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Coexisting with Disasters: A State-of-the-art Review of Resilience Assessment of Steel Structures under Extreme Hazards

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Abstract

The current era of structural design prioritizes safety, performance, and compliance with evolving standards. While these advancements have undoubtedly improved structural integrity, safety is no longer sufficient. The increasing frequency and intensity of natural disasters, including seismic events and tornadoes, along with human-induced hazards, such as blasts, demand a broader and more adaptive design philosophy. This paradigm is resilience, a concept that not only addresses immediate structural survival but also considers recovery, functionality, and the broader physical, social, and economic impacts of disasters. Resilience-based design surpasses conventional approaches by accounting for indirect consequences, such as downtime and cascading effects, and emphasizing recovery and long-term societal well-being. This paper presents a state-of-the-art review of resilience assessment for steel structures subjected to lateral loads from seismic, blast, and tornado hazards. Which impose significant demands on structural integrity and resilience due to the extreme forces they exert, making them critical in resilience assessment. The limitations of current design codes, such as the Eurocode, are critically examined, focusing on their emphasis on life safety over recovery and their lack of multi-hazard frameworks. Future directions are explored, including the adaptation of design codes to incorporate multi-hazard resilience, the integration of advanced materials, and the development of quantifiable resilience metrics. By addressing these challenges, this paper emphasizes the need to transform structural engineering to ensure that steel structures can coexist with disasters. The insights presented aim to promote the development of novel approaches and methodologies that enhance resilience as a core principle in structural steel design.

Keywords

ductility, multi-hazard resilience, recovery, cascading effects, conventional designs

1 Introduction

The 1994 Northridge and the 1995 Kobe earthquakes were violent reminders of nature's unpredictability — shattering not only cities but the very notion of preparedness. With over 6,000 lives lost, 37,500 injured, and hundreds of thousands displaced, the immense economic toll exceeded $140 billion [1]. The December 2004 Indian Ocean tsunami, the deadliest in history, claimed over 200,000 lives. Triggered by an Mw ~9 earthquake over 1,000 km long, its devastation was worsened by the lack of a tsunami warning system and insufficient preparedness [2]. The January 2010 Haiti earthquake, with a death toll of 230,000 and thousands buried under rubble, was over twice as deadly as any previous magnitude −7.0 event [3]. On May 22, 2011, an EF-5 tornado tore through Joplin, Missouri, destroying 8,000 structures, causing nearly $2 billion in losses, and resulting in 161 deaths — the highest from a single tornado since 1950 — along with over 1,000 injuries [4, 5]. On August 4, 2020, a chemical explosion at the Port of Beirut ignited ~2,750 tons of ammonium nitrate, unleashing a catastrophic blast. The supersonic shockwave killed 220, injured over 6,500, and devastated surrounding residential and commercial areas [6]. On January 20, 2022, an explosion in the Apeate Community near Bogoso, Ghana, occurred when a motorcycle collided with a truck carrying explosives for Chirano Gold Mines. A secondary blast affected 3,300 people, killing 17, injuring 59, and destroying 500 buildings, leaving 1,500 homeless while severely damaging roads [7]. On December 10, 2021,

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a tornado outbreak in the southern U.S. spawned over 70 tornadoes. In Kentucky, one tornado hit Mayfield and Dawson Springs, causing 57 deaths and over 500 injuries [8]. On February 6, 2023, two catastrophic earthquakes, Mw 7.8 and 7.5, struck Turkey's Eastern Anatolian Fault Zone, devastating 11 provinces and impacting 14 million people. The destruction was intensified by poor seismic code enforcement and high-risk construction [9].

The rising frequency and intensity of natural and human-induced hazards have amplified devastation in recent years. In the U.S., tornadoes now cause more annual fatalities than hurricanes and earthquakes combined, with most deaths occurring indoors [10]. Meanwhile, urbanization has magnified the destructive impacts of seismic events, once considered rare [11]. The escalating threat of terrorist attacks has further highlighted the shattering effects of blast loads on critical infrastructure [12].

Despite the increasing scale and frequency of disasters, responses remain insufficient. This is often attributed to limited access to reliable information and underestimation of risks. Many communities see extreme hazards as rare, creating a false sense of security that undermines preparedness and increases the risk of disaster [13]. Many place absolute trust in building codes and policies, overlooking their limitations and the need for continuous adaptation. Others see disasters as unavoidable, reinforcing inaction and leaving communities unprepared for extreme events [14].

1.1 Historical cases: lessons learned and missed opportunities

The February 2023 Turkey earthquake highlighted the severe consequences of overlooking lessons from past disasters. Many reinforced concrete structures collapsed due to preventable soft-story failures, emphasizing the outcome of poor code enforcement [9]. In contrast, the 1994 Northridge and 1995 Kobe earthquakes marked turning points, driving advancements in steel connection design and improving seismic performance of steel structures [15]. Similarly, Hurricane Ian in 2022 underscored the importance of modern codes; newer structures built to updated Florida standards, like a 2020 elevated home, remained intact, while older pre-1981 homes were completely destroyed, as shown in Fig. 1 [16]. These examples highlight the urgent need for enforcing building codes and learning from past failures, as neglecting these lessons leaves communities exposed to the avoidable consequences of disasters.

Fig. 1 Consequences of Hurricane Ian [16]

As demonstrated by the devastating events discussed earlier, the impacts of extreme hazards extend far beyond structural damage, resulting in economic losses, business disruptions, and interruptions to critical services such as healthcare and education. These cascading effects underscore the need for a broader approach to disaster preparedness — one that moves beyond life safety and structural integrity to address recovery and functionality.

1.2 The resilience revolution

Building codes for structural systems, including those for steel structures, provide essential baseline safety but often fail to prepare communities for multi-hazard resilience. This limitation underscores the need for resilience-based design, an approach that moves beyond simply designing for larger hazards, which can lead to unnecessary overdesign. Instead, it focuses on adaptability, rapid recovery, and long-term performance, ensuring structures can withstand and bounce back from extreme events.

Resilience-based design extends beyond preventing structural failure, emphasizing rapid recovery, long-term functionality, and adaptability. By mitigating both direct damage and broader impacts such as economic disruption and service loss, it reshapes how communities prepare for and endure extreme hazards [17]. Christchurch's post-earthquake reconstruction employed low-damage steel systems, such as, base isolation, buckling-restrained braces (BRBs), and rocking frames, driven by performance, constructability, and seismic resilience priorities [18].

This paper critically examines the resilience of steel structures under extreme hazards, including events often considered rare and infrequent, such as earthquakes, blast loads, and tornadoes. It highlights the necessity of shifting from performance-based to resilience-based design by addressing the common challenges posed by these hazards as lateral loads, their multi-hazard interactions, and cascading effects that amplify vulnerabilities. Existing resilience frameworks, such as dynamic analysis, fragility and vulnerability assessments, and recovery models are reviewed alongside key metrics like recovery time, residual strength, and economic impact. Additionally, the potential of emerging materials, such as self-centering systems, rocking systems, and other solutions, to improve adaptability and post-disaster functionality is explored. By analyzing these factors, this paper contributes to the ongoing research on resilience in steel structural design, providing assessments that can inform future design codes and preparedness strategies.

2 The impact of extreme hazards on steel structures

Steel structures may experience extreme lateral loads from seismic, blast, and tornado forces, which, despite inducing dynamic, time-dependent loading, requires specialized design approaches. Additionally, blast and tornado loads often rely on adapted seismic simulation methods due to the absence of standardized frameworks. Understanding these forces is critical for developing resilient steel structures that minimize damage, economic loss, and recovery time. This section examines their impacts and the challenges they present for engineering practice.

2.1 Seismic loads

Seismic analysis methodologies for steel frames have evolved significantly, but each comes with distinct advantages, limitations, and applications.

2.1.1 Seismic hazard characterization and modeling challenges

Extensive studies have analyzed steel moment resisting frames (SMRFs) inelastic behavior under varying ground motions, highlighting oversimplified assumptions, like ignoring P-Delta effects and higher-mode influences, as major limitations [19]. These findings underscore the need for refined methods that account for cumulative deformations, hysteretic energy demands, and panel zone behavior, often underestimated in seismic assessments.

Conventional seismic intensity measures overlook higher-mode effects and nonlinear period shifts, especially in multi-story frames, underscoring the need for improved methods [20]. Addressing uncertainties in seismic demand and capacity is also critical, as modern provisions and connections greatly improve collapse resistance over older designs [21].

2.1.2 Seismic engineering analysis approaches for steel structures

The Equivalent Lateral Force (ELF) method is practical for regular, low-rise steel structures but lacks accuracy for irregular or taller buildings due to its reliance on approximate periods and inability to capture higher-mode effects. In contrast, modal response spectrum and nonlinear response history analyses offer greater dynamic accuracy but face challenges in computational complexity and the need for peer review, limiting their widespread use [22].

Nonlinear static pushover analysis effectively identifies plastic hinge formation and collapse mechanisms in steel structures but tends to underestimate base shear and moment demands compared to nonlinear dynamic analysis, limiting its use in performance-based design [23]. However, it remains valuable for optimizing steel structural designs, such as reduced beam sections (RBS), which enhance seismic performance by shifting plastic deformations away from column faces, reducing stress concentrations, and improving energy dissipation [24]. Additionally, it facilitates targeted and cost-effective seismic retrofits in steel structures, by addressing factors such as column strength, inter-story drifts, and plastic hinge behavior [25].

Collectively, these studies underscore the trade-offs between accuracy and practicality in seismic analysis, emphasizing the importance of integrating advanced methodologies to address the limitations of traditional approaches while ensuring resilience and adaptability in steel structures.

2.1.3 Advances and limitations in seismic design

Advancement in seismic design codes for steel structures have addressed structural performance challenges under seismic loading. AISC 341-16 emphasizes ductility and capacity design but relies on simplified elastic methods that overlook inelastic behaviors like buckling interactions, cumulative cyclic damage, and force redistribution [26].

Eurocode 8 provides detailed guidelines for steel moments and braced frames, effectively addressing stiffness and P-Δ effects, particularly at lower behavior factors. However, it faces challenges such as overstrength due to drift limits, gravity load effects, brace behavior, and concentrated inelastic demands. Direct Displacement-Based Design (DDBD) offers lighter and more efficient solutions but struggles with adoption due to limitations in low-to-moderate seismic regions, iterative displacement spectrum optimization, and yield drift inaccuracies [27, 28].

While these approaches mark significant progress, their limitations highlight the need for further advancements to enhance seismic reliability and adaptability.

2.1.4 Seismic performance of steel structures

Steel structures face critical challenges under seismic loading, including limited plastic rotation capacity and rapid cyclic deterioration, particularly in reduced beam sections, complicating deformation and residual strength considerations [29]. The performance of steel moment frame connections depends on balancing ductility while preventing failure modes like fracture and tearing. Studies on welded-flange-welded-web, reduced-beam-section, and bolted-flange-plate connections show that tailored strategies are essential to mitigate deterioration [30]. Pre-Northridge connections in steel moment-resisting frames increased drift demands and collapse risks, while modern steel designs with gravity frames and ductile connections improve drift capacity, exposing the limitations of simplified centerline-based models [31]. These connection-level vulnerabilities and deterioration mechanisms directly impact key resilience metrics, including residual drift, reparability, and post-event functionality, as increased deformation demands often lead to higher downtime and limited re-occupancy following seismic events [32].

2.2 Blast loads

Blast loads are among the most extreme lateral forces, generated by explosive detonations that produce high-pressure shock waves. Defined by their impulsive nature, they involve rapid pressure rise, high peak overpressure, and short duration. Unlike seismic loads, which develop over time, blast loads impose instantaneous demands, requiring steel structures to absorb and dissipate immense energy within fractions of a second. Their complexity and destructive potential expose critical gaps in current design methodologies, which often lack tailored approaches for such transient forces.

2.2.1 Blast hazard characteristics and modeling challenges

Eurocode 8 (EC8) outlines seismic design methods, comparing elastic, nonlinear static, and nonlinear dynamic analyses, where simpler approaches are conservative, while nonlinear dynamic analysis offers greater accuracy but higher computational demands [33]. It also incorporates the behavior factor, which balances initial construction costs and seismic performance. However, excessively high values can underestimate seismic demands, particularly in mid- and high-rise structures, leading to potential safety concerns and inefficient material use [34].

Eurocode 1 (part 1-7) has limited provisions for blast-resistant design, recognized as accidental actions [35]. However, since seismic and blast loads share similarities as lateral forces, exploring the adaptability of the Eurocode seismic behavior factor for blast design could offer a structured approach to optimizing material use and improving cost efficiency in blast-resistant steel structures.

To complement these limitations, ASCE/SEI 59-22 provides dedicated blast-specific design provisions for steel and composite structures, including load characterization, detailing guidelines, and performance criteria [36].

Blast modeling is hindered by the lack of efficient assessment methods, as most existing approaches fail to capture blast wave unpredictability. While nonlinear static analysis provides a computationally efficient alternative to dynamic simulations, it struggles with displacement, drift, and plastic hinge accuracy [37]. The absence of Eurocode provisions and standardized blast modeling further complicates assessment.

2.2.2 Blast engineering implications for steel structures

Blast fragility in steel frames depends on structural geometry, blast location, column orientation, and standoff distance, yet standard design tools do not fully account for these factors. Plan irregularities increase failure risk, with re-entrant corners being more vulnerable, while convex and pyramidal structures improve resistance by dissipating blast energy. Standoff distance uncertainty affects fragility more than charge weight variations, complicating response predictions. Bracing enhances resilience at greater distances, while column orientation influences load distribution, making mitigation strategies case-dependent. Existing models also overlook progressive collapse, underscoring the need for refined analysis tools that integrate collapse mechanisms, geometric effects, and reinforcement strategies [38].

Blast loads increase rotational stiffness and reduce ductility in steel moment frame connections, amplifying dynamic shear forces. Neglecting strain-rate effects leads to unsafe predictions, but rate-dependent nonlinear spring models improve accuracy efficiently [39]. Reinforcing beam-column joints or relocating plastic hinges enhances blast resistance, though thicker plates reduce displacements at higher material costs. Idealized welds and uniform construction assumptions further limit real-world applicability, highlighting the need for refined, practical steel connection designs [40].

A practical solution involves using an equivalent static lateral force to approximate blast effects, combined with a single-degree-of-freedom (SDOF) model to determine target displacement, enabling analysis within nonlinear tools like OpenSees [41]. This method improves blast-resistant design of steel structures by balancing accuracy and computational efficiency, reducing reliance on costly dynamic simulations [42].

The localized and abrupt nature of blast-induced failures — particularly progressive collapse and overstressed connections, poses significant challenges to resilience metrics such as reparability, downtime, and functional recovery. In many cases, even when the primary structure remains intact, extensive non-structural damage, such as façade failure or interior system disruption, results in disproportionate repair costs and prolonged loss of building functionality [43].

2.3 Tornado induced forces

Tornado-induced forces pose extreme lateral loading challenges for steel structures, generating intense wind fields with uplift, suction, and lateral forces far exceeding conventional wind loads. Unlike seismic or blast forces, they vary spatially and temporally across a structure's footprint, complicating modeling and analysis. The unpredictability of tornado paths and their destructive potential expose critical gaps in current design practices, which often fail to address these unique hazards.

2.3.1 Tornado hazard characteristics and modeling limitations

Tornado-induced wind pressures depend on building orientation, roof angle, and swirl ratio. The highest pressures occur near windward surfaces at one vortex core radius, with lower swirl ratios producing higher coefficients [44]. The absence of standardized tornado wind profiles further complicates hazard assessment. While simplified profiles improve efficiency, they fail to capture structural responses accurately, emphasizing the need for refined pressure zoning and load assessment methods [45].

Tornado loads vary due to static pressure deficits and turbulence, yet current methods fail to capture their complexity. Load distributions shift unpredictably with structural orientation, speed, and vortex path, making accurate modeling challenging [46]. A quasi-steady approach using wind tunnel coefficients and empirical profiles improves load estimation, but further refinements are needed to better account for turbulence and static pressure variations, enhancing predictive accuracy [47].

Tornado-induced loads threaten high-speed rail systems, yet current models struggle to capture vortex dynamics, affecting the accuracy of dynamic amplification factors (DAF) and characteristic wind curves. Improved modeling is essential for accurate risk assessment and safety evaluations in tornado-prone regions [48].

2.3.2 Tornado engineering implications and resilience challenges for steel structures

ASCE 7–16 lacks provisions for tornado-specific effects such as swirl ratio and near-surface uplift, leading to underestimation of structural demands. ASCE 7–22 advances this with Chapter 32, introducing tailored tornado load criteria, including hazard maps, directionality factors, and pressure coefficients for critical facilities [10].

Tornado simulators are expensive, time-consuming, and limited in scale, reducing their ability to replicate real wind fields. Numerical simulations are more efficient but still face challenges in modeling turbulence and near-ground flow, requiring further refinement [49]. These issues limit accurate prediction of envelope-level failures in cladding, roofing, and openings. Such failures are critical to resilience, as they influence internal damage, post-event functionality, and recovery even when structural collapse does not occur. The absence of standardized resilience methodologies highlights the need for innovative frameworks that integrate tornado-induced forces into structural design, enhancing the ability of steel structures to withstand and recover from extreme localized effects.

2.4 Multi-hazard interaction and the need for integrated design

Seismic, blast, and tornado loads pose distinct yet overlapping demands on steel structures, creating challenges in multi-hazard design. Seismic design favors ductility and energy dissipation, while blast requires stiffness and rapid load absorption, often leading to conflicting detailing. Tornado forces introduce additional complexity with extreme lateral and uplift loads. Adapting seismic methods for blast and tornado analyses can neglect hazard-specific responses, underscoring the need for integrated approaches that address hazard concurrency, detailing conflicts, and resilience trade-offs.

3 Introduction to resilience

The concept of resilience emerges from the need to respond to the challenges posed by disasters and disruptions, shaped by catastrophic events, and refined through continuous adaptation. It extends beyond initial resistance to include recovery and long-term improvement.

3.1 Defining resilience in structural systems

In structural engineering, resilience is the capacity of a structure, system, or community to absorb, endure, recover, and adapt efficiently after a hazard while addressing socio-economic factors. It is defined by four key dimensions: robustness, redundancy, resourcefulness, and rapidity [50]. A typical resilience curve is displayed in Fig. 2, where it represents the functionality versus time graph, with the resilience index measured as the area under the graph.

Quantifying disaster resilience is challenging due to complex recovery trajectories, indirect impacts, and community interconnections. Existing methods struggle to balance detailed analysis with practical application, leaving gaps in addressing systemic vulnerabilities and guiding resilience planning [51].

3.2 Metrics and quantification of resilience

Applying resilience in practice means using measurable metrics to track functionality, downtime, and recovery. It is commonly assessed by comparing post-disaster functionality over time until full restoration. The framework in Eq. (1), first developed for seismic resilience [17] and later expanded [50], defines the resilience index (R) as the area under the functionality–time curve, shown in Fig. 2. This curve illustrates both the immediate drop in functionality following a disruptive event and the subsequent recovery trajectory. As shown, the index integrates the magnitude of loss and the speed of recovery, thereby capturing system performance over the entire restoration period.

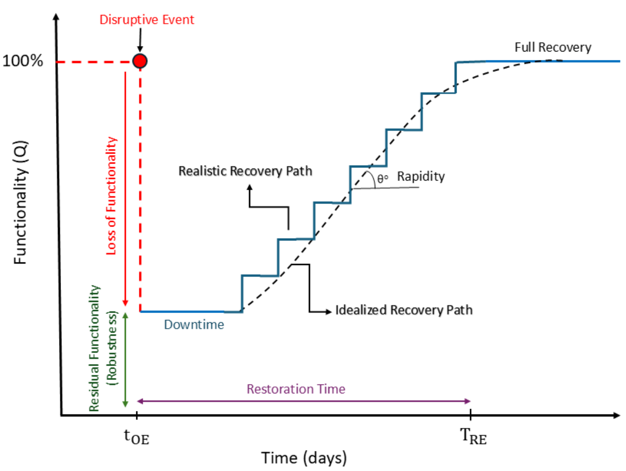

Fig. 2 Resilience functionality curve

$$R = \int_{t_{OE}}^{t_{OE}+T_{RE}} \frac{Q(t)}{T_{RE}} \quad (1)$$

Here, $Q(t)$ denotes functionality at recovery time T_{RE} with t_{OE} as time of impact. Functionality $Q(t)$ is further defined as

$$Q(t) = \left[1 - L(I, T_{RE})\right]\left[H(t - t_{OE}) - H(t + T_{RE})\right] \times f_{rec}(t, t_{OE}, T_{RE}). \quad (2)$$

Where $L(I, T_{RE})$ represents the loss function, accounting for direct and indirect losses as outlined in the HAZUS manual [52], while $f_{rec}(t, t_{OE}, T_{RE})$ models recovery path, influenced by preparedness and structural-community dynamics. The expressions summarized in Table 1 link the analytical calculation of resilience with its graphical depiction in Fig. 2.

4 Frameworks for resilience assessment

The resilience-based design framework integrates structural, infrastructural, social, and economic factors, providing metrics for resource allocation and recovery planning. By combining hazard, exposure, and vulnerability with community resilience, it enables large-scale quantitative assessments. A key parameter is the recovery process, but capturing variability across scenarios remains a challenge [53–55].

4.1 Resilience in performance-based design

Studies have explored resilience as a key metric in performance-based design, but its integration remains

Table 1 Resilience metrics and their role in steel structures

Quantitative resilience metric	Application to steel structures
Resilience index (R)	Measures overall system performance post hazard.
Functionality ($Q(t)$)	Describes structural operability over time.
Time of event (t_{OE})	Time when hazard occurs.
Recovery time (T_{RE})	Indicates restoration speed, used to evaluate repair strategies.
Loss function ($L(I, T_{RE})$)	Captures damage severity, structural and non-structural costs
Recovery function (f_{rec})	Reflects the effectiveness of structural and community responses to hazards.
Rapidity	Reflects how fast steel systems regain function.
Residual functionality (Robustness)	Dependent on structural system, design strategy, and damage level.
Downtime	Time before any repair begins; helps evaluate emergency response effectiveness.

incomplete due to a lack of practical implementation guidance. Traditional methods struggle to translate broad resilience objectives into actionable engineering solutions. However, resilience can still be incorporated where detailed structural and non-structural data is unavailable by using simplified pushover analysis as a preliminary tool [56, 57].

Conversely, resilience assessment for critical infrastructure and community-scale studies demands extensive data and advanced methods, such as nonlinear dynamic analysis, for precise evaluation [58].

4.2 Probabilistic approaches in resilience analysis

Probabilistic assessment enhances resilience analysis by integrating uncertainties into functionality loss and recovery time, improving prediction accuracy. Fragility, vulnerability, and recovery analysis form its foundation.

4.2.1 Fragility analysis

Fragility analysis quantifies resilience by incorporating uncertainties in hazard characterization, material strength, and geometry, influencing structural and non-structural performance, restoration, and cost-effective resilience strategies [59, 60].

This is achieved through detailed methodologies such as the nonlinear dynamic analysis [57]. Fragility curves relate hazard intensity to the probability of exceeding damage states, including immediate occupancy (IO), life safety (LS), and collapse prevention (CP). For example:

- Seismic fragility often relies on regression-based methods and incremental dynamic analysis.
- Blast fragility uses nonlinear time history analysis, incorporating uncertainties in charge weight, material properties, and structural geometry.
- In multi-hazard scenarios, captures sequential damage progression from hazard interactions [61].

4.2.2 Vulnerability analysis

Vulnerability analysis effectively evaluates community resilience across regions, offering more precise loss estimates than traditional fragility-based methods. Derived from structural performance levels, vulnerability curves enhance resilience index accuracy [47, 62, 63].

As per HAZUS guidelines [64], damage state probabilities are calculated as

$$\begin{aligned} P[ds = CP] &= P[ds \geq CP] \\ P[ds = LS] &= P[ds \geq LS] - P[ds \geq CP] \\ P[ds = IO] &= P[ds \geq IO] - P[ds \geq LS]. \end{aligned} \quad (3)$$

Vulnerability is quantified by summing the product of each damage state probability ($P[ds = DS]$) and its equivalent mean damage factor (MDF_{ds}), where ds ranges from 1 to n, representing the diverse damage states.

$$\text{Vulnerability} = \sum_{ds=1}^{n} P[ds = DS] \times \mathrm{MDF}_{ds} \quad (4)$$

Table 2, based on FEMA - 356 [52, 65], provides mean damage factors (MDFs) corresponding to each damage state.

4.2.3 Recovery phases

The resilience index depends on recovery time and recovery function, which reflect the effectiveness of structural and community responses to hazards. Recovery follows three patterns based on preparedness levels [50]. A linear recovery function represents an average-prepared community, while an exponential function models a well-prepared community with rapid recovery. In contrast, a trigonometric function captures delayed recovery, often used as a worst-case scenario.

The recovery function f_{rec} is expressed as

$$f_{rec} = a\left(\frac{t - t_{OE}}{T_{RE}}\right) + b \text{ linear} \quad (5)$$

$$f_{rec} = a\exp\left(-b\frac{t - t_{OE}}{T_{RE}}\right) \text{ exponential} \quad (6)$$

$$f_{rec} = \frac{a}{2}\left\{1 + \cos\left[\frac{\pi b(t - t_{OE})}{T_{RE}}\right]\right\} \text{ trigonometric.} \quad (7)$$

4.2.4 Challenges

Challenges in resilience analysis include modeling hazards, extending frameworks to multi-hazard scenarios, and integrating critical structures and system interdependencies. Balancing complex data with computational efficiency is difficult, as recovery uncertainties increase nonlinearly with hazard intensity [53, 55, 66–69].

Additionally, Bayesian-based methods improve fragility estimates by incorporating uncertainties in loads,

Table 2 Scale of damage factors [52, 65]

Damage states	Damage factor range (%)	Mean damage factor (%)
None	0	0
IO	>0–4	2
LS	4–96	50
CP	100	100

recovery times, and demand models but require extensive data and resources. Traditional code-based approaches often overlook these uncertainties, limiting their effectiveness in resilience assessments [70, 71].

While performance-based and probabilistic methods offer valuable insights into resilience, their practical use is limited by data demands, high computational costs, and lack of standardization in design codes. Techniques like Bayesian updating and multi-hazard recovery modeling require technical expertise and resources often unavailable in routine engineering.

5 Resilience of critical infrastructure

Critical infrastructure resilience is crucial for sustaining functionality during and after extreme events. Roads, bridges, hospitals, and networks must endure disruptions and recover quickly, yet current assessment frameworks often overlook hazard diversity, interdependencies, and human factors. Emerging methods, such as stress-based modeling, probabilistic recovery frameworks, and Bayesian networks, enhance insights but face challenges in scalability, data accuracy, and computational efficiency. Broad-spectrum resilience models, as in Fig. 3, offer a more comprehensive approach by addressing these gaps, integrating multi-hazard scenarios, and supporting large-scale resilience assessments.

The resilience of critical infrastructure relies on adaptive metrics that account for structural vulnerabilities, user impacts, and interdependencies, yet current methods

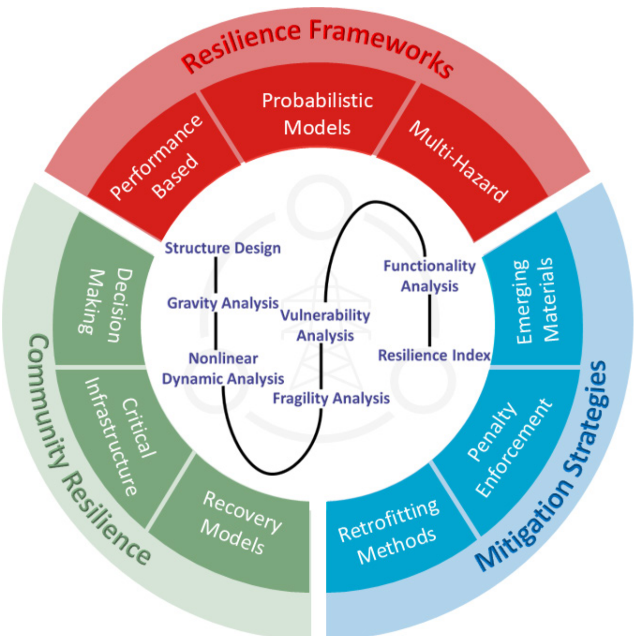

Fig. 3 Broad-spectrum resilience models

struggle with hazard diversity and effective decision-making [72]. Resilience assessments define robustness as a time-dependent function of disruption, restoration, and optimization but face challenges in parameter accuracy and computational feasibility [73].

Network resilience benefits from stress-based models that relate event severity to system performance, though scalability and data constraints limit their practicality [74]. In healthcare, resilience depends on socio-technical factors, yet frameworks struggle to quantify socio-cultural dimensions and interdependencies. Emergency departments manage waiting times under preparedness scenarios but fail under severe disruptions, highlighting the need for integrated structural and operational resilience models [75, 76].

Interdependent infrastructure resilience relies on absorptive, adaptive, and restorative capacities, with repair efficiency being a key factor. Balancing resilience costs with mitigation expenses remains a challenge [77]. Transportation frameworks incorporating fragility and restoration data reveal repair bottlenecks, such as elastomeric bearing failures in bridges, but need expansion to address traffic flow and climate uncertainties [78, 79].

Human factors shape resilience, yet socio-technical interdependencies and cognitive constraints remain underexplored. Integrating engineering and social sciences is crucial to uncover hidden feedback loops in disaster response [80]. Dynamic Bayesian Networks provide probabilistic insights into urban resilience but suffer from sparse data and expert-dependent models, requiring better validation [81].

Seismic resilience in hospital systems lacks robust recovery models, limiting generalizability. Strengthening probabilistic recovery frameworks for bridges and infrastructure networks is essential for predictive resilience planning [82, 83].

5.1 Community resilience and risk mitigation

Community resilience is the ability to sustain critical functions and recover swiftly by integrating infrastructure, public services, and social systems. Unlike traditional performance-based assessments, Resilience-Based Design (RBD) prioritizes interconnected recovery across essential lifelines, including transportation, energy, healthcare, and socio-economic networks. However, challenges remain in quantifying cascading failures, aligning structural goals with community-wide resilience, and standardizing metrics across hazards.

Seismic events, for example, not only damage buildings but also disrupt transportation, emergency response, and healthcare systems, delaying aid and prolonging recovery. Regional Seismic Resilience Assessments (RSRiA/RSReA) address these disruptions by integrating hazard analysis, fragility assessments, and functional recovery projections. Similarly, the Area Resilience metric (Arez) quantifies resilience across public health, socioeconomics, and infrastructure, dynamically identifying vulnerabilities over time. While these frameworks enhance resilience planning, gaps remain in uncertainty quantification, harmonizing computational tools, and adapting to multi-hazard scenarios. Strengthening community resilience requires generalized hazard models, interdisciplinary collaboration, and data-driven strategies to improve post-disaster recovery at a regional scale [59, 84–89].

6 Structural resilience response to extreme hazards

6.1 Seismic resilience strategies

Seismic resilience is assessed through fragility curves, resilience functions, and recovery models, yet challenges persist in quantifying infrastructure interdependencies and regional recovery dynamics [17, 60].

Modern simulation-based methodologies refine assessments by addressing outdated fragility assumptions and leveraging high-performance computing, though they require expertise in parallel computing and error reduction [90]. Comprehensive evaluations incorporate economic loss, downtime, casualties, and usability metrics, but gaps remain in modeling functional disruptions across diverse structures and interdependent networks [91].

Mitigation strategies like base isolation reduce structural damage and accelerate recovery, yet current models oversimplify recovery timelines and economic losses. Future research must refine resilience metrics, expand multi-hazard resilience applicability, and integrate real-time data for improved seismic risk management [92, 93].

6.2 Blast loading and progressive collapse resistance

Blast resilience assessments balance structural integrity and functional losses by considering topology, damage extent, and recovery dynamics. However, challenges remain in scaling to multi-hazard scenarios, integrating uncertainties, and expanding from single structures to community-wide resilience. Addressing interdependencies between structures and infrastructure networks is essential for broader applicability [94].

Blast resilience in steel moment frames depends on deformation control, column stability, and collapse mitigation. Conventional frames face challenges with excessive residual displacement and instability under extreme loads, with failure shifting from connection rotation in low rise structures to global instability in high rise ones. Sensitivity to charge weight and material properties highlights the need for robust design strategies. Under multi-hazard scenarios, sequential seismic and blast loads amplify structural vulnerabilities, often leading to irreversible damage. Advancing probabilistic reliability frameworks and adaptive design methodologies is essential for enhancing resilience against extreme loading conditions [95–97].

6.3 Hurricane-induced loads and structural integrity

Hurricane resilience must integrate hazard occurrence, cascading failures, and restoration across technical, organizational, and social dimensions. Challenges include limited data, reliance on simplified fragility models, and inadequate utility network representation. Advancing smart grids and adaptive emergency planning can strengthen resilience [98].

Windstorm resilience is hindered by the lack of wind-specific fragility models, as seismic-based methods fail to capture prolonged wind effects, cladding damage, and secondary impacts. Weak beam connections worsen recovery delays and costs, emphasizing the need for improved wind load profiles and comprehensive resilience frameworks [99].

Coastal resilience requires integrated socio-physical models linking infrastructure performance with population dynamics. Case studies, like Galveston Island, highlight the risk of multi-hazard scenarios, underscoring the need for strategic recovery prioritization, time-dependent damage modeling, and risk-informed decision frameworks [100].

6.4 Flood resilience and critical infrastructure

Flood resilience strategies, like compartmental detention and green rivers, reduce risks and improve adaptability, offering long-term benefits over traditional resistance-based methods despite higher initial costs [101].

Bridges, as critical transport links, remain highly vulnerable to flooding, yet resilience assessments lack comprehensive recovery models for traffic reinstatement and structural restoration. Recent frameworks prioritize damage-based restoration, but challenges persist in uncertainty quantification, regional variability, and network integration. Future advancements should leverage digital tools, global expertise, and probabilistic modeling for improved decision-making [102].

6.5 Multi-hazard interactions and cascading failures

Critical infrastructure resilience remains oversimplified, often assuming single-hazard scenarios or additive resilience indices, leading to inaccuracies. A comprehensive approach must integrate realistic fragility functions, restoration models, and sequential hazard impacts, as resilience is highly sensitive to secondary event timing and severity. Data-driven, adaptive risk management is essential for optimizing recovery priorities [61].

Multi-hazard assessments often overlook interconnected risks, treating earthquakes, floods, hurricanes, and fire in isolation. Methods like DEMATEL identify critical factors but rely on expert judgment and fail to model hazard evolution over time. Advancing these frameworks requires real-time hazard interactions, broader risk typologies, and data-driven validation [103].

Current multi-hazard design approaches prioritize single threats, neglecting hazard interactions such as earthquakes and heatwaves. Life-cycle cost analysis and dynamic energy simulations show seismic-resistant facades reduce financial losses, while energy resilience mitigates heatwave inefficiencies. However, uncertainty-based modeling for non-seismic hazards remains underdeveloped [104].

Building codes, including FEMA guidelines, fail to unify seismic and wind design criteria, leading to conflicting strategies. The SAC-FEMA method, extended for wind effects, offers one of the first multi-hazard probabilistic approaches, but updated performance-based design provisions are needed to reconcile ULS and SLS requirements [105].

For highway bridges, parameterized fragility-based multi-hazard risk assessment (PF-MHRA) improves evaluations by integrating surrogate modeling and stepwise logistic regression, yet expanding these models to correlated demands and life-cycle costs is necessary for broader applicability [105, 106].

Post-event fire resilience in tall steel moment frames remains underexplored. While steel structures may withstand blast or progressive collapse, fire-induced failures like column buckling and flange local buckling can cause catastrophic collapse within minutes. Conventional member removal techniques fail to consider fire degradation and traveling fire effects, requiring integrated extreme event analyses to enhance structural safety [107].

7 Resilience enhancement strategies and emerging materials

Past studies on seismic resilience enhancement of steel moment-resisting frames (MRFs) have explored infill configurations, post-tensioned self-centering systems, and column base connections, each targeting structural performance and post-earthquake recovery.

Infilled MRFs improve seismic resistance in low-rise structures, reducing damage compared to bare frames. However, openings in infills weaken performance, especially under higher seismic demands. Taller buildings face increased lateral displacement sensitivity and *P*-Delta effects, requiring height-specific resilience measures [108].

Post-tensioned self-centering systems and self-centering column bases in steel structures reduce residual drifts, repair costs, and recovery time by integrating friction devices for energy dissipation and post-tensioned bars for restoring forces. While effective in low- to mid-rise steel structures, their performance declines in taller buildings, where greater flexibility and mass reduce re-centering efficiency. Additionally, delayed repair initiation impacts resilience, underscoring the need for strategic resource allocation and scalability improvements for high-rise steel structures [63, 109, 110]. Experimental studies on self-centering joints with phased energy dissipation [111] and friction *T*-stubs [112] confirm minimal residual drift, stable hysteresis, and damage isolation in replaceable components. These results support their efficiency in mid-rise structures, while highlighting the need for improved scalability in high-rise applications.

NiTi SMA bolted connections, as re-centering materials, enhance resilience in steel moment frames by controlling damage, reducing residual deformations, and maintaining functionality under extreme loading. In blast scenarios, these nickel-titanium shape memory alloys improve resistance and accelerate recovery, particularly in shorter structures. Under seismic loading, they limit plastic deformations and sustain operational capacity, though resilience decreases with height. Their ability to optimize collapse mechanisms and distribute stiffness ensures superior performance across both hazard scenarios, making them a key solution for enhancing structural resilience [32, 113]. Rocking systems and high-performance damage-resistant frames using replaceable fuses, energy dissipators, or post-tensioned components have emerged as effective alternatives to self-centering systems, offering reduced residual deformation and faster recovery in seismic events [114, 115].

8 Resilience assessment of lattice towers

Lattice towers, essential to telecommunication and electrical networks, face multiple hazards including earthquakes, high winds, snow, and tornadoes. As part of interconnected systems, their failure can cause widespread service disruptions. Resilience depends not only on structural vulnerabilities but also on interdependencies within the network. A full assessment must address both physical integrity and functional role.

For urban telecommunication networks, seismic resilience depends on tower damage, service quality, and user overload, all linked to network dependencies on vulnerable buildings. Topology and operator cooperation are key to mitigating service disruptions, yet limited data and topology assumptions necessitate refined models for broader applicability [116]. For electrical substations, a Bayesian network-based framework integrates structural and functional assessments to optimize post-earthquake recovery. Repair path selection is critical to resilience, emphasizing the need for data-driven recovery strategies. While scalable, improvements in uncertainty modeling and multi-hazard integration are required [117].

9 Design codes and future directions

Outdated design standards limit the seismic resilience of concentrically braced-frame (CBF) office buildings, as early codes lacked ductility provisions, leading to brace-to-frame connection failures. Mid-rise steel structures in high-seismic regions face higher damage probabilities and slower recovery, requiring advanced retrofitting beyond ASCE/SEI 41-13. Code updates, tailored retrofits, and refined recovery models are essential for equitable resilience improvements [118].

For steel moment-resisting frames (MRFs), Eurocode 8 ensures robust collapse performance with significant safety margins, though IFBD (Improved Force-Based Design) enables material savings while maintaining seismic compliance. While IFBD-based designs exhibit predictable collapse performance and lower ductility demands, Eurocode 8 overestimates stiffness requirements due to P-Delta effects. Further research must generalize these findings across diverse building typologies and seismic conditions in Europe [119].

10 Conclusions

The increasing frequency and severity of extreme hazards demand an immediate shift toward resilience-based design. Ensuring the adaptability and long-term functionality of steel structures is no longer optional — it is a necessity. This review underscores critical advancements, persistent challenges, and the urgent need for action in resilience assessment and mitigation strategies.

- Multi-hazard resilience remains underdeveloped, with existing frameworks often failing to capture cascading failures and hazard interactions.
- Current design codes prioritize life safety but lack provisions for integrated resilience measures, requiring updates to address long-term recovery and economic sustainability.
- Resilience strategies for extreme hazards, often perceived as rare or infrequent, have advanced significantly, yet challenges persist in data availability, uncertainty quantification, and the need for simplified yet accurate modeling and simulation methodologies for practical applications.
- Emerging materials and self-centering systems offer promising solutions for post-disaster functionality in steel structures but require further validation for high-rise and complex structures.
- Resilience assessment methodologies must integrate real-time data, probabilistic modeling, and adaptive risk management to enhance decision-making and long-term performance.

Bridging these gaps requires a multidisciplinary approach, unifying engineering, policy, and computational advancements to establish a comprehensive resilience framework. Future research should prioritize practical implementation, standardized methodologies, and enforcement strategies to ensure resilient steel structures capable of withstanding extreme hazards.

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