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Review Article

Seismic Resilience of Steel-Braced Frames Incorporating Steel Slit Dampers: A Review and Comparative Numerical Analysis

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Abstract

Steel dampers, specifically steel slit dampers (SSDs), are crucial for enhancing the seismic resilience of buildings by absorbing energy and mitigating damage. SSDs are celebrated for their ability to produce stable hysteretic behavior, owing to the inelastic deformation of their strips, alongside benefits such as lightness, ease of manufacture, and straightforward post-earthquake replacement. This research extensively examines SSD applications, design principles, and innovations in their modeling, optimization, and production processes. The literature highlights SSDs' consistent performance in resisting both compression and tension, their adaptability in strength, ductility, and energy dissipation through modifications in strip configurations and the superiority of non-prismatic and hourglass-shaped designs over traditional options. Numerical analyses have been conducted to assess the effectiveness of non-prismatic slit dampers in comparison to their prismatic counterparts within braced frames. Three distinct braced frame configurations have been analyzed: one with a diagonal brace without a damper, another featuring a uniform prismatic slit damper, and a third incorporating a non-prismatic slit damper with an hourglass shape. The analysis primarily compared these systems' hysteresis behavior, ductility, and energy dissipation capacities. Results indicate a significant enhancement in performance when utilizing non-prismatic slit dampers. Notably, these dampers exhibited a remarkable 69% increase in cumulative energy dissipation compared to prismatic ones. Furthermore, the study reveals that a steel slit damper-braced frame, when equipped with optimally designed slit geometries, can tolerate inter-story drifts in excess of 2% while simultaneously achieving a greater than 12% increase in energy dissipation efficiency.

Keywords: Steel Slit Damper; Braced Frames; Hysteresis Curves; Ductility; Energy Dissipation.

1. Introduction

The energy generated by large earthquakes must be mitigated using tools that enable structures to withstand intense ground motions. A significant portion of the transmitted energy can be absorbed, attenuated, and reflected by enhancing the damping capacity of the structure. As a result, the energy transfer to structural members decreases, reducing the energy consumption required for these elements [1–3]. Steel-yielding dampers are widely recognized as effective techniques for controlling structure vibrations [4–6]. Utilizing metallic dampers of this kind aims to concentrate inelastic deformations and prevent damage to other prominent frame members [7–9]. Among the steel-yielding dampers, steel slit dampers are the most commonly employed [10]. These dampers offer additional advantages such as lightweight construction, ease of fabrication, and convenient replacement following large earthquakes.

Structures may often suffer severe damage from wind, traffic, and earthquakes, among other dynamic and environmental loads [11]. Over 132 buildings were destroyed in the Mexico City earthquake, and over 200 were

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damaged in the Loma Prieta earthquake in Northern California in 1989 [12, 13]. There are several ways in which structural vibration controls can be used to reduce or avoid such damage, and these techniques have been successfully implemented in several different civil structures for this purpose [14–16]. Control systems that manage structural vibration are crucial in various engineering applications [17–19]. These systems are classified into four main groups based on their method of operation: passive, active, semi-active, and hybrid types [20–22]. Passive control systems are designed to dissipate or absorb vibrational energy without requiring external power input [23, 24]. Common passive control devices include tuned mass dampers [25]. Active control systems utilize sensors, actuators, and controllers to monitor and counteract structural vibrations in real-time [26]. Semi-active control systems combine elements of both passive and active systems [26]. Hybrid control systems integrate multiple control strategies, combining the advantages of different approaches to optimize performance and efficiency [27].

Fundamentally, the utilization of energy-dissipation mechanisms has been extensively studied and applied in diverse fields [28]. Among these mechanisms, viscous fluid dampers, friction dampers, viscoelastic dampers, and metallic yielding dampers effectively absorb and dissipate energy [29–31]. Viscous dampers force a fluid [32–35], while friction dampers utilize the frictional force between surfaces to dissipate energy. These dampers typically comprise sliding interfaces with high-friction materials or devices such as friction plates [36]. Metallic yielding dampers employ yielding elements, such as steel plates or rods, designed to undergo controlled yielding or plastic deformation under load [6, 37–39]. Finally, viscoelastic materials exhibit viscous and elastic behavior, making them well-suited for energy dissipation applications [40, 41].

Over the past four decades, it has become common practice to install passive dampers to improve structures' hysterical behavior and dissipate energy with no external power source required [42, 43]. By using these systems, the main elements of the building suffer less damage, and energy is dissipated more efficiently [44–46]. As well as maintaining stability over a wide range of temperatures, these dampers have extremely high fatigue resistance due to their low cycle and displacement rates, bolted attachments, low fabrication costs, tolerances for large displacements, and long-term durability [47–49]. These advantages of steel-yielding dampers have made them a popular passive energy dissipation device among all kinds of dampers. Several passive vibration control devices have been developed and implemented in buildings, including steel plates with slits or openings susceptible to shear [50–52].

Generally, slit dampers are considered metallic-yielding dampers because the yielding of their steel strips determines their damping behavior [53]. A new device, the multi-slit damper, combines weak and strong slit dampers in series to retrofit soft-first story structures against earthquakes [54]. Its energy dissipation occurs in two stages: weak-slit damper yielding during minor earthquakes and activation of the strong slit damper through a gap mechanism during major earthquakes. Experimental and analysis results confirm the device's effectiveness in controlling seismic response [54]. In a subsequent investigation, SSDs were employed, revealing that they substantially enhanced the lateral load capacity by up to 40% and ductility by 1.88 [55]. Additionally, experimental and numerical testing has indicated the potential of single-plate SSDs to be incorporated as a component of seesaw brace systems, as an addition to conventional bracing, or as a beam-to-column connection [56]. These SSDs have effectively reduced the forces and displacements experienced by structures during seismic events.

SSDs have been the main focus of numerous studies, and various methods and devices have been proposed based on necessities. Due to some special characteristics, architectural aspects, and requirements, the design and retrofitting of building structures with SSDs have been of great interest. Therefore, it is crucial to evaluate existing designs and configurations and analyze the benefits, limitations, enhancements, and potential optimizations that can be implemented in the future. The research thoroughly reviews commonly used slit dampers in civil structures to ensure greater adaptability and reliability, focusing on improving performance.

This study embarks on a pioneering endeavor to conduct a comprehensive review of steel slit dampers, an area which, to the best of the authors' knowledge, has not been exhaustively explored in existing literature. This gap underscores the imperative to delve into the evolution and applications of these dampers within structural systems. The review meticulously scrutinizes the influence of slit dampers on structural performance, integrating insights from contemporary research. A methodical appraisal and citation of scholarly articles from 1998 to 2023 is undertaken. This approach ensures an extensive coverage of all pertinent facets of slit dampers, encompassing their diverse applications, design considerations, configurations, integration within steel-braced frame structures, and potential avenues for enhancement. Moreover, this paper assessed numerically the comparative efficacy of non-prismatic versus prismatic slit dampers in structural frames. This analysis is conducted across three distinct structural frame models: a diagonally braced frame, a frame equipped with a uniform prismatic slit damper, and another featuring an innovatively designed hourglass-shaped non-prismatic slit damper. Building on the insights gleaned from recent technological advancements, the review culminates in proffering strategic recommendations for future research trajectories in this field.

The research paper is organized into seven sections. Section one discusses the prior art and the research gap in the literature, while section two outlines the methodology employed in this research. Section three presents an overview of steel slit dampers, including their concept and basic theoretical analysis. Following this, section four comprehensively reviews various types of SSDs and discusses their applications and performance in braced frames. Section five conducts a comparative numerical analysis on three test frames using the finite element software ABAQUS. Specifically, one of these frames represents a special braced frame without a damper (SBF), while the other two frames are equipped with slit dampers—one utilizing a slit prismatic damper. Section six summarizes the conclusions drawn from the conducted research. Lastly, section seven outlines recommendations and proposes future avenues for applying SSDs in steel-braced frames, emphasizing their significance as crucial seismic fuses.

2. Research Methodology

In the field of building construction, slit dampers are recognized for their effectiveness in seismic mitigation through energy absorption and dissipation. These devices, composed of slender metallic strips, are integrated into the structure, playing a critical role during seismic events by mitigating the energy. This study reviews existing literature on slit dampers, focusing on aspects such as structural configurations, energy dissipation, hysteresis behavior, failure mechanisms, and ductility. The methodology, illustrated in Figure 1, includes a stringent review and selection process to identify relevant studies that shed light on the optimal design and implementation of slit dampers.

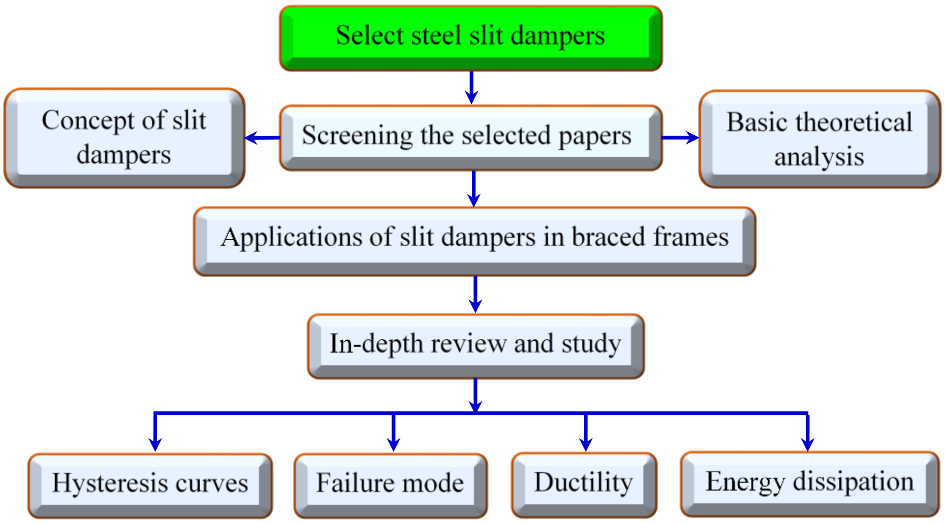


Figure 1. Flowchart depicting the methodology employed in this study

The aim is to assess the impact of slit dampers on the seismic resilience of buildings, leveraging data from prior research. Through a detailed analysis, this work synthesizes key findings and identifies best practices in the application of slit dampers for seismic protection. The outcome contributes to the body of knowledge by outlining strategies for enhancing building safety against seismic events.

3. Overview of Steel Slit Damper

3.1. The Concept of Slit Dampers

SSDs, or steel slit dampers, are widely recognized as one of the most prevalent passive dampers employed in structural engineering. These devices exhibit stable hysteretic behavior, highly resist temperature variations in the surrounding environment, demonstrate exceptional long-term reliability, and can be cheaply constructed [57]. Typically, SSDs are positioned between two structural elements or components, allowing for significant relative displacements. The energy generated during an earthquake can be effectively dissipated by subjecting to the cyclic movement of steel strips within the damper. Consequently, SSDs are extensively utilized in seismic design and earthquake retrofitting to ensure appropriate seismic response in structures. In the manufacturing process of SSDs, the damper plate can be perforated using various slits. Depending on the specific situation or element type, these slits can also be introduced in the web or flange of an I-section. In the manufacturing process of SSDs, the damper plate can be perforated using various slits. Depending on the specific situation or element type, these slits can also be introduced in the web or flange of an I-section. SSDs can be classified into two main categories based on their geometric characteristics: uniform prismatic and uniform non-prismatic slit dampers [58, 59]. Prismatic dampers maintain a consistent cross-sectional shape for all steel strips throughout the device's height, as their name implies. On the other hand, non-prismatic dampers exhibit varying cross-sectional shapes along their height (refer to Figure 2). A device in which all steel strips possess the same shape is considered uniform, whereas a device comprising different steel strip shapes is considered non-uniform, as depicted in Figure 3.

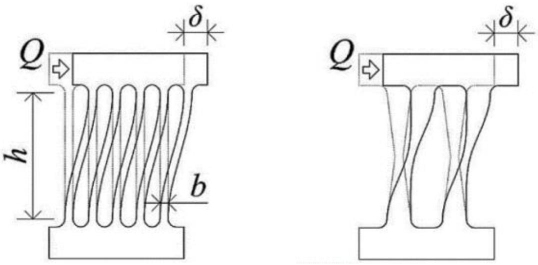


Figure 2. Traditional configurations of slit dampers and their lateral deformation; prismatic and non-prismatic [58]

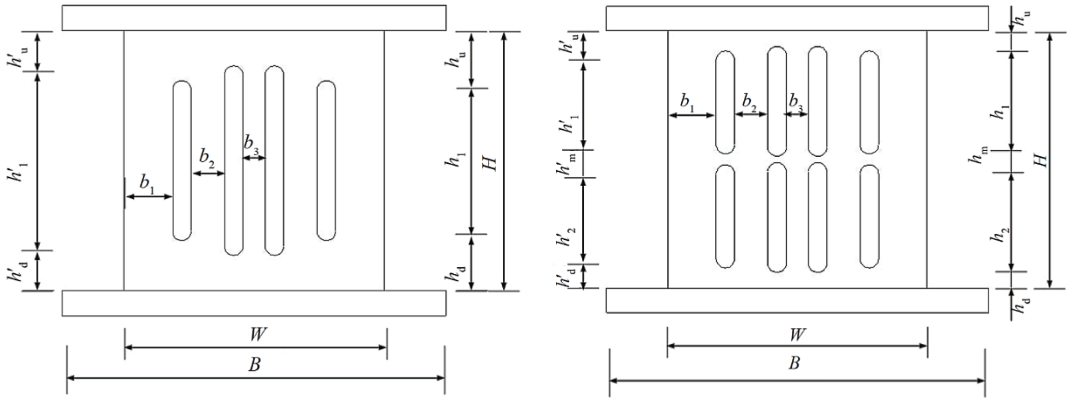


Figure 3. An example of a non-uniform slit damper configuration [59]

Oh (1998) [60] introduced SSDs in the literature, as depicted in Figure 4. A similar concept was further investigated and implemented experimentally by González-Sanz et al. [58]. Their study focused on steel slit plate dampers subjected to shear deformation. They derived analytical equations that predict these dampers' ultimate energy absorption capacity. Additionally, they observed that the resulting energy could be analytically estimated, with their experimental findings closely aligning with the analytical predictions. The energy dissipated by these dampers arises from the flexural yielding of their strips during inelastic cyclic deformation [61-63]. Each damper strip undergoes double curvature bending upon sufficient story drift, forming plastic hinges at both ends. Numerous studies have also focused on developing this type of damper [64, 65].

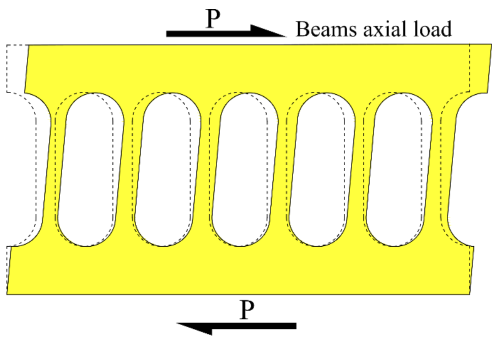


Figure 3. The configuration of steel slit damper and deformation under the lateral load [60]

Finally, SSDs can provide extensive design flexibility, permitting adjustments to parameters such as strip count, configurations (uniform prismatic or non-prismatic and non-uniform prismatic or non-prismatic), and dimensions (height, width, and thickness). This adaptability facilitates utilization across diverse load scenarios, drift conditions, and energy dissipation requirements. The performance of the SSDs can be modified by adjusting these parameters. This configurational flexibility empowers designers with a spectrum of design options. The analytical equations in the next section reveal that these parameters exert notable influence on the performance of slit dampers, impacting factors such as strength capacities, elastic stiffness, and yield displacement.

3.2. Basic Theoretical Analysis

The governing equations for SSDs can be rigorously deduced from the principles of strength of materials. Figure 5 illustrates how the strip ends of the damper were idealized to predict the yield strength and deformation when the round-shaped ends were replaced with straight ones [53].

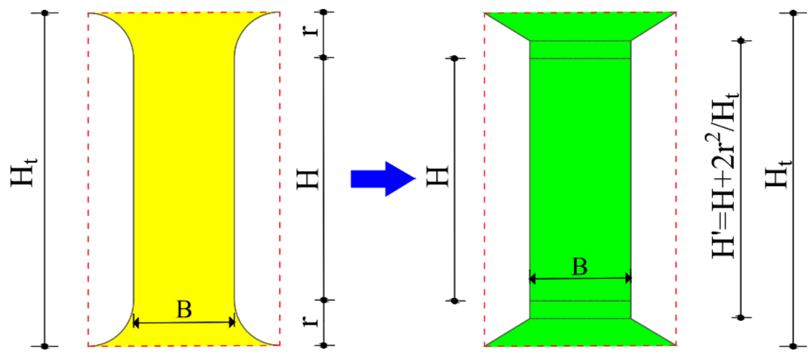


Figure 4. Idealization of strips

The flexural yielding loads at the ends of strips, denoted as $Q_{y,b}$, and the shear yielding loads of the strips, denoted as $Q_{y,s}$, represent the yield capacities of the slit plates. Additionally, the number of strips is represented by n. The total height of the strip is specified as H_t, the thickness of the slit gusset plate is denoted as t, the radius of the ends of the strips is indicated by r, and the strip width is denoted as B. The equivalent height, denoted as H' in Figure 5, is calculated using Equation 1.

$$H' = H + \frac{2r^2}{H_T} \tag{1}$$

Equation 2 is used to calculate the yielding displacement (δ_y) of the (SSDs) based on elasticity:

$$\delta_y = \delta_b + \delta_s = \frac{Q_y.(\acute{H}^3)}{nEtB^3}(1+3\ln\frac{H_t}{\acute{H}}) + \frac{3Q_y.(\acute{H})}{2ntBG}(1+\ln\frac{H_t}{\acute{H}}) \tag{2}$$

Where δ_b and δ_s represent the displacement components due to flexural and shear deformations. Q_y refers to the yielding strength of the SSDs, which is determined as the minimum between the flexural yielding ($Q_{y,b}$) and the shear yielding loads of the strips ($Q_{y,s}$), as described in Equation 3, E denotes Young's modulus, and G represents the shear modulus.

It can be observed that the strips exhibit behavior consistent with that of a series of partially fixed-ended beams and undergo double curvature under small relative displacement between both support ends. Consequently, it is possible to determine the yielding and ultimate strength of the slit damper analytically by employing the following simplification [63]:

$$\begin{cases} Q_y = min\{Q_{y,b}, Q_{y,s}\} \rightarrow \\ Q_y = min\left\{n\frac{tB^2}{2H'}\sigma_y, n\frac{2tB}{3\sqrt{3}}\sigma_y\right\} \end{cases} \tag{3}$$

Where n is the number of strips, and σ_y is the yield stress of the slit plate.

Plastic hinges are formed at the ends of each strip when a significant displacement occurs. As a result, the calculation of the ultimate strength of SSDs is performed according to the following procedure [63]:

$$\begin{cases} Q_B = min\{Q_{B,b}, Q_{B,s}\} \rightarrow \\ Q_B = min\left\{n\frac{tB^2}{2H'}\sigma_B, n\frac{2tB}{3\sqrt{3}}\sigma_B\right\} \end{cases} \tag{4}$$

Where Q_B refers to the ultimate strength, which is determined as the minimum between the flexural strength ($Q_{B,b}$) and the shear strength of the strips ($Q_{B,s}$). σ_B is the ultimate stress of the slit plate.

Certain observations can be emphasized based on the research conducted by Chan & Albermani [61] on the seismic behavior of slit dampers. The ends of the strips were rounded, and the overall length of the strips was considered during their derivations. Consequently, the equations for determining the yield strength (P_y) and stiffness (K_d) can be expressed as follows:

$$P_y = n\frac{\sigma_y t b^2}{3l_0} \tag{5}$$

$$K_d = cn\frac{Etb^3}{{l_0}^3} \tag{6}$$

The dimensions of the strips are denoted by the variables l_0 (length), t (thickness), and b (width). It is imperative to acknowledge that, to ascertain the elastic stiffness of the slit dampers (SSDs) via Equation 6, an underlying assumption is made regarding the strips' ends being partially fixed [61]. Moreover, the stiffness coefficient, c, was derived from experimental data and utilized to calibrate the elastic stiffness. In this context, the radius of the fillet at the end of the strips can be considered another factor influencing the behavior of the SSDs. Previous research findings suggest that a minimum value for this parameter should be observed to mitigate the risk of premature fractures caused by stress concentration at the strip's end regions [66].

The analytical equations reveal that such as strip count and dimensions (height, width, and thickness) exert notable influence on the performance of slit dampers, impacting factors such as strength, elastic stiffness, and yield displacement. It becomes apparent from the analytical expressions that the structural attributes of the damper, encompassing yield strength (refer to Equations 3 and 5) and ultimate capacity (as depicted in Equation 4), exhibit a linear correlation with the thickness of the slit damper. Consequently, as the thickness of the slotted plate increases, both the yield strength and ultimate strength will also increase linearly. In contrast, according to Equations (3 to 5), an inverse correlation exists between the length of steel strips and strength capacities. As the length of the strip increases, the yield and ultimate strength of the damper decrease. Additionally, widening the slit damper, as indicated by Equation 3 and 4, results in an augmentation of both yield and ultimate strength.

On the other hand, SSDs are known to be thin slit plates. Therefore, to ensure SSDs exhibit stable hysteretic behavior and effectively resist both compression and tension, the slit plates, particularly the strips within these dampers, must avoid out-of-plane buckling. Therefore, it is crucial to carefully select the dimensions of the strips, including their length, width, and thickness. Specifically, the slenderness ratios of length to width and width to thickness must adhere to the criteria to prevent buckling under critical conditions.

3.3. Summary

The strips' thickness, height, and width are crucial factors that significantly influence the strength capacities, stiffness, and other key parameters of slit dampers. It should be emphasized that appropriately modifying these parameters can improve the seismic performance of slit dampers. Moreover, when the bending behavior governs, slit dampers generally exhibit stable performance levels that are deemed acceptable. Finally, these equations afford a computational avenue to discern pivotal mechanical parameters intrinsic to the SSD system, thereby preventing the prerequisite for exhaustive simulation and empirical testing.

4. Application of the Steel Slit Damper in Braced Frames

Numerous earthquakes have recently occurred worldwide, significantly damaging buildings and bridges. To withstand lateral loads, concentrically and eccentrically braced frames have been widely employed [67-69]. These frames have desirable stiffness and strength, making them suitable for earthquake-resistant structures [70, 71]. However, it should be noted that CBFs exhibit lower ductility compared to moment frames and eccentrically braced frames. This system dissipates energy through the inelastic deformation of braces, which can buckle, yield, and undergo inelastic deformation following a major earthquake [72-74]. Extensive research has been conducted to enhance the seismic performance of CBFs. For instance, investigations have focused on preventing brace buckling through restraining mechanisms, examining connection details of corner and middle gusset plates, evaluating the type and size of braces, and optimizing the arrangement of the braces [75-77]. For instance, a buckling-restrained brace (BRB) is engineered and employed to bolster strength, stiffness, and ductility against lateral loads. BRBs mitigate structural damage and augment the braced structures' seismic resilience [78, 79].

Recently, several studies have been conducted to address enhancing brace performance by incorporating energy dissipation devices. This approach aims to absorb the plastic action and prevent damage to other crucial components [80-84]. Significant advancements have been made in the system based on the "weak gusset plate-strong brace member" concept. Various techniques have been proposed to implement this concept, such as utilizing gusset plates with a low yield point. For instance, Chen & Chang [39] investigated the impact of gusset plates with low yield points. Their findings demonstrated a reduction in the pinching effect of braced frames resulting from corner gusset plate buckling.

Benavent-Climent [84] conducted experimental studies on slit plates subjected to shearing deformations to assess their ultimate energy absorption capacity. The study considered three parameters: strip width to plate height (B/H) ratio, material properties, and the loading pattern. Based on the assumptions made, the ultimate energy absorption capacity was determined by combining the energy dissipated by the structural skeleton and the Bauschinger component. In 2002, Lee et al. [83] proposed and developed an alternative device for efficient and cost-effective dissipation of seismically-induced energy. This device, known as a hysteric plate slit damper, could be easily installed in cross-braced frames and was primarily subjected to shear forces (see Figure 6). Subsequently, it became the first steel slit damper utilized in a V-braced system [60]. Another energy dissipation device, known as a tube-in-tube damper (TTD), was introduced by Benavent-Climent for braces [84]. TTDs involve cutting slits through the device's outer hollow section, generating strips attached to the inner section through welding. The strips dissipate energy through flexural/shear yielding when TTDs move toward the brace. A schematic view and detailed illustration of the TTD are presented in Figure 7.

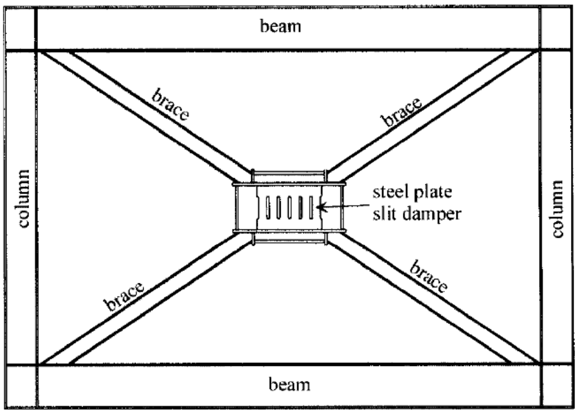


Figure 5. Slit plate damper in a cross-braced frame [83]

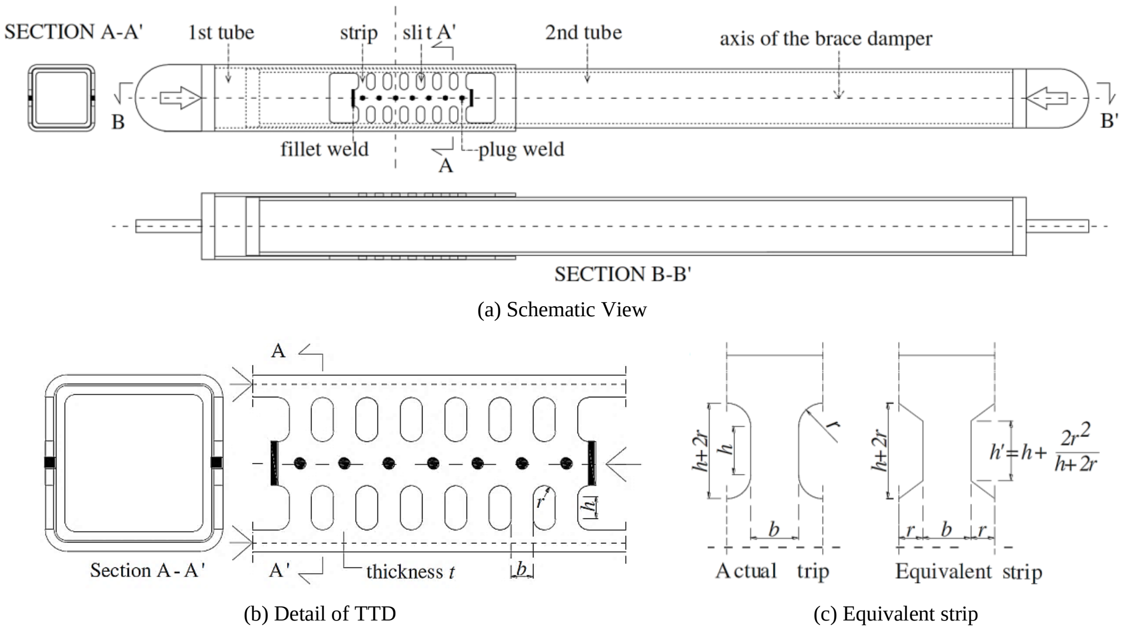
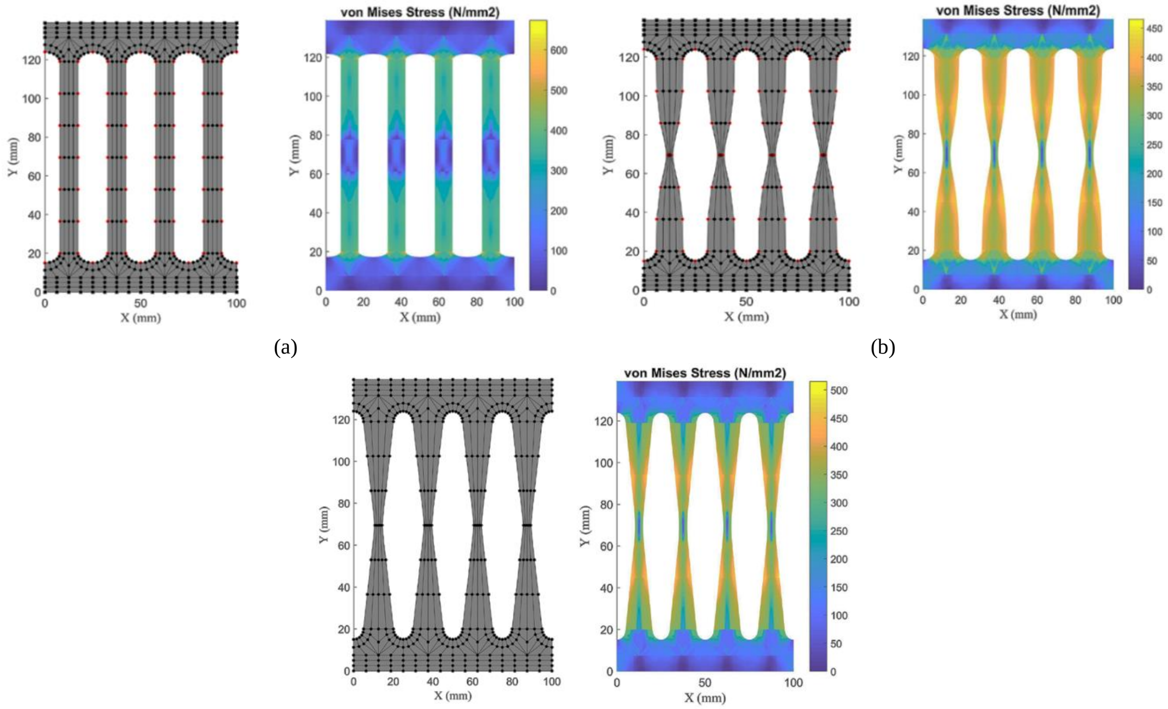


Figure 7. TTD as brace-type seismic damper [84]

To address the strain concentration at the ends of strips and determine the optimized shape of the slits, Ghabraie et al. [85], by utilizing the bidirectional evolutionary structural optimization technique, were able to optimize the shape of the slits and develop an effective configuration. The device's energy dissipation capacity and fatigue resistance under low cycling conditions were significantly enhanced by incorporating this configuration. In addition, A numerical model was used by Aminzadeh et al. [86] to obtain optimal boundary shapes for slit dampers. They employed the iso-geometric analysis method, allowing precise modeling of complex geometries for nonlinear damper analysis. Using B-splines with non-uniform rationality, an optimized shape was generated to simulate a conventional steel slit damper under a volume constraint. The newly proposed steel slit damper was compared with other shapes from the literature, and an optimization process was proposed and evaluated based on its performance. The optimal shape demonstrated a 12% increase in energy dissipation. The stress distribution in the proposed damper and the compared dampers can be seen in Figure 8.

González-Sanz et al. [58] investigated the development of a mild steel damper with non-uniform vertical slits. The study aimed to analyze the relationship between different forms of vertical slits on the core energy plate and their ability to dissipate energy and resist buckling. The researchers formulated theoretical equations to determine key damper parameters and validated numerical models using experimental data. By analyzing earthquake time-history data, they demonstrated the effectiveness of the dampers in reducing seismic responses of the prototype frame and achieving satisfactory energy dissipation. In another study, Tagawa et al. [87] utilized SSDs in a seesaw system, where the bracing members remain in tension during lateral movements (see Figure 9). The researchers conducted cyclic loading tests on the framed structure with this proposed system and found that it exhibited stable hysteretic behavior and had substantial energy dissipation capacity. Furthermore, all specimens showed yielding of the slit dampers at a story rotation angle of 0.001 rad.



(c)

Figure 6. Stress distribution in slit dampers with various configurations; (a) conventional slit dampers [86], (b) optimal shape [86], and (c) proposed shape by Ghabraie et al. [85]

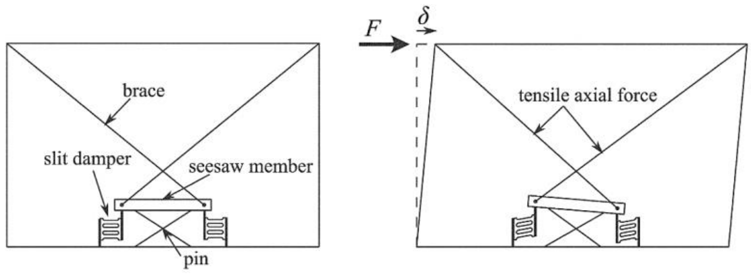
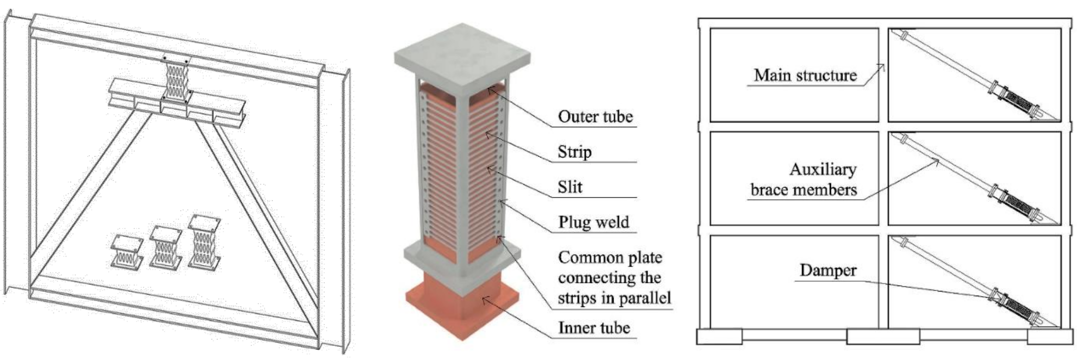


Figure 7. General and deformed configurations of a seesaw system equipped with SSDs [87]

Furthermore, Tagawa et al. [87] implemented slits as dampers in chevron-braced frames. A separate investigation by Ahmadie Amiri et al. [47] found that incorporating a block slit damper (BSD) can enhance chevron frames' performance. The BSD consists of a steel block with multiple slits, and it offers several desirable characteristics, such as high shear strength, energy absorption and dissipation capabilities, and favorable economic implications. The BSD can be integrated into a chevron frame, as Figure 10(a) illustrates. Building upon the previous study by Katal Mohseni et al. [88], further optimizations were made to steel BSDs to enhance their energy absorption capacity. Various geometric dimensions were examined, and the findings indicated that the frame equipped with BSDs exhibited significantly improved ductility and stiffness [88] compared to the earlier study [47]. Consequently, the energy absorption during hysteresis cycles experienced a substantial increase.



(a) (b)

Figure 10. Braced frames equipped with BSD and SS-TTD dampers; (a) BSD device configuration [47] and (b) View of the SS-TTD in general and a typical building frame [58]

In a study by Kim [89], an investigation was carried out on a box-type SSD and a multi-SSD system. Gonzalez-Sanz et al. [58] explored a novel type of stainless-steel tube-in-tube damper (SS-TTD) composed of two telescopic tubes. The energy dissipation in the brace-type damper occurs through flexural plastic deformations of the strips when subjected to forced axial displacements. The exterior tube walls of the SS-TTD feature a series of slits that form the strips, which are connected to the interior tube (refer to Figure 10(b)). The seismic behavior of the SS-TTD was evaluated using quasi-static and dynamic shaking table tests. Comparative analysis revealed that the SS-TTD exhibits approximately four times higher cumulative ductility than slit-type plate dampers. Furthermore, its dissipation capacity is three times that of mild steel dampers and sixteen times that of high-strength steel dampers. Guo et al. [90] proposed an adjustable steel damper with replaceable steel strips, utilizing bolted connections for framed structures. Figure 11 illustrates this damper, along with potential installation locations in frames. To achieve maximum plasticity and fully use the load-bearing capacity of the steel strips, they must yield simultaneously and distribute energy uniformly across the entire section. The pumping hysteresis loops observed in the strips effectively dissipate potential energy. The bending moment strength primarily depends on the width of the central region.

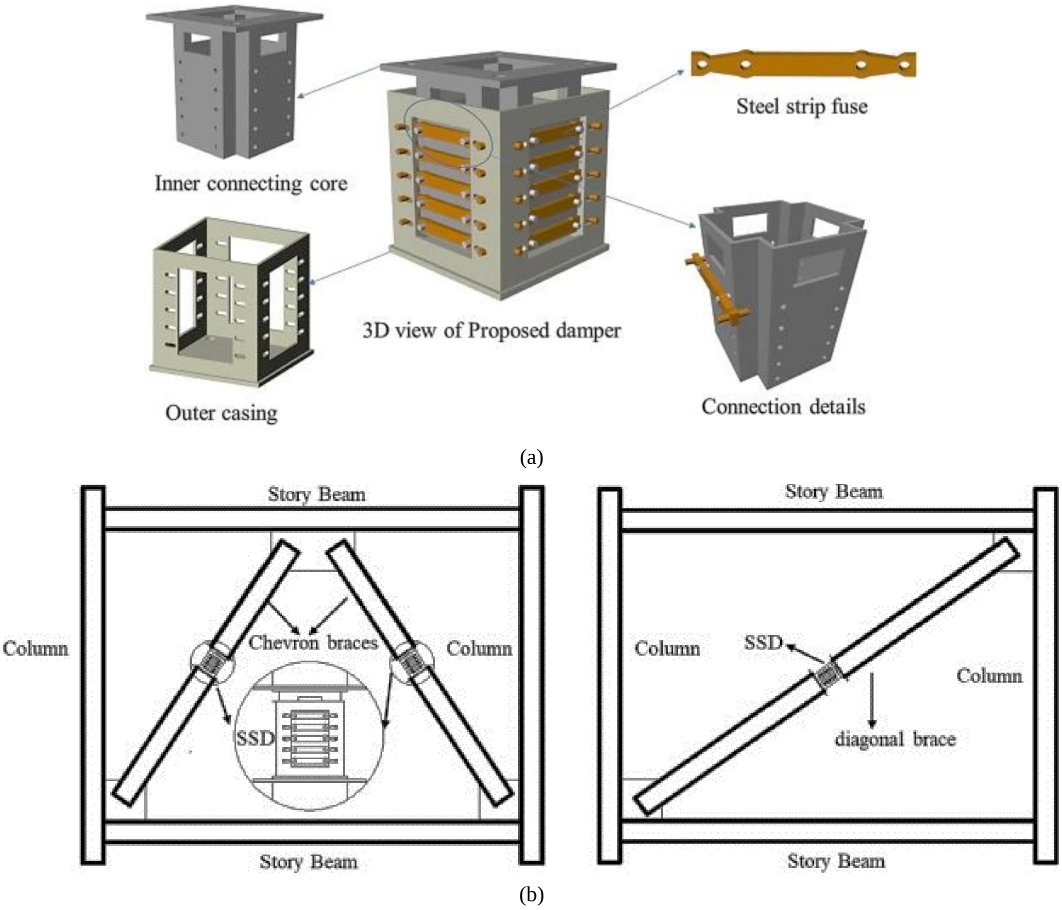
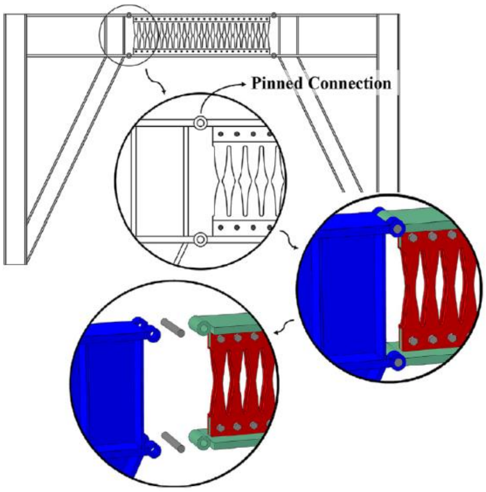
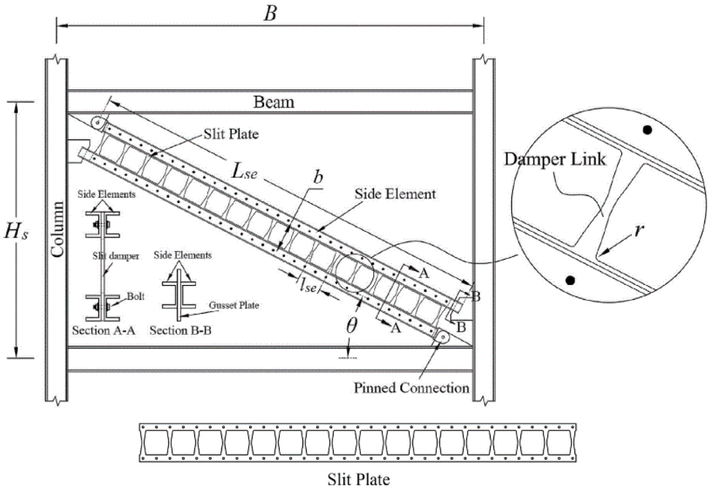


Figure 8. Illustration of the proposed damper and the location of potential installations in frames [90]

As an alternative to conventional link beams, Askariani et al. [66] introduced the concept of a slit link beam to enhance the structural performance of eccentrically braced frames (EBFs). Vertical strips can be formed by incorporating perforations in the web to create the link beam (refer to Figure 12(a)). The authors derived formulas to analyze the characteristics of the slit link beam and validated their findings using the ABAQUS software. Askariani also proposed a concept involving replaceable components [91]. Numerical simulations were conducted on a structure equipped with a novel brace-type slit damper (BSD), evaluating the influence of geometrical parameters on the frame's performance. The slit plate has two diagonals on each side, with links designed and arranged based on a specific geometry (see Figure 12(b)). A gusset plate is utilized to restrict the out-of-plane displacement of the diagonal members at one end, while a pin is employed at the other end. It was observed that all examined frames exhibited stable hysteresis curves under various loading conditions. Furthermore, upon completion of loading, no cracks were detected in the damper links. The results indicate that the proposed damper is an effective energy-dissipating device suitable for implementation in building structures. In subsequent research, Zhao et al. [92] developed a new type of damper known as the perforated web H-type brace damper (PWHBD). The H-profile brace used in their damper system features multiple slits along its length (see Figure 13), allowing for seismic energy dissipation through flexural yielding of the perforated webs under in-plane shear. The hysteretic curves exhibited stable and substantial behavior, further supporting the effectiveness of the damper in dissipating energy during seismic events.

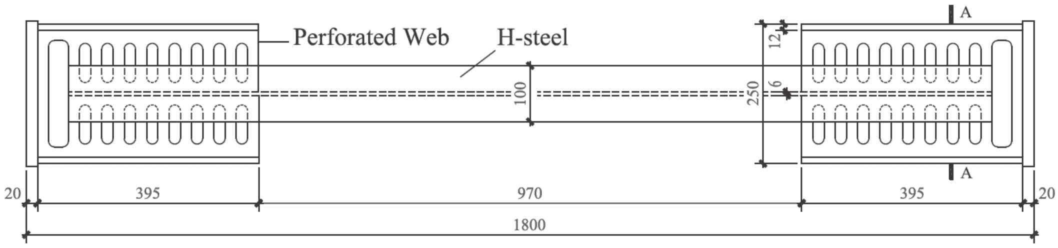


(a)

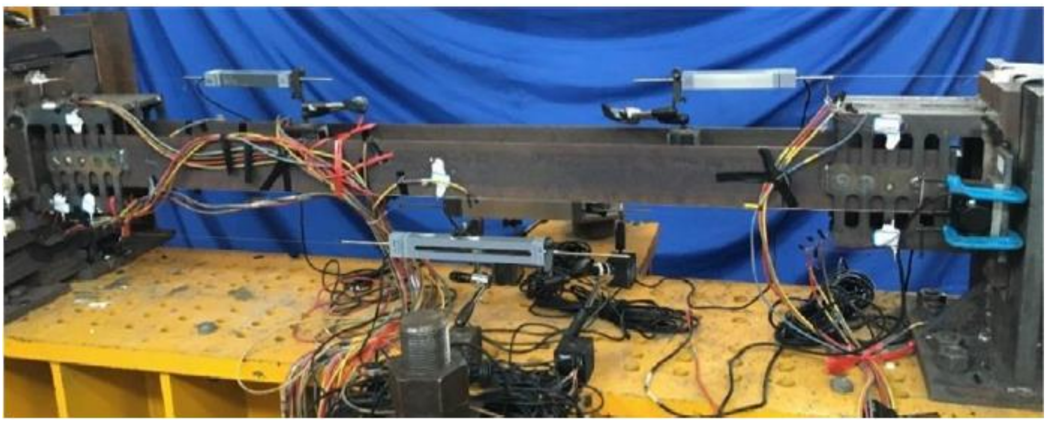


(b)

Figure 12. Eccentrically and concentrically braced frame equipped with slit dampers; (a) eccentrically braced frame with slit link beam [66] and (b) brace-type slit damper [91]



(a)



(b)

Figure 13. An example of a PWHBD test specimen [92]; (a) specimen dimensions and (b) view of the overall test setup

Based on a study by Javidan et al. [93], a steel multi-slit damper (MSD) has been proposed as a retrofit solution for partition walls. The study involved experiments on reinforced concrete frames comprising two stories, both with and without the suggested dampers. The study's findings indicate that implementing the MSD retrofit strategy enhances the hysteretic behavior of the structures. Similarly, Benavent-Climent et al. [94] have developed a novel metallic damper employing mild steel plastic deformation (refer to Figure 14). This damper is designed to dissipate energy during severe or extreme earthquakes. Including a gap mechanism in the damper helps prevent high-cycle fatigue damage. Additionally, the damper exhibits a remarkable energy dissipation capacity when subjected to large deformations caused by extreme ground motion. Dynamic shake-table tests were conducted on dampers installed in reinforced concrete structures alongside static cyclic tests of dampers isolated from the structure to evaluate their performance. The test results have enabled the development of a hysteresis model that accurately predicts the force-displacement curve of the damper under different cyclic loadings. The proposed hysteresis model can effectively capture increased stiffness and strength at large deformations. Furthermore, dampers' energy dissipation capacity is influenced by the phase in which they fail, suggesting new equations for predicting this behavior. The test results and a simple numerical model demonstrate that the damper exhibits a stable hysteresis response, predictable cyclic behavior, and a reliable ultimate energy dissipation capacity.

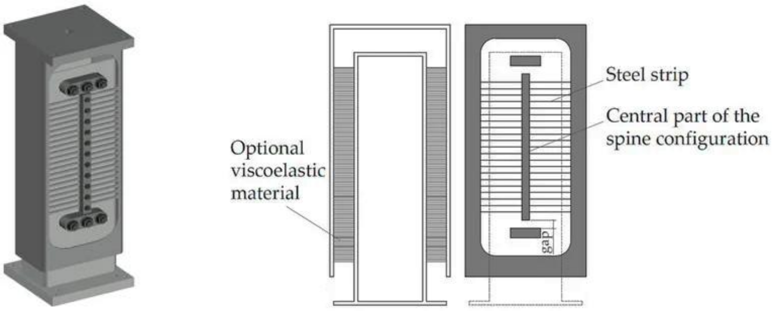


Figure 14. Details of the proposed damper by Benavent-Climent et al. [94]

According to a recent study by Almohammad-albakkar et al. [95-97], a novel damper that enhances the seismic performance of X-CBFs (Cross-Braced Frames) has been developed and tested numerically and experimentally. The proposed design consists of two cross braces with two segments each, where a grooved gusset plate damper (GGPD) was utilized to connect the four segments at the bay's midpoint. This connection prevents plastic action or buckling in the braces and other structural members. Figure 15 illustrates the addition of stiffener plates to the inner and outer edges of the GGPD, which effectively limits the occurrence of local instability in the grooved gusset plate. Specifically, it prevents early-stage out-of-plane buckling during story drift.

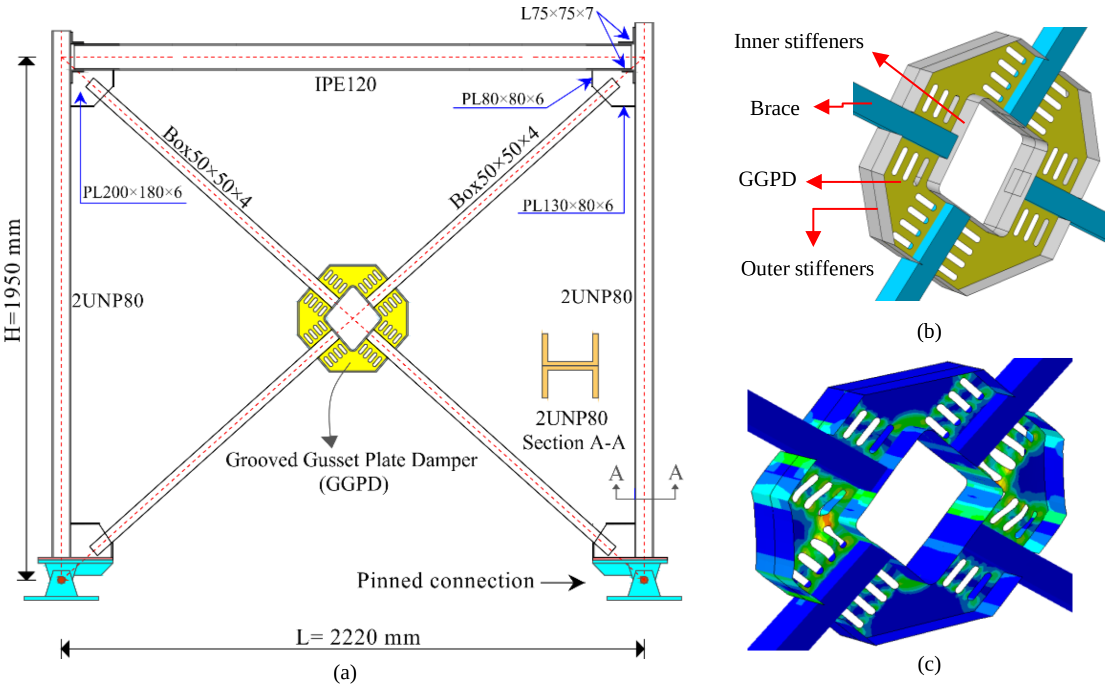
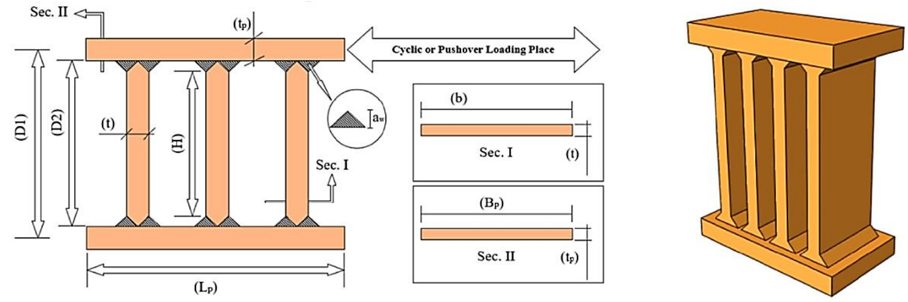


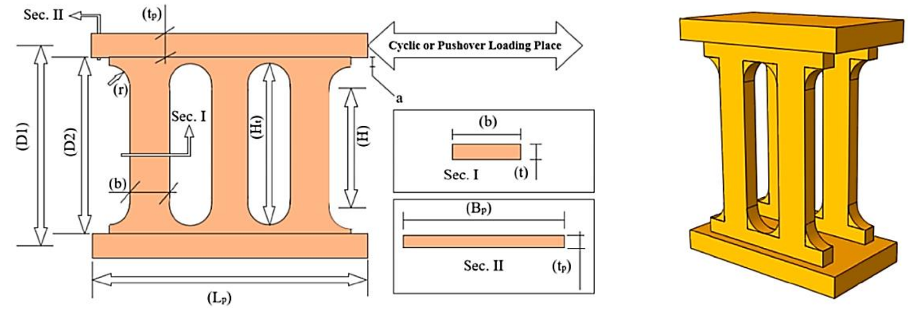
Figure 15. The grooved gusset plate damper (GGPD) [95]; (a) installation of GGPD in a cross-braced frame, (b) configuration of GGPD, and (c) the distribution of plastic strain

The working mechanism of the GGPD relies on the yielding of the gusset plate strips in in-plane bending, resulting in the dissipation of seismic energy. The experimental results indicate that the innovative system (GGPD) can tolerate a more than 3% relative drift. Additionally, a computational simulation was performed using the finite element software ABAQUS to assess the performance of this novel system. Additionally, the yield and ultimate capacities of the damper were analytically calculated using derived formulas. A comparison was made between the numerical outcomes and the results obtained from the analytical equations. The comparison results demonstrate a good agreement between the numerical and analytical findings.

In a recent study by Heyrani & Shooshtari [98], the hysteresis performance of new SSDs under cyclic loading. FEA was employed to simulate different slit sizes and the number of slits in single-column and dual-column SSDs. Sample SSDs with the highest ultimate strength were then subjected to testing. The findings indicate that dampers featuring steel strips of elliptical openings demonstrate enhanced energy dissipation compared to the tested specimens. Dual-column SSDs also show higher initial strength than single-column SSDs. In addition, single-column SSDs exhibit stable hysteresis performance, minimizing strength loss during displacement cycles. Rousta et al. [3] introduced vertical steel panel flexural yielding dampers (VSPFYDs) to enhance the cyclic behavior and overall performance of SSDs (Figure 16). Numerical methods using ABAQUS software and extensive parametric studies were employed to validate and investigate their study. Comparison with traditional SSDs confirmed that VSPFYDs exhibited improved seismic parameters. Notably, VSPFYDs with a height of 15 cm demonstrated superior performance in various aspects. The plate connection construction was found to have a significant impact on the performance and hysteresis behavior of VSPFYDs compared to SSDs.



(a)



(b)

Figure 16. Schematic view and geometric parameters of the proposed system by Rousta et al. [3]; (a) VSPFYD and (b) SSD

Hui et al. [99] introduced and conducted experimental assessments on an economical double-sided slotted steel tube shear damper (refer to Figure 17). This device leverages elastic-plastic deformation within the plane of the slotted steel plate on the steel tube's side to absorb seismic energy, effectively mitigating vibrations. Quasi-static tests were systematically conducted to investigate the influence of various design parameters on operational efficiency, energy dissipation capacity, and failure characteristics. The test results demonstrated the damper's robust plastic deformation capabilities, outstanding seismic performance, and substantial energy dissipation capacity. The hysteretic curve exhibited both symmetry and completeness, resembling a shuttle shape. Notably, increasing the bending element's width and the steel tube's wall thickness yielded significant improvements in energy dissipation.

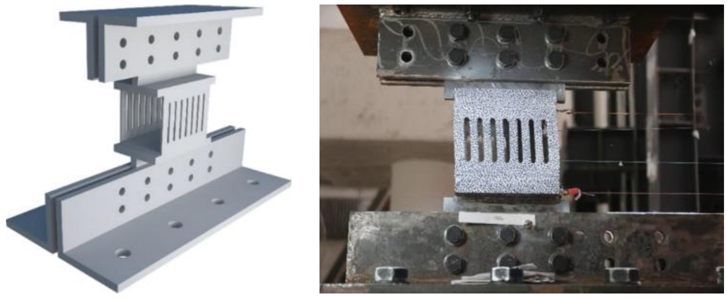
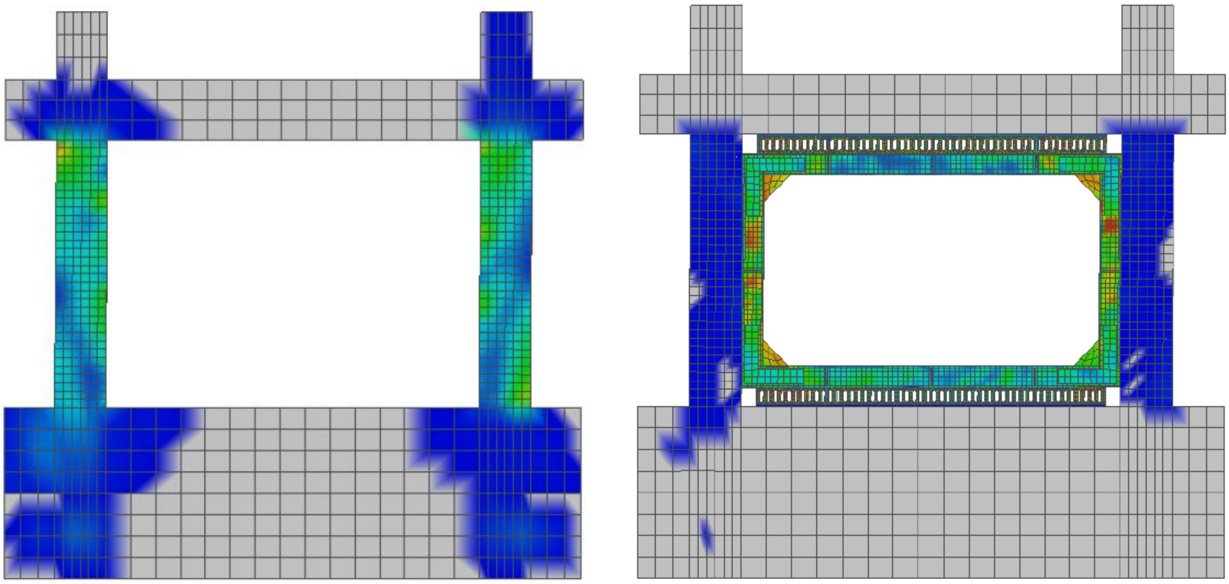


Figure 17. Double-sided slotted steel tube shear damper [99]

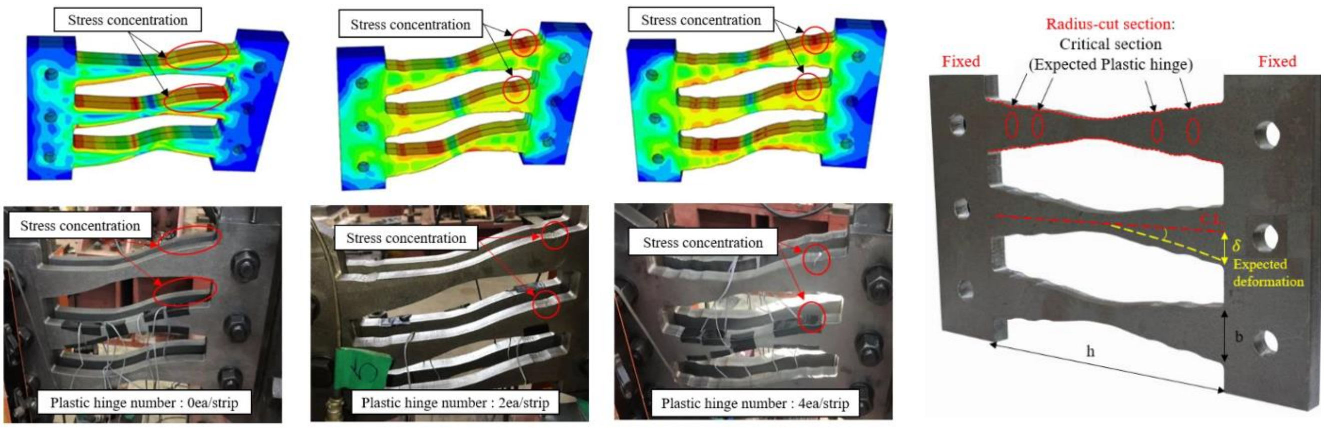
In the interest of comprehensiveness, Kang et al. [100] developed a seismic retrofit scheme using a combination of a steel moment frame and SSDs to mitigate earthquake damage in buildings. The hybrid system underwent a cyclic load test within an existing reinforced concrete frame. The device demonstrated energy dissipation capabilities similar to slit dampers, with a slight reduction in stiffness compared to traditional steel frame reinforcement methods. The results of a finite element analysis validated the test outcomes, showing a significant enhancement in structural strength and ductility when using slit dampers compared to bare structures. The model structure effectively reduced its seismic response below the target limit state by implementing slit dampers. The stress distribution in the test structures, obtained from the finite element analysis, is depicted in Figure 18.



Without slit dampers After retrofitting by slit dampers

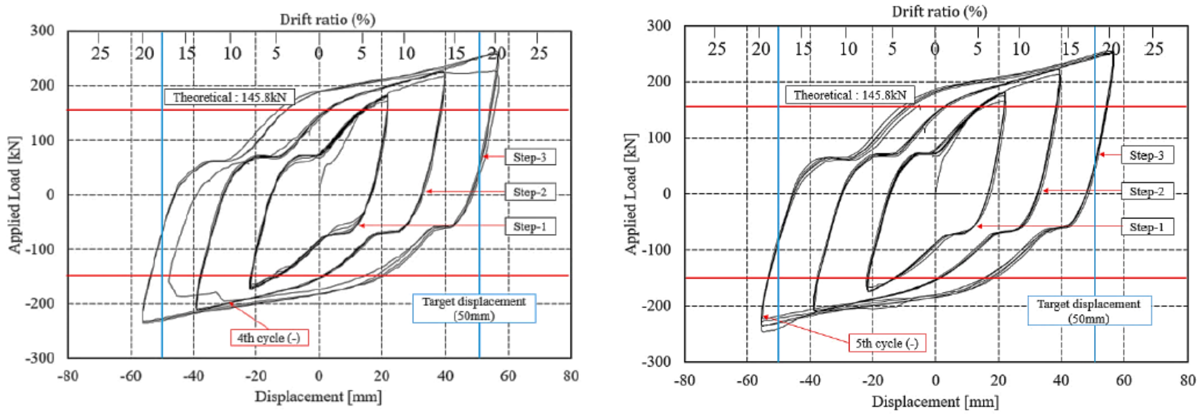
Figure 18. The stress distribution in the test structures resulting from the finite element analysis [100]

Traditionally used slit dampers are prone to cracking and breaking because of stress buildup at the ends of the strips when used for earthquake retrofitting. Bae et al. [101] proposed an improved damper design using radius-cut coke-shaped strips to address this issue and enhance ductility. Figure 19 illustrates the von Mises stress distributions for the three analysis models. By applying the reduced beam section method, the height-to-width ratio of the strip was increased to induce more bending deformation than shear deformation. Plastic hinges were intentionally created by focusing stress on the radius-cut section. This design specimen has higher inelastic deformation capacity and reduced fracture fragility. The experimental approach resulted in a finite element analysis demonstrating the coke-shaped damper's improved ductility. During cyclic loading, the radius-cut section was identified as the location of the final fracture, indicating sustained energy dissipation. The hysteresis curves of this damper are presented in Figure 20.



(a) (b)

Figure 19. Radius-cut coke-shaped strip damper [101]; (a) Reduced beam section models (plastic hinges number: 0, 2, and 4ea/strip) and (d) An explanation of the strip with four plastic hinges



(a) (b)

Figure 20. Hysteresis curves of radius-cut coke-shaped strip damper [101]; (a) first specimens (without reduced beam section) and (b) second specimen (with two plastic hinges)

A new double C-section steel slit damper (DCSSD) was introduced to examine the impact of strip aspect ratio, flange thickness, damper length, and steel grade on its resistance and hysteretic behavior [102]. Experimental results revealed that the DCSSD exhibited favorable structural characteristics. All DCSSD specimens displayed an equivalent damping ratio above 0.45, with Q160 exceeding this threshold and achieving a damping ratio exceeding 0.50. Moreover, the DCSSD utilizing Q160 demonstrated a cumulative displacement of approximately 1500 mm. Numerical models were subsequently developed for the test specimens, demonstrating excellent agreement with the experimental findings. He et al. [103] studied the structural performance of steel slit shear panels (SPs) in MRSF structures. The time-history analysis results indicated that installing SPs reduced floor displacement responses but increased floor acceleration responses. Among different SP types, the low-yield SP was the most effective in reducing maximum and residual inter-story drift.

In recent years, Block Slit Dampers (BSDs) have emerged as a promising solution for passive structural control, particularly in high seismicity regions where highly ductile systems like SMRFs are required [104]. BSD devices with secondary hardening in their hysteretic curves have demonstrated the ability to meet performance objectives for flexible steel SMRFs in such regions. Additionally, BSD devices effectively reduce inter-story drift ratios and regulate absolute floor accelerations (AFAs), minimizing damage to non-structural elements. Thus, BSD devices offer a suitable solution for designing and retrofitting flexible steel SMRFs, providing hysteretic behavior and enhanced performance. Two experimental boundary conditions were employed in another study by Oh and Park [105] to examine the performance of this particular damper: i) shear loading alone and ii) combined shear and tensile loading. The combined shear-tensile loading resulted in a butterfly-shaped hysteresis curve for the damper, while shear-only loading produced a parallelogram-shaped curve [105]. The damper's properties are influenced proportionally by adding additional tension, contingent upon the damper's aspect ratio and maximum deformation angle. According to the cyclic hysteresis analysis, the damper's plastic deformation capacity remains similar under both tensile and exclusive shear loading conditions. Furthermore, the energy absorbed up to failure is equal to that observed when the damper is only subjected to shear loading. However, when subjected to additional tensile loading, the damper dissipates a notable amount of unstable energy due to out-of-plane deformation. The damper exhibits lower hysteresis under additional tension than the predicted curve used for evaluating plastic energy based on test results.

Non-buckling slit dampers (NBSDs) integrated into a window-type seismic control system (WSCS) offer a viable solution for developing an effective seismic control system for existing reinforced concrete buildings [106]. Buildings retrofitted with NBSD-WSCS frames demonstrated minimal damage during seismic events, even under the highest recorded seismic intensity in Korea, reaching approximately 300 cm/s², resulting in only minor or moderate damage. Lee et al. [106] successfully developed and validated NBSD-WSCS as an efficient method for seismic retrofitting.

4.1. Summary

According to existing research, the incorporation of steel slit dampers in braced frames has been found to enhance the overall ductility of structures. In particular, using SSDs has demonstrated the ability to achieve an inter-story drift ratio of over 2% when implemented in braced frames. The failure mechanism associated with these dampers typically involves the failure of the strips at their ends. Consequently, optimizing the configuration of these damper strips can enhance their performance and delay fracture. Significantly, the utilization of an optimized configuration not only increases the energy dissipation capacity but also improves fatigue resistance. Optimal-shaped SSDs have the potential to achieve an energy dissipation improvement of over 12%. Comparatively, non-prismatic and hourglass configurations have exhibited greater efficiency than conventional configurations. In terms of the hysteresis curve configuration, it is generally observed that this type of damper shows a parallelogram-shaped curve when subjected to shear loading.

5. Numerical Analyses and Discussion

5.1. Description of Frames and Dampers

The present study is dedicated to conducting a comparative analysis of three test frames. Specifically, one of these frames is a special braced frame without a damper (SBF), while the remaining two frames are equipped with slit dampers.

One of the frames is of slit prismatic damper (FSPD), while the other features a non-prismatic damper (FSNPD). In this study, the damper is affixed to the lower end of the brace, ensuring consistency across all three samples by maintaining meticulous dimensions and sections for the primary structural element within the braced frame. These dimensions include a height of 3.0 meters and a span of 3.5 meters. Subsequently, a comprehensive comparison is carried out, encompassing the evaluation of hysteresis curves, ductility, and dissipated energy among the results of the three numerical analyses. For visual reference, Figure 21 displays the frame used in this research. Additionally, Figure 22(a) and Figure 22(b) provide detailed illustrations of the uniform prismatic and non-prismatic slit dampers utilized in the other frames, respectively. The steel frame elements consist of an HSS steel section of 100×100×6 for the brace, an IPE220 for the beam, and an IPB140 for the column.

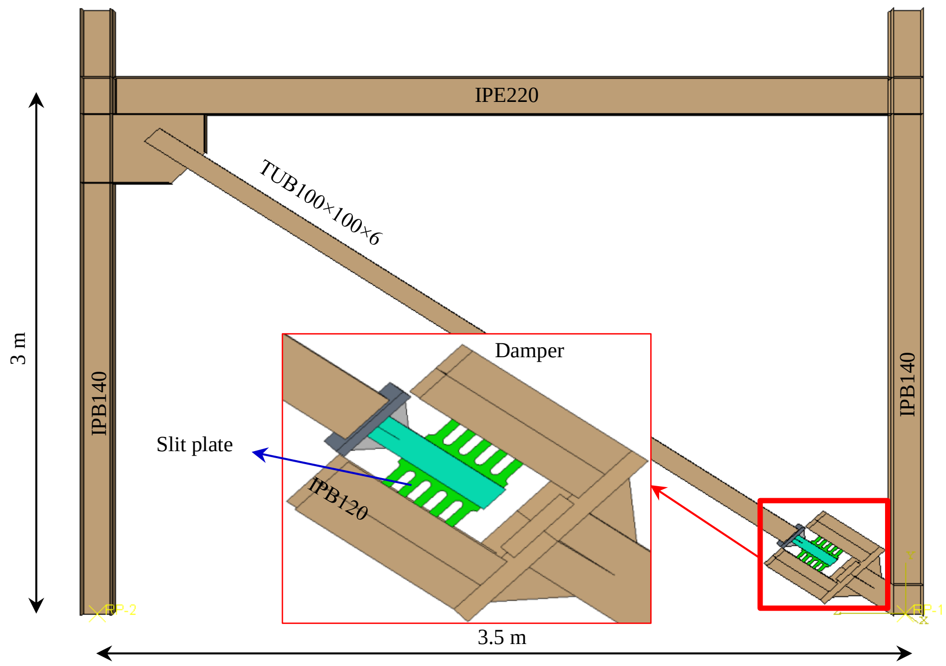


Figure 9. Details of the braced frame, along with the proposed damper

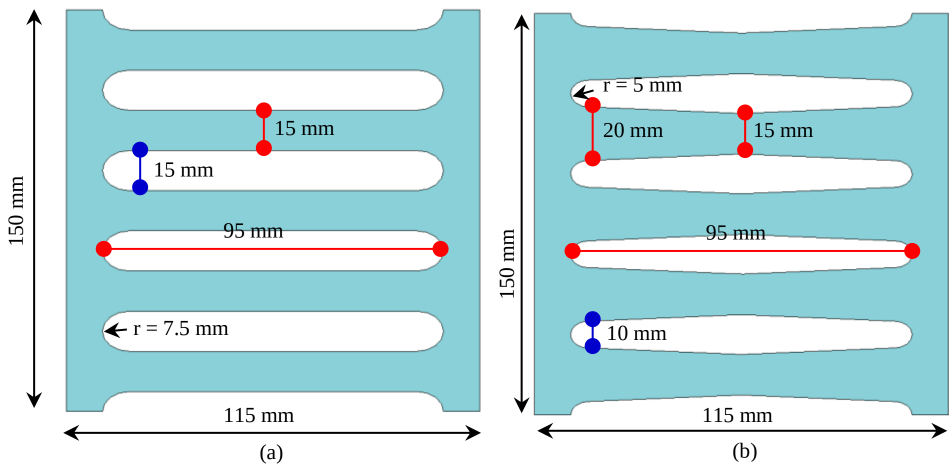


Figure 10. Comparative details of slit dampers: (a) uniform prismatic slit damper and (b) uniform non-prismatic slit damper

5.2. Modeling Techniques

The numerical investigations in this study, which encompassed the analysis of all specimens, accounting for both geometric and material non-linearities, were conducted using the nonlinear finite element (FE) software ABAQUS

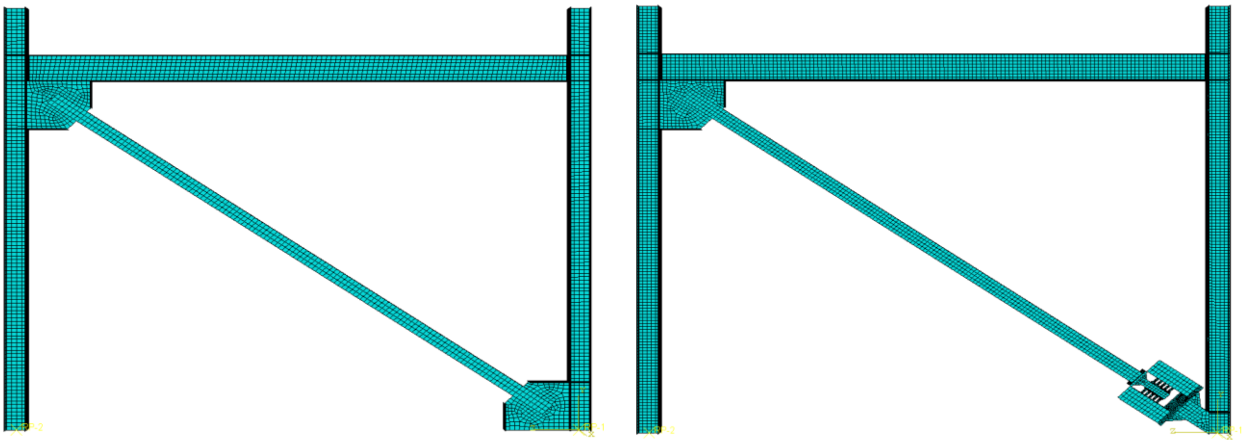
[102]. A 4-node doubly curved thick shell element with reduced integration (S4R) was chosen to represent the test specimens accurately. This approach effectively captures the intricate structural behavior under examination.

A sophisticated combined cyclic model, which incorporates both kinematic and isotropic hardening components, was employed to simulate the cyclic response of the material, guided by the Von Mises yield criterion. It is worth noting that this material model has previously undergone validation for its efficacy in replicating the inelastic behavior of steel, as evidenced in references [55, 56]. The FE models were constructed using St37 steel, and the elastic-plastic response of this material was modeled through a comprehensive nonlinear approach that integrates isotropic and kinematic hardening properties. The mechanical properties of the material are systematically outlined in Table 1.

Table 1. Mechanical characteristics for FEA models

Material	F_y (MPa)	F_u (MPa)	E (GPa)	ν
St37	240	370	200	0.3

It is essential to emphasize that the FE modeling framework in this study intentionally excluded considerations of fracture evolution and material degradation. The bases of the specimens were modeled as pinned connections to effectively constrain any degrees of freedom that might result in unintended movements. Out-of-plane deformation was prevented at the upper column ends to mitigate out-of-plane buckling of the frame induced by lateral loads. The mesh size for the dampers was set at 5 mm, while other frame elements were adjusted to approximately 20 mm, as illustrated in Figure 23. The testing protocol for specimen examination adhered to the SAC guidelines [103], as shown in Figure 24. The testing regime was rigorously conducted up to a drift level of 3%.



(a) (b)

Figure 11. Mesh configuration of the test frames: (a) SBF and (b) FSPD and FSNPD

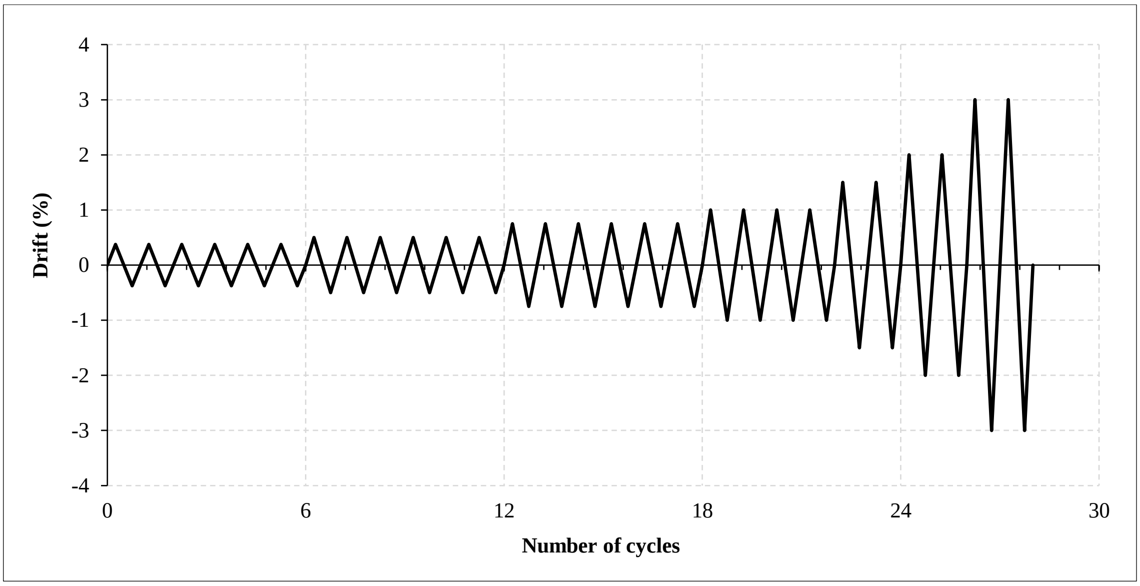


Figure 12. Protocol for cyclic loading

5.3. Results and Discussion

5.3.1. Force-Displacement Relationship

The force-displacement curves derived from finite element (FE) models are illustrated in Figure 25 for three configurations: a frame without steel slit dampers (SSD) and frames equipped with SSD dampers, one encompassing prismatic and the other non-prismatic slit dampers. The analysis indicates that the maximum positive and negative load capacities of the frames with SSDs are closely aligned with those without SSDs. However, a noteworthy distinction emerges in their hysteresis behavior. The frame with no SSD exhibited diminished strength under compressive loads. This reduction is primarily attributed to brace buckling at a peak displacement of 6.7 mm, corresponding to a relative drift of 0.22%. Conversely, frames integrated with SSD devices showcased enhanced hysteresis behavior without any signs of instability. Notably, these frames achieved up to a 3% drift (90 mm) without a concomitant decrease in strength, a significant improvement over the non-damper frames. This finding is consistent with the outcomes reported by Almohammad-albakkar et al. [95, 96], who observed that the cross-braced frames equipped with a steel slit damper achieved a relative drift exceeding 3%. A distinctive butterfly shape, indicative of improved energy dissipation capabilities, characterizes the hysteresis curves for damper-equipped frames. The butterfly-shaped hysteresis curves observed in the braced frame with SSDs closely resemble those documented in the literature for block slit dampers [47]. Further analysis reveals a marked difference between the frames equipped with different types of dampers. Frames with non-prismatic slit dampers exhibited a more pronounced hysteresis curve, especially in the initial cyclic loading phase, while maintaining comparable strength to those with prismatic slit dampers.

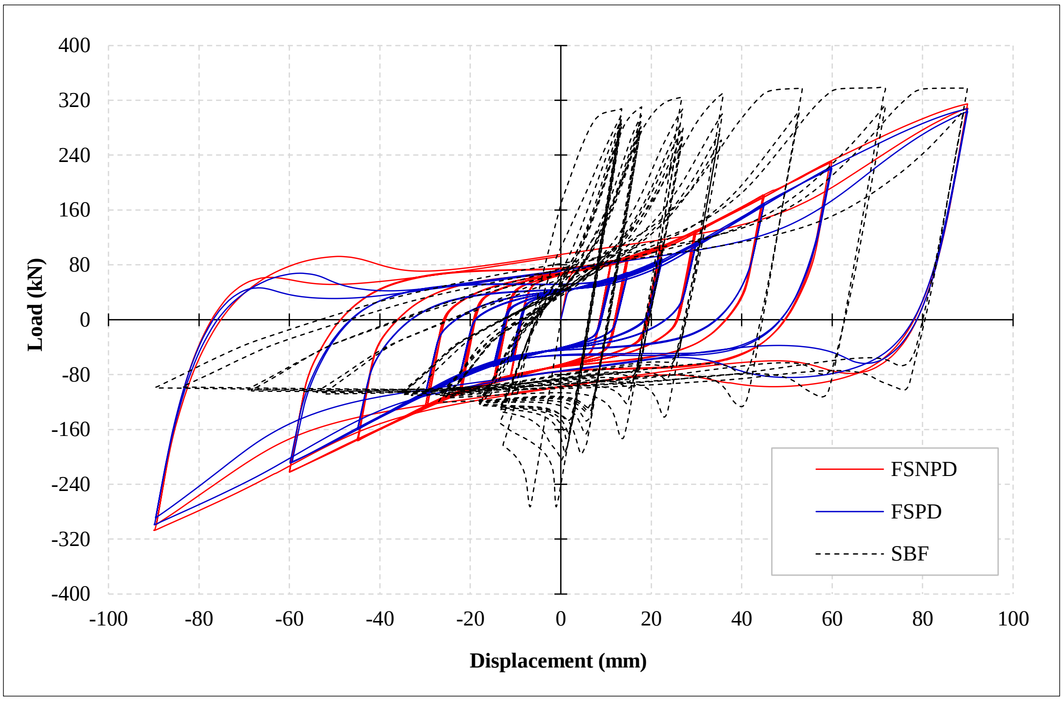


Figure 13. Force-displacement relationship

Table 2 presents a detailed comparative summary of these findings. It shows that the ultimate strength of the frame without a damper (SBF) marginally exceeds that of the frames with SSDs. In the positive phase, at a maximum displacement of 90 mm, the SBF attained a maximum load of 338.3 kN, compared to 307.6 kN and 314.7 kN for frames with prismatic and non-prismatic slit dampers, respectively. On the contrary, during the negative phase, the SBF achieved its highest load of 272.8 kN at a displacement of 6.72 mm, whereas frames FSPD and FSNPD exhibited peak loads around 299.1 kN and 307.2 kN at a displacement of 90 mm, respectively. The table also shows the comparable test results of frames' elastic stiffness and energy dissipation, discussed in the following sections. Furthermore, when comparing the outcomes derived from FSNPD with those of FSPD, it is evident that the non-prismatic shape boosts elastic stiffness by more than 25% compared to the prismatic configuration.

Table 2. Comparison of the ultimate strength, ductility, and energy dissipation of the test frames

Test frames	Ultimate strength (kN)		Elastic stiffness (kN/mm)	Energy dissipation	
	$^{+}$Pu	$^{-}$Pu		(kJ)	Ratio with (SBF)
Special braced frame (SBF)	338.27	-272.81	41.39	141.99	1
Frame with slit-prismatic damper (FSPD)	307.62	-299.07	26.55	178.46	1.26
Frame with slit-non-prismatic damper (FSNPD)	314.71	-307.22	33.73	240.17	1.69

In terms of hysteresis behavior, both prismatic and non-prismatic slit dampers exhibit a butterfly-shaped curve, albeit with noticeable differences. The hysteresis curves of non-prismatic slit dampers appear broader, particularly during the initial loading stages. Consequently, non-prismatic slit dampers dissipate energy more effectively compared to prismatic dampers, with the former exhibiting approximately 35% greater dissipation. Regarding ductility, both damper types boast a similar ductility level, around 3%, as per the obtained results. However, it should be noted that according to prior experimental research [85], the use of a non-prismatic slit damper can notably enhance the damper's performance under fatigue.

5.3.2. Distribution of Plastic Strain

Figures 26 and 27 show the distribution of Von Mises stress across the evaluated frames. A noticeable reduction in stress is observed in the frame outfitted with steel slit dampers (SSD) devices, particularly evident at panel zones and gusset plate junctions. In contrast, the frame without SSD devices exhibited stress intensities approaching the material yield threshold, predominantly at the panel zones and the base of columns. This disparity underscores the efficacy of the SSD intervention in mitigating stress concentrations in frame structures subjected to cyclical or dynamic loadings. Additionally, Figures 27 to 29 show that both FSPD and FSNPD exhibit significant strain and stress concentrations at the root of the strips. Specifically, the FSNPD strips exhibit a more uniform stress distribution at their root, contrasting with the variations observed in FSPD. This observation underscores the influence of the non-prismatic shape of the strips on their ability to enhance the damper's performance, particularly in absorbing and dissipating energy.

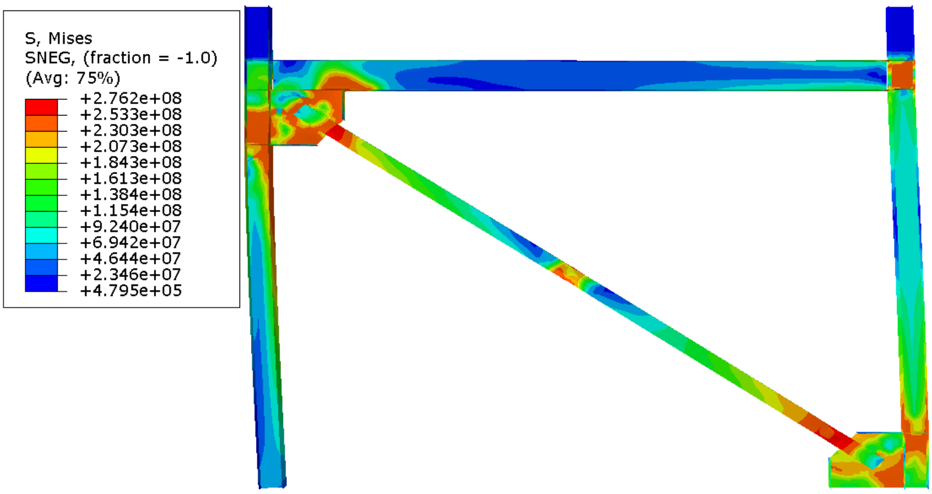


Figure 14. The Von Mises stress distribution for the frame without damper (SBF)

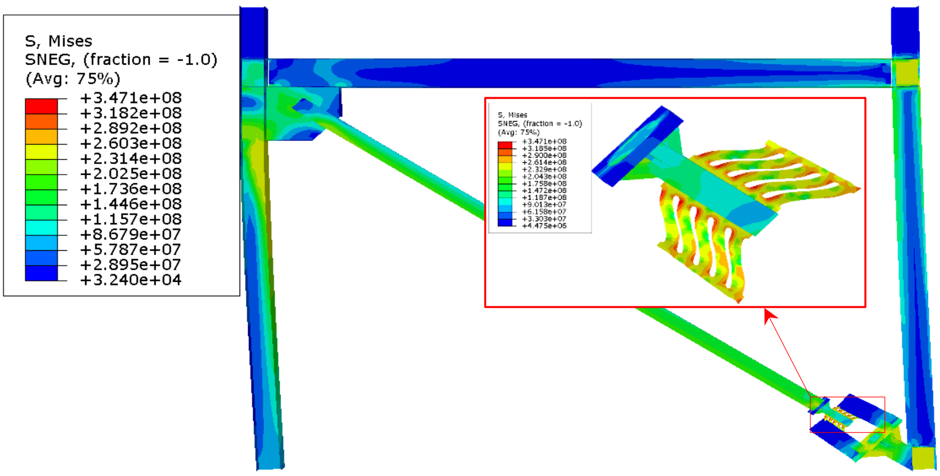


Figure 15. The Von Mises stress distribution for the frame equipped with non-prismatic slit damper (FSNPD)

Further explanation is provided in Figures 28 and 29, which compare the deformation shapes of frames equipped with and without SSD devices under lateral load conditions. The plastic strain is more uniformly distributed across the dampers in the frame incorporating SSD. This phenomenon can be attributed to the inherent design characteristics of the SSD devices, which ensures that the steel strips within the dampers yield preferentially. Consequently, this pre-emptive yielding predicts the emergence of pronounced stress concentrations at other critical junctures within the frame structure.

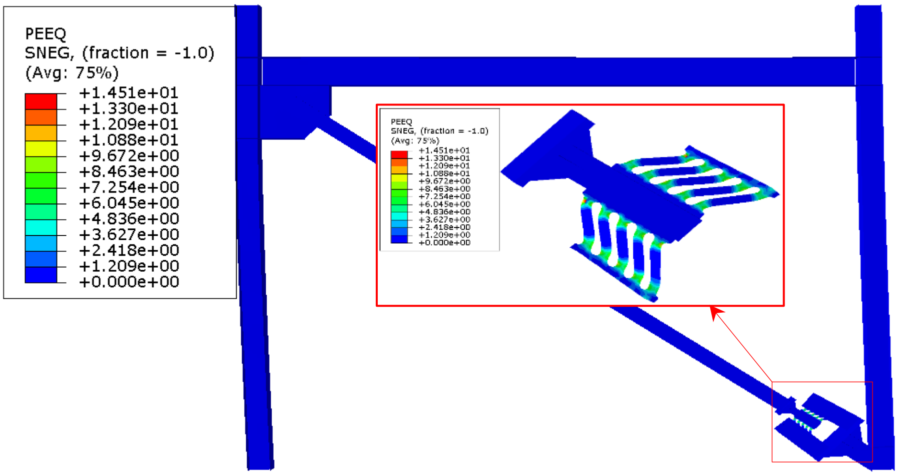


Figure 16. Distribution of equivalent plastic strain (PEEQ) within the slit damper of the prismatic damper (FSPD)

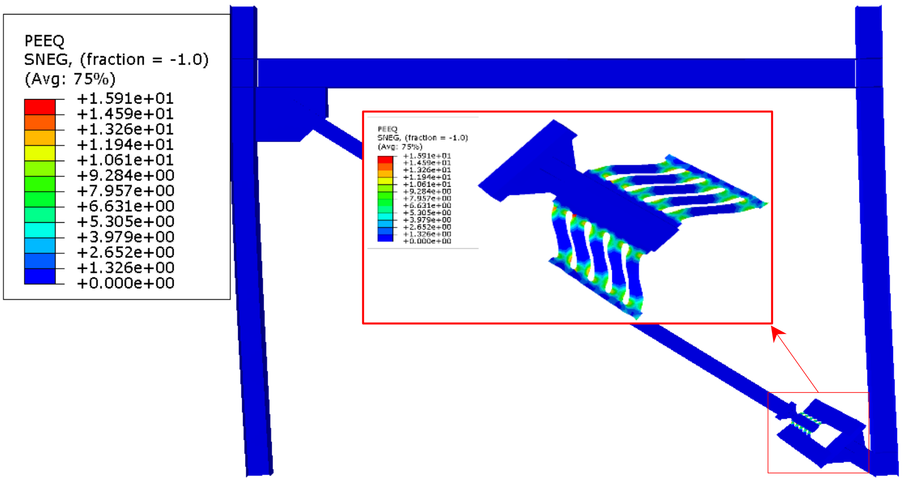


Figure 17. Distribution of equivalent plastic strain (PEEQ) within the slit damper of the non-prismatic damper (FSNPD)

5.3.3. Energy Dissipation Analysis

Figure 30 presents a detailed depiction of the cumulative energy dissipation in the frames. This figure distinctly highlights the enhanced energy dissipation capacity of frames when integrated with a non-prismatic slit damper. Specimen FSNPD demonstrates greater stability and superior energy dissipation capabilities than the other specimens. Complementing this graphical representation, Table 2 provides quantitative insights into the cyclic energy dissipation observed in these frames.

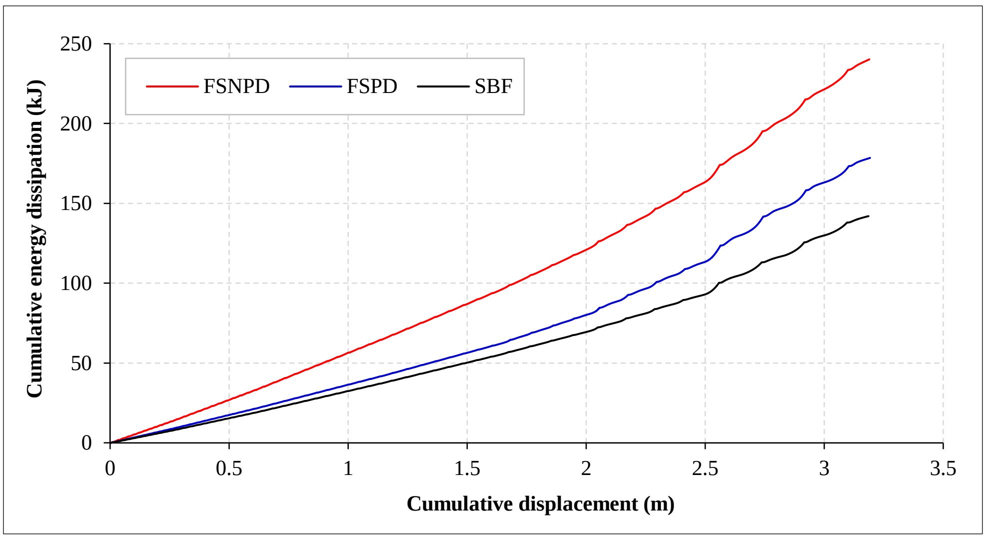


Figure 18. The cumulative energy dissipation of the frames

A notable observation from this data is the disparity in energy dissipation between the braced frame without the slit damper and those outfitted with prismatic and non-prismatic slit dampers. The quantitative analysis reveals an increase in energy dissipation by 26% and 69% for frames with prismatic and non-prismatic slit dampers, respectively. Such findings indicate the substantial impact that damper design can have on the energy dissipation characteristics of frames. Additionally, upon comparing the results obtained from FSNPD with those from FSPD, it becomes evident that the non-prismatic shape enhances energy dissipation by over 35% compared to the prismatic shape. These findings are consistent with those of previous studies on slit dampers in the literature. The previous research revealed that utilizing a tapered shape can enhance energy dissipation by approximately 37% compared to the conventional initial shape in literature [85] and around 12~50% in the literature [86].

5.4. Summary

The results derived from the finite element analysis provide compelling evidence for the efficiency of Steel Slit Damper (SSD) devices in enhancing the cyclic performance of frame structures under lateral loading conditions. These devices, notable for their simplicity, low mass, and cost-effectiveness, demonstrate a significant capacity to attenuate lateral loads. This is evidenced by the force-displacement hysteretic curves generated for the frame equipped with SSD devices, which markedly outperform the bare frame. Notably, the frame incorporating non-prismatic slit dampers exhibited a superior cumulative energy dissipation compared to its counterparts. Quantitatively, the integration of non-prismatic dampers resulted in a 69% increase in the cumulative energy dissipation of the frame, highlighting the potential of these devices in structural engineering applications.

6. Conclusions

This study comprehensively evaluates Steel Slit Dampers (SSDs) in steel-braced frames, focusing on their consistent hysteretic behavior, customizable configurations, and significant enhancement of seismic resilience. Comparative analysis has been conducted on a Special Braced Frame (SBF) without dampers and two other frames, one with prismatic and the other with non-prismatic SSDs dampers. The following can be concluded from the research conducted:

- Slit dampers used in braced steel frames provide significant strength, ductility, and dissipation capabilities, and they provide stable and predictable hysteretic behavior, displaying uniform force resistance in tension and compression.
- SSDs performance can be tailored by their geometry by adjusting the strips' number, dimensions, and configuration. Notably, SSDs with non-prismatic and hourglass shapes exhibit superior characteristics. Damper designs featuring steel strips as elliptical slits demonstrate the highest energy absorption.
- Optimal-shaped non-prismatic SSDs have the potential to achieve an energy dissipation improvement of over 12% compared with conventional non-prismatic dampers. Furthermore, optimized dampers exhibit significantly larger cumulative displacement than conventional SSDs, indicating a higher inelastic deformation capacity.
- The installation of SSDs in braced frames has demonstrated their ability to withstand an inter-story drift ratio of up to 2%. Through experiments and numerical analyses, a non-prismatic damper has been identified as exhibiting greater ductility.
- When subjected to combined shear and tensile loading, SSDs of prismatic and non-prismatic dampers exhibit a butterfly-shaped hysteresis curve, whereas shear-only loading results in a parallelogram-shaped curve.
- In the conducted numerical analysis, it was recognized that the frame outfitted with non-prismatic slit dampers exhibited an improved cumulative energy dissipation, surpassing that of the frame with prismatic configuration. Quantitatively, this enhancement in energy dissipation was calculated to be 69%, signifying a substantial increase attributable to the incorporation of the non-prismatic damper.
- The numerical results further demonstrate an enhancement in the strength during the negative phase of loadings for frames equipped with FSPD and FSNPD.

The findings of this study conclusively demonstrate that the integration of dampers into structural designs significantly improves their capability to withstand high levels of relative drift, thereby enhancing their ductility. This increased ductility significantly reduces the seismic forces exerted on the structure, promoting cost-effective design strategies. Buildings enhanced with damping systems can maintain critical performance standards necessary for immediate occupancy (IO) and life safety (LS) in the aftermath of seismic events.

A key insight from this research is the localization of damage to the dampers, which significantly reduces the economic impact associated with post-earthquake restoration efforts. Consequently, the strategic implementation of damping mechanisms in building design is highlighted as an effective measure for enhancing structural durability and safety in earthquake-prone areas while offering a cost-effective solution for initial construction and subsequent earthquake recovery processes.

6.1. Recommendation and Future Work

The research provides a comprehensive review and numerical analyses of the use of steel slit dampers (SSDs) in braced frames, identifying several critical avenues for future research. These recommendations are pivotal for advancing our understanding of SSDs in seismic-resistant design. However, to enhance the academic rigor and clarity of the recommendations, certain modifications and expansions are suggested:

- It is highly commendable to explore the advantages of using alternative SSD materials for SSDs, such as low mild yield and stainless steel.
- Investigate SSD behavior under low-cycle fatigue, as SSD failures can be attributed to concentrated stress at the strip ends.
- Investigating the use of hybrid systems that combine slit dampers with other types of dampers is an insightful approach.
- Conducting comprehensive research on the behavior of SSDs under various force combinations, including shear force with moment and/or axial force, is essential. Specifying force combinations or scenarios of significant interest, including extreme loading conditions or varying frequency and amplitude, would be advantageous.

The recommendations above would offer a more targeted direction for future investigations.

7. Declarations

7.1. Author Contributions

Conceptualization, Z.A. and M.A.; methodology, Z.A. and M.A.; software, M.A.; validation, Z.A. and M.A.; formal analysis, Z.A. and M.A.; investigation, Z.A. and M.A.; resources, Z.A. and M.A.; data curation, M.A.; writing—original draft preparation, Z.A. and M.A.; writing—review and editing, Z.A. and M.A.; visualization, Z.A. and M.A.; supervision, Z.A.; project administration, Z.A. and M.A.; funding acquisition, Z.A. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7.3. Funding

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7.5. Conflicts of Interest

The authors declare no conflict of interest.

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