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Development of Steel Yielding Seismic Dampers Used to Improve Seismic Performance of Structures: A Comprehensive Review

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ABSTRACT

Seismic excitation can cause significant energy to be released within structures. By using special devices, this energy can be consumed and dissipated without deforming structural members significantly. Due to this, structural damage is minimized, casualties are prevented during earthquakes, and structures are extended in their useful life. Over the past five decades, it has been widely acknowledged that steel yielding dampers are among the best energy dissipation devices. It has been stated that the hysteretic behavior of steel yielding dampers could vary slightly depending on their geometry. From a practical point of view, they are suitable for the improvement of seismic safety in new and existing structures. The purpose of this paper is to present a review related to steel yielding dampers, their development, various types, and applications, in order to help understand the role of these dampers in improving the seismic performance of structures. In terms of their shape, steel yielding dampers can be categorized as steel plate dampers, pipe dampers, curved dampers, and slit dampers. The most common use of steel plate, such as ADAS and TADAS, and pipe dampers is within braced frames, whereas U-shaped, J-shaped, and S-shaped dampers are mostly seen in frames with chevron bracing. Steel curved dampers with a 60° angle in a steel-braced frame, on the other hand, provide the best energy dissipation and frame strength. In this direction, until today, steel slit dampers have been found to be the most commonly used steel yielding dampers.

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1. INTRODUCTION

A variety of dynamic and environmental loadings can affect civil structures, such as wind, traffic, and earthquakes. Especially during earthquake events, buildings structures can be significantly damaged. This observation has been experienced all over the earthquake prone countries of the world like those in the Middle East, southern Asia and Europe, North and South America, and Japan [1, 2]. Structural vibration control methods have been developed in a number of ways to minimize or prevent such damage, and they are being used skillfully in a variety of locations within civil structures [3-5]. There are four major classifications of structural vibration control systems: passive, active, semi-active, and hybrid systems [6-8] while several articles have addressed each of these categories in greater detail [6, 9-18]. For example, the optimal control algorithm developed by Momeni and Bagchi [18] was designed to improve the efficiency of the semi-active controller. It combines replicator dynamics with an improved non-dominated sorting genetic algorithm (NSGA), NSGA-II. MR dampers, which are semi-active control devices, were then utilized in the new control system to alleviate the vibrations of the isolated highway bridge. Optimal replicator controllers achieve better performance than classical control algorithms, as mentioned in the results.

The passive energy dissipation device has been proposed, tested, and used as an effective tool for improving seismic performance and energy dissipation capacity of structures over the recent decades [19-21]. Passive energy dissipating devices do not require external power sources, unlike active, semi-active, or hybrid systems. In general, passive energy dissipating

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devices consume energy by yielding metals, rubbing surfaces together [22], and deforming viscous or viscoelastic materials [23]. Therefore, the wide variety of passive dampers is categorized based on their mechanism of action, including fluid viscous dampers [24-26], tuned liquid dampers [27-29], viscoelastic dampers [30, 31], hysteretic (or, yielding) dampers [32-34], and friction dampers [35]. As a result of their several advantages, steel-yielding devices have been widely used in structures among all kinds of passive energy dissipating devices. They are the focus of this review. Some of these advantages include resistance to fatigue due to low cycles and high displacements, bolted attachments, low fabrication costs, tolerance of large displacements, low sensitivity to ambient temperatures, and high long-term reliability [36-39]. For instance, Behnamfar and Soltanabadi [40, 41] developed a new type of damper that was both numerically and experimentally tested in order to enhance the seismic performance of steel moment connections, and to be repaired following an earthquake. A metal yielding damper can be divided into four types based on its way of yielding, namely axial yield, shear yield, flexural yield, and combined yield. Considering the versatility of steel yielding dampers in terms of application and development, these dampers are of great importance. A number of these yielding devices have been developed and applied to actual buildings, including shear panel damper, pipe damper, and steel plates with slits or with honeycomb-shaped openings subject to shearing [42-47].

To gather the scattered information on yielding dampers into an integrated literature compiling their chronological evolution and advancement from early 1970s to the current day devices, a comprehensive number of the related research tasks is reviewed in this paper to understand the role played by these dampers in improving seismic performance of structures. In this regard, steel yielding dampers can be categorized into four types based on their shape as steel plate dampers, pipe dampers, curved dampers, and slit dampers.

2. CLASSIFICATION OF STEEL YIELDING DAMPERS

In recent years, many solutions have been suggested to alleviate the effects resulting from earthquakes. This process was a reason to innovate a diverse number of control devices for dissipation of seismic energy. Most of these devices have advantages of being simple in construction and quick to repair or replace after an earthquake. Furthermore, as will be shown later, these energy dissipaters mostly not only could exhibit a high and stable energy absorption capacity, but also exhibit the same behavior under tension and compression. It is possible to further categorize steel yielding dampers into four types in terms of shape: steel plate damper, curved damper, pipe damper, and slit damper.

According to Figure 1, the review is conducted using the following flowchart. The review begins with the development of control systems and selecting the investigated control system. After that, the type of passive control system is selected. In this review, the steel yielding dampers are chosen and categorized into four types in terms of shape. The methods used to evaluate the yielding damper are discussed and a brief comparison is then conducted with the other passive dampers. At the end of the review paper, the conclusions and suggestion for future research are summarized.

2. 1. Steel Plate Dampers

As early as the 1970s, Kelly et al. [48] invented the first steel dampers. Skinner et al. [32] developed and tested hysteretic dampers for earthquake-resistant structures, including U-strip dampers, torsional beam dampers, flexural beam dampers, and single-axis dampers. It is possible to install torsional beam dampers at the base of structures to prevent structural uplifting caused by severe earthquakes because they have a high load-bearing capacity. The flexural beam damper, however, is a bit more complicated where it can dissipate seismic loads bidirectionally. For the first time, trying out tapered-steel plates as energy dissipation devices has been proposed by

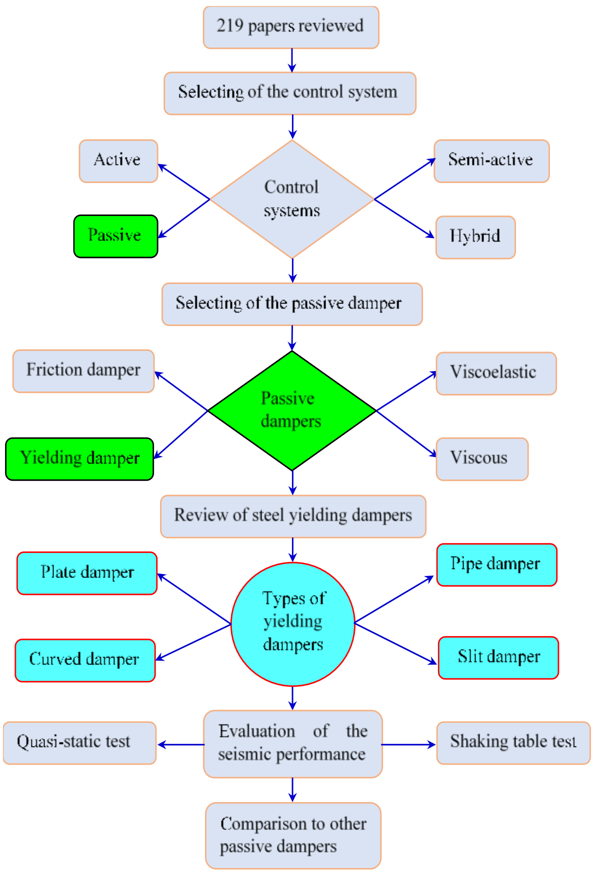


Figure 1. The flowchart adopted in this review paper

Tyler [49]. The damper consists of a steel plate that is welded to the anchorage plate at the base in order to form a cantilever and energy is consumed by steel material's plastic deformation. Thereafter, Bergman [50] suggested a steel damper and called it the added damping and stiffness (ADAS) damper, as shown in Figure 2(a). As proposed by Bergman, ADAS uses X-shaped steel plates that are bolted in parallel to the base plate to provide additional damping and stiffness. Steel X-plates ADAS elements, which are patented by Bechtel Power Corporation, were investigated in a study by Whittaker [51]. Two main goals were sought in the study: (a) investigating the effectiveness of ADAS in seismic applications, and (b) retrofitting ductile moment-resisting frames. A work hardening model based on elastic-perfectly plastic behavior was developed by Tsai and Chou [52] in order to accurately predict the hysteretic performance of the ADAS devices. Similarly, welded triangular-plates utilized for added damping and stiffness were developed and tested under cyclic loading by Tsai et al. [53-55] and Dargush and Soong [56], which are known as TADAS (see Figure 2(b)). TADAS devices are similar to ADAS and both of them can be used for moment resistant frames or braced frames [57-59]. Despite numerous yielding reversals, TADAS seemed to maintain stiffness and strength without deterioration. Afterwards, a one-dimensional fiber model was introduced by Tsai and Chou [60] to predict the experimental responses of the TADAS devices.

In the following years, Shih et al. [61, 62] created rhombic ADAS made of low yield strength steel. Experimental and numerical tests were conducted on this damper. Rhombic ADAS was shown to be capable of stably absorbing earthquake energy. According to the proposed model, rhombic low yield strength steel plates were capable of predicting the hysteretic energy dissipation behavior. Figure 2(c) illustrates a schematic view of this damper. Li and Li [63] invented what is called a dual-function metallic damper (DFMD), as depicted in Figure 2(d). DFMDs are able to achieve structural stiffness as well as reasonably good seismic energy dissipation. To assess the seismic performance of DFMDs quasi-static tests were conducted. As part of the seismic response and dynamic characteristics verification of a steel structure with DFMDs, shaking table tests were conducted on a steel structure with DFMDs under four earthquake ground motion records. It was also confirmed that placement of such X-plate dampers affects the response of buildings in a study by Pujari and Bakre [64]. As compared to the other placement schemes considered, it was reported that the optimal placement of the damoers resulted in a greater reduction of response. Equally, it is also important to note that the optimal placement of dampers is dependent upon the nature of the excitation force, the number of dampers used as well the way they are modelled. Especially, when structures equipped with

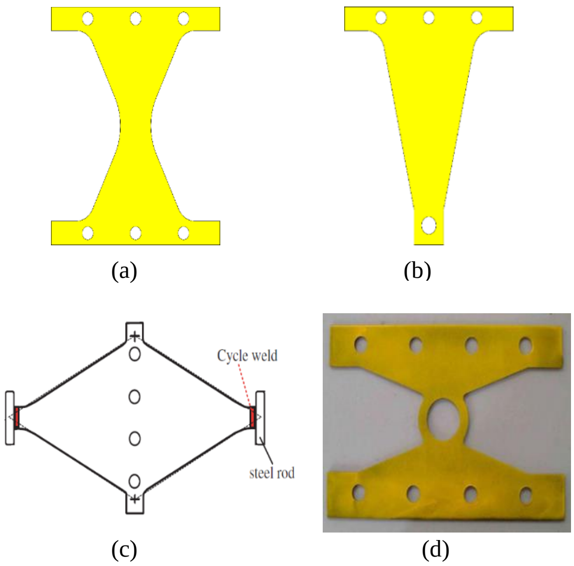


Figure 2. (a) ADAS damper; (b) TADAS damper; (c) Rhombic ADAS; (d) single round-hole steel damper [63]

TADAS dampers undergo large deformations, these members could be vulnerable to serious damage due to possible improper geometric characteristics [65]. It is therefore important to evaluate the behavior of TADAS dampers under large deformations. In this regard, in a study conducted by Mohammadi et al. [65], it was observed that stiffness of the TADAS damper increased abruptly when its pins hit the top of their holes, causing the damper to behave like a rigid element when subjected to large deformations. As a result of the stiffening behavior, the structure's beams and bracings were affected adversely.

Gray et al. [66-68], introduced the yielding brace system (YBS) by the work conducted in the development of ADAS and TADAS devices for which the YBS connectors are triangular in shape to promote spreading plasticity throughout. Due to the fact that "fingers" of the connection experience large deformations during a design level earthquake, the ends of the yielding fingers are bolted to the splice plates through long slotted holes that will accommodate the geometric changes in the fingers as they experience a large deformation like the TADAS. Based on the yielding brace system prototype design and testing program, it has been concluded that such braced frames can dissipate energy effectively and are capable of being displaced up to large displacements. Different applications of YBS in braced structures are shown in Figure 3.

In light of all of this, it should be noted that a hinge support should be used for this type of damper in order to reduce unfavorable axial force on the plate. In addition, low yield strength steel can be used to reduce local fractures in steel plate dampers, which enhances the damper's efficiency of dissipating energy and ductility.

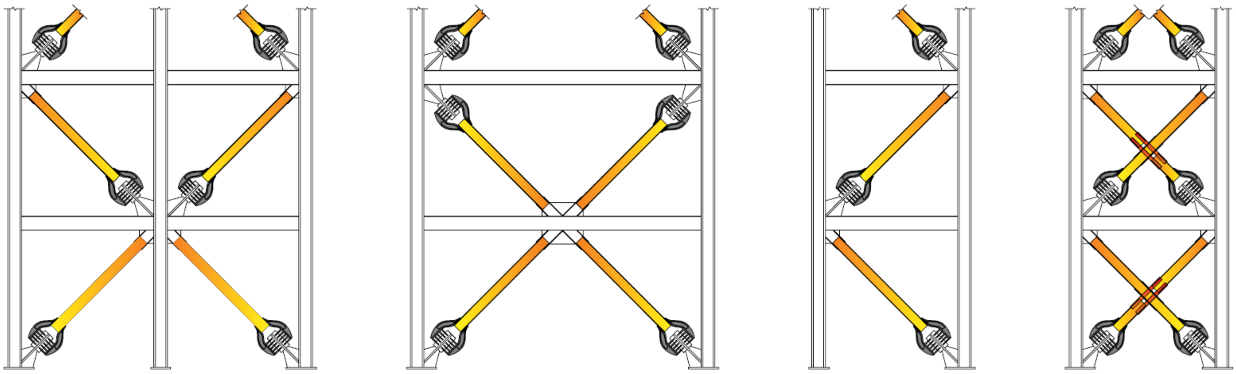


Figure 3. Different applications of YBS in braced structures [67]

On the other hand, it is possible to mitigate welding effects on damper performance by using damper symmetry like rhombic ADAS when clamped connections are achieved through welding. In terms of practicality, braced frames are most commonly equipped with ADAS and TADAS dampers to increase their damping and ductility.

Zibasokhan et al. [69] developed a pure bending yielding dissipater for seismic protection of structures with specially detailed concentrically braced configurations. Several transverse plates are inserted in this proposal into a box at the middle of a diagonal brace to form the device. The dissipater plates bend perfectly under the axial force of a concentric brace in a 4-point pure bending condition. Stable hysteretic behavior and excellent energy dissipation characteristic of the brace as well as similar behavior under tension and compression was observed when equipped with the proposed dissipater device. Labibi et al. [70] used the finite element method to simulate the behavior of a simple trapezoidal steel plate as a steel yielding damper and investigated geometrical parameters that affect absorption and cyclic behavior. In accordance with the results of the study, geometrical parameters can significantly influence energy absorption levels and improve damper hysteresis loops and ductility during specific cyclic loading conditions. In addition, use of the proposed steel damper will reduce the building's base shear and roof acceleration to a significant degree.

In a more recent study, a new damper with pistonic performance was presented by Ghandil et al. [71], which could be utilized effectively for controlling structures during earthquakes. The energy dissipating part of this device is a series of rectangular metallic yielding plates, which are contained within a rigid steel box and can move with only one degree of freedom. These plates were arranged in such a way that they would work in pure bending mode during cyclic motions of the damper. As a result of this configuration, the damper was able to produce a high level of force capacity and damping ratio. Thus, the device was capable of being used as a tension/compression piston with sufficient stability in other directions as well. Various types of structural systems were shown to be able to be accommodated by the proposed metallic-yielding pistonic damper (MYP), including moment-resisting frames, braced frames, and even shear wall systems with the capability of multiple installations in every frame bay. Besides, it was able to significantly reduce the structural responses and residual deformations as well as the out- of-plane frame motions. The details of the damper can be seen in Figure 4.

2. 1. 1. Steel Shear Panel Dampers Yielding shear panel devices (YSPDs) are relatively new passive energy dissipation devices that are designed to absorb earthquake energy by exploiting the capacity of metallic plates to deform plastically in shear. Due to the YSPD's low cost and ease of manufacture and installation, it may prove to be a viable commercial product that can be directly used in the design practice [72, 73]. A shear panel is capable of sustaining large deformations without pinching hence without experiencing a sudden decrease of strength. This enables the use of it as a passive energy dissipating damper in building and bridge structures for the purpose of absorbing seismic energy through inelastic deformation of steel material [74-78]. Generally speaking, the shear-panel dampers are examples of metallic dampers made from low yield point steels, enabling them to dissipate seismic energy well [79-81]. This type of damper has been invented in 1994 by Nakashima et al. [79]. In a subsequent study by Nakashima et al. [82], an experimental program was conducted to investigate the hysteretic behavior of the low-yield steel shear panels. According to the results obtained, the amount of energy dissipated by the tested shear panels was 1.5-2.0 times greater than that consumed by an equivalent linearly elastic, perfectly plastic system. Furthermore, Takahashi and Shinabe [83] performed experimental studies on the restoring force characteristics of thin steel plate elements under shear.

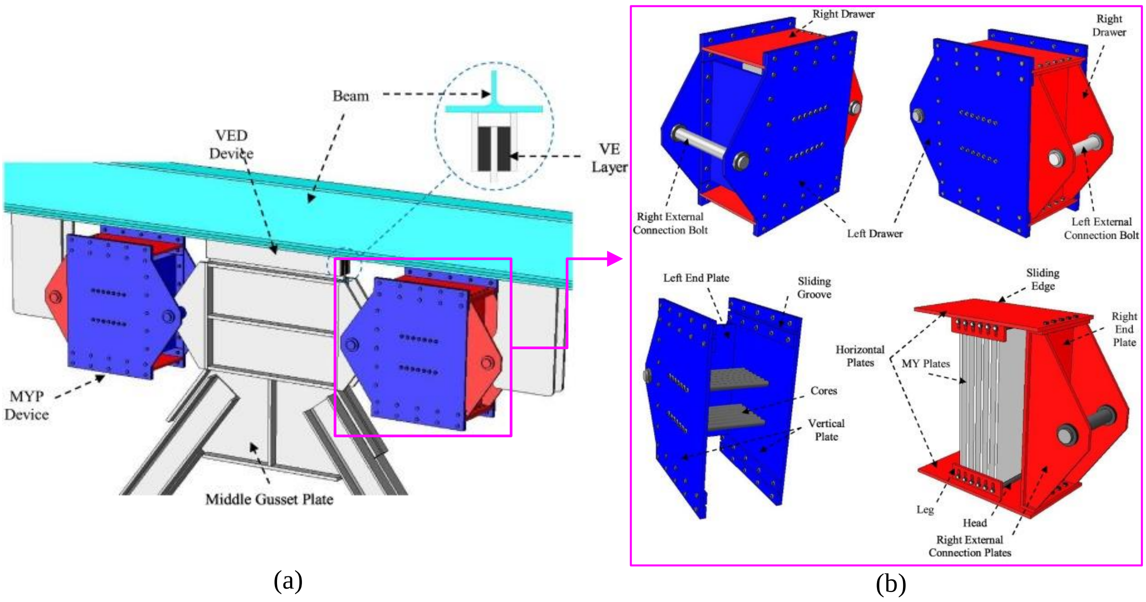


Figure 4. Metallic-yielding pistonic damper [71]: (a) chevron braced frame equipped with the MYP device; (b) details of the MYP device

Tanaka and Sasaki [84, 85] demonstrated in their studies that the curves of the panels using the same steel showed a common envelope irrespective of the width-thickness ratio of the panels.

Under cyclic loading, also, Tanaka and Sasaki [86] verified the hysteretic performance of shear panel dampers with ultra-low yield strength steel (100 MPa). These panels displayed an excellent cyclic performance, which is appropriate for hysteretic dampers [86]. Typical fracture modes of the specimens can be seen in Figure 5 [86]. Using this concept, Matteis et al. [87] studied the seismic response of MR steel frames with low-yield steel shear panels.

In the research works afterwards, Chan et al. [77] investigated a new earthquake damper, called yielding shear panel device (YSPD), for civil structures. This system was capable to dissipate the seismic energy through the plastic shear deformation of an external diaphragm steel plate that was welded inside a square hollow section. As mentioned before in this section, a metallic shear panel damper is commonly designed using low-yield-strength steel, owing to its high ductility [88, 89]. In this regard, Ming-hasiang et al. [61] reported that steel shear plate device with a low yield strength was capable of dissipating or absorbing input energy in a stable behavior. In order to simulate the hysteretic behavior of this device, the authors developed an analytical model and displayed the fact that the model was valid for simulating the reciprocal energy dissipation behavior. Dusicka et al. [90] investigated the cyclic behavior of a steel plate damper under large inelastic strains with constant amplitudes between 1% and 7%. Study of different types of steel plates found that their fatigue life at low cycles was similar and that the strain rate had no significant effect on that. For conventional grade steel, the maximum cyclic stress exceeded the yield strength by approximately 2.0 times; for low yield point steel, it exceeded by 4.8 times. In response to the maximum cyclic stress, it was found that the manufacturing specifications were more important than the yield strength. Similarly, Aoki et al. [91, 92] performed a dynamic shear test of low-yield steel panel dampers to evaluate their seismic performance. In another study, YSPD finite element models were developed by Hossain et al. [73] using ANSYS. Additionally, Zhang et al. [93, 94] have previously focused on development and testing of a low-yield-strength steel shear panel damper (LYSPD) with an elongation ratio of around 60%. In addition to static and dynamic constant cyclic tests, further research was conducted on the performance characteristics of the developed LYSPD, including fatigue characteristics. Based on the test results, it appeared that the seismic performance of the LYSPD was likely to be underestimated by static tests. Dynamic tests were therefore necessary to ensure the reliability of LYSPD.

It should be noted that Narayanan et al. [95, 96] investigated the concept of perforated plates. Notably, it was reported that Chan et al. [97] in order to develop a new yielding shear panel device, perforated a thin yielding shear panel and welded it inside a short length square hollow section. It is considered a modified version of the Yielding Shear Panel Device (YSPD). This device is known as a Perforated Yielding Shear Panel Device

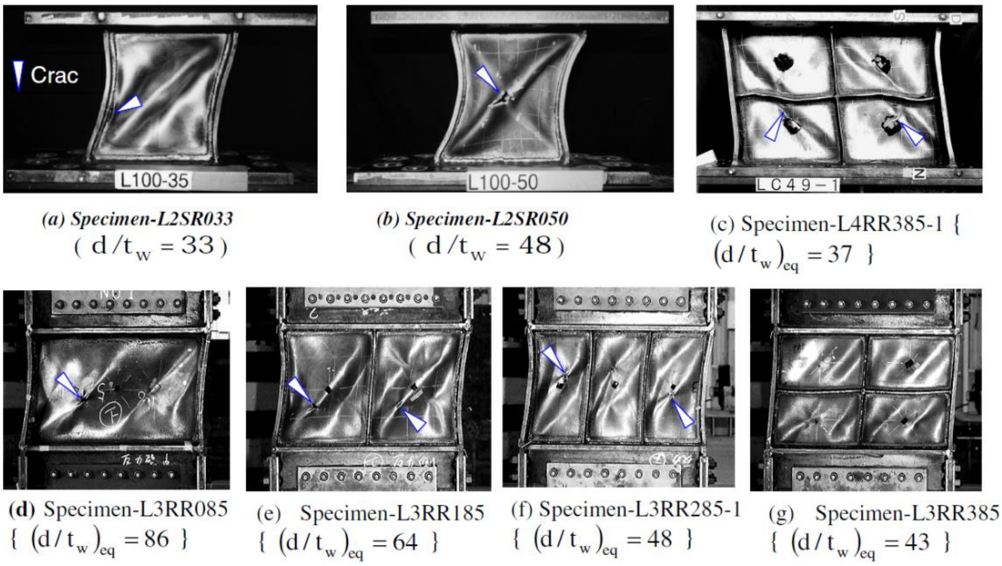
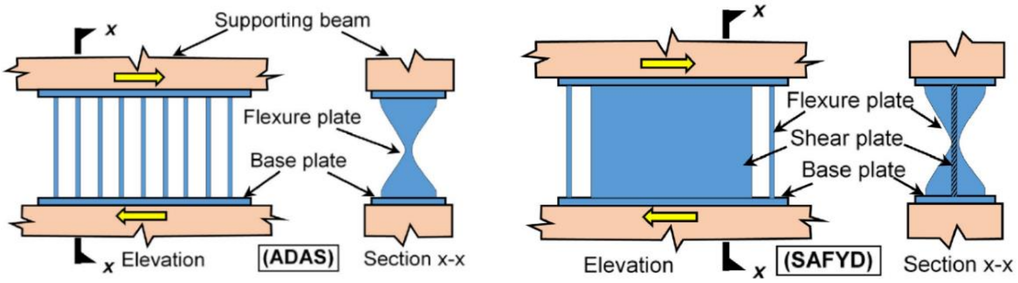


Figure 5. Fracture modes of the shear panel samples [86]

(PYSPD). The energy dissipation capability of devices with certain plate slenderness was large under quasi-static conditions and was characterized by a stable and repeatable force-displacement hysteresis. A perforated specimen has a lower elastic stiffness and yield strength than one that is not perforated. Due to the lack of study on the shape of the steel shear panel damper plate (SSPD), with the use of the finite element method, Liu and Shimoda [98] and Deng et al. [99] presented a shape optimization method for improving the deformation capacity [98] and the low cycle fatigue performance [99] of steel shear panel dampers. Using a shape optimization approach, a shear panel damper could be significantly improved in terms of deformation capacity. Moreover, a significant improvement in the low cycle fatigue performance of the SSPD was found, and the global optimal solution was found to be more effective than the local optimal solution [99]. Later, in a study by Sahoo et al. [100], an experimental investigations was conducted on a passive energy dissipation device made of steel plates that were capable of yielding under cyclic loads both in flexure and shear. It was possible to dissipate energy through shear yielding on the rectangular web plate of the device while two end plates in an X-configuration were allowed to yield under flexural action (see Figure 6). The device was called SAFYD in brief. For the same level of lateral strength and energy dissipation, SAFYD devices could save considerable materials and costs. It was found that the hysteretic energy could be dissipated at drift levels up to 12.5% without fracture by X-shaped flexural plates and reentrant corners in SAFYD devices [100].

In a similar study by Zhu et al. [101] it was proved that optimized dampers exhibit a much more uniform distribution of plastic deformation than the non-optimized dampers, and the stress concentration was significantly reduced as compared to the non-optimized dampers. Whilst, Shi et al. [102] developed a theoretical model of the shape gradient function by using the Lagrange multiplier method that takes into account optimality conditions for maximizing the plastic work. The developed shape optimization method to design



(a) (b)

Figure 6. (a) ADAS device; (b) SAFYD device [100]

SPDs made of low yield steel was applied and results of the study indicated that the optimization method developed by the researchers enhanced the plastic work of SPDs effectively. In addition, this method had the advantage of allowing SPDs to be designed more efficiently when thickness variation was taken into account. Figure 7 presents a view of the low yield steel shear panel dampers, which includes an initial shape (Figure 7(a)) and the optimal shape without considering thickness variation (Figure 7(b) and (c)). Recently, buckling restrained shear panel damper was modified indirectly by Lin et al. [103] and was called the indirect buckling restrained shear panel damper (IBRSPD). This modified damper consists of stiffeners and energy dissipation units formed from hot-rolled H beams. It was found that the modified damper can reduce the seismic response. It has been indicated that the shear buckling of the core plates and the premature failure of the boundary plates are considered two of the most common challenges associated with shear panel dampers that cause insufficient energy dissipation and undesirable ultra-low cycle fatigue performance.

In a more recent study by Yao et al. [104], steel square tubes were used as out-of-plane stiffeners to support a low-yield-point steel core plate, and a reduced flange plate section was used to limit the fracture damage at the end (see Figure 8(b)). It has been demonstrated that steel perforated shear panel dampers may have detrimental hysteretic performance if pinching effects and softening occur due to cumulative damage caused by lateral-torsional buckling that may occur when plates are excessively thin and delimited by contiguous perforations [105]. Many research works have been conducted to investigate how geometric parameters affect panel hysteretic response, particularly with regard to pinching effects induced by buckling. Among the factors to be considered are the width-thickness ratio, corner perforation, stiffening rib size, perforation diameter, minimum spacing between holes, depth of the non-perforated area, and the boundary constraints of shear panel dampers [81, 105-107]. Moreover, the shear plastic behavior of SPDs was described with and without consideration of the cyclic hardening by Chaofeng et al. [108]. Their developed model is suitable for describing the mechanical properties of large plastic strains. A follow-up study was conducted to determine whether FEM could be used to assess the deformation capacity of a shear panel damper [109].

Steel shear panel dampers are often subject to low cycle fatigue damage near the welded stiffener, which negatively impacts their fatigue performance. In light of this fact, these dampers were stiffened to experience a high-performance. Experimental studies were also conducted on stiffened shear panel dampers in order to develop high-performance damping mechanisms by Koike et al. [110]. In parallel, a buckling restrained shear panel damper (BRSPD) was introduced and proposed as a novel steel shear panel damper by Kailai et al. [111]. In their model, there are two main components of a BRSPD, an energy dissipation plate and two restraining plates. Energy dissipation plates do not have any stiffeners welded to them. Bolts on each side of the two restraining plates prevent out-of-plane buckling of the energy dissipation plate. Based on the results of the tests, it could be concluded that restraining plates of sufficient stiffness and strength can effectively prevent the out-of-plane buckling of the energy dissipation plate [111]. More recently, Quan et al. [112, 113] developed a classical shear panel damper using a corrugated steel plate. As a result of the experimental studies, it was demonstrated that direction of the corrugated shear panel modified the plastic failure modes of the dampers, which resulted in out-of-plane failure of a demountable horizontal corrugated shear panel damper (DCSPD-H) and the local buckling failure of a demountable vertical corrugated shear panel damper (DCSPD-V). Zhao al et. [114, 115] proposed a bent shear panel damper and examined it experimentally and numerically, which can be installed in eccentrically braced composite frames to effectively improve the stiffness and strength of such frames. On other hand, it should be noted that several previous studies have also studied and examined this idea in the context of walls [116-119].

In accordance with the previous research, low-yield-strength steel is typically used for steel shear panel dampers for dissipating or absorbing input energy. Whilst, it has been shown that steel shear panel dampers suffer from local buckling failure, which is considered to be the most common problem associated with shear panel dampers that result in inadequate energy dissipation caused by pinching effects induced by buckling and undesirable ultra-low cycle fatigue performance. In light of this fact, stiffening the shear plate will be helpful in overcoming the challenges associated with this drawback where stiffeners will prevent out-of-plane buckling, which will result in high plastic deformation. A second approach is that the steel shear panels can be perforated to prevent general buckling of the shear plates, thereby developing high performance.

2. 2. Steel Pipe Dampers Pipe dampers are among the steel yielding dampers, which can be utilized as a possible hysteretic damper. This system operates on the principle of passive energy dissipation. Some experimental studies have been conducted to investigate the effect of steel pipes on shear transmission. For instance, Frosch [120] tested the effect of steel pipe connectors on the transfer of shear between precast infill wall panels and concrete elements of the building frame.

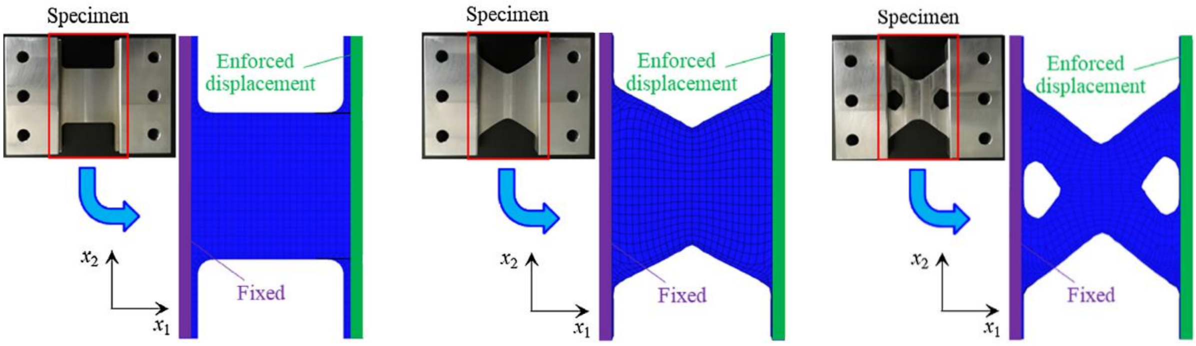


Figure 7. View of low yield steel shear panel dampers (SPDs) [102]: (a) The initial shape; (b) and (c) the optimal shape without considering thickness variation

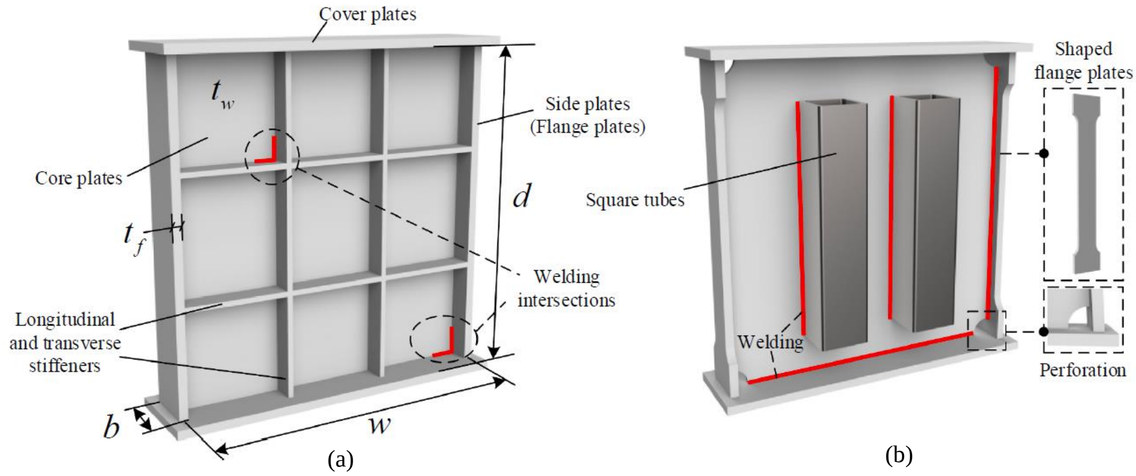


Figure 8. Schematic view of shear panel dampers: (a) with conventional stiffeners [99]; (b) with square steel tubes [104]

As well, Deam et al. [121] investigated transfer of shear force between a concrete slab and a laminated veneer lumber beam using steel pipe. Kafi [122] performed numerical and experimental research on the effects of hollow steel pipes on the seismic behavior of CBFs. It was shown that use of the hollow steel pipe significantly improved the ductility of the frames and delayed buckling of the braces. Maleki and Bagheri [123] studied two types of steel pipe dampers, filled and unfilled with concrete, under a cyclic shear load. Their study aimed to assess whether the segments can be used as seismic dampers. Under severe cyclic shear loading, the bare steel pipes exhibited a stable hysteretic behavior as they could absorb a considerable amount of energy. It has been demonstrated that concrete-filled pipes under shear loading fail in a non-ductile manner due to concrete crushing even though the pipe itself is unharmed. Further, according to Maleki and Mahjoubi [124], a new pipe damper was introduced, which was called the dual-pipe damper (DPD). The DPD was tested and investigated analytically. In order to build the device, two pipes were welded at specific locations and loaded in shear at different points. The pipes dissipate the energy of the inelastic cyclic deformation by flexing their bodies. There are a number of advantages of the DPD, including its light weight, ease of fabrication, and affordability. About 36% of its height can be deformed without losing its structural integrity. In addition, it was reported that a DPD is more efficient than two single pipe dampers in terms of strength, stiffness, and energy dissipation. Installation of DPDs in structures can be classified into four types based on their application, as depicted in Figure 9. In a subsequent study by Maleki and Mahjoubi [125], the two welded pipes had main pipes and inner pipes and the spaces between the pipes were filled with metals such as lead, zinc, etc. This type of pipe dampers is named infilled-pipe damper or IPD. Compared to an equivalent DPD damper, IPD dampers have significantly higher strength and stiffness, as well as higher energy dissipation capacity. Due to the energy absorption properties of lead, the lead-IPD exhibited a superior performance. Furthermore, lead-filled IPDs dissipate more energy than zinc-filled IPDs due to cracks that began forming in zinc during the initial loading cycles. It is generally recommended that the main pipe diameter be 1.5 and 1.40 times the inner pipe diameter for IPDs filled with lead and zinc, respectively. In terms of efficiency and reliability, IPDs with diameter-to-thickness and length-to-diameter ratios of 20 and less than 0.6, respectively, are extremely effective. The single pipe damper and dual-pipe damper can be seen in Figure 10(a). As another example, Javanmardi et al. [126] proposed an innovative vertical pipe damper (VPD) consisting of a short vertical pipe segment welded to two anchor plates. It was found that VPDs possess greater ductility and energy dissipation capability than PDs and DPDs. VPDs are also capable of dissipating energy bidirectionally. An X-shaped pipe damper is constructed by welding two oppositely positioned pipe halves together to form an X-shaped core, and connecting the X-shaped core to the side plates by fillet welds or circumferential welding as depicted in Figure 10(c) [127]. With only half pipe usage, the XPDs can provide similar lateral load resistance as dual pipe dampers. In all cases, the XPD specimens showed stable and bulged hysteretic loops, and showed a steady increase in strength following yielding until fracture failure [127]. There was a general failure at welds in fillet weld specimens, as well as tensile tearing at the pipe plates in circumferential weld specimens.

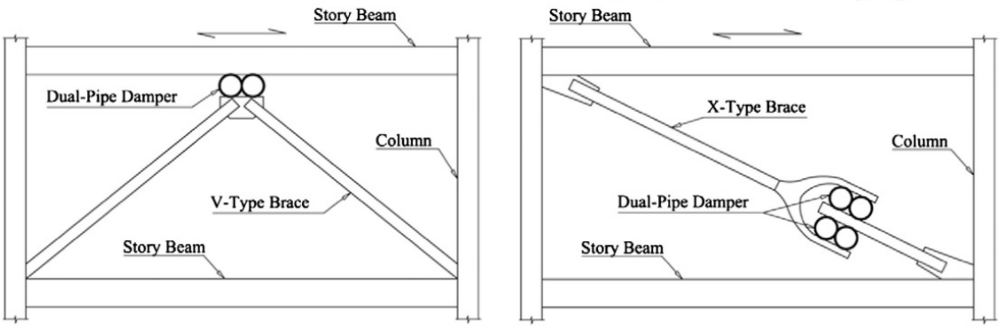


Figure 9. Schematics for DPD installation [124]

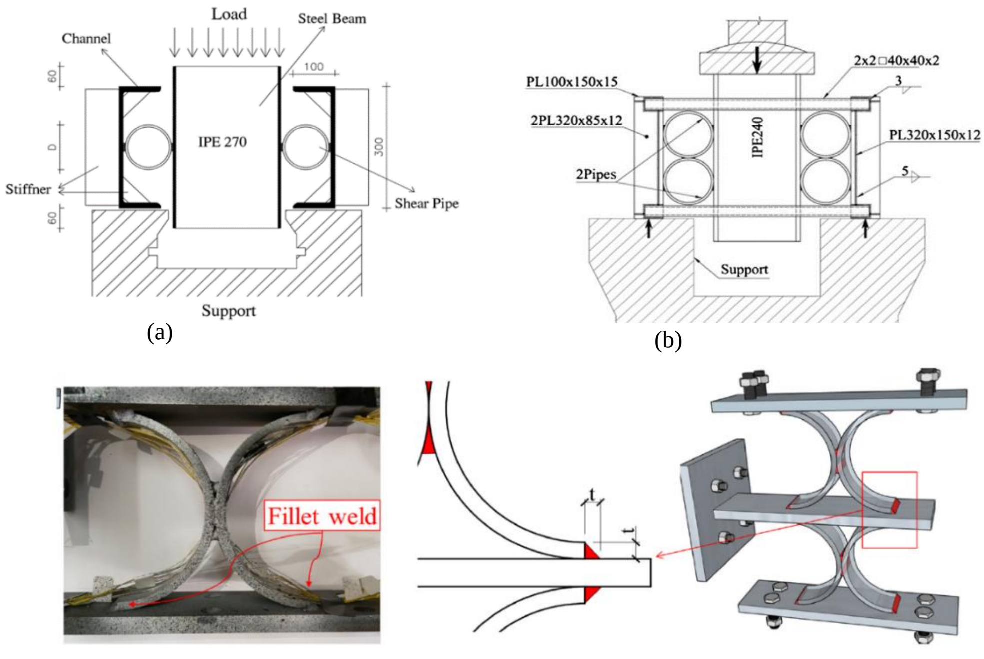


Figure 10. Details of steel pipe damper: (a) single pipe damper; (b) dual-pipe damper; (c) X-shaped pipe dampers

Recently, researchers have been interested in the application of two-level control systems. This system is based on the concept of combining two different control devices with different strengths and stiffness that results in dual seismic behavior as a result of their different energy dissipation levels. This concept has also been applied by using a multi-pipe damper.

Cheraghi and Zahrai [128, 129] evaluated the seismic performance of a multi-level pipe-in-pipe passive control system under cyclic loading analytically and experimentally. Afterwards, the attained hysteresis curves exhibited a highly ductile behavior. In addition, obtained hysteresis curves show that the multilevel system as expected can reliably dissipate energy at different energy levels leading to ductility ratios of about 15 to 37 and equivalent viscous damping ratios of about 36 to 50%. A modification of this system was made by the same authors [130] in another study in which zinc or lead was injected into the inner pipe or a diaphragm was slit within the pipe. According to the results, adding lead infill does not have a considerable effect on damper stiffness, whereas adding zinc infill and slit diaphragm can significantly increase damper stiffness, sometimes up to ten times, depending on the plate thickness and pipe diameter. It was found that the seismic response of steel structures equipped with multi-level pipe dampers [131], MPDs, was reduced and the maximum displacement and roof acceleration were lowered at 19-42% and 11-16%, respectively, in comparison to those of bare frames [131]. A new pipe-fuse damper (PFD) was proposed by Aghlara et al. [34] to enhance the seismic response of structures. This damper has been assessed experimentally and numerically and the location suggested for the installation of PFDs are illustrated in Figure 11. The damper showed a stable hysteretic behavior, easy replacement after each failure, less pinching effects and considerable energy dissipation. The effective dimensions of the pipes used in a DPD were recently developed such that they can be implemented in a steel building frame [132, 133]. It was mentioned that the structures equipped with dual-pipe dampers [132, 133] and multi-pipe dampers exhibited better seismic retrofitting properties than bare frames.

Despite the pipe dampers being able to be manufactured easily without requiring casting or precision cutting tools, making them one of the most cost-effective passive metallic dampers, they have some challenges. To guarantee ductile behavior, mild steel pipes must have high elongation in tensile coupons. A further problem was that cracks originated in the pipe material adjacent to the welds which linked the pipe to the plates, propagated throughout the thickness and length of the pipe, causing the pipe to fail. Therefore, it is important to carefully choose the welding type and position so that this behavior is enhanced. In light of the above, it may be possible to consider better connecting methods such as bolted connections for pipe dampers in future studies.

2. 2. 1. Steel Ring Damper Steel ring dampers have been extensively used to improve seismic performance of structures. The use of steel ring dampers as passive seismic dampers has been confirmed by several studies [134-138]. Single and dual-ring damper have been sketched in Figure 12(a and b), respectively. A new system comprising one or two concentric steel rings installed vertically within cross-braced bays was proposed by Behnamfar et al. [138] This system was capable of increasing the ductility of cross-braced frames to levels comparable to those seen in ductile moment frames. It has been designed so that the steel rings fail in bending before the braces fail in compression. In this case, the rings serve as seismic fuses with multiple bending plastic hinges. Studies based on nonlinear pushover and cyclic analyses suggested the desirable use of the proposed system.

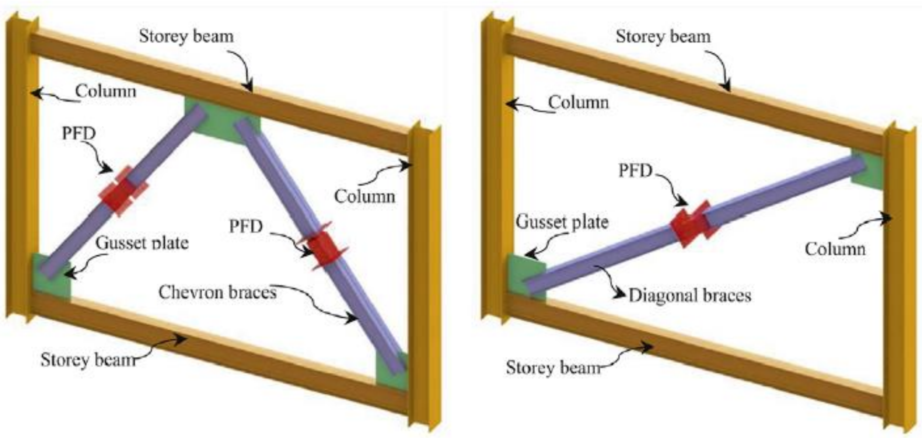
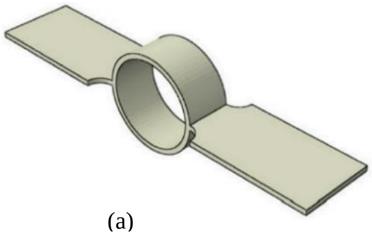


Figure 11. Location suggested for the installation of the pipe-fuse damper [34]


(a)

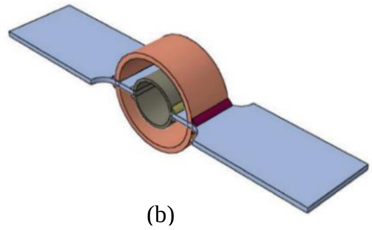

(b)

Figure 12. Steel ring dampers; (a) single ring; (b) dual-ring

2. 3. Steel Curved Dampers

2. 3. 1. Steel U-Shaped Plate Damper

The U-shaped plate damper has been invented by Kelly et al. [48] in 1972. It is a very simple damper. The strip begins in a semicircular configuration with two equal straight sections on either side. Once one side is moved relative to the other, the strip will take on a semicircular shape. The U-strip damper exhibits very large deformations in the elastic range because it is deformed in one direction. There is a common use for U-shaped dampers in isolation system. It starts working when the isolation layer is subjected to a relative displacement. Importance of seismic isolation systems in the world has been widely acknowledged following the Hanshin-Awaji (Kobe) earthquake. In this context, the displacement of isolators can be controlled by adding supplemental damping to the isolation systems. An example is the use of friction in base isolation systems by Abed et al. [139] to reduce structural response and enhance energy dissipation under lateral loads. They mentioned that these systems should be studied under bidirectional loading since further research and study is required before these systems can be implemented in practical applications in real life. Skinner [140] and Yoshikawa et al. [141] applied U-shaped dampers to base isolation systems with rubber bearings, which are described as typical hysteretic dampers. To evaluate the inelastic flexural deformation of U-shaped plates, Shultz and Magana [142] performed a number of experiments. According to Suzuki et al. [143], the horizontal property, velocity and temperature dependence of U-shaped steel dampers were discussed, as well as the results of experiments [143]. In a study by Kishiki et al. [144], a U-shaped damper that was capable of being used with an isolation bearing was designed (Figure 13(a)). In order to reduce the seismic demands of low- or medium-rise structures, Sang-Hoon et al. [145, 146] developed a base isolating system. This system was studied experimentally using shake table tests. In the study, they [145, 146] considered a base isolating system comprising of laminated-rubber bearings and U-shaped hysteretic (UH) dampers made of high toughness steel (HTS), and which are fabricated with slotted holes to increase deformation resistance. According to a shake-table test, a base-isolated structure with UH dampers could limit its seismic demands by extending the structural period. In addition, U-shaped dampers have been added to the beam-column connection by Iwasaki et al. [147]. Tagawa and Gao [148] added this system to frames. The system depletes seismic energy into the structure by yielding U-shaped steel dampers (Figure 13(b)). As reported by Deng et al. [149], in their study, an innovative crawler steel damper was designed and installed in bridges, which can work with isolation bearings. The damper was composed of two U-shaped steel energy dissipation plates connected by two connection plates, and each U-shaped plate was bolted to the upper and lower connection plates. Among the most important controls on the damper performance are the thickness and height of the plates used for energy dissipation. According to Figure 13(C), plates were arranged according to a specific pattern. It was recommended that shape optimization be implemented in order to improve the hysteretic performance of the U-shaped damper [150].

Atasever et al. [151, 152] modeled the hysteretic behavior of U-shaped dampers (UDs) by ABAQUS finite element software and developed U-shaped steel dampers with perforated and nonparallel arm configurations (Figure 14). According to their study [151, 152], the developed damper device could be used in seismic applications. Qu et al. [153] introduced and described a new replaceable U-shaped steel damper. Stable hysteretic behaviors and satisfactory energy-dissipating capacities were obtained from their test results. In addition to being robust, the damper was also rupture-tolerant and it was demonstrated that the damper that was repaired following a severe earthquake by replacing the U-shaped steel plates continued to operate satisfactorily in the event of another earthquake. From an applied point of view, to combine the advantages of the yielding dampers and the buckling resistant braces (BRB), U-shaped dampers were utilized in braces by Taiyari et al. [154]. After several cycles of large inelastic deformations, the bracing system remained stable and dissipated energy well. More recently, U-shape dampers were added to a steel tank isolated by multiple friction pendulum bearings, which were studied by Yu et al. [155] where their effects on earthquake responses of an isolated inner steel tank were investigated. It was found that the U-shaped dampers were effective at controlling the displacement of the isolators.

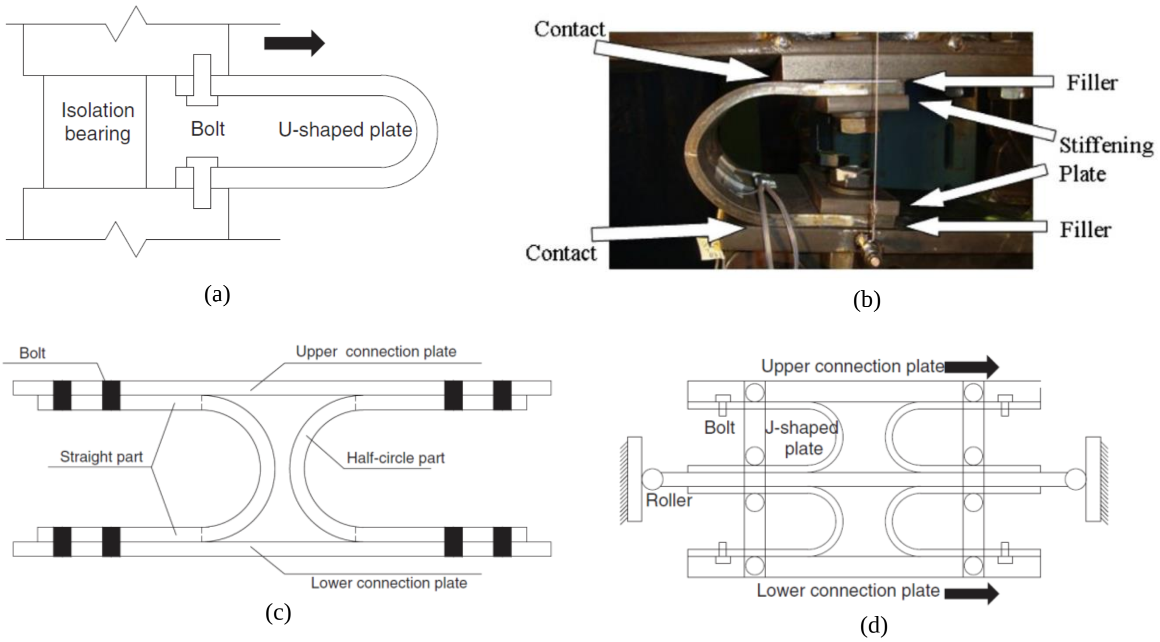


Figure 13. (a) U-shaped damper for bridges; (b) U-shaped damper under compression deformation; (c) Crawler steel damper and (d) schematic view of J-shaped damper

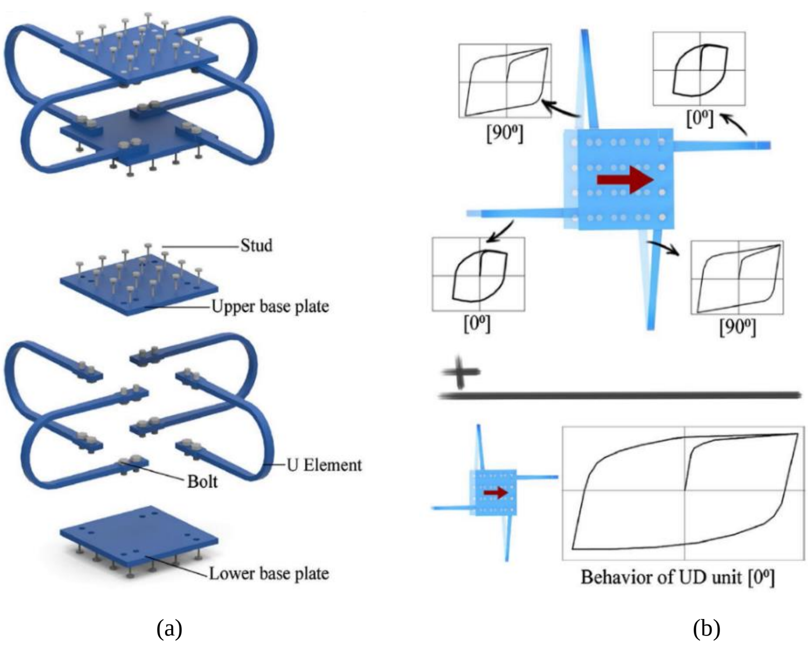


Figure 14. (a) configuration of UD; (b) hysteretic behavior of the UDs [151]

It is concluded from the previous results that the height and thickness of the U plates are the two most important factors that affect the dampers' performance where increasing thickness increases dissipation capacity, yield force, and initial stiffness, while increasing height decreases the mentioned parameters. In cases where higher levels of strength and energy dissipation capacities are required for the damper, either thicker U-shaped steel plates can be used or U elements can be added or subtracted easily to modify seismic characteristics. The results of the tests indicate that the damper has a high level of robustness and is not easily damaged by ruptures in the U-shaped steel plates. Ultimately, a further investigation on the influence of the thickness of the U-shaped steel plate on the fatigue life of the corresponding damper will be required in the future.

2. 3. 2. Steel Cushions Damper Steel cushions were invented by Özkaynak [156] and tested experimentally. In theory, they were supposed to be installed between chevron-type bracing elements and beams within an RC frame. It was determined by the numerical and experimental investigation that the steel cushions enhanced the RC frame's energy dissipation and damping properties.

2. 3. 3. Steel J-Shaped Damper Conventional approaches to earthquake-resistant building design are based on the assumption that the building's strength, stiffness, and inelastic deformation capacity are sufficient to withstand the effects of an earthquake at a given level. In most modern structures, however, seismic energy is mitigated before it reaches the structural elements as part of the modern approach.

The J-dampers were invented by Kato et al. [157, 158] in 2005 and used in a spatial structure at a location between the upper structure and the substructure of the system. It was demonstrated that J-dampers can experience large deformations during severe earthquakes. Following this study, hysteresis devices designed in the shape of Js were discussed in terms of their mechanical properties [159]. Figure 13(d) illustrates the schematic view of the J-shaped damper.

In addition, for the sake of practical applications, using steel cushions, and U- and J-shaped steel plates with longitudinally slotted holes on one flange makes the damper easy to install. Meanwhile, premature ruptures were observed at perforated plate cross-sections due to concentric plate yielding. As a consequence, it is essential to design the working flange width in accordance with the maximum probable displacement demands on the damper.

2. 3. 4. S-Shaped Steel Plate Damper Zhai el at. [160] have developed a new metallic structural fuse for seismic resistant applications. This device is known as an S-shaped steel plate damper (SSPD), which has been tested experimentally and numerically. SSPDs are constructed from two S-shaped plates, which are easy to fabricate, install, inspect, and replace. The related damper, SSPD, is demonstrated in Figure 15. An S-shaped arc plate deforms flexibly in the plastic zone when it experiences small or medium displacements. This enables seismic energy to be dissipated. When a relatively large displacement is present, deformation changes from a flexural to a tensile pattern. There is a stable hysteresis loop characteristic for the SSPD, good energy dissipation and large deformation and ductility capacity. The predominant failure mode is characterized by fractures of the end plates as well as squeezed indents when there is a large displacement at which the fatigue performance becomes more critical. Dampers possess properties such as high strength-to-mass ratios, secondary stiffness, and overstrength coefficients as well as stable flexural-tensile behavior. In a study by Wang et al. [161], the axial tension and compression corrugated steel plate damper (ATCCSPD) was proposed for applications in axial tension and compression. It was demonstrated that the ATCCSPD specimens have stable and exhibit full hysteretic curves, as well as a satisfactory degree of ductility and energy dissipation capacity. The proposed formula was found to be conservative when compared with the test results and, therefore, suitable for engineering applications.

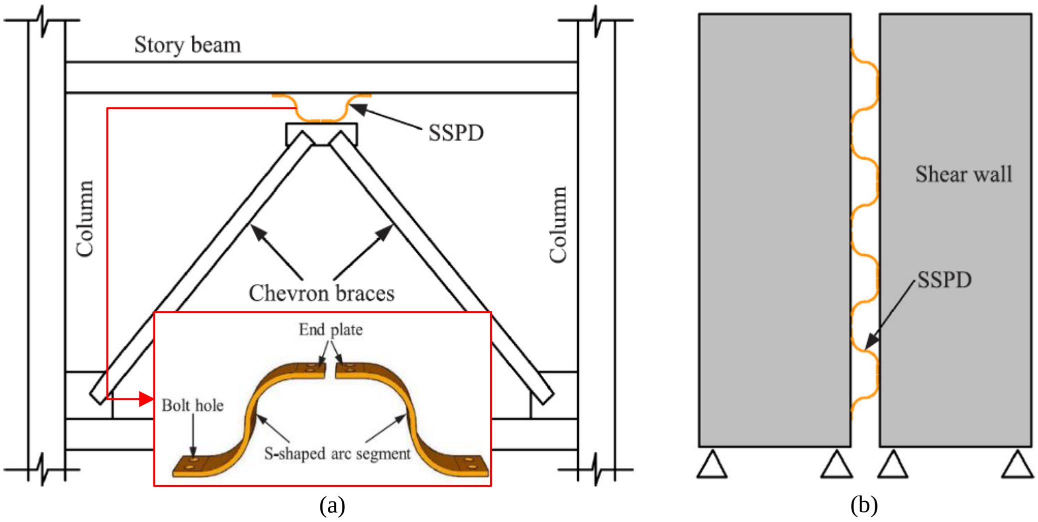


Figure 15. The potential applications of SSPD [160]: (a) Chevron braced frame equipped with SSPD; (b) Rocking wall system

The discussed U-shaped, J-shaped, and S-shaped steel plate dampers have the benefit of avoiding the drawbacks associated with standard damper systems that are commonly used with chevron bracing. On the other hand, these dampers have not been investigated regarding problems related to the use of them in braces. In order to assess design criteria for codification and practical applications, further experiments and numerical analyses of this scenario are needed in order to reach the final outcome.

2. 3. 5. Steel Curved Damper A metallic damper dispenses energy satisfactorily, is inexpensive, and is easy to install, which makes it widely used. In various applications, structural curved steel dampers are used to effectively mitigate damages at specific points in the structure. It has been highlighted that the shape of a curved-shaped damper determines the stability and saturation of hysteretic behavior in the in-plane direction [162]. The length and angle between the two ends of a curved damper influence its behavior. Curved plate dampers have three main parameters: thickness (t), width (b), and radius (R) and there is a relationship between the damper performance and these parameters.

A new generation of steel dampers was suggested and introduced by Hsu and Halim [163] by completing their previous investigation on knee braces, which is known as steel curved damper. Hsu and Halim [163] designed and installed this damper in moment-resisting frames. Steel plates are used to fabricate the damper, which has a curved shape. Afterwards, an experiment was conducted to test the performance of the damper in a beam-to-column connection. A result of the lateral movement was generation of eccentricity within the curved damper, which consequently increased the lateral stiffness of the beam-column connection. Based on the test results, it was proved that a smaller damper angle increased the frame strength. Moreover, the test results showed that the curved dampers significantly improved the strength, stiffness, and energy dissipation of the moment resisting frames when they were installed. Also, the curved damper was applied in a braced frame by Hsu and Halim [164]. The new brace equipped with the curved damper (see Figure 16(a)) displayed a significant viscous damping ratio of approximately 26–37%. It was found that the new system tolerated story drifts of around 5% without significant deterioration in strength, and displayed stable hysteretic behavior throughout the complete loading process, especially when the plate depth/thickness ratios of the curved dampers were lower than 4. Specifically, the curved plate damper was studied analytically and experimentally by Zheng et al. [165], and key parameters of the curved plate damper were derived, including elastic lateral stiffness, yield strength, and yield displacement. Based on the results of the investigation, it was determined that the damper had a large initial stiffness, that no obvious damage was present, and that the hysteresis loop was full. In terms of deformation and energy dissipation, the dampers tested performed well.

Afterwards, Ghabussi et al. [166, 167] used this damper in frame structures to improve their seismic performance. In both the pitched roof symmetric portal frame and the mono pitch portal frame, dampers with a 30° and 60° angle were most effective at reducing energy dissipation and maintaining frame strength. Additionally, both types of portal frames showed marked improvements in seismic performance. Figure 16 illustrates the use of a curved damper in the braced frame and beam-to-column connections of the building, which can significantly improve the stiffness and ductility of the structure.

A combined damper was proposed by Shojaeifar et al. [168], which is combined of triangular added damping and stiffness (TADAS) dampers in combination with curved dampers and is called Curved-TADAS damper (Figure 17). This combined damper was installed in a moment resisting steel frame (MRSF) in the beam-column connection region and its seismic performance was assessed numerically using the finite element method by ABAQUS. Width of the curved damper, thickness of the TADAS damper and number of the TADAS dampers were considered as variable parameters. Based on the results of the study [168], Curved-TADAS dampers were successfully used to reduce structural responses to seismic loads and prevent structural failure as a result of dissipation of a large amount of seismic energy.

Furthermore, Using the recently developed curved dampers (CDs) with conventional steel trusses, a novel system called "curved damper truss moment frame" (CDTMF) was developed by Fathizadeh el at. [169, 170]. An illustration of the geometry of the curved damper truss moment frame can be seen in Figure 18. A comparison of this system was made with the recently proposed buckling restrained knee braced truss moment frame (BRKBTMF) system. Based on the results of the pushover analysis, CDTMF structures were much more ductile and have higher energy dissipation capacities than BRKBTMF structures. In a follow-up study by Fathizadeh el at. [171], seismic responses of multi-story buildings equipped with CDSRMFs were examined through the use of both nonlinear static and nonlinear dynamic analyses. Added curved dampers significantly enhanced the stiffness, strength, and energy dissipation of CDSRMFs compared to RMF and SRMF structures. For instance, there has been an increase of more than 100% in the energy absorption capacity of three-story CDSRMF structures compared to SRMF structures, followed by an increase of more than 190% for six- and

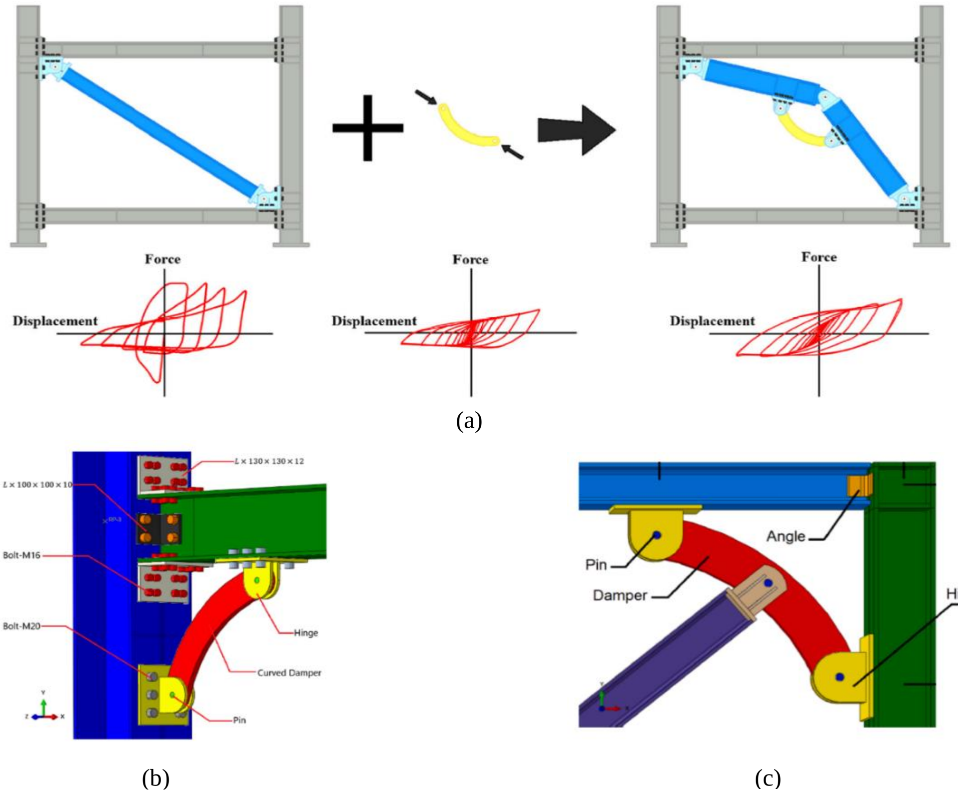


Figure 16. (a) brace with steel curved damper; (b) semi-rigid frame equipped with 60° steel curved damper (SRF-SCD); (c) braced frame equipped with steel curved dampers

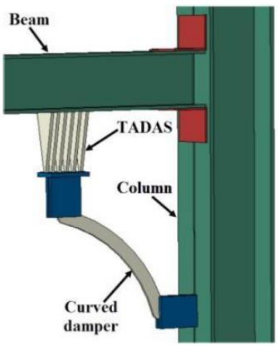


Figure 17. Curved-TADAS damper [168]

nine-story CDSRMF structures. Finally, based on the performed research tasks, it could be concluded that no visible cracks and no obvious damage were observed in curved dampers during the standard and the fatigue loadings. In addition, full hysteresis loops were observed under both loading conditions. In comparison with the knee system, curved damper elements have proved to be an effective structural fuse that absorbs earthquake energy and is easily interchangeable, as opposed to knee elements, which can form plastic hinges at the joints between the brace and column and the brace and beam.

According to the previous results, a curved steel damper can dissipate energy effectively in seismic applications. A final point worth mentioning is that the choice of the damper dimensions and angle affects seismic performance and can be investigated by optimization algorithms in future research. According to the recommendations, curved dampers should have an angle between 30° and 60°. A 60° damper in the steel-braced frame is the most effective steel curved damper in terms of energy dissipation and frame strength.

2. 4. Steel Slit Dampers There are various types of slit dampers, but on the whole, they are considered to be metallic yielding dampers owing to the fact that their damping behavior is influenced by the yielding of steel in one way or another. Steel slit dampers are the most commonly used passive energy dissipation devices [4]. This type of dampers was developed and applied experimentally by Benavent-Climent et al. [47] who conducted research on steel plate slit dampers subjected to shear deformation and attached to semi-rigid connections. Accordingly, Chan and Albermani [23] proposed installation of a slit steel damper as one of the first slit steel dampers in a V-braced system. They obtained analytical equations to predict the ultimate energy absorption capacity and mentioned that the

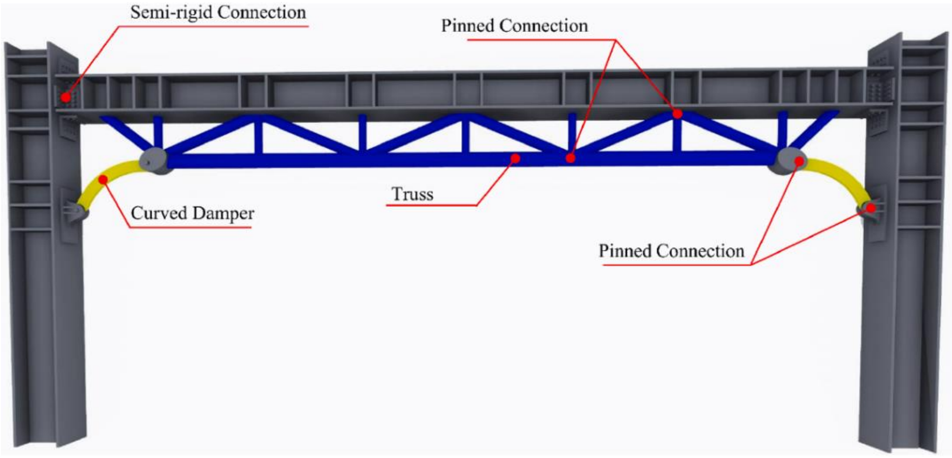


Figure 18. The geometry of the curved damper truss moment frame (CDTMF) [170]

energy dissipation attained could be analytically predicted and in fact, it was found that experimental and analytical results were in good agreement. The energy is consumed by these devices as a result of the flexural yielding of their strips evident between the slits when the device undergoes an inelastic cyclic deformation [23, 39, 172-174]. When a sufficient story drift is applied, each strip of the damper bends in double curvature, and therefore accepts plastic hinges at both ends [39]. In Figure 19, an idealized version of a slit damper is illustrated.

Afterwards, these dampers have been expanded in several other studies [173, 176-178]. For example, Benavent and Climent [179] proposed an alternative slit damper in braces that contained a series of strips in a tube-in-tube structure. Moreover, an effective

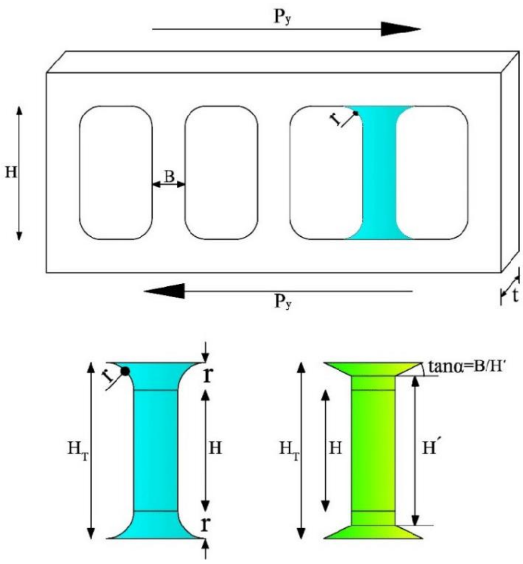


Figure 19. Idealization of a slit damper [175]

configuration was proposed by Ghabraie et al. [177, 180] for solving the strain concentration problem in slit dampers. As a result of using the suggested configuration, the device was able to dissipate more energy and was more resistant to low cycle fatigue. In a study conducted by Vaseghi et al. [181], a buckling restrained brace (BRB) and a tube-in-tube damper (TTD) were individually assessed for retrofitting steel structures. Due to their simplicity in construction and execution, TTD metal dampers have also garnered a great deal of attention in this field. As well as offering better performance than BRB, this damper could also be constructed more easily, leading to lower costs, which made it possible for countries without sophisticated technology to adopt it. In their study, Perform 3D software was used to perform a nonlinear dynamic analysis of the structures before and after retrofitting. As a result of the observation of both systems results, the positive effects of these energy dissipation systems were reduced with an increase in the number of building stories. This indicated that short-order structures are more benefited by such systems. The conductors of another study, Amiri et al [36], proposed a different type of the slit damper, described as a block slit damper. It consists of a box containing a steel block with several slits. In addition to its large shear strength, the damper also showed a high energy dissipation capacity, a stable hysteresis curve, and positive economic characteristics. Askariani et al. [182] suggested using slit link beams in EBFs. Their proposition was to create slits in the web of the link beam so that it could be divided into several vertical strips. An analytical formula was derived and applied in their study to characterize the behavior of the slit link beam. Later, Zhao et al. [183] developed a new damper. In their study [183], a number of slits in the H-profile brace were located along its length in the damper system. According to the results, the perforated webs were yielded under the influence of in-plane shear, which resulted in dissipation of seismic energy. Meanwhile, it also showed full and stable hysteretic curves.

In a recent research by Almohammad-albakkar and Behnamfar [39], in order to modify the seismic behavior of X-CBFs, the authors proposed a system consisting of two cross braces, each divided into two segments. In the middle of the bay, the four segments are connected by means of a grooved gusset plate damper (GGPD). By bending of strips developed in the gusset plate in its plane, strips in the GGPD dissipate the seismic energy. A mathematical formula was provided for determining the elastic stiffness as well as the yield and ultimate capacities of the damper. As a result of the calculations, it could be concluded that the analytical formulas and the numerical results were in good agreement. Further, specimens displayed full and stable hysteresis curves, and they behaved similarly in tension and compression. This system is also capable of dissipating significant amounts of energy and can tolerate more than 4% story drifts [39]. As shown in Figure 20, the cross-braced frame equipped with GGPDs undergoes no plastic deformation when subjected to lateral loads (Figure 20(b)).

Using slit dampers in the beam-to-column connections was also considered and applied. Specifically, after suffering of several steel buildings from severe damage during the Northridge (1994) and Kobe (1995) earthquakes, which had been designed firmly to prevent collapse, avoiding human deaths [184, 185]. A considerable amount of damage occurred at the welded connections between the beams and columns, including brittle fractures. Although there was no way to avoid this type of damage for older steel structures that had nonductile connections, it also occurred in some relatively new buildings designed in compliance with current seismic codes [186, 187]. Following the Northridge earthquake and the Kobe earthquake, significant experimental programs were implemented on beam-to-column connections and many improvements were applied [188-192].

In order for steel structures to be considered ductile and strong, beam-to-column connections must be able to achieve the same performance. It is important to note that classical steel connections have a limited rotational capacity due to their design. In this way, as mentioned above, the connection could fail prematurely and in a brittle manner before the plastic hinge could be formed

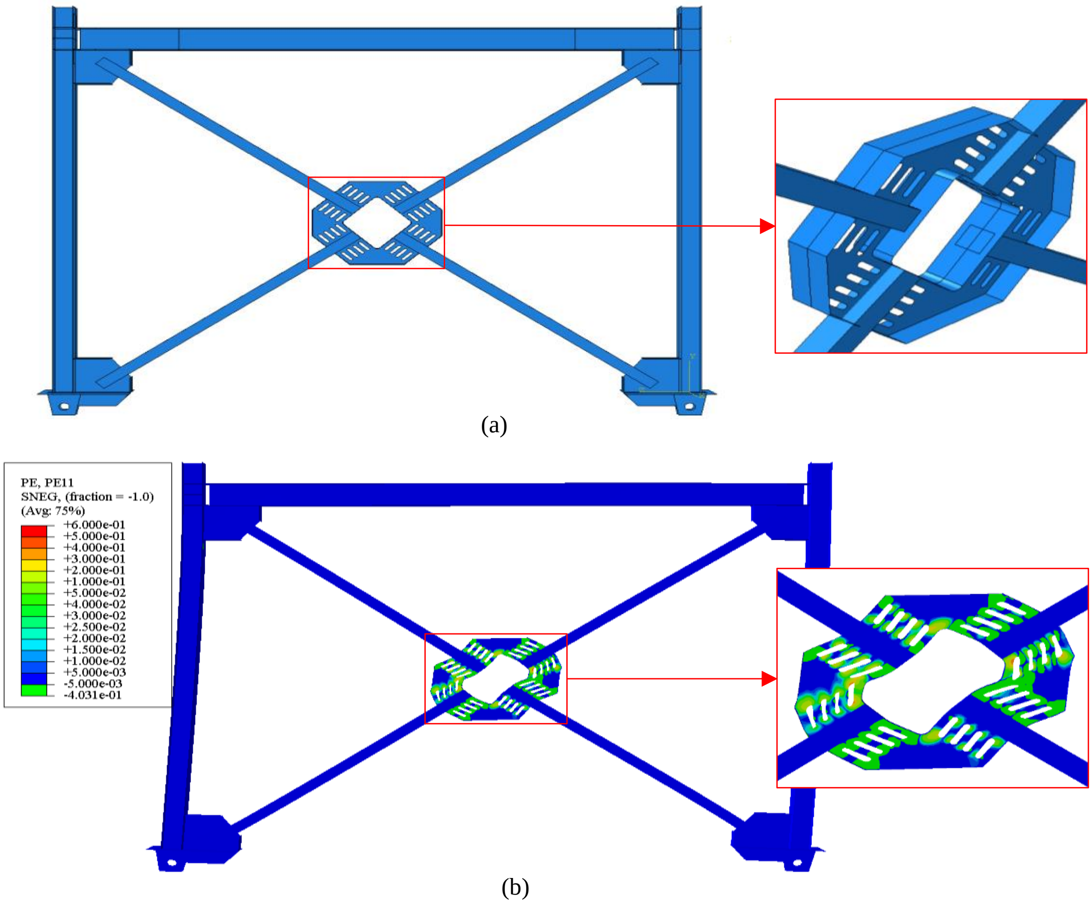


Figure 20. (a) cross-braced frame equipped with the GGPD; (b) distribution of plastic strain in GGPD [39]

in the beam, which is contrary to the principle of a "weak beam with a strong column". It was proposed during these years that methods could be employed involving reducing the beam sections or strengthening the connections by dampers to provide rotation, stiffness, and strength at the proper level. Therefore, a number of studies have been conducted on the causes of premature and brittle failure of steel connections [193, 194]. In light of this, it would be considered a suitable option to design the moment connection using the plastic behavior of beam or additional devices. As has been mentioned in the previous section, to create a plastic hinge in a beam, an approach was developed by reducing the beam section where a part of the beam flange [195-199] or the beam web [200] was deliberately cut. This concept was first proposed and applied by Plumier in 1990 [201] through creating trapezoidal cut profiles in the beam flanges.

Considering the recent dampers, steel slit dampers are the most widely used. This damper has first been developed and applied in the beam-to-column connections by Oh et al. [173]. According to these authors, a slit damper was installed at the bottom beam flange to absorb seismic energy. One of the major advantages of this system was concentration of plastic deformation at the bottom of the flange in the slit damper. For the verification of the seismic performance of the proposed connection, specimens with conventional welded frame structures were cyclically tested along with three full-scale steel structures fitted with slit dampers. The seismic behavior of beam-to-column connections was studied in a similar study conducted by Shahri and Mousavi [174]. Elliptic slit dampers were installed at the bottom of the beam flange. The effect of steel slit dampers on beam-to-column connections was investigated experimentally and numerically by Köken and Köroğlu [202]. The same authors [203] have also tested beam to column connections with different shapes of steel slit dampers in another study [203] under cyclic loading in both experimental and numerical experiments. It was concluded that the steel slit dampers can enhance several performance characteristics of the connections, including energy dissipation capacity, hysteretic behavior, and stiffness. Park and Oh [204] described an innovative connection. The proposed connection consists of two main components, which are the upper and lower connectors (see Figure 21). The beam and column were connected by bolts and the mentioned connectors. The lower part is a horizontally arranged steel slit damper that is used to absorb energy. It was found that when the connection is equipped with the proposed system, the plastic deformation is primarily concentrated in the damper. In addition, it was discovered that the hysteresis loops of the proposed connection had a similarly stable behavior in both negative and positive directions. This system complies with the SMF requirements since the full plastic moment of the beam was reached at a rotation angle of 0.04 rad. Therefore, this system can provide a design methodology for low- and mid-rise steel structures.

As a high-performance hysteretic damper, there are several characteristics that distinguish slit dampers from other types of dampers, including strength, ductility, and dissipative ability, which can be adjusted by altering the configuration of the slits. Additionally, these dampers are also distinguished by advantages over other dampers with their ability to be used for braced frames, beam-to-column connections, and shear walls. This makes slit dampers the most commonly used steel yielding dampers in steel structures. More importantly, slit dampers can be configured in several ways, including prismatic and hourglass configurations, which are very effective. Alternatively, it is possible to improve seismic performance of the slit dampers by obtaining their optimal shape. For beam-to-column connections, the effect of the beam effective length and bolt tightening force, etc., should be investigated in follow-up studies.

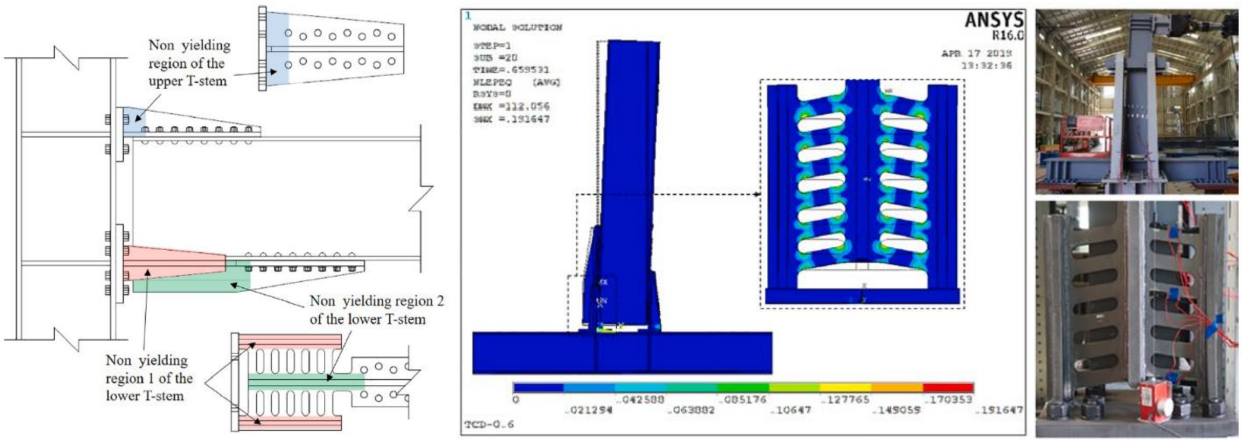


Figure 21. Distribution of the PEEQ and test ultimate state at a rotation angle of 0.04 rad of the proposed connection [204]

Generally, SSDs with short heights tend to buckle due to their shear behavior. It is a fundamental weakness of SSDs that needs to be addressed.

There is another kind of the yielding damper, referred to as the bar damper. This damper can be used for frame structures. The BDs are constructed from steel sections that are commonly used in the steel industry, such as hot-rolled Square Hollow Sections (SHS), C-Channels, plates, and bars [205]. An innovative form of this hysteretic metallic damper was developed by Ghaedi et al. [206, 207], called a bar damper (BD), which is composed of a number of solid bars sandwiched between two plates. As a result of flexural yielding, BD causes input energy due to vibration loads to be dissipated by the solid bars. It should be noted that the damper, despite its simplicity, can be optimized more by optimizing the geometry of the plates and the solid bars in order to ensure uniform stress and strain distributions. From the hysteresis loops of the tested specimens, a substantial cumulative displacement was obtained without significant loss of strength. A new device called fuse-bar damper (BFD) has been proposed by Aghlara and Tahir [205]. The device dissipates energy through use of replaceable bars that act as sacrificial elements. In addition to being economical and easy to install, it also doesn't require any special fabrication techniques. Round steel bars are used as energy absorbing components in the BFD, and these can be easily replaced if they are damaged. Under cyclic loads, this device exhibits stable hysteretic behavior with two important features: adequate energy dissipation and replaceable fuse parts. These factors make this device useful for protecting structures from plastic deformation and failure in multiple situations. In this regard, the BFD is capable of acting as a passive seismic damper.

3. EVALUATION OF THE SEISMIC PERFORMANCE OF STEEL YIELDING DAMPERS

3. 1. Testing Methods Based on FEMA 461 [208], there are two tests that can be applied to assess the seismic performance of steel yielding dampers: (1) the quasi-static cyclic test and (2) the shaking table test. Outcomes of these tests, which are performed on steel yielding dampers, determine the mechanical factors of steel yielding dampers such as yield displacement (Δy), ultimate displacement (Δu), yield strength (Py), ultimate strength (Pu), and ductility (μ). By analyzing the hysteresis curves of these dampers, the required information will be obtained and the seismic performance will be evaluated. A steel yielding device is tested in a quasi-static manner on its own or on a structure that is equipped with such a device. Cyclical quasi-static tests are standard procedures for determining the energy dissipating capacity of devices under deformation [208]. The quasi-static cyclic test is a displacement control procedure that involves multiple incremental or constant amplitudes of displacement cycles under testing conditions that include shear, bending, or torsion. Conversely, shaking table tests require dampers to be assembled on a scaled or full-scale structure, depending on the size of the shaking table. A ground motion record could be artificial or actual, depending on the input loading used in the test.

3. 2. Loading Protocols Several loading protocols are more common for steel structures tests, including FEMA 461 [209], SAC [210], AISC 2005 [211], and ATC-24 [212]. In general, FEMA 461 (2007) has been created and developed for testing of drift sensitive nonstructural components and can be applied for testing of drift sensitive structural components such as dampers. In this case, the maximum amplitude of deformation is targeted as Δ_m and the loading begins with $a1=0.048\Delta_m$, and $a_i+1=1.4a_i$. It is recommended to apply two cycles per amplitude. Targeted maximum deformation amplitude, Δ_m, can be obtained from a monotonic test where a value 0.03 is recommended in terms of story drift index (δ/h) [213]. In accordance with AISC 2005, cyclic loading protocols are expressed in terms of inter-story drift angle. The characteristics of this protocol is descripted in Table 1. For testing beam-to-column moment connections in special or intermediate moment frames, the American Institute of Steel Construction recommends using this loading protocol. The SAC protocol described here is identical to that used by AISC 2005 to test beam-to-column connections. As a result of the observed Northridge weld fractures that occurred before yielding, SAC and AISC include more small elastic cycles [214]. One of the first formal protocols developed for evaluating the seismic performance of steel components using a cyclic loading history was the ATC-24, which was specifically applied for steel structures components. In this case, the amplitude of deformation is based on the yield displacement, Δ_y, which can be calculated from a monotonic test.

3. 3. Hysteresis Behavior A bilinear or trilinear elastoplastic model is often used to simplify the stress-strain relationship of steel materials. Steel yielding dampers may exhibit slightly different hysteretic behavior depending on their geometry. There is a similarity in the hysteresis trends of steel yielding dampers [38, 215]. An overview of the hysteresis loops of steel materials can be found in Figure 22 [38]. Steel material has a nonlinear behavior, which makes their hysteretic properties beneficial for dissipating dynamic energy, particularly in linear systems. In response to static loading, steel material undergoes plasticization when their elastic limit (Δ_y) is exceeded, and if the level of stress is increased, it undergoes stress hardening.

TABLE 1. Number of cycles and amplitudes of loading protocols

Step	Amplitudes				Number of cycles			
	FEMA [a_i/Δ_m]	SAC [rad]	AISC [rad]	ATC [Δ_y]	FEMA	SAC	AISC	ATC
1	0.048	0.00375	0.00375	Δ_y	4	6	6	3
2	1.4(0.048)	0.005	0.005	$2\Delta_y$	2	6	6	3
3	2.8(0.048)	0.0075	0.0075	$3\Delta_y$	2	6	6	3
4	4.2(0.048)	0.01	0.01	$4\Delta_y$	2	4	4	3
5	5.6(0.048)	0.015	0.015	$5\Delta_y$	2	2	2	3
6	7(0.048)[a]	0.02[b]	0.02[b]	$6\Delta_y$[c]	2	2	2	3

[a]Keep with increments of $a_{i+1}=1.4a_i$, and apply two cycles at each step
[b]Keep with increments of 0.01 rad, and apply two cycles at each step
[c]Keep with increments of $1\Delta_y$, and apply three cycles at each step

When a material is loaded cyclically, its elastic modulus (E) recovers as it is unloaded. In this context, when a material is subjected to a load in the opposite direction, this will lead to it yielding and softening at a lower stress level than its yield stress. This effect is called the Bauschinger effect [216]. Despite hysteretic behavior, the steel material can keep performing as long as the strain is not greater than the yield plateau, and the maximum positive and negative stresses are not greater than the yield stress ($\pm F_y$). Even after unloading from stresses greater than the yield plateau, the material retains its original elastic stiffness. All in all, when the material reaches the maximum strain, the Bauschinger effect will be more dramatic. In this range of cyclic loading, the material offers a certain level of post-yield stiffness, and the yield plateau disappears [216].

4. COMPARSION WITH OTHER DEVICES

Based on all previous discussions, results, and test observations, it can be said that steel yielding dampers, besides being inexpensive, easy to install, and less affected by temperature, are also easy to maintain, as a result, they can be used for all kinds of building structures. In addition, they are effective and economical for reinforcing and reconstructing existing and new structures. In general, as a result of elastic-plastic deformation of steel materials, the steel dampers can absorb and consume energy. The design and construction of earthquake-resistant structures is the most important factor in preventing human and financial losses due to the high energy of this natural disaster. As discussed in previous sections, the use of yielding dampers in recent decades has been suggested by researchers as one of the best ways to absorb and dissipate this destructive energy. In comparison to other passive energy dissipation devices, the steel yielding damper has a relatively larger hysteretic loop than its counterparts, indicating that it is capable of dissipating more energy per cycle. Additionally, performance of these devices is not affected by the ambient temperature [10]. In addition to increase of energy dissipation capacity, it should be highlighted that the simplicity in implementation, low cost, ease of adjustment, high speed of repair and replacement after an earthquake are among the other advantages of these damper [217]. Moreover, inexpensive maintenance and repair can be considered other benefits of using this new device. Generally, this dissipater not only can exhibit high energy dissipation capacity but also uniform force resistance in tension and compression and their hysteretic behavior are stable [10]. Then. in light of this review, it is noteworthy that this device can be used to design new structures as well as in the seismic improvement of existing structures which is considered another significant advantage. The design capacity of this damper can be easily selected since the number, width, thickness, geometry and shape of their plates can be chosen by the designer which can allow the designer to use the damper with diverse loads, drifts and energy dissipation capacities.

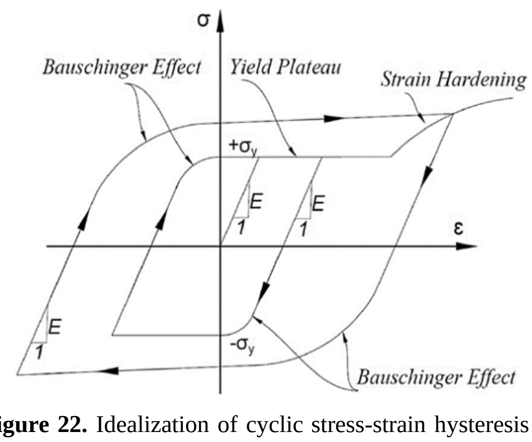


Figure 22. Idealization of cyclic stress-strain hysteresis of steel elements [38]

By comparison, a friction damper has similar characteristics to yielding dampers, including nonlinear behavior, insensitivity to ambient temperature, and stable hysteretic behavior. There are, however, a number of uncertainties associated with sliding surfaces that cause its reliability to be questioned [218]. It is also somewhat difficult to analyze friction dampers due to their highly nonlinear behavior. It should also be mentioned that restoring incapability may result in permanent deformation if no external restoring mechanism is coupled with the damper [218]. In terms of controlling base shear, friction dampers outperform metallic dampers slightly; however, when it comes to controlling the lateral displacement, metallic dampers are marginally better [219]. In contrast, viscoelastic dampers have restoring properties, and they are activated at low displacements in contrast to metallic, viscous, and friction dampers. The yielding damper is compared with other passive energy dissipation devices in Figure 23 [10].

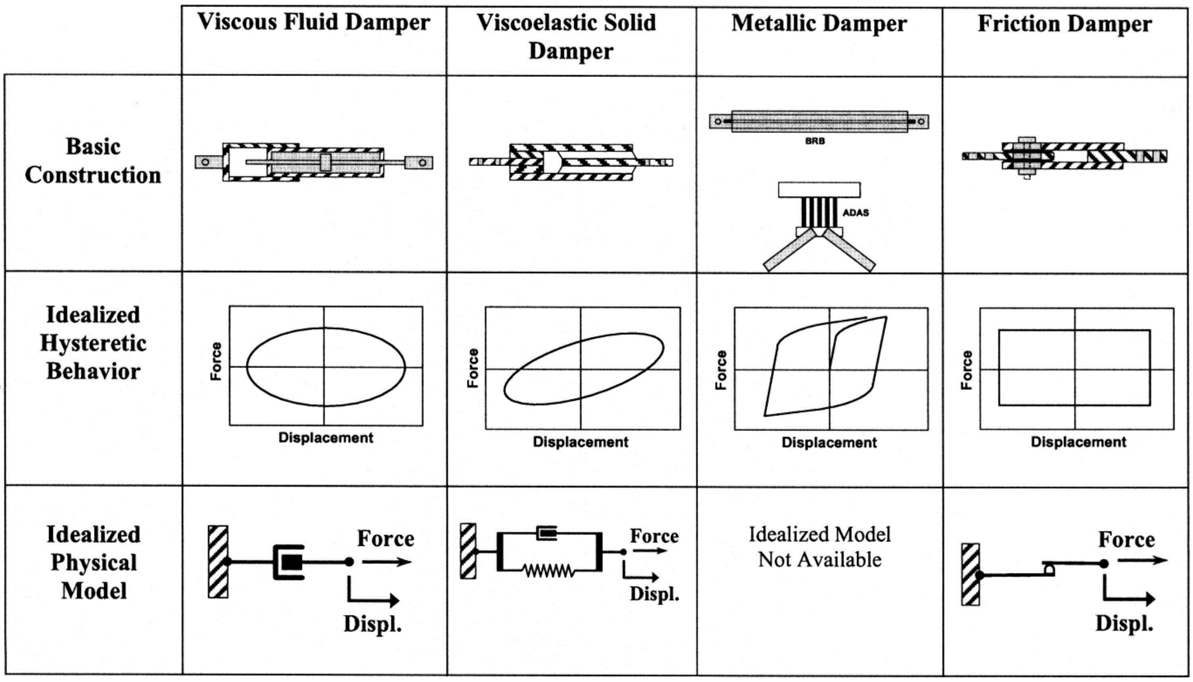


Figure 23. Yielding dampers compared to other passive energy dissipation devices [10]

5. CONCLUSIONS

Based on the information presented in this review, the following conclusions can be drawn:

- **Importance:** The state-of-the-art of steel yielding dampers since the 1970s is summarized in this comprehensive review. Steel yielding dampers can be classified according to their geometric configuration to four categories: steel plate damper, pipe damper, curved damper, and slit damper. These dampers are designed and used to provide safety during earthquakes and prevent the loss of lives. In addition to minimizing structural damage, they also enhance the structure's strength and life expectancy.
- **Main findings:**
  1. Steel plate dampers such as ADAS and TADAS should have hinge supports to reduce unfavourable axial forces. In terms of practicality, ADAS and TADAS dampers are most commonly used in braced frames to increase their damping and ductility.
  2. In steel shear panel dampers, low-yield-strength steel is typically used to dissipate or absorb input energy. The most common failure associated with shear panel dampers is local buckling failure, which results in inadequate energy dissipation caused by pinching effects due to buckling. This fact makes stiffening the shear plate helpful in overcoming the challenges associated with out-of-plane buckling. This will result in high plastic deformation.
  3. While pipe dampers are simple to manufacture without casting or precision cutting tools, they suffer from cracks that originate in the pipe material adjacent to the welds that linked the pipe to the plates and propagated throughout the pipe thickness and length. The welding type and position must therefore be carefully chosen.
  4. The use of steel plate dampers such as U-shape, J-shape, and S-shape dampers is most common with chevron bracing since they can alleviate the disadvantages associated with other types of dampers.

5. Among the main factors affecting the seismic performance of curved dampers are their dimensions and angle. Curved dampers should be angled between 30° and 60° according to the recommendations. A 60° damper in the steel-braced frame is the most effective steel curved damper in terms of energy dissipation and frame strength.
6. Hysteretic slit dampers can be adjusted by altering the size and configuration of the slits, which are available in a variety of configurations, such as prismatic and hourglass designs, both of which are highly effective. Furthermore, these dampers offer advantages over other dampers for braced frames, beam-to-column connections, and shear walls. As a result, slit dampers are most commonly used in steel structures as steel yielding dampers.

- **Suitability:** The performance of steel yielding dampers is not affected by the ambient temperature. The high energy dissipation capacity, simplicity in implementation, low cost, ease of adjustment, high speed of repair and replacement after an earthquake are among the other advantages of these dampers. Moreover, steel yielding dissipater displays a stable hysteretic behaviour and uniform force resistance in tension and compression. Besides, both new structures and existing structures can benefit from seismic improvements created by these dampers.
- **Preference:** Preference between the dampers can be determined depending on the type of force applied, the damper location in structures, and the type of connection between the damper and the structure, i.e., welding or screws. The clamped connection between the damper plates and the support is accomplished through welding or screws such as ADAS, TADAS, and XPD. When welding is used to create an end connection in the plates, ductility of the steel in that area decreases unfavourably. SPDs are also characterized by stress concentration in the weld areas of the stiffeners connected. Also, in the areas around the places where welding is used to connect the SSDs to the support, ductility of the plate is reduced. Based on the above explanation, it is preferred to use a screw connection whenever possible for yielding dampers.
- **Seismic performance:** Steel yielding dampers may exhibit slightly different hysteretic behavior depending on their geometry. There is a similarity in the hysteresis trends of steel yielding dampers. The seismic performance of steel yielding dampers can be evaluated in two ways: (1) the quasi-static cyclic test and (2) the shaking table test. Outcomes of these tests, which are performed on steel yielding dampers or on structures equipped with these devices, determine the mechanical factors of steel yielding dampers such as yield displacement, ultimate displacement, yield strength, ultimate strength, and ductility. By analysing the hysteresis curves of these dampers, the required information will be obtained and the seismic performance will be evaluated. For performing cyclic tests, the most common loading protocols are FEMA 461, SAC, AISC, and ATC-24.
- **Limitations:** Even though yielding dampers can provide a variety of benefits, they suffer from several flaws where the use of a significant amount of welding reduces their ductility; in turn, this reduces the ductility of structures. Additionally, such dampers have the disadvantage that they absorb seismic energy only when they undergo inelastic deformation. Therefore, low yield strength steel is used because it has excellent ductility properties, which overcomes this limitation. On the other hand, during large deformations caused by second-order effects and/or gravity loads, an axial force is created inside the damper plates and in fact, the axial force reduces damper ductility fundamentally. In large lateral deformations, when the axial force increases, the stiffness of the plates increases, resulting in damper ductility being reduced. In parallel, shear plate dampers are characterized by high yielding force, in addition to shear buckling before yielding.

6. SUGGESTIONS FOR FUTURE RESEARCH

Steel yielding dampers are still a vast field that needs to be explored in terms of their development and application. As a result, the following recommendations have been summarized as a means of further understanding, developing, and applying steel yielding dampers:

- Studies on the effect of far-field and near-field earthquakes on steel yielding dampers are limited. To better understand, develop, and apply the general steel yielding damper, more investigations are required regarding the influence of near and far-field ground motions.
- As far as their use in braces is concerned, curved dampers have not been studied exhaustively. In order to assess design criteria for codification and practical applications, further experiments and numerical analyses of this scenario are needed. Also, there will need to be further studies in the future concerning the influence of the thickness of the curved steel plates on their fatigue life.
- Additionally, the quality of welding is an important consideration in the manufacture of metallic dampers as this can result in premature failure or reduce the ductility of the dampers during operation. So, this aspect should be investigated further. In future studies, it may be possible to consider more efficient methods of connecting pipe dampers, such as bolted connections.
- There has been limited research on the occurrence of buckling due to the shear behaviour of steel yielding

dampers with short heights. Future research should address this fundamental weakness.

- In most studies, axial force has not been taken into account when studying steel slit dampers. This force reduces the deformation of the damper before experiencing large deformation, particularly at the beam-to-column connections where the steel slit damper is installed in the beam.
- For beam-to-column connections equipped with slit dampers, the effect of beam effective length, bolt tightening force, etc., should be investigated in follow-up studies. Generally, SSDs with short heights tend to buckle due to their shear behaviour. It is a fundamental weakness of SSDs that needs to be addressed.
- In case of braced frames, it is important to consider the effects of the location and connection of the yielding damper. Thus, new configurations can be explored to address these issues in a constructive way.

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Persian Abstract

چکیده

تحریک لرزه ای می تواند باعث آزاد شدن انرژی قابل توجهی در سازه ها شود. با استفاده از دستگاه های خاص می توان این انرژی را بدون تغییر شکل قابل توجهی در اعضای سازه مصرف و تلف کرد. به همین دلیل آسیب های سازه ای به حداقل می رسد، از تلفات جانی در هنگام زلزله جلوگیری می شود و عمر مفید سازه ها افزایش می یابد. در طول پنج دهه گذشته، به طور گسترده ای پذیرفته شده است که دمپرهای تسلیم فولاد یکی از بهترین دستگاه های اتلاف انرژی هستند. بیان شده است که رفتار هیسترتیک دمپرهای تسلیم فولاد بسته به هندسه آنها می تواند کمی متفاوت باشد. از نقطه نظر عملی برای بهبود ایمنی لرزه ای سازه های جدید و موجود مناسب هستند. هدف این مقاله ارائه مروری در رابطه با میراگرهای تسلیم فولاد، توسعه آنها، انواع مختلف و کاربردهای آن است تا به درک نقش این میراگرها در بهبود عملکرد لرزه ای سازه ها کمک کند. دمپرهای تسلیم فولاد را از نظر شکل می توان به دمپرهای صفحه فولادی، دمپرهای لوله، دمپرهای منحنی و دمپرهای شکافی تقسیم کرد. رایج ترین استفاده از ورق فولادی مانند ADAS و TADAS و دمپرهای لوله در قاب های مهاربندی شده است، در حالی که دمپرهای U شکل، J و S شکل بیشتر در قاب هایی با مهاربندی شورون دیده می شوند. دمپرهای منحنی فولادی با زاویه ۶۰ درجه در قاب فولادی مهاربندی شده، بهترین اتلاف انرژی و استحکام قاب را فراهم می کنند. در این راستا، تا به امروز، میراگرهای شکاف فولادی به عنوان متداول ترین دمپرهای تسلیم فولادی شناخته شده اند.