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Improving the Seismic Performance Of Eccentrically Braced Frame (EBF) Steel Structures Through the Application of Medium-Length Links

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Abstract— Eccentrically Braced Frames (EBFs) are widely recognized for their capacity to combine structural strength, stiffness, and ductility, making them an ideal solution for earthquake-resistant design. At the core of this system lies the link beam, whose inelastic deformation behavior determines the overall energy dissipation capacity of the frame. Traditional link designs favor short and long configurations, which are characterized by shear or flexural yielding, respectively. However, medium-length links—capable of simultaneously activating both shear and flexural mechanisms—offer an advantageous compromise between strength and ductility. Despite their potential, medium-length links are underutilized due to historical design conservatism and limited code recognition. This paper presents a comprehensive analysis of the performance characteristics of medium-length links through a synthesis of recent experimental and computational studies. It also identifies emerging innovations in detailing, materials, and modeling approaches that can optimize EBF systems for enhanced seismic resilience. The results support a performance-based shift in design philosophy that leverages medium-length links to improve the safety, reliability, and sustainability of steel buildings in seismic regions.

Keywords: Eccentrically Braced Frames (EBFs), Medium-Length Links, Seismic Performance, Structural Steel, Energy Dissipation, Finite Element Analysis, Self-Centering Systems

1. INTRODUCTION

As global urbanization increases in seismically active regions, the demand for resilient building systems has intensified. Steel structures, due to their high strength-to-weight ratio and ductility, are prominent candidates for seismic design.Eccentrically Braced Frames (EBFs) are widely utilized structural systems in earthquake-resistant steel buildings, known for their effective combination of strength, stiffness, and ductility. EBF systems merge the advantages of moment-resisting frames and concentrically braced frames by incorporating specially engineered link beams that dissipate seismic energy through controlled inelastic deformation (AISC, 2022). These link beams are typically classified as short, medium (intermediate), or long, depending on their length relative to the plastic modulus and yield strength of the section (Popov &Engelhardt, 2021). Each category of link utilizes different mechanisms for energy dissipation: short links primarily rely on shear yielding, while long links depend mainly on flexural yielding (Mazzolani et al., 2023). In contrast, medium-length links activate both shear and flexural yielding mechanisms, resulting in a balanced hysteretic response that is advantageous for seismic performance (Roh et al., 2024). In recent years, significant research has focused on optimizing link designs to enhance the seismic performance of EBF systems, especially through the application of medium-length links.

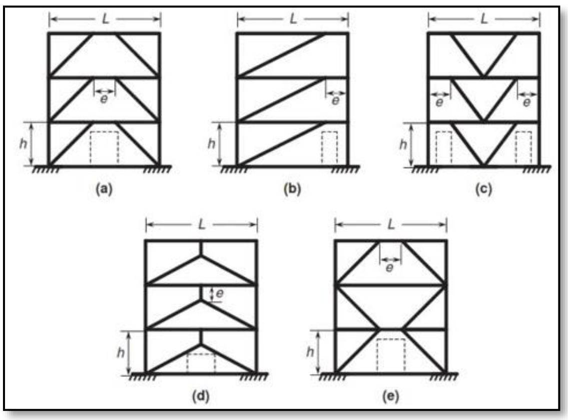

Figure 1. Some possible types of bracing configurations for the EBF system are shown in Figure 1; (a) D Braces, (b) Split K-Braces, (c) V-Braces, (d) Split K & Inverted Split K-Braces, (e)) (Source: A NSI/AISC).

These links are recognized for their ability to dissipate energy efficiently while avoiding typical failure modes seen in short links (such as web fractures) and long links (such as flange local buckling) (Gioncu&Mazzolani, 2022). Both experimental and numerical studies have confirmed that appropriately designed medium-length links can substantially improve the overall resilience of structures and reduce permanent deformations following seismic

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events (Roh et al., 2024; Chen et al., 2023). Although current seismic design standards like AISC 341-22 encourage optimization of link design for specific performance goals, traditional design approaches still often favor short shear links due to their simplicity and well-documented behavior, potentially overlooking the advantages offered by medium-length links (AISC, 2022).

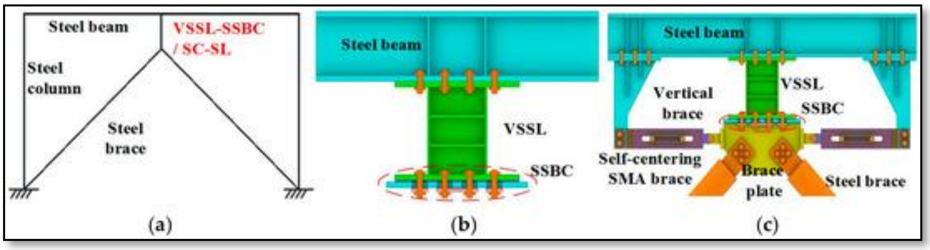

Figure 2. A Novel Eccentrically Braced Frame Applied With SC-SL:
(A) EBF; (B) VSSL-SSBC; (C) SC-SL (Xinyuet all. 2025)

Technological advances in finite element modeling and experimental analysis have enabled more accurate prediction of medium-length link performance under cyclic loading, illustrating their potential to extend the service life of EBF systems and minimize post-earthquake repair needs (Engelhardt et al. 2023). Additionally, recent developments in materials and detailing techniques such as the use of high-strength low-alloy steels and enhanced link stiffeners have been shown to improve the cyclic stability and performance of medium-length links by reducing susceptibility to local failure (Zhou et al., 2024). These innovations contribute to more consistent and stable energy dissipation throughout seismic loading cycles. Considering the global emphasis on developing resilient and sustainable building systems, the optimization of EBF structures through the use of medium-length links presents a promising opportunity. Improved link designs can lead to more effective seismic energy dissipation, enhanced structural redundancy, and increased reliability in post-earthquake conditions (Roh et al., 2024). This research focuses on conducting an in-depth evaluation of the seismic behavior of EBF steel structures incorporating medium-length links, comparing their performance against conventional short and long link configurations. The study aims to determine optimal link dimensions and cross-sectional characteristics that maximize energy absorption while minimizing seismic-induced damage. The outcomes are expected to inform future design standards, contributing to the development of stronger, more resilient steel building systems in earthquake-prone areas.

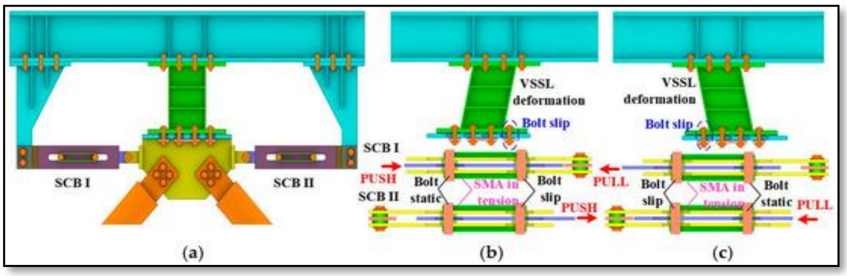

Figure 3. Working principle for EBF with SC-SL during cyclic loading:
(a) SC-SL; (b) Positive moving; (c) Negative moving. (Xinyuet all. 2025)

2. BACKGROUND AND CURRENT ISSUES

Eccentrically Braced Frames (EBFs) have become one of the primary seismic-resistant systems used in modern steel structures due to their ability to balance structural strength, stiffness, and ductility effectively (AISC, 2022). These systems merge the benefits of moment-resisting frames, which provide ductility, with those of concentrically braced frames, which offer high stiffness and strength. The unique feature of EBFs lies in the use of *link beams*—critical elements designed to absorb seismic energy through controlled inelastic deformation, thus protecting the primary structural members from damage during seismic events (Popov &Engelhardt, 2021).Typically, link beams in EBFs are categorized as *short, medium (intermediate),* or *long* based on their length relative to the plastic section modulus and yield strength. Each link type exhibits distinct energy dissipation mechanisms: short links primarily dissipate energy through shear yielding, long links rely on flexural yielding, while medium-length links activate both mechanisms simultaneously (Mazzolani et al., 2023; Roh et al., 2024). This dual-yielding mechanism in medium-length links contributes to a more stable and balanced hysteretic response, making them potentially superior for seismic applications.Despite their theoretical advantages, medium-length links are often underutilized in current engineering practice. This is partly due to conventional design standards like AISC 341-22, which tend to prioritize short shear links because of their well-established behavior and simpler design requirements (AISC, 2022).

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However, short links are susceptible to premature failure modes such as *web fractures*, whereas long links face issues like *local flange buckling*, both of which can limit the energy dissipation capacity and structural integrity of EBF systems (Gioncu&Mazzolani, 2022).

In recent years, a growing body of research has focused on optimizing link beam designs, especially medium-length links, to enhance the seismic resilience of EBF structures. Experimental and numerical studies have demonstrated that medium-length links, when properly designed, offer superior energy dissipation while reducing structural degradation and residual deformations post-earthquake (Chen et al., 2023; Roh et al., 2024). Moreover, innovations in materials such as the application of high-strength low-alloy steels and advanced detailing techniques like link stiffeners have shown to improve the cyclic stability of medium-length links, reducing local failure modes and ensuring consistent energy dissipation throughout seismic loading (Zhou et al., 2024).Advancements in finite element modeling techniques further allow for more accurate predictions of link behavior under cyclic loading, providing engineers with powerful tools to explore and optimize link designs beyond the limitations of traditional code-based approaches (Engelhardt et al., 2023). However, despite these technological advancements, current design standards provide limited guidance for fully exploiting the potential of medium-length links, representing a gap in existing design methodologies (AISC, 2022).In the context of global sustainability goals and the push for more resilient infrastructure, improving EBF systems through the optimization of medium-length link design represents a critical research direction. Optimized medium-length links can enhance seismic energy dissipation, improve structural redundancy, and facilitate faster post-earthquake recovery, contributing to the development of more robust and sustainable steel structures (Roh et al., 2024).

3. RECENT INNOVATIONS AND EXPERIMENTAL ADVANCES

Recent advancements in the design and application of link beams within Eccentrically Braced Frames (EBFs) have significantly improved the seismic resilience of steel structures. One of the most noteworthy innovations is the introduction of self-centering link mechanisms, specifically the Self-Centering Shear Link (SC-SL) proposedby Liu et al. (2025). This novel system integrates a V-shaped link configuration with sliding shear mechanisms**s**and post-tensioned tendons to offer a unique combination of energy dissipation and self-centeringbehavior. Unlike traditional link designs, which often experience residual deformations after major seismic events, SC-SL systems are engineered to return to their original position after load removal, thereby minimizing permanent damage and enhancing the reparability of structures.The SC-SL mechanism is composed of a dual-action linkelement: one part resists lateral forces through controlled plastic deformation (shear yielding), while the other introduces self-centering capabilities via elastic restoring forces. This dual mechanism allows the system to dissipate substantial seismic energy while reducing residual drifts, a major challenge in conventional EBFs. In experimental tests conducted by Liu et al. (2025), SC-SL units exhibited hysteresis loops with minimal pinching and large energy dissipation areas, indicating stable cyclic performance under repeated loading conditions. Furthermore, nonlinear finite element simulations confirmed that SC-SL links maintained their structural integrity and ductility over multiple loading cycles, even under high displacement demands.In addition to self-centering innovations, detailing enhancements have played a critical role in improving the seismic performance of medium-length links. As highlighted by Zhou et al. (2024), specific modifications such as flange reinforcement, web stiffening, and non-prismatic cross-sectional profiles have led to significant gains in the cyclic stability, ductility, and fatigue resistance of link beams. These detailing strategies mitigate common failure modes such as web shear buckling or flange local buckling, especially in medium-length configurations where both shear and flexural demands are significant.

Moreover, the use of advanced materials, including high-strength low-alloy steels (HSLA) and steels with enhanced strain-hardening capabilities, has further contributed to the resilience of link beams. These materials enable greater energy absorption without premature yielding, thus extending the service life of EBF systems. For instance, experimental results reported by Chen et al. (2023) showed that medium-length links fabricated with HSLA steel exhibited up to 35% higher energy dissipation compared to conventional mild-steel links, alongside reduced deformation residuals after seismic loading.Another noteworthy development is the integration of smart monitoring systems in to link components. These systems, based on embedded sensors and real-time data acquisition, allow for accurate tracking of inelastic deformation and damage accumulation during seismic events. The real-time feedback can be used to assess post-earthquake structural health and guide maintenance or retrofitting decisions.Collectively, these innovations ranging from mechanical configuration (SC-SL) and detailing techniques **to**material improvements and monitoring systems demonstrate the growing potential of medium-length link beams as high-performance seismic energy dissipators. They also align with the broader goal of performance-based earthquake engineering, where structures are not only designed to survive seismic events but also to remain operational and easily repairable afterward.

4. KNOWLEDGE GAPS AND RESEARCH OPPORTUNITIES

AlthoughDespite substantial advancements in enhancing the seismic resilience of Eccentrically Braced Frames (EBFs), notable research deficiencies persist—especially regarding the implementation and performance of

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medium-length link beams. These unresolved challenges continue to impede the widespread integration and refinement of medium-length links in contemporary seismic design strategies. Therefore, additional in-depth investigation is warranted. Medium-length links serve as an intermediate category between conventional short shear links and long flexural links, displaying a combination of both shear and flexural deformation behaviors. This dual mechanism introduces analytical complexities in forecasting their response under various seismic excitations, particularly under complex loading conditions such as bi-directional ground motions or near-fault pulses. While the behaviors of short and long links are relatively well-understood shear yielding and flexural yielding, respectively medium-length links necessitate a more sophisticated analytical approach to fully capture their hybrid response during cyclic seismic loading. Unfortunately, current theoretical models and design methodologies fall short in accurately representing these nonlinear and interactive mechanisms (Chen et al., 2023; Roh et al., 2024). Although laboratory experiments and finite element analyses have provided valuable insights into medium-length link performance, their effectiveness under full-scale, real-world seismic conditions remains largely unverified. Most research to date has focused on small-scale specimens or quasi-static conditions, which do not replicate the full complexity of seismic forces such as inertia effects, dynamic response amplification, and multi-directional input. This lack of holistic validation limits the translation of findings into practical applications and inhibits incorporation into prevailing structural design codes.

Beyond structural behavior, other practical considerations such as fabrication feasibility, geometric tolerance during assembly, connection design, and cost-efficiency are also inadequately explored. While some studies have demonstrated the superior energy dissipation characteristics of medium-length links, limited work has been done to assess their impact on long-term structural durability, inspection ease, and post-earthquake reparability. These aspects are particularly important under performance-based seismic design (PBSD) frameworks, which prioritize functional recovery, minimal downtime, and overall lifecycle cost-effectiveness. As modern buildings increasingly aim for high seismic resilience alongside sustainability and reusability, medium-length links are uniquely positioned to support such multidimensional performance goals. Emerging technologies including self-centering mechanisms, advanced high-strength steel alloys, and smart sensing systems provide new possibilities for improving the cyclic stability and post-yield behavior of EBF systems. However, these innovations are often examined in isolation and have not yet been integrated into a cohesive, large-scale design framework. A coordinated research effort is needed that merges materials science, structural dynamics, and advanced modeling to enable the next generation of resilient EBF systems (Zhou et al., 2024; Liu et al., 2025). In summary, although medium-length links offer a compelling alternative to traditional link configurations by delivering a balanced hysteretic response and enhanced energy absorption, their potential is far from fully realized. Bridging current research gaps will require a comprehensive strategy encompassing full-scale testing, improved analytical models, codified design standards, and lifecycle-oriented evaluations to ensure their effective deployment in future earthquake-resistant building systems.

4.1. Inadequacy of Design Standards

Current seismic design provisions, including those outlined in AISC 341-22 (AISC, 2022), provide detailed specifications for short and long links but offer limited guidance for medium-length link design. The classification of link types is still largely based on simplified shear-span-to-depth ratios, which may not accurately capture the complex hybrid yielding mechanisms inherent to medium-length links. This results in ambiguous design boundaries and underutilization in engineering practice. Furthermore, the integration of performance-based seismic design (PBSD) methodologies—wherein structural components are tailored to meet specific performance targets under varying seismic intensities—has not been fully extended to medium-length links (Roh et al., 2024; Mazzolani et al., 2023). The absence of refined design equations, deformation limits, and detailing recommendations under PBSD frameworks restricts engineers from leveraging the full potential of medium-length links in resilient and reparable structures.

4.2. Limited Comparative Studies

Comparative experimental and numerical studies involving short, medium, and long link beams under full-scale dynamic or multi-directional seismicloading remain scarce. Most existing data are derived from quasi-static tests or simplified models that do not fully replicate real-world seismic demands. As a result, there is insufficient evidence on how medium-length links perform relative to their short and long counterparts under complex load histories, including near-fault ground motions with high velocity pulses or bi-directional inputs (Chen et al., 2023). Such data are crucial to validate the hybrid energy dissipation mechanisms and to quantify parameters such as residual drift, plastic hinge distribution, and failure modes across different link lengths.

4.3. Underexplored Material Innovations

The utilization of modern high-performance steels, such as high-strength low-alloy (HSLA) steels and advanced strain-hardening alloys, in medium-length links has not been fully investigated under multiaxial seismic conditions. While recent studies have shown promising results for their use in improving ductility and fatigue resistance (Zhou et al., 2024), their long-term behavior under cyclic and torsional loading, thermal variations, and cumulative damage remains uncertain. Furthermore, the compatibility of such materials with self-centering

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mechanisms or advanced detailing strategies requires deeper exploration. Without robust material-based design guidance, structural engineers are hesitant to incorporate these innovations into mainstream practice.

4.4. Life-Cycle and Post-Earthquake Performance

Another critical gap lies in the lack of research on the life-cycle performance of EBFs utilizing medium-length links. While significant attention has been given to initial stiffness and energy dissipation, fewer studies have addressed repairability, maintenance strategies, cost-effectiveness, and environmental impact across the service life of a building. For instance, understanding how easily a damaged medium-length link can be replaced or retrofitted after a major earthquake without disrupting the overall system—is essential for promoting resilient construction (Engelhardt et al., 2023). Similarly, life-cycle cost analysis (LCCA) and carbon footprint assessmentassociated with different link configurations are necessary to support sustainable design decisions in seismic zones.

4.5. Future Research Directions

To close these gaps, several avenues of future research are recommended:

- Conductlarge-scale shake table experimentsand full-building simulations using medium-length links under various seismic scenarios, including aftershocks and vertical accelerations.
- Develop and validate performance-based design criteria, including damage control thresholds, repair indices, and allowable deformation limits specifically for medium-length links.
- Investigate the synergistic use of smart sensing technologies, such as fiber optic sensors or digital twins, to monitor the real-time performance and post-event condition of link beams.
- Establish a unified design procedure that integrates structural, economic, and environmental considerations for selecting link length, material, and detailing in EBFs.

Addressing these research opportunities will not only improve the reliability and efficiency of seismic designs but also support broader goals in resilient infrastructure, sustainability, and post-disaster recovery planning.

5. CONCLUSION

Eccentrically Braced Frames (EBFs) play a key role in earthquake-resistant buildings by combining strength, stiffness, and flexibility. In these systems, link beams absorb earthquake energy through inelastic deformation. While short (shear-dominated) and long (flexure-dominated) links are well studied and widely used, medium-length linkswhich involve both shear and flexural behavior—are still underused. This is mainly due to limited design guidelines, code support, and lack of experimental data.Recent developments, including lab tests, simulations, and new materials like high-strength steel and self-centering mechanisms, show that medium-length links can improve seismic performance by reducing damage and making structures easier to repair. However, there are still challenges in applying these links, such as lack of performance-based design (PBD) standards, full-scale testing, long-term durability studies, and integration with sustainable materials.Current design codes like AISC 341-22 provide limited guidance for medium-length links, which creates confusion for engineers. Also, there are few large-scale studies comparing different link lengths under real earthquake conditions, and the effects of modern materials in complex seismic events are not well understood.To overcome these issues, future research should focus on full-scale dynamic testing, better design standards, smart monitoring systems, and sustainable construction methods. With these improvements, medium-length links could play a bigger role in making steel buildings more earthquake-resilient and sustainable.

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