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Research Article

The Controversial Points of Earthquake Resistant Design of Steel Structures

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Keywords

Connection design, Steel structures, Semi-rigid connections, Moment-rotation behavior, Earthquake Resistant.

Abstract

The current study examines the critical aspects of earthquake-resistant design (ERD) for steel structures, with a particular emphasis on connection detailing, semi-rigid configurations, bracing systems, and material behavior. Although the recent advances in seismic engineering, the latest studies highlight the gap between design approaches and actual seismic behavior, especially in terms of rotational stiffness, energy dissipation capacity, and failure mechanisms. The study critically reviews the seismic performance of semi-rigid and bolted connections, efficiency of different types of bracing-systems as well as the impact of material variability on the response during seismic action. The applicability of performance-based design methodologies and international building codes (Eurocode 8 and AISC specifications) to contemporary seismic design is likewise examined. Grounded in a synthesis of experimental data, numerical modeling, and case studies, this paper outlines inadequacies in existing design methodologies and proposes innovations on the horizon, like self-centering bracing systems and advanced cyclic testing of connections. These research contributions add to the discussion on how to best optimize seismic design strategies to improve the life-safety of structures, limit damage, and enhance performance following an earthquake.

1. Introduction

Modern construction has seen the steel building in common usage as a result of its strength, versatility, and adaptability. However, its seismic performance involves challenging engineering problems and controversies. How then can the structures be designed to withstand the random and often destructive forces of earthquakes? What are the most important factors governing their seismic behaviour, and why are some design approaches still debated by engineers? This paper addresses controversial issues of earthquake-resistant steel structure design, motivated by these concerns.

This paper can be considered a thorough investigation that discusses the nuanced and integrated problems of seismic design and steel-specific seismic detailing. It is essential when designing against earthquakes to find a balance between resistance to structural damage and energy dissipation to prevent catastrophic failure. In this context, key design parameters including connection design, semi-rigid configurations, bracing systems, and foundation solutions are investigated with respect to their contribution to the overall structural resilience. The basis of this research is that these elements are influenced by the material properties, structural behavior, along with adherence to international and regional building codes. More precisely, many theoretical models do not tend to match the physically measured performance under extreme levels of severe seismic events, despite improved seismic engineering practice.

This paper has been structured to identify and critically analyze the complexities and concerns that influence the seismic design of steel structures and presents the more controversial aspects within the discipline. The study examines the rotational stiffness within semi-rigid connections and their resistance to failure, compares the effectiveness of bracing systems in improving lateral stiffness and dissipating energy through movement, and examines how variability in material properties can inform and influence design principles. In addition, the study examines the potential for performance-based design methods to be integrated into current building codes. Using experimental studies, numerical models, and case studies, we synthesize evidence and explore discrepancies between design assumptions and observed seismic performance.

The method uses a comprehensive integration of peer-reviewed literature, technical codes, and test results to reach these goals. The analysis is based on documents such as Eurocode 8 or AISC specifications. Methods

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of comparison are used to compare the design methodologies with key developments, including self-centering bracing systems and state-of-the-art cyclic testing of semi-rigid connections, critically incorporated to provide support for recommendations. One exploratory theme of this examination has been the differences between design models in relation to theory and performance for steel structures under seismic activity, and the connection and bracing behavior.

The paper is structured to enable this exploration. The title of the work reflects that of the earlier one; it begins with a summary of seismic design principles, including design philosophies, performance objectives, and material behaviors that lead to earthquake-resistant structures. Later chapters deal with the detailed aspects of steel structures: the connections and bracing systems, their configuration, material aspects, and impact on design practice. The final section summarizes the findings to address the proposed research questions, considering aspects for further improvement and a look into future developments in seismic design research and practice.

2. Seismic Design Fundamentals

The core principles of seismic design are centered on protecting human lives and construction works from seismic forces using state-of-the-art engineering techniques. The three following sections discuss principles of design philosophy, material properties and connection behavior of the main factors at play with its resistance to seismic loading. Through exploration of the interrelationship of these elements, the study provides an extensive basis for grasps the details and newness of current seismic design practice. This background is necessary to understand the following inquiry into the design of connections and bracing systems, and the pertinent problems in the wider context of structural engineering.

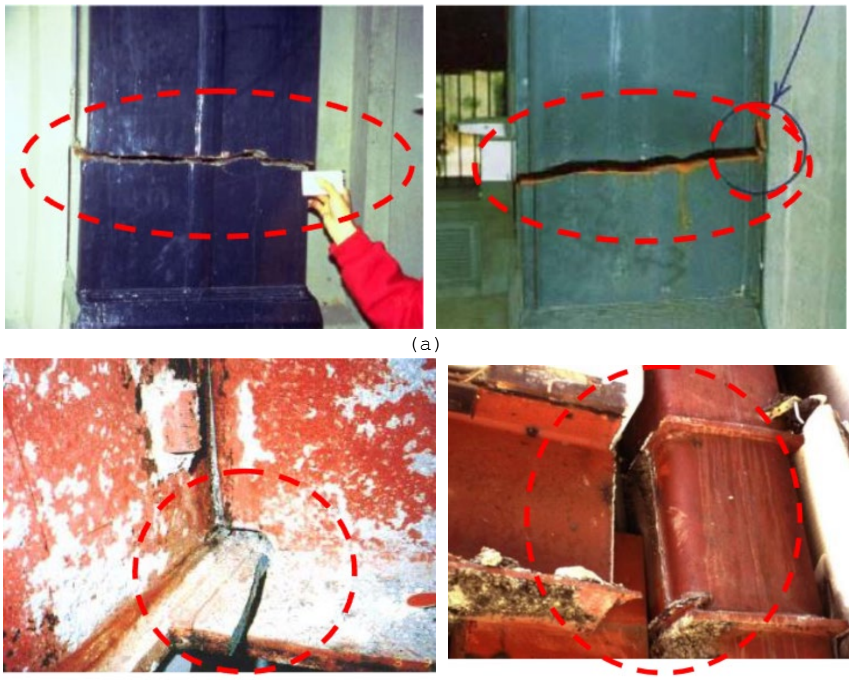
2.1. Design philosophy and performance objectives

The seismic design philosophy is primarily driven by the objective to prevent the loss of human life and to minimize structural damage during earthquakes. It combines two components: death-avoidance and operation-continuation steering principles. As argued by Elnashai, the former is the ultimate guarantor of safety for two reasons. One is that otherwise; the potential loss of human life cannot be quantified beforehand. Two, in the context of urban and high-risk locations where the ability to continue essential services, including safeguard service activities, is a considerable factor in the recovery effort. For this reasoning, in urban and high-risk areas, an increasing part of earthquake safety, based on past experiences, shifts from a primary emphasis on the prevention of loss of life to an integrated emphasis on a structure's operational safety. Thus, the seismic design philosophy, no matter how advanced, requires ongoing adaptation to address the specifics of high-risk and high-density areas.

Seismic design performance targets are specifically defined according to differing demands of seismic loading, ranging from operational post small earthquakes to collapse prevention post large earthquakes. While target level operation aims for no damage for critical facilities such as hospitals, collapse prevention targets minimum life safety for less critical infrastructures [1]. Such graded objectives highlight the fact that risk-based design should be sensitive to either regional seismic hazards or the distinctive functional requirements of structures. For example, stricter standards can be established in high-risk areas, protecting human life and preserving operational capacity in times of disaster. Historical experiences from past seismic disasters, like the 2011 Tohoku earthquake in Japan, demonstrate that the operationalization of objectives facilitates disaster response and mitigates additional threats. However, the diversity of seismic effects requires more investigation in order to create and unify performance-based design practices worldwide.

The process of energy dissipation, promoted by mechanisms such as plastic hinges, is still a fundamental principle of the seismic design philosophy. These mechanisms localize structural inelastic behavior, which increases their resistance and avoids instabilities that jeopardize the safety of the total system [2]. Braces with high strength and ductile behavior, like Buckling Restrained Braces (BRBs), behave more like a spring and absorb energy during earthquakes. This development is a major breakthrough in modern steel construction methodology. Failures experienced in previous seismic events, such as brittle cracks in beam-column joints, highlight the need for further advances in energy dissipation devices. Currently, an investigation is underway to tackle these vulnerabilities and enhance existing bracing systems to make them more suitable for the new specifications of seismic loading. However, analytical models for energy dissipation need to be highly refined in order to simulate in-field behavior, particularly when facing the uncertain characteristics of seismic loading.

Despite advancements in design practice, the discrepancies between idealized models and real-world seismic performance have remained an enduring research topic. Moderate accelerations observed in earthquakes such as the 1995 Kobe event have led to unexpected damage in structures (Fig. 1) and have highlighted the flaws in many design procedures [3]. This indicates that parameters characterizing seismic shaking, such as earthquake duration or frequency content, as well as soil-structure interaction — both of which are normally idealized in theoretical studies — have a significant influence on seismic response. In addition, non-structural components not included in the models, such as infill walls, have been heavily damaged during earthquakes. The failure of some of these components during moderate earthquakes indicates a need for their inclusion in analytical and design practice, for example. While promising, these alternative methodologies have not been substantiated by ongoing field studies for daily in-field application and thus remain a considerable point of comparison to computational software, non-linear dynamic analysis, and other developments.



(a)

(b)

Figure 1. Structural Failures in the Kobe Earthquake: (a) Column Damage, (b) Beam-to-Column Fracture [4]

International external seismic codes, like Eurocode 8 and AISC specifications, contribute to codified frameworks aiming at achieving homogeneity across international seismic design practice. However, the generalization of their applicability is quite often limited by regional variances of parameters such as soil profiles, seismic activity levels and construction practices [5]. In regions where good quality materials or testing laboratories don't exist, for example, compliance with such codes might be impractical and the achievement of the capacity design philosophies will be compromised [2]. Moreover, differences between international codes and regional aspects lead to discrepancies in seismic performance, like prescription on flexural rigidity. This discrepancy calls for global alignment of the seismic standards. Examples of regional innovations like New Zealand described above are able to create flexible and efficient international codes. But consistency is still a daunting goal, and contributions are required from a variety of disciplines, and across regions.

The capacity design principles aim at directing inelastic response towards ductile elements while avoiding brittle modes of failure, while making sure to control the energy dissipation mechanisms and not to compromise structural stability [2] . Their seamless implementation, however, is hampered by material variability, especially for steel yield stress. For example, various coupon tests performed on British Steel show variations which could cause discrepancies in structural ductility and inelastic response predictions. Historical case studies like the beam-column joints that failed in brittle ways in the Northridge earthquake have put into perspective the near-importance of strict adherence to capacity design principles. Recent developments in material technology and quality control will reduce these vulnerabilities and promote the robustness of seismic structures. In addition, further developing the capacity design philosophy associated with the use of high-performance steel and new connection designs like advanced bolted systems could be crucial to improving their reliability.

The ramifications of past earthquakes confirm the need for performance objectives and design methods to be appropriately adapted to the variabilities implied by extreme seismic demands. Diverse outcome of the Northridge earthquake proved that the exclusive dependence on rigid welded connections was not-adequate since semi-rigid and bolted connections have thus gained acceptance due to their improved flexibility and ductility [5]. Such advancements highlight the importance of ongoing research and innovation to further improve seismic design practice. Despite this, gaps developed during some previous failures would need to be filled, and computational simulation with experimental testing, coupled with advances in material sciences are essential. Additionally, the reliable behavior of riveted steel structures during historical seismic incidences served as the basis for advances in modern bolted connections, combining classical resilience with modern construction methodology. In order for such lessons to be meaningfully translated into practice as seismic design principles evolve in response to emerging challenges and technological advancement, cooperation between academia, industry and regulatory agencies is essential. Fig. 2 illustrates the fundamental components of seismic design philosophy, encompassing earthquake hazard assessment, design objectives, structural systems, analysis methods, and resilience strategies essential for ensuring structural integrity and life safety in seismic events.

To sum up, the iterative process of seismic design is the vehicle has historically informed the current practice whilst the latter contributed to the performance and resilience of structures in seismic zones. This combination of research, empirical data, and state-of-the-art methods continues to be provide crucial insight into the complexity of seismic activity, toward the overarching goal of reducing risk to human life and infrastructure.

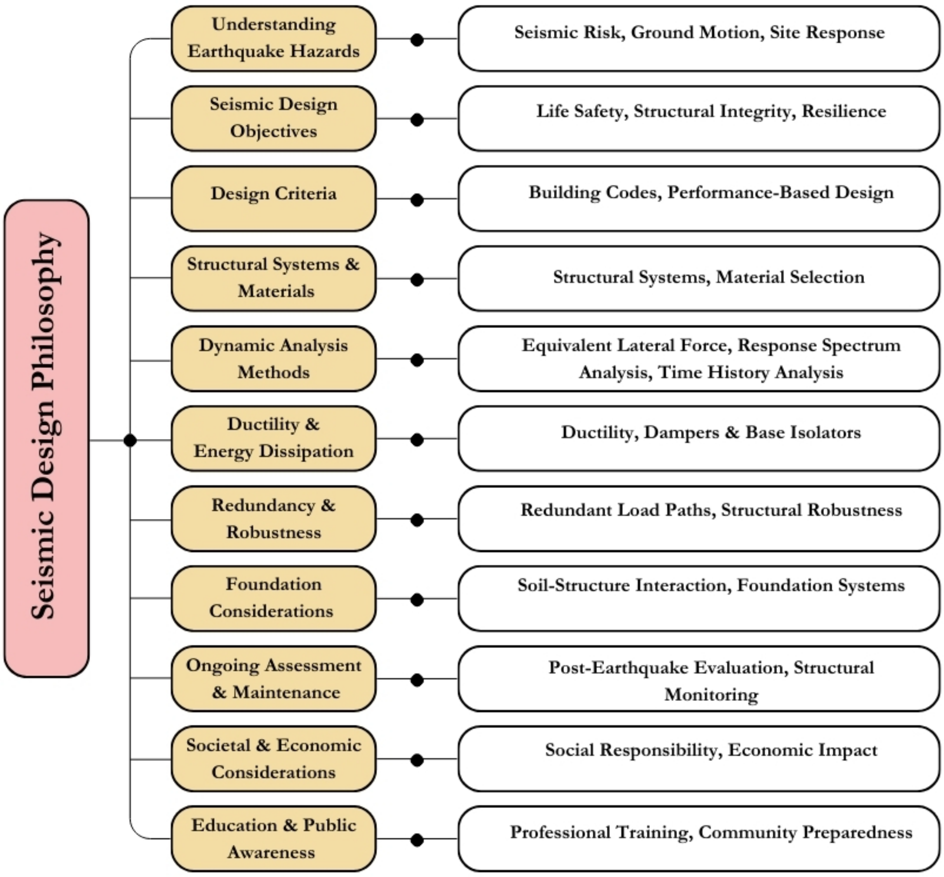


Figure 2. Fundamental principles of seismic design

2.2. Material properties and behavior

The mechanical behavior of high-strength structural steel (HSSS) has different implications under cyclic and monotonic load conditions, which is an important consideration for seismic design (Fig.3). Loss of ultimate strength and premature failure due to damage accumulation have been shown to occur in high strength steels such as Q460D when subjected to cyclic loading. This loss of stability in the necking area leads to a considerably smaller energy dissipation capacity for the entire material compared to its more stable response under monotonic loading conditions [6]. These differences shed light on the fragility of these kinds of materials under different levels of seismic loading, and the engineering designs should be taken into account accordingly. The use of constitutive models that ignore this gap in performance under seismic loading will underestimate failure and this demonstrates the need for constitutive models with enhanced modeling capability to effectively characterize this material behavior.

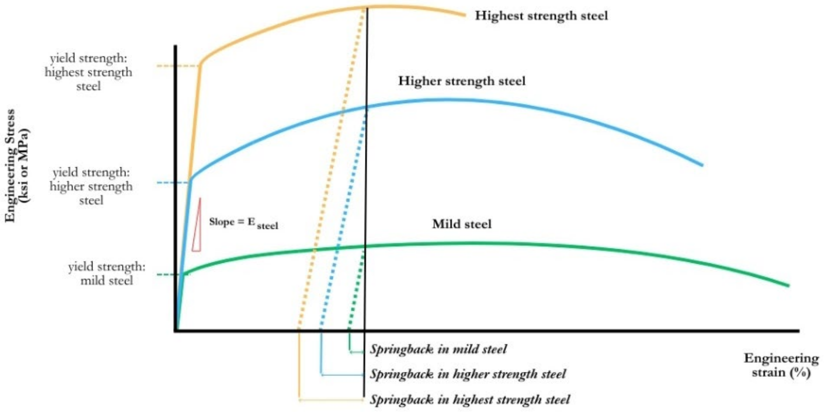


Figure 3. Comparison of engineering stress-strain behavior in different steel grades

However, inherent material variability in structural steel, most significantly yield stress, is a major barrier to predicting structural behaviour under seismic loading. Inconsistency; the variability from coupon tests of British Steel leads to deviations with direct implications on the formation of the plastic hinge and predictability of inelastic deformation [2]. Such variability violates capacity design concepts in which intended gross mechanism failure mechanisms create unintended minor yielding brittle failures. Seismic-resistant designs are successful today, when the quality of materials used is assured, to be confident in the performance of the structure for the range of seismic events, which is regularly compromised due to poor quality control systems. Moreover, the application of probabilistic models or scenario simulations is required to estimate a range of probable responses, and to mitigate the risk of structural failures in seismic events, owing to the variability noted for the yield stress of steel.

The local buckling in cyclic steel members is highly dependent on the width-to-thickness ratio (b/t) that impacts the ductility of the structural members under seismic load. Experimental data indicates that members with b/t ratios from $52/\sqrt{Fy}$ to $95/\sqrt{Fy}$ show different ductility, and these ratios are not enough in high seismic areas such as Zones 3 and 4 and, while ductile enough in lower seismic areas [5]. Such observations highlight the need for design requirements to be made in a region-specific manner to be able to accommodate seismic demands that need not only to be offset but with measure enough who can optimize energy dissipation and prevent stability loss. Low b/t ratios or using other materials would reduce local buckling risk in high seismic regions. This is also highlighting the need for specific modification in guidelines for increasing the energy dissipation performance of steel members and adjusting the performance of such members to satisfy the demands of a given seismic region.

For seismic application, steel has numerous material benefits like high strength-to-weight ratio which is helpful in minimizing the total seismic loads without adversely affecting structural performance. The subsequent success of steel for earthquake-resistant design is therefore evident. The drawback, however, is that relatively lower damping capacity of the material requires supplementary energy dissipation mechanisms (i.e., dampers or an innovative bracing system) to compensate for the inherent weakness of the material. Another area that needs more care with respect to careful detailing is the potential for brittleness of connections, especially in areas with significant plastic hinge formation. If not furnished with proper design consideration, these regions can fall short, and this can cause premature failures that may compromise the composite seismic behavior of steel structures. Corrosion-resistant protective coatings change which environmental conditions are available to threaten the material and, thus, most importantly help to intercept environments that depend on exposure to heat and that in the coastal or humid climate serve to amplify the material disadvantages with seismic load.

Flexural ductility of steel moment-resisting frames is controlled by complex parameters including shear yielding of the panel zone and geometric properties such as beam depth, flange thickness, and beam aspect ratio. For example, the shear yielding of the panel zone has been found to decrease the flexural ductility of beams significantly, adversely affecting the energy absorption ability of moment-resisting frames [7]. But deeper beams, common in modern design in the interest of large spans, can have an adverse effect on the inelastic deformation capacity which diminishes resilience to earthquake loads. Likewise, design variables, including beam-flange thickness and the ratios of beam spans to their respective depths, have been found to be important contributors to stress distribution, since flanges that are too thin or span-to-depth ratios that are too large are especially prone to localized buckling, which most inhibits the material's ductility.

The stress-strain behavior of high-strength steel subjected to cyclic loading has been a topic of research leading to the development of advanced constitutive models for an appropriate seismic analysis. Models developed with assistance from the program ABAQUS that demonstrate progressive degradation and early necking and damage accumulation under cyclic loading conditions [6]. These advanced models permit non-linear time history analysis which allows engineers to evaluate how structures respond dynamically under the impact of real-world seismic events, providing a far more plausible basis for performance-based seismic design. However, the use of these tools in day-to-day design practice still needs to be validated though large experimental tests to see how they perform in practice environments. These models are most widely used in regions with high seismic risk, where it is known that classical design approaches are insufficiently able to capture complex steel responses when subjected to extreme cyclic loading.

It is known that the experience of strong earthquakes led to the introduction of sensitive coefficients in standard codes in order to account for the risk of over-designs associated with the incidence of damage to construction, such as unintentional plastic hinge formation, loss of stiffness, and loss of strength. Renowned scientists from all over the world are focusing on understanding such facets, which will help create better predictive models, data-informed engineering decisions, and improved resilience against seismic activity. Our worldwide experience with seismic events indicates that more materials and methodologies will be affected by the complex demands of seismic activity.

3. Performance and Design of Connections

Connections that weld the different elements of a frame together govern the structural integrity and overall seismic resistance of buildings. The following section introduces the different types of connection that steel members can have—ranging from rigid joint to semi-rigid design—and the role they play in resisting seismic loads. The treatment lays the groundwork for an appreciation of their impact of the connections on the improvement of global performance, which is needed to maintain safety and serviceability under seismic demands, consistent with the fundamental concepts developed in prior sections of the document.

3.1. Types of steel connections

Steel connections play a vital role in the structural behavior and seismic performance of steel structures because they assume a fundamental functionality in transferring loads among different structural components. The importance of appropriate connection design and detailing is closely linked to the overall seismic performance of the structure [2]. To this end, the response of rigid, semi-rigid and flexible connections (Fig.4) has been studied intensely owing to their different rotational stiffness, strength and energy dissipation capacities.

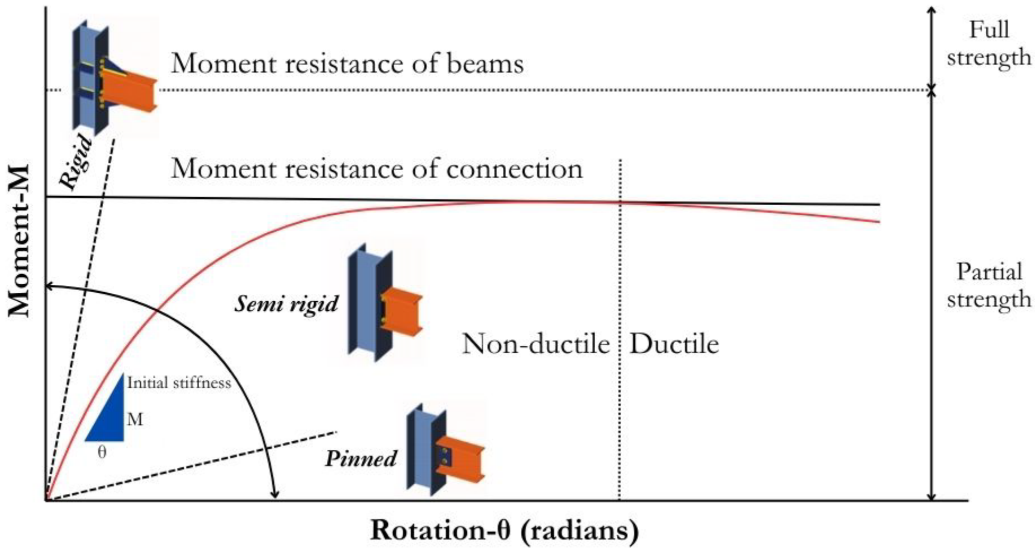
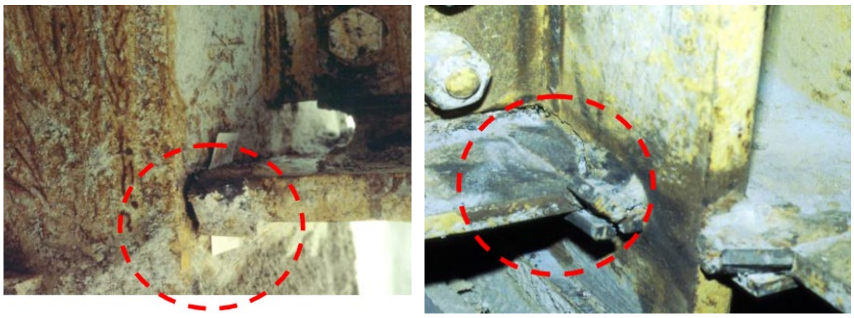


Figure 4. Moment-Rotation Behavior of Common Steel Connections

Although these connections are most commonly seen in seismic design due to their high stiffness and resistance to rotation, they have been found to have critical weaknesses in previous seismic events. The 1994 Northridge earthquake was another wake-up call, as the extensive damage included brittle fractures in welded connections (Fig.5), raising questions regarding the adequacy of traditional design practice as well as quality control [4]. The cracks posed significant threats to structural integrity, leading to revisions of design codes and practices. Research conducted from 1994 onwards concluded that the brittle failures were compounded by poor weld and/or material properties and brought into question the over-reliance on these types of connections in high seismic regions. Stronger welding-techniques and tougher inspection requirements have also been proposed to mitigate these weaknesses. Nonetheless, concerns remain regarding the capacity of such joints to resist the effects of different seismic phenomena, prompting further studies to investigate the strength of rigid welded joints.



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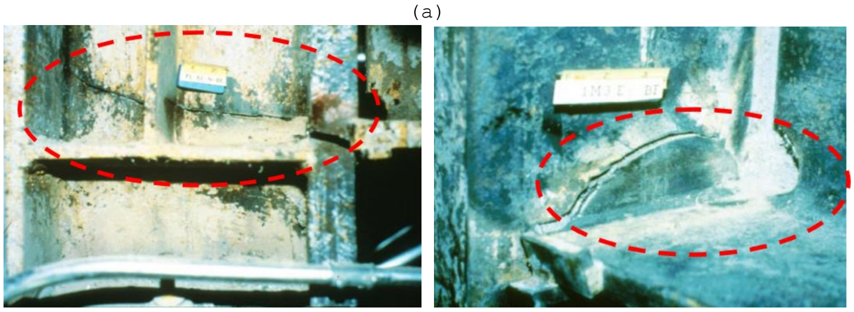

(b)

Figure 5. Common structural failures observed after the Northridge earthquake: (a) Fracture at fuse zone, (b) column fracture, and (c) column flange 'divot' fracture [4]

Bolted connections have great advantages in the seismic-resistant design compared with welded connections. Their ability to dissipate energy and ductility make them less susceptible to brittle failure in cyclic loading conditions [5]. Bolted joints are more inspectable and retrievable than welded connections, thus improving their adoptability in seismic retrofitting and post-event maintenance procedures. Bolted specimens have exhibited about double the rotational ductility when compared to welded specimens, indicating their greater flexibility in withstanding repeated seismic event occurrence. Additionally, bolted connections facilitate modular construction, which can shorten construction schedules while ensuring seismic performance. However, issues like achieving consistent tension on the bolts and avoiding wear over time are still sectors where innovation is needed. Improved testing procedures and material advancements could address these issues and pave the way for bolted connections to assume a commonplace role in seismic design.

Realizing both structural and economic efficiency, the semi-rigid connection, having features of between flexible and rigid design, provides a pragmatic solution. Experimental tests like shaking table tests confirm that the seismic performance of semi-rigid frames can be compared to that of rigid frames with only marginally higher drift ratios. With the force reduction, this small increase in drift is offset by the large cost savings in reduced material consumption and construction costs, making semi-rigid connections viable for low- and high-seismic regions [8]. Moreover, their intrinsic flexibility gives them the capacity to dissipate energy, reducing the likelihood of local failures. However, the modeling and analysis of semi-rigid connections is complex, as the intermediary stiffness disrupts prediction models. Sustainability and seismically resilience are of utmost importance therefore need better computational software and more sophisticated design to fully realize their benefits.

The double C steel joints with gusset plates are a more recent advancement in the design of seismic-resistant connections [9] whereby a good combination of high bending capacity, stable strength degradation, and high energy dissipation capacity has been proven. Experimental results have shown them to be effective in maintaining the structural integrity during seismic loading exposure and especially when design parameters such as bolt-truss spacing and gusset plate thickness are optimized. In addition, the long-term monitoring study on the shear behavior of steel-timber composite joints found that increasing the bolt spacing effectively increases the bearing capacity of the joint, while increasing the gusset plate thickness can significantly improve the strength and stiffness of the joint [9]. These new findings not only showcase the versatility of these kinds of connections but also how critical proper detailing is when it comes to achieving their best seismic performance. Although these new joints are promising but their broader use is depending on the rigorous field testing and bringing standard guidelines for uniform application in practice.

This variation of steel material properties, and in particular inhomogeneity of yield stress, plays a crucial role in the behavior and performance of steel connections under seismic actions. Such inhomogeneities, as demonstrated by British Steel coupon tests, preclude the attainment of capacity design targets, as good ductile mechanisms give way to undesired brittle failures. This demands stringent quality control and the inclusion of probabilistic approaches in design to capture the variability of materials. Moreover, the manufacture of higher grades of steel endowed with more stable characteristics would reduce such weaknesses and align material behavior with capacity design ideals. Advancements in testing techniques and material technologies thus allow steel connections to respond to the growing needs of unpredictable seismic actions in a cost-effective way.

The behavior of steel connections is related to the structural performance of the structure, and the integrity and safety of steel buildings are affected by these connections; therefore, design of steel connections is a key aspect of earthquake-resistant design, followed by the more detailed behaviour of them. These alternative solutions, which have a more advanced state of development than bolted connections and semi-rigid connections, have their challenges, including material variability issues and complex modeling considerations. The reliability and toughness of steel connections for these different types of design are such that additional research, advancement and thorough recognition is warranted.

3.2. Semi-rigid connections

There is a recognized evolution in seismic design of semi-rigid connections that represent a trade-off between rigidity and flexibility [10]. Such a balanced is particularly advantage because it reduces stress concentrations in the structural members, and prevents brittle failures, which are more common in fully rigid connections. The semi-rigid connections possess intermediate stiffness, which results in greater energy dissipation, thus reducing the seismic forces transferred to the structure's foundations and improving system resilience [5]. However, increased application of semi-rigid connections is still contingent on addressing matters related to their design, including accurately predicting their behavior under dynamic conditions and improving analytic models to include these connections more effectively in seismic resistant systems.

The improvement in yield rotation capacity of semi-rigid connections under seismic loading is mainly attributed to larger rotations capacity without losing structural integrity (Fig.6). Under the same connection conditions, empirical findings have invariably shown that bolted semi-rigid connections provide approximately two times the rotational ductility available with conventional rigid welded connections. This property allows steel frames with semi-rigid connections to resist inelastic ductilities during earthquakes while preserving life safety and usability. This observation emphasizes the importance of continued development of materials and detailing methodologies that maximize ductility, particularly in areas with high seismicity where these performance attributes are most advantageous.

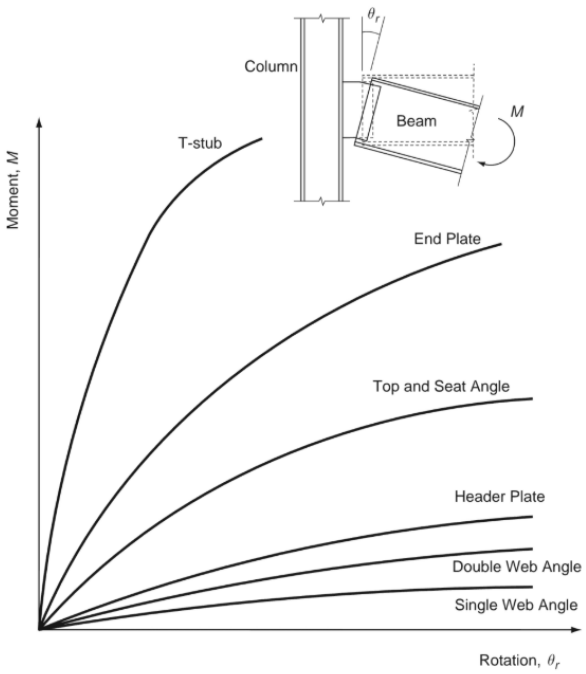

Figure 6. Moment-rotation curves of semi-rigid connection (Chen, W. F., 2011)

The semi-rigid connection layout and its location in a steel frame critically affects the global performance of the structure under seismic loading. As an example, frames with more semi-rigid connections will tend to result in larger fundamental periods, and therefore lower seismic demand, although at the expense of larger corresponding roof drift ratios [11]. This trade-off requires strategic allocation of semi-rigid connections enabling a reasonable trade-off between flexibility and stability. Although further flexibility may help to improve energy dissipation, the increased induced drifts can affect non-structural elements and building functionality, hence the application of semi-rigid connections must be carefully performance-based designed.

Shaking table tests and experimental studies have presented close seismic performance between semi-rigid frames and rigid frames only at slightly greater drift ratios. For example, semi-rigid bolted frames undergo around 10 percent more drift when compared to rigid welded frames, yet they present highly significant benefits in lower construction costs and greater flexibility. These benefits make semi-rigid details an incredibly strong option for projects where economic considerations are most critical. More work is needed, however, to complement these incremental increase in drift with long-term structural performance assessments for better optimized cost-to-performance ratios through any new model-based caliber design methods.

The performance-based connection database is an innovation of semi-rigid frame design, by dramatically improving semi-rigid frame design efficiency. By categorizing connections according to their rotational rigidity and moment-resisting capacity, the database helps designers identify connections that satisfy predefined functional requirements and thus minimizes lengthy trial-and-error design iterations [12]. Another advantage is the portability of such a database to be used in multiple projects, helping maintain design practice consistency. However, augmenting the scope of this DB to include region-specific seismic demands and more detailed performance measures would improve its usefulness, especially in heterogeneous and high-seismic areas.

Colonna has also advocated for semi-rigid connections in precast concrete structures, suggesting they can be optimized for a better seismic response. The figures of merit can be optimized with parameters such as stiffness, strength, and energy dissipation, leading to improved collapse resistance of steel structures [13]. This discovery raises an immediate requirement to introduce more sophisticated computational algorithms capable of predicting the near-optimal designs of semi-rigid joints under different seismic loads. Any such encompassing of the design process towards improving potential seismic resilience would be systematic, though of course, their use in day-to-day practice would require large-scale experimental validation.

The end-fixity factor, which is a measure of the beam-to-column connections rotational stiffness, has been shown from experimental research to have a value around 0.6 [11]. Such a reduction of stiffness will increase the fundamental period of the structure, indicating a global reduction of stiffness. This effect may more strongly attenuate seismic demand, thus, it needs to be properly modeled to fully represent its influence on the structural performance. Correct representation of these properties in seismic design then becomes important to ensure possible advantages of semi-rigid connections can be gained without compromising other structural performance during seismic response.

Experimental evidence supports the efficiency and feasibility of using semi-rigid connections for seismic design. Based on dynamic shakihg table tests, it is confirmed that semi-rigid (PD-EMD) bolted frames have the same behavior as rigid welded frames while offering very low costs [5]. This indicates their applicability to a large number of seismic design scenarios, particularly for where cost-saving paves the way without compromising resilience. Wider use of semi-rigid connections necessitates determining modeling and analysis solutions, as well as establishing criteria that ensure a consistent response for different earthquake scenarios.

Finally, semi-rigid connections are a favorable intermediate connection between the lightest possible solution and the higher seismic demand connections. It is nevertheless welcomed with the prospect of further application and continuation of development in concert with advances in computational modeling, experimental validation and performance-based approaches which are needed to address the wide range of demands presented by the different characteristics of seismic environments.

3.3. Experimental investigations and full-scale testing

The investigation of semi-rigid and bolted connections through experimental studies and full-scale testing has provided extensive insights into the non-linear behavior, cyclic performance, and overall structural resilience of modern steel and composite constructions. Experimental studies have consistently demonstrated that semi-rigid bolted connections exhibit a non-linear moment–rotation response, where the rotational stiffness begins to deviate from linearity at moment levels corresponding to approximately 50–60% of the connection’s design bearing capacity [14], [15]. This phenomenon, observed in long-term testing of L-type models, indicates that once a critical load level is reached, the connection’s ability to transfer moments may decrease in a non-linear manner, potentially affecting the global frame performance.

In addition to static testing, cyclic loading investigations have been pivotal in assessing the seismic resilience and hysteretic behavior of these connections. For instance, Vatansever and Yardımcı [16] conducted cyclic tests on semi-rigid frames that resulted in simplified design criteria for seismic zones, affirming that semi-rigid connections can effectively dissipate energy during cyclic events. Complementary studies emphasize that while welded connections may be prone to brittleness due to residual stresses, bolted connections offer improved ductility and post-earthquake reparability [17]. Shaking-table tests further confirm that full-scale semi-rigid connections not only provide enhanced damping but also reduce lateral drift—an essential feature for seismic resilience [18].

Furthermore, the influence of connection geometry, bolt configuration, and loading type has been extensively examined. Alemdar and Balaban [15] illustrated that misjudging the stiffness of semi-rigid connections can lead to erroneous predictions of lateral deformation capacity and story drift ratios. This finding is supported by cyclic and pseudo-dynamic testing of bolted connections in cold-formed and portal frames [19], where full-scale experiments revealed that proper detailing—such as the precise assembly of top and seat angles and web plates—critically governs the connection’s overall behavior. Extended end-plate connections have also received significant attention, with full-scale tests confirming that these semi-rigid connections improve structural damping and prolong load-displacement hysteresis cycles, features that are particularly beneficial in seismic design [20], [21].

Comprehensive full-scale experimental investigations combined with numerical analyses have thus established reliable design models that capture the non-linear and hysteretic behavior intrinsic to bolted semi-rigid connections. These studies underline the necessity of full-scale testing to validate theoretical models and ensure that simplified design criteria do not underestimate lateral flexibility or overestimate stiffness and strength [15], [22]. The breadth of experimental research, encompassing static, cyclic, and shaking-table tests, not only enhances our understanding of individual connection behavior but also assists in calibrating finite element models for full-scale structural analyses [21], [22].

In summary, experimental investigations and full-scale testing of semi-rigid and bolted connections have proven essential in detailing the critical parameters—such as moment capacity, rotational stiffness, and failure mechanisms—that govern connection performance. The integration of these experimental insights with advanced numerical modeling facilitates the development of robust design criteria, ensuring that modern structures are both efficient in material usage and resilient under extreme loading conditions.

3.4. Innovations in semi-rigid and bolted connections

Below is an extensive discussion on the innovations in semi-rigid and bolted connections, synthesized from multiple experimental, numerical, and analytical studies. The evolution of these connections has been primarily driven by the need to overcome the limitations of fully rigid welded joints and by the pursuit of enhanced energy dissipation, improved ductility, and optimized load-transfer behavior under diverse loading conditions [14], [23]. Innovations have been directed toward not only understanding moment–rotation phenomena but also incorporating novel design elements that enhance overall structural resilience and cost-effectiveness. Early studies highlighted the nonlinear behavior of semi-rigid connections and demonstrated the potential of bolted systems to provide reliable and ductile alternatives to welded joints [24].

The initial wave of innovation in semi-rigid connections focused on the empirical characterization of moment–rotation behavior, with particular emphasis on the onset of nonlinear deformations reaching approximately 50–60% of the connection’s design bearing capacity. Researchers employed full-scale experiments and long-term load tests to capture the progressive degradation of stiffness that occurs under sustained loads. The experimental evidence not only confirmed the nonlinear trends but also spurred the development of simplified design models and predictive algorithms aimed at capturing these behaviors. As a result, a more nuanced understanding of the rotational behavior of semi-rigid bolted connections emerged, one that better informed design and analysis frameworks.

Subsequent innovations have been achieved by integrating numerical modeling techniques such as finite element analysis (FEA) with experimental observations, enabling researchers to simulate the nonlinear response of bolted connections more accurately [25]. Several studies have demonstrated that the combination of FEA with experimental calibration allows for precise prediction of stress concentrations, plastic hinge formation, and progressive stiffness degradation within the connection. These numerical methods have been further refined by incorporating real-life imperfections and material non-linearities.

Another notable innovation has been the development of new semi-rigid connection typologies, such as those employing top and seat angles with double-web reinforcement to enhance ductility and energy absorption[25], [26]. The incorporation of stiffened angles and innovative bolt arrangements has allowed these connections to exhibit favorable load-displacement hysteresis characteristics and improved performance under cyclic loads. As a result, these connections provide a viable alternative in seismic design, ensuring not only safety but also cost efficiency in construction projects. Experimental studies have confirmed their robustness under extreme loading conditions.

Innovative practices have also emerged from the integration of advanced materials into connection design, such as the application of carbon fiber-reinforced polymer (CFRP) sheets [17]. The application of CFRP has been shown to enhance the ductility and energy-dissipating capabilities of semi-rigid beam–column joints while mitigating brittle phenomena. These innovations have been particularly influential for retrofitting existing structures, as they offer efficient ways to improve joint performance without full replacement.

Concurrently, research efforts have been devoted to optimizing the geometric detailing of bolted connections to achieve a balanced compromise between stiffness and ductility [27]. Such geometrical optimizations are crucial as they help adjust the moment-resisting behavior of connections while controlling axial force levels in adjacent truss elements.

A great deal of attention has also been paid to innovative designs allowing rapid assembly and modular construction [28], [29]. These approaches eliminate the need for complicated bolt-tightening procedures while meeting stiffness and strength requirements. The synergy between design and construction efficiency has advanced modular systems in practice. Advanced innovations have emerged in non-traditional connection systems that combine semi-rigid behavior with damping mechanisms [30]. These connections support intentional plasticity, enhance energy dissipation, and reduce the likelihood of brittle failure under extreme events.

The introduction of threaded bars as alternatives to conventional stiffeners promotes uniform load distribution and reduces fabrication complexity. These solutions improve durability while maintaining economic feasibility in construction. Innovative studies have further examined connection performance under bolt loss scenarios [31], revealing the capacity for continued load-bearing and highlighting the importance of redundancy in bolted systems.

Artificial neural networks (ANNs) have also advanced predictive modeling and performance optimization of flush end-plate connections [32]. Combined with structural health monitoring, ANNs enable real-time assessments and reduce trial-and-error in design. In parallel, topology optimization techniques have improved material efficiency and connection performance [33], and their integration into conventional design supports sustainable practices. Other innovations include novel bolted systems for CFST columns, improving tension capacity while simplifying fabrication [34]. The inadequacy of welded joints under seismic action has prompted a shift to semi-rigid and bolted systems [24] reinforcing their importance in performance-based seismic design. Full-scale tests [35] and extended end-plate connections [20] have provided essential data on hysteretic behavior and stiffness.

Innovative strategies in timber construction have also leveraged semi-rigid mechanisms with high-strength fasteners [36]. In steel connections, T-stub design optimization has enhanced strength prediction [37], while multi-scale modeling has provided insights into the interaction of local and global connection behavior [38]. Full-scale experimental comparisons between numerical predictions and dissipative joint systems have validated the effectiveness of partial-strength connections [30]. AI-driven tools [39] have also improved degradation trend prediction and maintenance strategies.

Sensitivity analyses on small geometric variations in joint profiles have yielded design improvements [40]. Emerging studies on gap elimination [41] offer promising solutions to fatigue control and stiffness reliability. Extended blind bolts [22] and angle stiffeners [26] contribute to enhanced load transfer and seismic resilience. These developments, particularly in prefabricated systems [34], reflect a broader shift toward sustainable, modular, and repairable structural design.

In conclusion, the cumulative innovations in semi-rigid and bolted connections—ranging from refined numerical models, advanced experimental techniques, and technology-driven assembly methods to hybrid material systems and AI-enabled monitoring—underscore a transformative shift in structural engineering practices. This integrated approach ensures safer, more resilient, and sustainable structural systems by combining empirical insights with modern design philosophies.

4. Bracing Systems and Design Challenges

The significance of seismic resilience in modern structural engineering continues to gain traction, with effective bracing systems serving as the primary means of enhancing lateral rigidity and minimizing earthquake-induced damage. The following sections discusses bracing systems of different types and arrangements regarding characteristics, behavior, and associated design considerations. Through recognition of these phenomena, this discussion is consistent with the general treatment of connection detail and material behavior as components of a broader discussion addressing the optimization of the structural before and during the 'event' for seismic safety and performance.

4.1. Types and configurations

Bracing systems (Fig.7) are one of the most effective methods for improving the elastic behavior of steel structures by improving the lateral stiffness and strength to prevent lateral displacement and damage during seismic excitation.

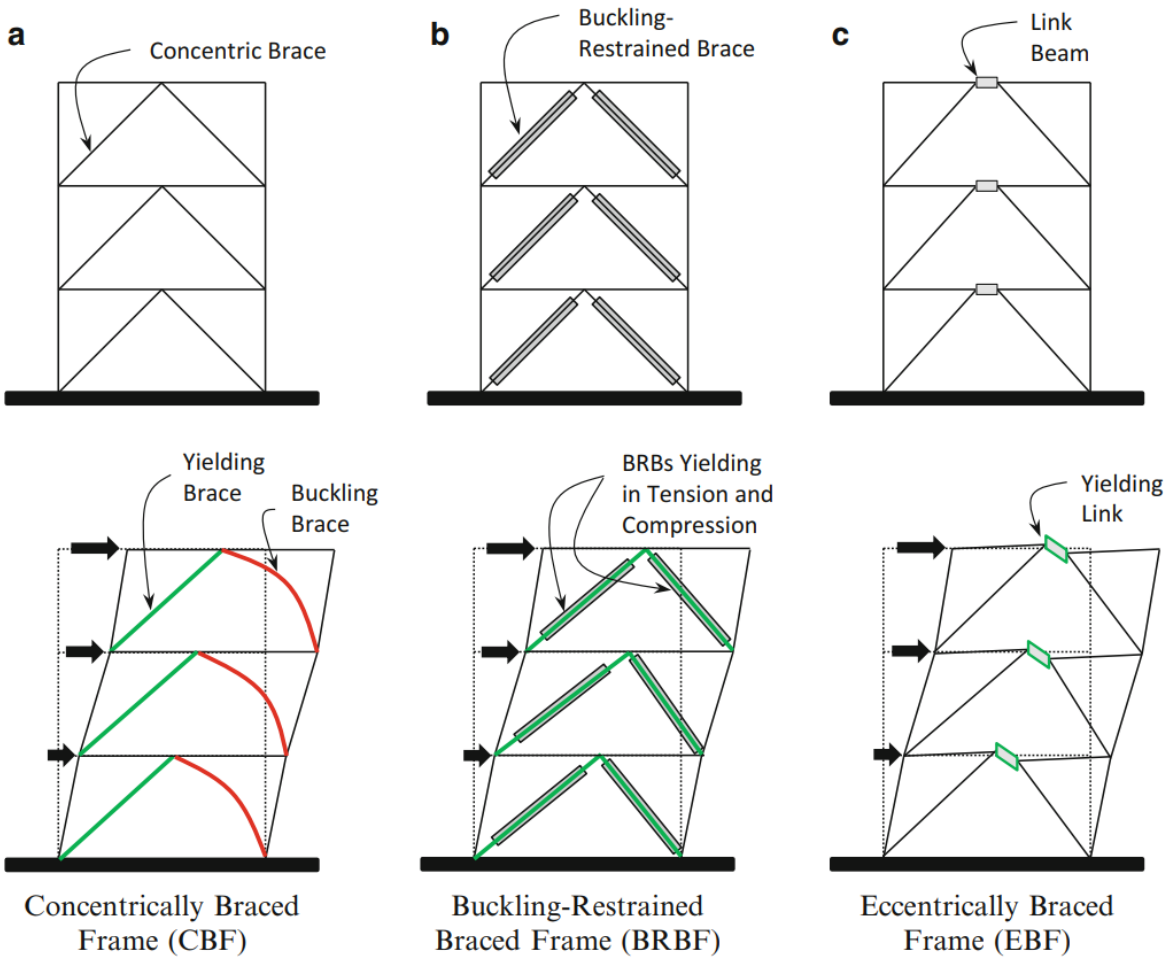

Figure 7. Types of steel braced frames [42]

In this regard, concentric braced frames (CBFs) are deservedly in the spotlight due to the high monotonic stiffness and strength that can be obtained with CBFs, while controlling relative displacement during the initial steps of the seismic excitation [43]. CBF systems are susceptible to stiffness degradation under cyclic loading, specifically as a result of the buckling of the bracing members. This shortcoming is alarming as it can severely affect long-term performance and structural integrity particularly in the later stages of construction through events exposed to repeated seismic waves. Improving these matters involves infestation of setups to oppose varying degrees of ground shaking and design approaches, which sits well with the continued development of predictive models that better predict the behavior of CBF in the event of complex seismic activity.

On the other hand, eccentrically braced frames (EBFs), include ductile shear or flexural links engaged to ensure energy dissipation in a controlled manner via plastic [43]. This design grants EBFs a much larger level of ductility, resulting in proper use in areas of high seismicity. Where you place those links is one of the important design decisions because it allows damage to be contained in individuals members; you don't compromise the integrity of the whole structure. Additionally, allowing for this localized damage mechanism fosters repair after the occurrence of an earthquake since only the damaged links need repair. Fine-tuning the positioning and detailing of these bonds is yet to come.

More advanced bracing systems, like buckling-restrained braced frames (BRBFs), improve upon traditional braced frames by preventing buckling in compression. Higher energy dissipation capacity due to stable hysteresis response, together with a preference for high strength and ductility, make shape memory alloys attractive for structures. The use of BRBFs is particularly useful in tall structures wherein lateral stability under extreme earthquake loading becomes extremely critical for their performance. But ensuring the consistent performance of BRBFs in transforming them through existing design practices over well-defined standards requires rigorous testing and sophisticated computational models. In addition, their relatively high initial costs in comparison with traditional bracing systems have significantly limited the potential for widespread adoption, warranting further investigations into cost-effective and scalable production processes that will enable their implementation.

Retrofitting of steel structure with bracing systems has shown to be highly effective in enhancing the life and safety of aging buildings, particularly in urban areas where aged concrete structures are prevalent. For three-story buildings, retrofitting with inverted V braces increases base shear capacity by 43.49%, and for X braces, it is increased by 51.34% [44]. However, these enhancements are not significant in taller buildings, where six-story buildings with inverted V braces and X braces increased base shear capacity by 15.37% and 20.68%, respectively (Harsha & Nikhil, 2020). This disparity highlights the importance of bespoke retrofitting approaches informed by building height and configuration to maximize earthquake resistance. This is followed by the need for further experimental investigations and analyses for enhancing assessment retrofitting procedures and better utilizing bracing systems in different structural environments.

One potentially disruptive innovation for seismic design is a self-centering energy dissipative (SCED) bracing system (Fig.8), which consists of frictional energy dissipation mechanisms coupled with tensile Aramid elements that allow the system to deform into extreme axial ranges without permanent damage [45]. However, the removal of residual displacements after an earthquake is already a revolutionary feature for critical facilities like hospitals or emergency centers that need to work immediately after a seismic episode. While SCEDs have been experimentally verified to achieve targeted performance levels, their long-term durability and scalable feasibility remain uncertain. Further research needs to take place regarding the implementation of the aforementioned technologies in a real world setting, concerns of cost, maintenance, and integration within current building codes.

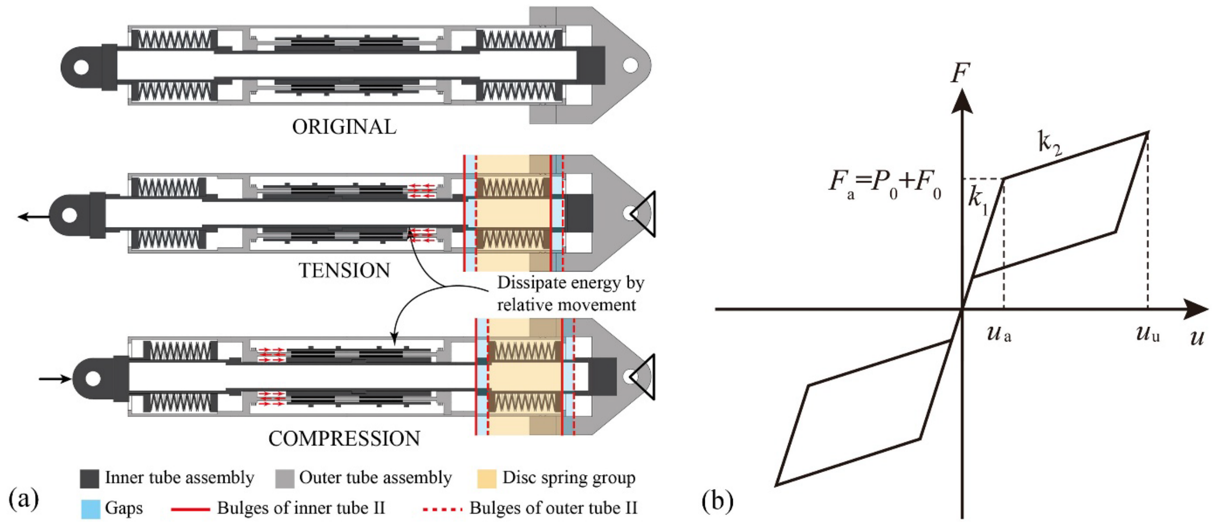

Figure 8. Structural behavior of the SCED bracing system under cyclic loading: (a) Tension and compression mechanisms, (b) hysteretic response [37]

Double-angle bracing systems are well-known for their performance under cyclic deformations; however, their effectiveness and stability during seismic events need accurate design parameters. The effective length factor (K) for in-plane buckling is only about 0.5 and is nearly 1.0 for out-of-plane buckling [46]. This distinction is critical in mitigating the individual failure modes during a seismic event. Also, the occurrence of plastic hinges, particularly at mid-span and end gusset plates, requires advanced modeling and design of components to improve ductility and prevent premature failures. Optimizing the geometry and material of these members can play an important role in their improved performance under cyclic loading.

Bracing systems also allow a merging between structural performativity and architectural aesthetics. Interventions around retrofitting in Istanbul, for example, incorporated decorative patterns and Art Deco motifs, showing how seismic safety and aesthetic beauty can go hand-in-hand [47]. This two-tiered approach not only satisfies the demands for safety but also the needs of urban planning to maintain the cultural and historical heritage embodied by previous structures. However, balancing these aesthetic considerations with structural needs is a delicate process, as there is a need for continuous communication between engineers and architects to make sure visual upgrades do not negatively affect the structural performance of bracing systems.

This technology includes the braced ductile shear panel (BDSP) system. BDSP systems have high base shear capacities (about 1,700 kN vs. 1,000 kN for traditional moment-resisting frames) and mitigated structural drift, which are key tenets of performance-based design [48]. BDSP systems are a revolution in strength-ductility coupling, and are used in high-seismic regions. its necessity of their wide applications has to be justified by extensive testing and standardization to validate their reliability within different structural contexts.

Ultimately, even though bracing systems are significant improvements to the seismic behavior of steel structures, their conceptualization, applications, and implementation should go hand in hand with further progress, careful assessment, and fine-tuning to unique seismic environments. Exploration of new materials, computational modeling, performance-based design approaches will continue to provide the major means of optimizing such systems.

4.2. Limitations and provisions of code

The Eurocode 8 code provisions provide a basis for the seismic design of steel structures, but this basis has recently been questioned. One of the critical issues has been that modern structural typologies, in particular buckling-restrained braces (BRBs) and dissipative truss moment frames, are not included in modern seismic codes even though there is a wealth of evidence showing that such systems can provide significantly improved seismic performance due to their increased energy dissipation and buckling resistance capacities. Such developments have been codified in American building codes, in contrast to Eurocode 8, and, as a result, have contributed to the safety and resilience of seismic design in the United States. In fact, Piluso [49] points out that the late incorporation of those advancements in Eurocode 8 discourages the advancement of innovative designs against earthquake actions in a European context by forcing professionals to keep using outdated protocols. It also raises questions about how well Eurocode 8 can adapt and keep up with modern seismic challenges, strongly hinting at the need for regular updates to better reflect up-to-date research and new techniques. As shown in Table 1, several studies have highlighted structural and regulatory weaknesses in Eurocode 8, providing insights into necessary updates for enhanced seismic resilience.

Table 1. Key studies highlighting weaknesses in Eurocode 8

Paper	Main findings
Plumier (2000) [50]	European research on seismic design of composite steel-concrete structures highlights poor global guidelines.
Elghazouli (2008) [51]	Eurocode 8 for steel frames has issues in stability, drift, and capacity design.
Mazzolani et al. (2009) [52]	Eurocode 8 provisions for steel and composite structures need improvements.
Faggiano et al. (2014) [53]	Eurocode 8 & Italian code for X-braced frames have weaknesses, requiring enhancements.
Faggiano et al. (2016) [54]	Eurocode 8 criteria for concentrically braced frames need revision.
Faggiano et al. (2017) [55]	Chevron-diagonal braced frames in Eurocode 8 have critical design issues.
Porcu (2017) [56]	Eurocode 8 provisions may cause inconsistencies in non-linear seismic analysis.
Tsitos et al. (2018) [57]	Eurocode 8 steel frames face high lateral demands & seismic drifts.
Araújo & Castro (2018) [58]	Eurocode 8 & ASCE41-13 seismic assessment provisions need review.
Costanzo et al. (2019) [59]	Eurocode 8 leads to poor energy dissipation in steel moment frames.
Silva et al. (2020) [60]	Chevron-braced frames perform worse than other Eurocode 8 designs.
Silva et al. (2021) [61]	Eurocode 8 X-braced steel frames need modifications for efficiency.
Gutiérrez-Urzúa et al. (2021) [62]	Eurocode 8 for steel frames requires updates to align with research & US codes.
Tartaglia et al. (2022) [63]	Eurocode 8 steel moment frames are costlier but have higher rigidity than US frames.
Landolfo et al. (2022) [64]	Lightweight steel buildings lack explicit design rules in Eurocode 8.
Gómez-Martínez & Pérez-García (2023) [65]	Eurocode 8, Italian NTC & Spanish NCSE-02 have weaknesses in inelastic response.

One such structurally dominant typology found in Eurocode 8, Concentrically Braced Frames (CBFs), suffers from stability and resistance limits when subjected to seismic loading. Critical deficiencies are identified by Piluso [49], who highlights that for high seismic actions, stability and resistance indexes of Eurocode 8 are often violated. These performance deficiencies arise from conservative code assumptions that do not account for the dynamic behavior of CBFs during earthquake loading. Nonlinear seismic analyses indicate these deficiencies because the prescribed provisions fail to provide a realistic response. These shortcomings justify the enhancement of the Eurocode 8 stability and resistance guidelines for CBFs, including dynamic analyses as well as modified material properties, in order to ensure reliability and minimize the potential of collapse.

One of the most important limitations in Eurocode 8 relates to the employment of real ground motion records in nonlinear dynamic analysis. Though theoretically allowed, in regions of moderate to high seismicity, it is practically precluded by the impossibility of easily obtaining matching accelerograms. Iervolino et al. [66] show that the limited provisions of Eurocode 8, along with the lack of existing records for complex design spectra, lead to the limited use of Eurocode 8 in practice. In addition, the code has a limited ability to take into consideration local site conditions, which are of paramount importance in terms of realistic evaluation of seismic demands. Although applications such as REXEL can help select records of ground motion that match a specified seismic requirement, their utility is limited when it comes to extreme seismic conditions. This highlights the gap that we need to bridge by establishing larger databases and improved methodologies that will overcome these boundaries, thus permitting a better and more site-specific implementation of nonlinear analysis.

The Eurocode 8 approach pays no attention to what could be considered a very basic aspect of seismic risk: structural damage is caused during earthquakes with moderate accelerations. Moderate accelerations (say, between 0.3g and 0.8g) can cause extensive damage to structures [3], , especially in the case of non-ductile response systems. In addition, Elnashai [2] emphasizes the discrepancies between calculated design capacities and actual performance on a moderate scale and confirms that even moderate seismic events are more than enough to make a building unsafe. This deficiency in Eurocode 8 exposes structures to a wider spectrum of seismic conditions, implying that there is room for improvement by extending the applicability of the code to encompass the entire range of seismic demands. Filling this void would necessitate the inclusion of performance-based design approaches and criteria that are more sensitive to risks associated with intermediate-scale events.

A third important issue that Eurocode 8 addresses is the variability of the material, particularly the inhomogeneities in steel yield stress. British Steel experiments have shown large variability in yield stress, making the application of the principles of capacity design difficult. Given such inhomogeneities, accurate prediction of structural performance on the basis of 'ductile mechanisms' can therefore be supplanted by more catastrophic and high-energy brittle behavior. This compromises both the safety of steel constructions and the effectiveness and robustness of the design procedures. If Eurocode 8 includes probabilistic analyses and more stringent material testing procedures, these issues will be resolved since the structural design will be able to properly take into account the variability of material, and the overall robustness of steel structures will be improved.

The seismic resilience enhancement potential of performance-based design approaches is significant yet still underexploited within the Eurocode 8 context. One example of developing systems that are not addressed in the code is innovative BISPs (Buckling Inhibited Shear Panels) that significantly reduce structural drift and increase base shear strength, as described by Piluso [49]. Such omissions lead to a disconnection between state-of-the-art research and prevailing practice, and limit the broad adoption of experimental advances. Closing such a gap would require a far-reaching redrafting of Eurocode 8 to embrace performance-based design methodologies and the latest technology. The new technical criteria would also help enhance the efficiency and effectiveness of seismic design and make European practice more consistent with international practice.

In conclusion, while Eurocode 8 serves as a fundamental standard for the seismic design of steel structures with its many advantages, its limitations prevent it from properly addressing contemporary challenges. What needs to be improved are the late integration of new structural typologies, the insufficiencies in CBF provisions, and the complexities of applying real ground motion records. Moreover, the neglect of moderate acceleration earthquakes, the uncertain characterization of material properties, and the lack of performance-based design procedures adopted by the code also emphasize the necessity for its thorough re-examination. These issues will require prompt revision and extensive testing of the code to ensure its relevance and reliability within the evolving context of seismic design practice.

4.3. Retrofitting strategies for existing bracing systems

The seismic retrofitting of existing bracing systems has attracted considerable research interest over the past decades as engineers seek to enhance the lateral strength, ductility, and energy dissipation capacity of aging structures while minimizing the additional weight and cost associated with conventional interventions. Innovations in this arena have been achieved through a series of strategies that modify or supplement existing bracing configurations. These strategies include the application of buckling-restrained braces (BRBs), the incorporation of energy dissipation devices, the use of novel materials such as fibre-reinforced polymers (FRP) and shape memory alloys (SMAs), and the integration of optimal design methodologies backed by probabilistic and performance-based assessments.

A major thrust in retrofitting strategies is the transformation of existing braces into buckling-restrained systems. Experimental investigations have demonstrated that BRBs can significantly improve the seismic performance of reinforced concrete (RC) frames by providing nearly symmetric hysteretic behavior and enhanced ductility [67], [68], [69]. This retrofit approach not only increases the lateral resisting strength and stiffness without a significant increase in mass [70] but also improves the overall energy dissipation of the frames under cyclic loading [71], [72]. Shake table tests and full-scale experiments have validated these benefits by showing reduced inter-story drifts and delayed onset of local buckling in retrofitted members [67], [73].

Hybrid retrofitting strategies further exploit the combined use of traditional bracing with supplementary dissipative mechanisms. The introduction of devices based on self-centering technology or viscous dampers has been shown to mitigate residual deformations and further enhance energy absorption capacity [74], [75].

Numerical investigations into diagonal bracing systems incorporating SMAs illustrate that such systems can effectively restore the lateral stiffness of soft-storey buildings, contributing to a more resilient seismic response [76], [77]. These approaches benefit from the inherent advantages of SMAs such as superelasticity, which can be particularly effective when integrated into retrofitting schemes for braced frames [78].

Alternative strategies specifically targeting RC frames have focused on converting existing steel X-bracing systems. Retrofitting with steel X braces tends to improve the lateral load distribution and reduce vulnerability to soft-story collapse while offering a cost-effective alternative to shear walls [79], [80]. Full-scale tests and pushover analyses indicate that the introduction of these bracing systems can substantially enhance both the strength and ductility of RC frames [81], [82]. Additionally, probabilistic performance assessments and index-based methodologies have been applied to evaluate the efficacy of various retrofit options, thereby enabling optimal selection of retrofit strategies tailored to the specific deficiencies of existing structures [83], [84].

The use of composite materials in retrofitting is another innovative pathway toward achieving sustainable strengthening of bracing systems. FRP retrofits have been successfully applied to enhance the stiffness and ductility of RC frames without imposing significant dead loads [81], [85]. In certain cases, hybrid retrofitting approaches combine conventional steel bracing with FRP overlays or external steel jackets to meet the dual objectives of structural safety and architectural preservation [85], [86]. Furthermore, innovative connection upgrades—for example, the reinforcement of brace-to-frame joints using self-tapping screws in glulam-steel systems—have been shown to overcome issues related to brittle failures while promoting ductility in retrofitted systems [84].

Optimization techniques based on multi-criteria decision-making and mathematical programming are increasingly employed to fine-tune retrofitting solutions. These approaches allow for the simultaneous consideration of multiple performance indicators such as strength, stiffness, ductility, and constructability [84]. By integrating sensitivity analyses with full-scale experimental validations, researchers have developed retrofit design guidelines that ensure the reliable performance of braced structures under seismic excitations while minimizing unintended adverse effects on adjacent structural elements [87], [88]. Such comprehensive evaluations are critical in the context of aging infrastructure, where existing deficiencies need to be addressed without complete structural replacement.

Overall, the evolution of retrofitting strategies for existing bracing systems reflects a convergence of innovative materials, advanced testing methodologies, and sophisticated design optimization techniques. The integration of BRBs, hybrid energy dissipation approaches, FRP reinforcements, and optimal design frameworks represents a robust pathway to improve the seismic resilience of existing structures. These innovations, validated by experimental and numerical studies [80], [89], [90], provide engineers with a comprehensive toolbox for designing retrofits that address both performance and serviceability requirements in a cost-effective manner.

5. Post-Earthquake Damage Assessment and Recovery Strategies

Post-earthquake damage assessment and recovery strategies in steel structures are critical areas of research and practice in seismic engineering, driven by the need to rapidly evaluate residual risks and implement effective repair measures to restore structural integrity. After an earthquake, a comprehensive evaluation begins with a systematic inspection of welded steel moment-frame buildings to determine potential safety hazards. Traditional methods, as outlined by Phipps [91], include multi-step procedures often referenced in FEMA-352, which guide engineers through visual inspection, instrumentation-based evaluation, and residual displacement measurements to provide an initial indication of overall performance and the need for detailed repair.

Recent advances in assessment techniques have significantly enhanced the rapid evaluation of post-earthquake damage. For instance, remote sensing methodologies have emerged as innovative tools for rapid damage estimation. Kaplan and Kaplan [92] demonstrated the utility of a response spectra-based approach supplemented with satellite remote sensing data to rapidly identify unsafe, heavily damaged buildings, underscoring the importance of integrating spatial data with traditional structural analysis. Similarly, Zhou et al. [8] explored the feasibility of utilizing surveillance camera images to perform pixel-level damage assessments, further reducing the time required for post-earthquake evaluation and enabling real-time decision-making. Additionally, fragility assessments of existing low-rise steel moment-resisting frames have shown that repeated aftershocks can exacerbate cumulative damage, and probabilistic models can play a substantial role in understanding damage accumulation and guiding recovery strategies [93].

On the recovery side, the post-earthquake repair of steel structures often necessitates targeted interventions to address localized deficiencies. Sarno et al. [94] provided a case study emphasizing the need for detailed damage investigations—not only to document the extent and type of deformations but also to inform the design of effective retrofitting strategies. Repair methodologies may involve the rehabilitation of welded connections through repair welding or the replacement of severely damaged members with bolted connections, which offer greater ease of inspection and facilitate post-repair verifications [91]. Furthermore, the incorporation of design improvements such as self-centering mechanisms helps restore the original functionality of the structure while minimizing residual deformations, thus enhancing rapid post-earthquake recovery [95]. Emerging recovery strategies also emphasize the use of advanced decision-support algorithms, enabling rapid evaluation of structural performance and optimal allocation of repair resources based on both measured displacements and inferred damage levels [96].

The integration of these approaches into a holistic post-earthquake management framework ensures that safety assessments and recovery operations are both effective and efficient. By combining traditional inspection methods with modern remote sensing, fragility analysis, and advanced computational algorithms, engineers can more accurately evaluate the residual capacities of steel structures and implement repair measures that restore performance under future loading scenarios. This multidisciplinary approach contributes not only to immediate post-earthquake recovery but also informs long-term retrofitting and resilience-enhancing strategies, ultimately leading to safer and more sustainable structural systems in seismic regions.

6. Conclusion

The main aim of this study was to investigate the controversial aspects of the earthquake-resistant design of steel structures, especially in terms of connections, bracing systems, and material behavior. The above objective was fulfilled through the integrated findings of experimental work, computational work, and case studies, in an effort to bridge theoretical models with actual structural response upon seismic excitation. The research aimed to explore difficulties in designing to achieve seismic resilience while accounting for the constraints of current design codes and material properties. This case study provided insights into measures that could be taken to improve the performance of steel structures in seismic zones through the use of advanced engineering techniques and materials.

These observations point out that seismic design concepts are regulated by hierarchical performance levels that range from maintaining functional operability for small earthquakes to life safety and collapse prevention for high seismic hazard levels. One of the emphases was on the capacity design principles for increased ductility that would ensure the prevention of brittle fracture failure modes. However, the effectiveness of these concepts can be significantly influenced by material properties, such as the variability in steel yield stress, which complicates the accurate prediction of seismic response. Nevertheless, the introduction of mechanisms such as energy dissipation through plastic hinge zones has proven to be a cornerstone of seismic design philosophy, corroborated by the better performance of structures built according to modern codes compared to those that failed in historic collapses, such as the 1994 Northridge earthquake.

Particularly, the behavior of high-strength structural steel under cyclic loading, a special condition triggered during an earthquake, was under the spotlight. The studies showed that the cyclic response of steel is often less certain than the monotonic response, and serious problems such as the early development of necking and low energy absorption capacity are indeed a matter of concern. The variability in yield stress also helped us identify inconsistencies that can compromise capacity-design goals. It was discovered that parameters such as the width-to-thickness ratio of steel members could directly impact factors such as local buckling, ductility, and energy absorption, thus highlighting the necessity for devising region-specific design criteria in accordance with varying seismic hazards. These results emphasize the importance of developing advanced test protocols and improved constitutive models for predicting the material response to actual seismic loading scenarios.

The study revealed that among the various factors that influence the seismic resistance of steel structures, their connection behavior was the most significant, thus leading to a focus on the behavior of steel connections. Although rigid welded connections have always been preferred due to their high strength and stiffness, their disadvantage, namely brittle fracture in the event of seismic loading, has resulted in a shift towards more flexible connections. It was thus found that bolted connections possess several noteworthy advantages over welded connections, such as ductility and the capability of being repaired, thus making bolted joints an ideal choice for seismic retrofitting. Semi-rigid connections, which may be characterized as a reasonable compromise between rigid and flexible connections, were considered as such due to their capability to experience larger rotations while preserving structural integrity. Notably listed as an advantage were their seismic performance and economic viability, while their modeling and detailing require further development for optimization. It was also found that some emerging developments, such as double C steel joints with gusset plates, can enhance seismic resistance through energy dissipation and damage localization control.

Bracing systems were studied, and their critical importance in providing lateral stability and reducing seismic damage was highlighted. Low-period building frames were identified as those with initial cyclic behavior displaying less strength and stiffness than concrete and non-concentric braced frames due to cyclic strength degradation and high-energy absorption plastic areas. Buckling-restrained braced frames were developed as alternative structural systems capable of developing high strength and ductility without buckling, enabling their use in high seismic risk regions. On a broader scale, their application is limited by higher costs and the requirement for accurate verification of their performance. Novel solutions such as self-centering energy dissipative braces, which show promise in terms of overcoming residual displacements, were promising for revolutionizing critical infrastructures, yet challenges around scaling solutions and codifying solutions remained. Furthermore, it revealed that retrofitting approaches are needed for different regions, as different bracing systems yield different levels of improvement depending on factors ranging from height to structural properties.

This research not only achieved its main goals but also explored the larger seismic design landscape by identifying shortcomings within current design codes. One widely used framework, Eurocode 8, was found to be insufficient to account for recent advances, including buckling-restrained braces and dissipative truss moment frames. The code conservatively defines parameters such as stability indices and material properties, which can be inadequate in reflecting the dynamic behavior of a structure during an earthquake, with significant potential for improvement. In addition, its emphasis on high ground accelerations overlooks the extensive damage caused in moderate seismic events, which tend to affect structures with non-ductile response modes. These lacunae suggest that design codes should be periodically updated, and a performance-based approach that incorporates the full range of seismic demands and innovation in material and structural systems should be broadly adopted.

Their combination of experimental results, computer simulations, and case studies makes the research findings a useful contribution to the ongoing task of seismic design. These results are also consistent with prevailing trends in research, such as work done by Astaneh-Asl on semi-rigid connections and Fang et al.'s Experimental Tolerance Investigations on Braced Ductile Shear Panel Systems, while also introducing new information concerning the integration of advanced masonry systems and novel connection systems. The results are of practical significance for the hope of more constructive efficiency and economy in the execution of high-tech systems such as semi-rigid connections and braced frames. For now, this discrepancy between the imaginary world of ideal seismic performance and the real world serves as a reminder of the engineering challenge to overcome the research-practice gap.

Despite its contributions, this research has several limitations. Because the studies mentioned have compared existing studies, this also introduced constraints in terms of experimental setup variability and geographic variations. In addition, certain findings (e.g., the response of semi-rigid connections or special bracing systems under extreme seismic excitation) need to be validated through large-scale tests and/or full-scale constructions. The validity of the conclusions across a variety of seismic zones and building types is a question for further investigation. More advanced experimental investigations of connection rotational behavior and the cyclic response of high-strength steel will be needed, as will the development of more sophisticated computational software for analyzing non-linear structural response, to address these limitations.

Moving forward, the findings highlight the importance of multidisciplinary approaches and collaborative efforts to improve seismic design practice. In forthcoming studies, the implementation of innovative bracing systems such as self-centering energy dissipative braces within performance assessment design frameworks should be a priority, together with the investigation of the aesthetic qualities of seismic design elements within architectural design, as presented later on by the retrofit practice in Istanbul. Also, the advancement of design codes, e.g., Eurocode 8, should emphasize the acceptance of new techniques and performance-based approaches, making them relevant to solving modern seismic issues. By making use of methods advanced in materials science, experimental techniques, and computational modeling, the field can continue to develop and create harmony between theoretical modeling and practice.

Overall, the study reaffirms that it advances the existing knowledge of earthquake-resistant design and tackles the key problems manifested by seismic forces. It echoes the difficulty of seismic safety design while stressing that the prevailing orthodoxy in structural design and material technology has endured. On a personal level, this investigatory approach has led to an appreciation of the intricacies among materials, connections, and structural systems themselves in achieving seismic safety. It expresses a renewed commitment to addressing new solutions and contributing to the continued pursuit of safer and more resilient steel structures in seismically prone areas. By applying these research results to actual practices, much can be done by the industry to alleviate risks to human life and infrastructure and to improve the functionality of structures during and after the occurrence of seismic events.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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