post-earthquake fire (PEF) in their earthquake resistance design considerations. As a result, structures designed solely for seismic resistance may be insufficiently protected in a PEF scenario. This concern is particularly relevant for "ordinary" structures, such as residential and educational buildings, which constitute a significant portion of the urban landscape [50]. Historical data indicates that following an earthquake, it takes considerably longer to extinguish a fire due to damaged infrastructure and hindered access for firefighters [66]. Research has shown that the fire resistance required in a PEF situation is significantly greater than that required for a fire occurring in isolation [50]. Consequently, buildings should be designed to endure PEF events for a minimum duration to allow for the safe evacuation of occupants [3]. It is crucial to consider PEF as a design scenario when developing performance-based provisions for areas prone to strong earthquakes [75]. Several studies have confirmed that structures compromised by seismic activity exhibit heightened vulnerability to fire compared to undamaged structures [50,65,75]. For example, research on steel moment-resisting frames has revealed a significant reduction in fire resistance when these structures have been previously subjected to earthquakes [75,99,100]. Notably, damage to fireproofing materials, such as those used in steel structures, is a major concern in PEF scenarios [72]. Earthquakes can cause these protective materials to detach, exposing structural components to direct flames and potentially leading to rapid collapse [3,100]. The lack of specific regulations addressing post-earthquake fire (PEF) in current design standards underscores the need for a comprehensive investigation into the response of various urban structures to PEF loads. This is particularly critical for irregular structures, which are more susceptible to earthquake damage [71]. Moreover, research should explore the influence of various variables on PEF resistance, some examples being the following:

- Fire scenarios: The location and spread of fire within a structure significantly affect its PEF resistance [71].
- Material behavior: The degradation of material properties at elevated temperatures is crucial in determining PEF resistance [31,68].
- Performance levels: Structures designed for different performance levels (e.g., Immediate Occupancy, Life Safety) exhibit varying degrees of vulnerability to PEF [66].

In conclusion, integrating PEF considerations into building codes and analysis processes is essential for ensuring the resilience of structures in earthquake-prone regions. This integration requires the development and adoption of comprehensive analysis methods that accurately capture the combined effects of earthquake damage and fire, ultimately leading to safer and more robust structural designs. Such integrative approaches will enhance the safety and durability of structures, ensuring they can withstand the dual threats posed by earthquakes and subsequent fires.

Additional Insights

In addition to underscoring the need for integrating PEF considerations into building codes, the literature also discusses several critical advancements and considerations:

- Advanced Numerical Tools: The utilization of advanced numerical tools, such as SAFIR and ABAQUS, is essential for conducting sequential analysis of structures under PEF conditions [68,98]. These tools provide a detailed understanding of how structures respond to the combined effects of seismic and fire loads, thereby enabling more precise and effective design strategies.
- Performance-Based Fire Curves: The development of performance-based fire curves, such as the iBMB curve, allows for more realistic fire simulations in PEF analysis [24]. These curves are specifically tailored to reflect the actual fire behavior observed in post-earthquake scenarios, offering a more accurate basis for assessing structural resilience.
- Vertical Fire Spread: The significance of considering vertical fire spread in tall buildings is emphasized [75]. Understanding how fire propagates vertically in high-rise structures, especially after an earthquake, is crucial for devising effective fire mitigation and evacuation strategies.

- Innovative Solutions: The application of innovative materials, such as fiber-reinforced polymers (FRPs), is highlighted for enhancing the PEF resistance of both existing and new structures [65,66]. FRPs offer significant benefits in strengthening and retrofitting structures to withstand the dual impacts of earthquakes and fires.
- Further Research Needs: There is an urgent need for additional research on the performance of various structural systems and connections under PEF conditions. This includes investigating different construction materials, structural designs, and connection types to identify the most effective solutions for enhancing fire resilience post-earthquake.
- Data Collection and Risk Prediction: The importance of collecting post-earthquake fire data is underscored to improve risk prediction models and validate existing research findings. Comprehensive data collection will enhance the accuracy of predictive models and inform future building codes and standards, ensuring they are grounded in empirical evidence.

In conclusion, addressing these considerations and incorporating PEF analysis into building codes will significantly enhance the resilience of urban structures in earthquake-prone regions. Advanced numerical tools, realistic fire simulations, innovative materials, and comprehensive data collection are all crucial in developing robust and reliable design methodologies for mitigating the risks associated with post-earthquake fires.

8.3. Factors Influencing PEF Performance and Damage Assessment

Several factors influence the performance and damage assessment of reinforced concrete (RC) and steel structures during post-earthquake fires (PEF):

- Geometric Damage Parameters: Concrete cracking, spalling, and residual deformation significantly impact the thermal performance of RC columns under PEF conditions [13]. Among these, concrete spalling is the most critical factor, followed by cracks, while residual deformation has the least impact [61]. As the depth of spalling and interlayer displacement angle increase, residual deformation also increases, leading to a reduction in fire resistance [36]. Cracks and spalling contribute to a non-uniform axial thermal field distribution within the column [61].
- Mechanical Parameters: Axial compression ratio, reinforcement ratio, and eccentricity are key mechanical parameters affecting the fire resistance of damaged RC columns. The axial compression ratio is particularly influential, significantly impacting both the fire resistance and load-bearing capacity of RC columns subjected to PEF; therefore, it should be meticulously controlled. Eccentricity alters the axial pressure on a damaged column, causing it to become biased, which negatively affects its fire resistance. In contrast, the reinforcement ratio has a negligible effect on the fire resistance of PEF-damaged columns [61].
- Performance Levels: Structures designed for varying performance levels, such as Immediate Occupancy (IO) and Life Safety (LS), exhibit different degrees of damage under PEF conditions. For instance, at the IO level, minor damage occurs with no significant impact on PEF resistance. However, at the LS level, extensive damage in beams and ductile columns can lead to spalling of the concrete cover, compromising fire resistance [16,66].
- Fire Scenarios: The extent of fire spread and its duration play a critical role in determining PEF performance [101]. In steel moment-resisting frames, the location and extent of the fire can affect the failure mode and the time the structure can withstand fire [71]. Fire scenarios considering simultaneous fire onset, as well as delays of 5 min and 25 min in a multi-story steel frame, result in varying fire resistance durations [75].

- Stiffeners and Connections: The presence and type of stiffeners and connections are crucial in determining PEF performance. In steel structures, internal ring stiffeners significantly enhance the fire resistance of tubular T-joints under PEF conditions. The degree of damage greatly influences the fire resistance of both stiffened and unstiffened T-joints [79]. In gusset plate moment connections (GPMC), the presence of stiffeners and the magnitude of vertical load significantly affect connection performance during PEF [98].
- Material Properties: The degradation of material properties in both concrete and steel at elevated temperatures critically impacts overall structural behavior. The thermal properties of concrete and rebar are essential considerations when analyzing PEF in RC structures [65].

It is important to note that these factors are interrelated, and their combined effects determine the overall PEF performance and damage assessment of a structure. Further research is essential to fully understand these interdependencies and to develop accurate predictive models for assessing PEF performance.

8.4. Importance of Sequential Analysis and Performance Correlation

Sequential analysis is critical for evaluating the performance of structures under post-earthquake fire (PEF) conditions. This analytical approach involves a series of steps that simulate the loading history of a structure, including gravity loads, earthquake loads, and subsequently, fire loads [50,75]. By incorporating the residual deformations and damage inflicted by the earthquake, this method provides a more realistic assessment of the structure's fire resistance [66,68]. Understanding the correlation between performance levels is essential in evaluating how earthquake-induced damage influences structural behavior under fire. This process involves correlating seismic performance levels, such as Immediate Occupancy (IO) and Life Safety (LS), with fire resistance [3]. For example, studies on steel moment-frame beam–column connections have shown that while various parameters influence seismic performance, only the intensity of the vertical load and the presence of stiffeners significantly affect the connection's performance under PEF conditions. In conclusion, sequential analysis offers a comprehensive evaluation of structural performance in PEF scenarios by considering the cumulative effects of multiple loading conditions. This approach enhances our understanding of the interplay between seismic damage and fire resistance, ultimately contributing to the development of more resilient and safer structural designs.

9. Conclusions

Earthquake-damaged structures exhibit heightened susceptibility to fire, as seismic events significantly compromise their fire resistance. This increased vulnerability results in a greater likelihood of structural collapse during subsequent fires. The extent of earthquake-induced damage directly influences fire resistance, with more severe damage leading to faster structural failure.

Concrete structures are particularly vulnerable in post-earthquake fire (PEF) scenarios. Seismic damage often causes spalling and cracking, removing the protective concrete cover and exposing the reinforcement to direct heat, which weakens the structural components. Similarly, steel structures, even when fireproofed, face challenges due to the potential damage to fireproofing materials. Brittle fireproofing layers can delaminate under seismic loads, reducing their effectiveness in a subsequent fire.

Existing building codes lack specific provisions for PEF scenarios. More comprehensive guidelines are necessary to account for the combined effects of earthquakes and fire, ensuring adequate structural resilience. The current approach of treating seismic and fire hazards separately fails to address the synergistic effects of these events, increasing structural risks.

The combination of reduced strength and stiffness due to earthquake damage significantly weakens structures, making them more susceptible to fire-induced failure. Additionally, seismic events can compromise fire protection systems, such as sprinklers and fireproofing, rendering them less effective. Earthquake damage can also obstruct access for firefighters and emergency responders, delaying fire suppression efforts and exacerbating structural damage. This poses a severe threat to occupant safety by reducing evacuation time and increasing the risk of injury or fatality.

Current performance-based design philosophies inadequately address PEF scenarios. Most frameworks consider seismic or fire events in isolation, failing to account for the compounded effects of an earthquake-damaged structure exposed to fire. This gap increases the likelihood of underestimating structural failure risks in multi-hazard conditions.

Addressing the PEF threat requires advanced analytical tools and numerical models capable of accurately simulating damage mechanisms and fire behavior in earthquake-damaged structures. Full-scale experimental tests are essential for validating these models and improving our understanding of real-world PEF behavior. Additionally, investigating the interaction between concrete and rebar at high temperatures, along with long-term effects such as creep and shrinkage, will improve PEF modeling.

Establishing a comprehensive PEF fragility database is essential for assessing structural vulnerabilities under PEF conditions. Expert opinions can serve as an interim solution, but advanced numerical models and experimental research are required to develop accurate fragility assessments. Furthermore, current PEF ignition models often focus on limited triggers, such as damaged utility systems. Expanding these models to include additional ignition sources, such as overturned flammable objects or damaged electrical and gas systems, will enhance PEF risk assessment.

Future building codes must incorporate explicit provisions for PEF scenarios, outlining performance requirements and design methodologies to enhance structural resilience. Fire safety regulations should distinguish between structures in seismic and non-seismic regions, requiring more stringent fire resistance criteria for buildings exposed to potential seismic actions. Tall buildings, which house large numbers of occupants, must be designed to withstand a specified duration of fire exposure even after an earthquake. Additionally, irregular structures—due to their increased vulnerability—require more stringent fire resistance measures.

The complexity of PEF scenarios necessitates continued research and innovation in engineering solutions. Addressing current knowledge gaps and integrating multi-hazard design principles will be crucial in enhancing structural resilience and protecting lives and property in earthquake-prone regions.

10. Future Research Needs and Potential Directions for Advancement in PEF Engineering

There is a significant need for expanded research on the impact of post-earthquake fire (PEF) on full-scale structures, particularly multi-story buildings [52,65,98]. Most existing studies focus on individual structural elements or materials, leading to a gap in understanding the behavior of entire building systems under PEF conditions [65,98]. Further investigation is required to comprehend the complex interaction between concrete and rebar at high temperatures in PEF scenarios. The long-term effects on concrete, such as creep and shrinkage, also demand more attention, as they can significantly influence the accuracy of PEF analysis [65]. Future research should prioritize the following areas:

- Developing a deeper understanding of mechanical and thermal effects on reinforced concrete elements, ensuring that both physical and numerical models account for a sufficient number of mechanical and thermal degrees of freedom [65];
- Conducting additional studies on hybrid fire simulation for PEF effects, as this domain remains relatively underexplored [101];
- Expanding PEF research to include a broader spectrum of building types and fire scenarios, considering the influence of traveling fires and non-uniform temperature distribution [52,67];
- Investigating localized damage phenomena in PEF events to enhance the understanding of site-specific effects [67];
- Developing more sophisticated numerical models and conducting experimental tests to examine earthquake-induced damage on structural members and passive fire protection systems [63].

Further research is also essential in the following areas:

- PEF ignition probability: Future studies should explore various causes of PEF ignition beyond damaged utility systems, including factors such as electrical appliances and internal gas piping. Establishing a robust database for probability estimation is critical for accurate risk assessment [15].
- Structural analysis methods: There is a need for improved numerical analysis methods tailored to PEF scenarios, focusing on incorporating uncertainties related to fire growth, spread, suppression, and the performance of active fire protection systems. This will lead to more efficient and effective analysis techniques [15].
- PEF fragility: Expanding the PEF fragility database is a crucial research area. Collaborative efforts are required to conduct experimental research on various structural engineering systems, fostering consensus within the engineering community and enabling accurate consequence assessments [15].

Additional research needs are as follows:

- Performance Criteria: Existing research highlights the absence of clearly defined performance criteria for structures under PEF scenarios. Future work should focus on establishing clear performance objectives for PEF-resistant design, considering factors such as evacuation time and fire suppression capabilities [72].
- Code Integration: Current building codes lack sufficient provisions for PEF scenarios [50]. Future research should aim to develop specific regulations and guidelines for PEF-resistant design, integrating these provisions into existing fire and earthquake codes [66,75].

The existing literature underscores the necessity of a comprehensive and multi-faceted research approach to advance PEF engineering. Addressing these identified research gaps is crucial for enhancing building resilience, ensuring occupant safety, and bolstering community preparedness in the face of PEF events.

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