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A Review on Slit Steel Shear Walls: Development, Implementation, and Performance

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Abstract **Review Article**

Over centuries, natural phenomena have claimed a large number of lives and caused large amounts of damage. However, they were the reason for the development of knowledge and science. In engineering, there is no doubt that earthquakes were the driving force behind many design philosophies and advanced technologies. In this regard, steel plate shear walls (SPSWs) represent one of the technologies employed in both new constructions and existing structures to bolster lateral load resistance. In addition to its high elastic stiffness and strength, SPSWs often experience significant pinching during their hysteretic response unless heavily stiffened. Thus, numerous investigations have been performed recently to enhance the seismic behavior of SPSWs during severe ground shaking. The shear walls of steel plates have been studied in various ways, including stiffened and unstiffened steel plates, low yield strength steel plates, SPSWs perforated with circular holes or vertical slits, steel walls with stiffened and unstiffened openings. A stiffened SPSW panel dissipates significantly more energy than an unstiffened panel, as well as exhibiting a ductile and stable behavior. In view of its high elongation, the SPSW with low yield point has the best damping capacity. It has been demonstrated that steel walls perforated with circular holes have improved energy dissipation, in addition to allowing utilities to pass through their openings. Vertical slits on steel plate shear walls produce an exceptionally full hysteresis loop with improved performances. Slit steel walls (SSWs) can sustain a drift of over 3% while experiencing minimal hysteresis degradation. Additionally, a frame with a SSW can endure up to 6% drift without significant damage, surpassing expected ductility levels of a special moment frame, particularly with efficient slit geometry.

Keywords: Dissipation energy; Ductility; Hysteresis curves; Perforated steel panels; Review paper; Slit steel shear walls.

1. INTRODUCTION

Studies on steel plate shear walls (SPSW) date back to the early 1970s. SPSW have been employed in buildings for more than 50 years as one of the primary lateral force resisting systems. Over the past decades, SPSW systems have been subject to extensive research. With proper design and construction, SPSW systems can dissipate substantial amounts of energy with stable hysteresis. SPSWs system exhibits relatively high stiffness at the beginning, since the tension field of the web functions as a diagonal brace [1]. An unstiffened Special Steel Shear Wall, SPSW, was tested under cyclic lateral loads and constant gravity within a quasi-static condition by Elwi *et al.*, [2]. AISC341-16 [3] presents the results of the research on SPSW so far as an approved design approach. Considering that the surrounding frame members are subjected to significant forces due to the typically high strength of steel shear walls [1]. Steel shear walls can be modified to reduce their negative aspects by using low yield steels (LYS) [4-6], cutting circular holes or vertical slits in the steel plate.

Passive damage control is commonly achieved with metallic dampers. Over the last forty years, passive dampers have become common practice for enhancing earthquake performance and dissipating energy, without the need for external power sources [7-12]. Behnamfar and Almohammad-albakkar noted that steel yielding dampers have gained widespread recognition as some of the most effective energy dissipation devices due to their ability to generate stable hysteretic loops. These loops allow for the absorption of energy through inelastic deformation [13]. In these dampers, the energy applied to them dissipates when they pass the yield point and undergo plastic deformation [13]. Using these systems reduces damage within the building and improves energy efficiency [14]. It's possible to reduce building damage by using these systems and dissipate energy more efficiently [5]. This damper maintains stability over a wide range of temperatures, and is exceptionally fatigue resistant because of its low cycle and displacement rates, low fabrication costs, tolerances for large displacements, and long-term durability [15-18]. Lightweight, easy to fabricate, and easily exchanged after large earthquakes are other advantages of these dampers. Since steel yielding dampers possess these advantages, they have become a popular form of passive energy dissipation. Inelastic deformations are concentrated with this type of metallic damper, preventing damage to other main frame members [19-21]. Steel slit dampers are popular among steel yielding dampers [22]. In this regard, Almohammad-albakkar and Behnamfar [18, 23] employed slit steel dampers within cross-braced frames. Their findings indicated that this innovative system, Grooved Gusset Plate Damper (GGPD), significantly boosts the ductility and energy dissipation of the cross-braced frames. The experimental results indicate that the GGPD system can tolerate a relative drift of more than 3% [24].

Perforated steel shear walls (PSSWs) are a popular choice in construction for their high strength, stiffness, and seismic resistance. These walls consist of thin steel panels with regularly spaced perforations that allow them to absorb lateral loads and resist shear forces. In 1991, the hysteresis curves of SPWs were investigated at small scales by Sabouri-Ghomi and Roberts [25, 26] using 16 unreinforced thin panels, some with openings. In their test, for pure shear, loading and unloading were done along diagonals. Each panel demonstrated adequate ductility and was capable of dissipating a substantial amount of energy.

SSWs are typically versatile and suitable for a range of structural uses. This system should therefore be evaluated to ensure greater adaptability and reliability, including assessing their advantages, limitations, enhancements, and optimizations in the future. This study mainly reviewed the seismic performance of SSWs commonly used in structures. There has not yet been a review published on SSWs, to the best of the author's knowledge, which explains the development and applications of this in structures. Recent studies and the effects of SSWs on structural performance will be discussed. In order to achieve this goal, many literature articles have been systematically reviewed/referenced, providing a comprehensive overview of all aspects of SSWs, including applications, configurations, and implementations in various structures. In addition, this review offers some recommendations for future research after reviewing recent developments.

2. METHODOLOGY

A description of the methodology for this study can be found in Fig. 1. Numerous investigations have been undertaken in the scientific literatures on the use of perforated steel walls. Numerous articles containing keywords related to slit/perforated steel walls in structures have been reviewed and screened by the authors using platforms such as Google Scholar, Scopus, and Science Direct. For research papers to be considered, they must include at least one of the following perforated steel walls features: configuration and optimal shape, hysteresis curves, failure mode, ductility, and dissipation energy. After this, the authors analyzed and discussed previous studies' data in depth. In this study, the authors identified best practices and key findings for the design and implementation of slit steel walls through a screening process.

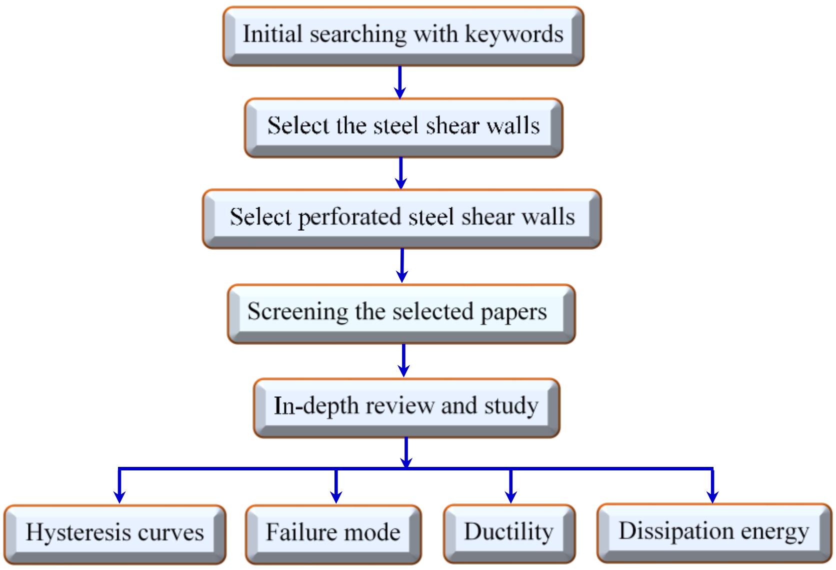

Fig. 1: Methodology flow chart for this study

3. Mechanism of Perforated Shear Walls

Through the perforations in the steel plates, the shear walls can be weakened, thereby diminishing the forces exerted on the boundary elements. It is therefore possible to use PSSWs as a means of dissipating energy while maintaining its capacity to resist seismic forces when combined with a frame. By decreasing the rigidity and robustness of the structure, it mitigates certain drawbacks associated with traditional steel shear walls. An effective technique for improving SPSW behavior is to introduce perforations such as holes or vertical slits. In 1973, Muto *et al.,* [27] in Japan invented a reinforced concrete structural wall with vertical slits that improved its properties. Traditionally, shear walls experience the maximum flexural moment caused by lateral loads at the base. Thus, only the base of the shear wall dissipates energy through the plastic hinge. So, the ductility of the other part of the wall is not utilized. Due to the installation of holes or slits, more plastic hinges will form and thus more energy will be dissipated by distributing degradation to the wall height. Also, the slits allow flexural torsional buckling of the flexural links rather than global buckling of the steel plate [28]. They provide ductile responses without out-of-plane stiffening by segments between the slits which are called slit wall flexural links.

4. Slit Steel Shear Wall in Structures

4.1. Overview

In the early 1970s, researchers began researching SPSW. Japan has been conducting extensive research into stiffened SPSW systems that provide improved buckling stability and high seismic performance. Especially in North America, unstiffened SPSW are being studied which have lower buckling and energy dissipation capacities. The first experimental analysis of SPSW was performed by Takahashi, Mimura, and Akiyama [29, 30]. Generally, in this review paper, SPSW studies are categorized into two types: solid SPSW and SPSW with openings, such as slits or perforations.

Extensive research has been conducted on utilizing the shear capacity of steel plates to absorb the energy generated by seismic forces acting on structures [31]. An example of this type of element would be a steel shear wall. Numerous research efforts have investigated the behavior of steel plate shear walls, resulting in the establishment of design guidelines for their construction [32]. An analytical technique developed by Thorburn *et al.* [33] can be used to study the force transfer in steel panels subjected to shear. Their approach acknowledges the significance of the post-buckling strength of a web in contributing to the overall resistance against shear. This type of shear wall was later designed using a new analytical approach developed by Timler and Kulak [34]. Replacing traditional steel with low yield steel (LYS) has been proposed as a means to mitigate the adverse effects associated with steel shear walls [35]. It has also been proven that perforating steel walls with circular holes [36-39] or vertical slits [40-42] is a more effective method of weakening steel walls and increasing their ductility. Also, several hybrid systems, a combination of steel walls and steel dampers, have been proposed in many scholarly papers [43, 44].

4.2. Slit Steel Shear Wall

Earlier research by Ohmori et al. [27] and Muto et al. [45] introduced the concept of utilizing slits to bolster the earthquake resistance of reinforced concrete shear walls. Hitaka *et al.,* [46] studied steel building frames incorporating steel bearing walls with slits (see Fig. 2). In the study, two types of bearing walls were considered; one of which had a stronger and stiffer structure than the other. In both cases, the walls were constructed using standard steel with a yield stress of around 300 MPa, and they underwent cyclic horizontal loads. The bearing walls under relatively small story deformation were found to greatly increase energy absorption capacity. Known as a shear wall with vertical slits has been introduced by Hitaka and Chiaki [40] enabling the wall to respond more ductility without heavy stiffening as an earthquake-resistant element. It was noted that the inelastic behavior is primarily located at the upper and lower ends of their flexural links. Testing reveals that employing slit walls can maintain approximately a 3% drift with minimal hysteretic degradation, provided that the width-to-thickness ratio in the flexural links remains below 20. In a subsequent investigation conducted by Hitaka *et al.,* [47], they examined SPSWs featuring vertical slits installed in three steel frames comprising a single storey, as well as four concrete-filled tube (CFT) moment frames spanning three storeys. Up to more than 4% drift, the SPSWs and moment frames exhibited ductility without abrupt degradation of strength. An equivalent brace model has been derived from these tests and complementary analysis. With sufficient transverse stiffening, this innovative shear wall design offers maximum plastic strength and maintains its hysteresis behavior without degradation.

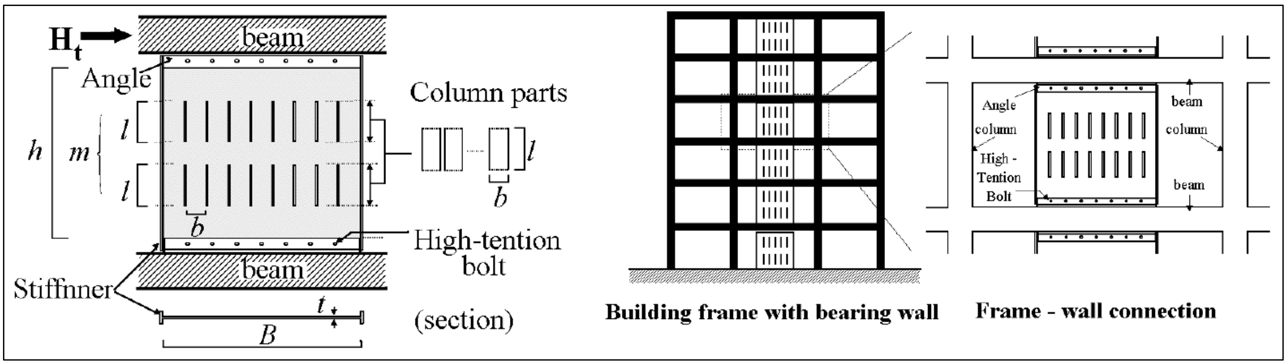

Fig. 2: Slit steel walls [46]

In another investigation, Jacobsen and colleagues [48] introduced a novel variant of slit wall. These modified slit walls are achieved through adjustments to the configuration of the slit (refer to Fig. 3), thereby enhancing the capabilities for condition assessment. FEM was performed to show that the modified slit configuration is feasible. A three-story building was also investigated experimentally for the performance of SPSWs with different slit configurations. It has been found that the slit steel shear walls display stable hysteresis, which allows them to dissipate energy efficiently and to be ductile.

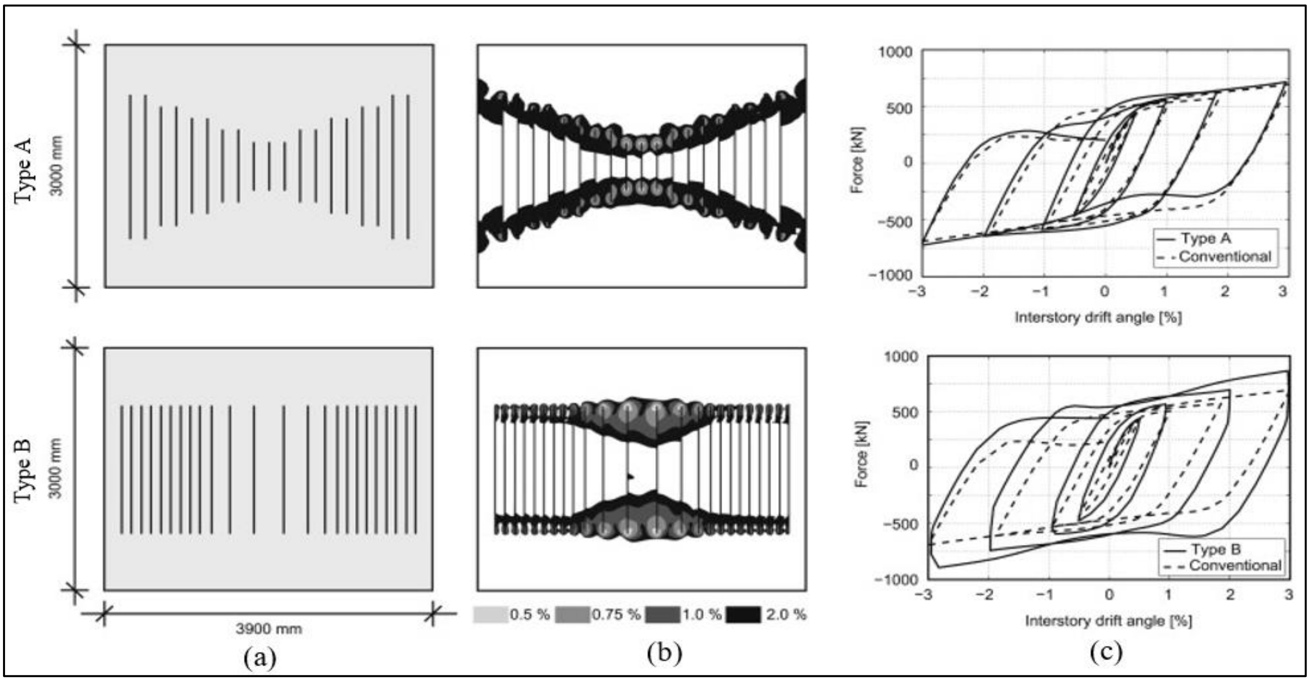

Fig. 3: Modified slit walls [48]: (a) Slit types. (b) Stress distribution. (c) Hysteretic behavior

A novel seismic resistance system has been introduced and designed by Cortés and Liu [49-51], which is known as the steel slit panel–frame. In this case, beams were bolted to columns and beams. The structure comprises steel plates featuring vertical slits, which collectively create a sequence of flexural members. All stiffness, energy dissipation, and resistance are provided by the steel slit panel system. In all tests, it was determined that SSPs can withstand relative drifts of at least 5% without experiencing a decrease in their load-bearing capability to below 80% of their maximum strength. The steel shear walls with slits and held together by wood panels were investigated by Taniguchi *et al.*, [52]. Using the stiffening panels, it is found that the pinching degree in cyclic behavior is controlled by the stiffness of the stiffening panels and the propagation of cracks from the slit ends controls maximum strength. To ensure effective performance of the wall system, it is necessary to maintain a balance between crack propagation and out-of-plane deformation, and the walls reinforced with wood panels perform better than those reinforced with steel panels. In slit shear walls, residual out-of-plane deformation of links can be used to generate a hysteretic damper that works immediately after an earthquake [53]. By determining the dimensions of the torsionally deformed links that demonstrate significant torsional deformation at the desired deformations, the maximum drift ratio will be evaluated. So, by employing a double-tapered design for the links, as shown in Fig. 4, it is possible to greatly enhance the out-of-plane deformation. To link dimensions with torsional deformation and test the assessment scenario, Kurata *et al.*, [53] conducted numerical simulations and cyclic loading tests on individual and grouped links. Test results indicate that the hysteretic damper can be predicted from design equations with a high degree of accuracy. A lateral bearing capacity equation of slit walls that takes into account the effect of edge stiffeners has been introduced by Lu *et al.*, [54]. When compared to experimental findings, the simplified model reliably forecasted the lateral stiffness and strength of the steel slit wall with an error margin of under 10%. The findings indicated that the steel slit wall effectively shielded the beams and columns from earthquake-induced damage, serving as a proficient energy dissipation element. It was concluded that, by using the steel slit wall, an earthquake could be prevented from damaging beams and columns, and the steel slit wall was a great energy dissipator [54].

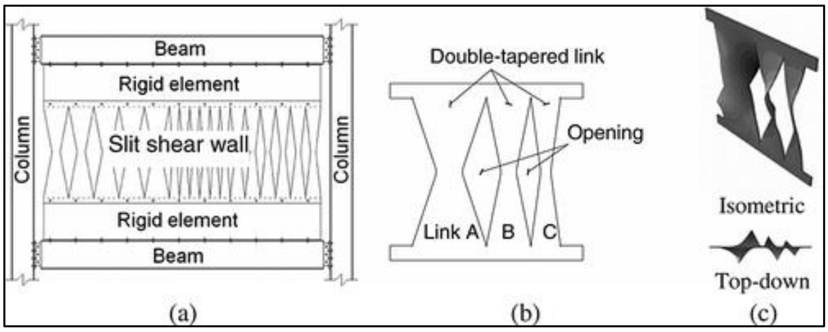

Fig. 4: Slit wall with double-tapered links [53]

In other experimental study by Lu *et al.*, [28], finite element software and tests have been used to determine the performance of two kinds of steel walls with non-uniform spacing slits (SPWNS) as depicted in Fig. 5. There were no differences between SPWNS and uniform spacing slits (SPWUS) in terms of ultimate capacity and lateral stiffness. Conversely, SPWUS exhibited significantly greater ductility and capability to dissipate energy. A follow-up study conducted by Lu *et al.*, [55] performed finite element analyses and experimental investigations on specimens with multilayer slit. Based on Fig. 6, vertical flexural links were established within the infill steel plate through the creation of slits. These flexural links consume energy through in-plane bending deformation under lateral loads, resulting in the formation of plastic hinges at both ends of the flexural links. According to the results, out-of-plane buckling of the flexural links was more likely to occur when SPSWs have a single-layer slit. In this case, the lateral stiffness and ultimate bearing capacity were comparatively diminished when maintaining a constant total height for the vertical slit. Alternatively, multilayer slit steel plate shear walls tended to buckle globally during failure. Compared to single-layer plate shear walls, multilayer specimens displayed better energy dissipation capacity. Additionally, Lu *et al.*, [56] investigated steel walls with unequal length slits, as shown in Fig. 7. In comparison with traditional SPSWs with slits, the proposed wall, featuring slits of unequal lengths, effectively disperses energy, demonstrates commendable ductility, and boasts high lateral stiffness and ultimate bearing capacity.

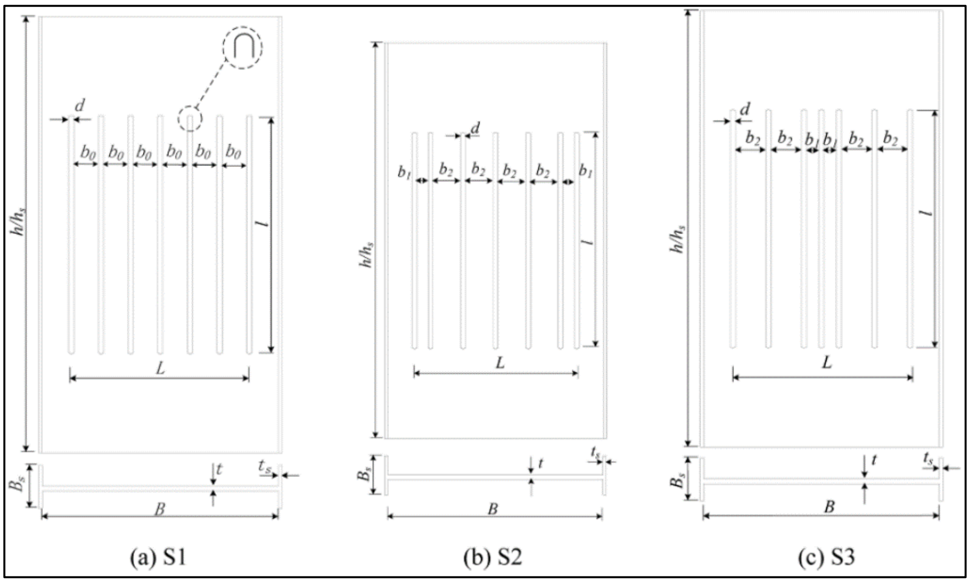

Fig. 5: Slit walls with non-uniform spacing [28]

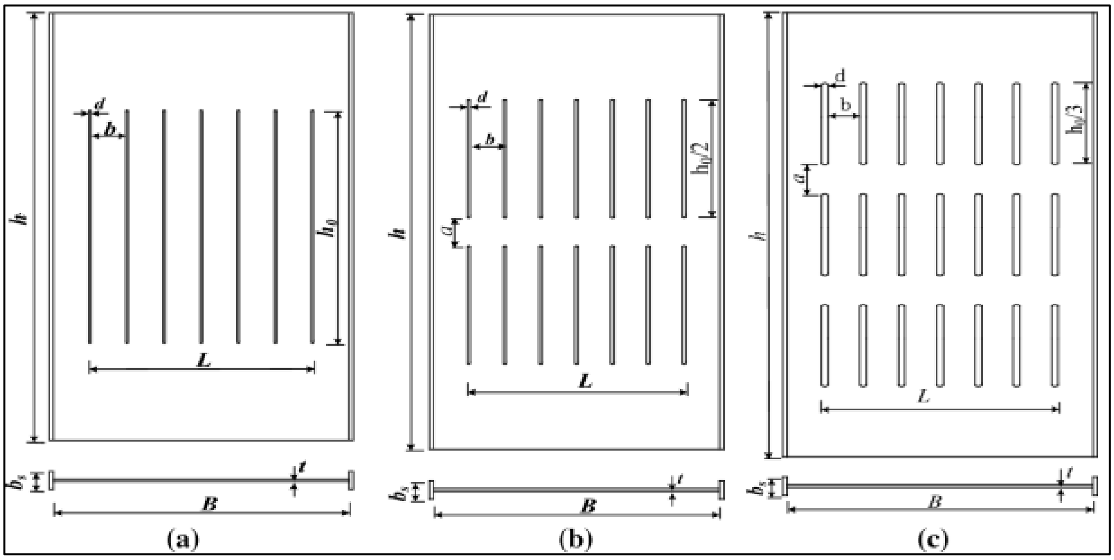

Fig. 6: Patterns of steel walls with multilayer slits [55]: (a) Single-layer slit. (b) Two rows of links. (c) Three rows of links

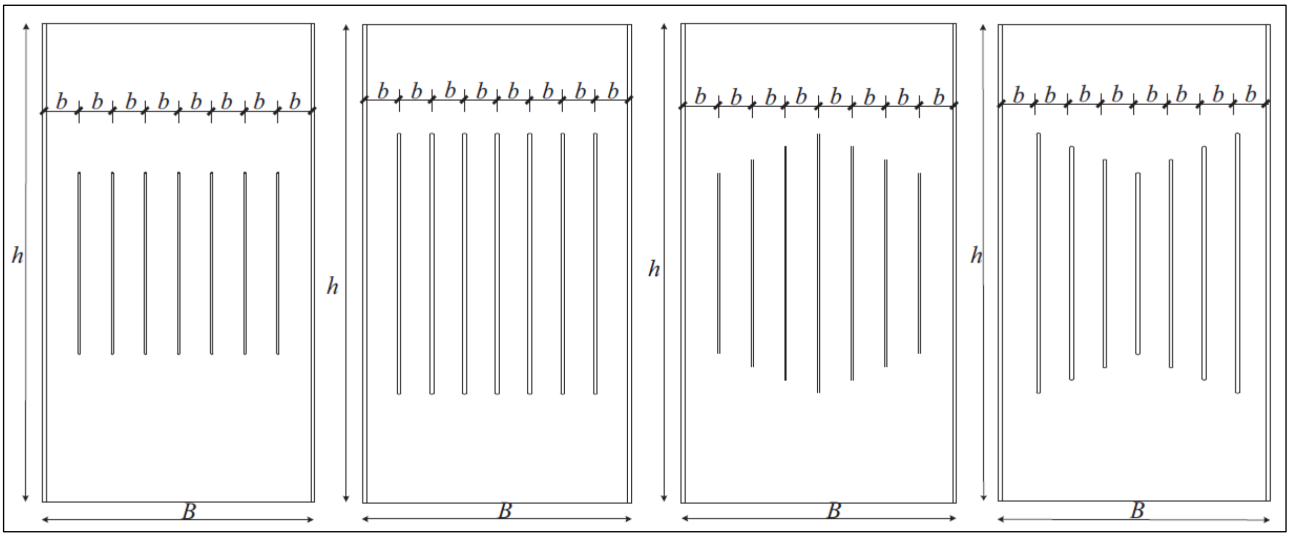

Fig. 7: Patterns of steel walls with unequal length slits [56].

Wang *et al.*, [57] have introduced a novel seismic load-resisting structural element that integrates recentering capabilities and energy dissipation. This innovative system, known as the self-centering modular panel with slit steel shear walls (SCMP-SW), is depicted in Fig. 8. The SCMP-SW is integrated within a steel frame that allows beams to pass through it, with the slit wall designed to function as a replaceable element, absorbing and dispersing energy. Test findings indicate that SCMP-SW can recalibrate itself after unloading while still dissipating energy at a reasonable rate.

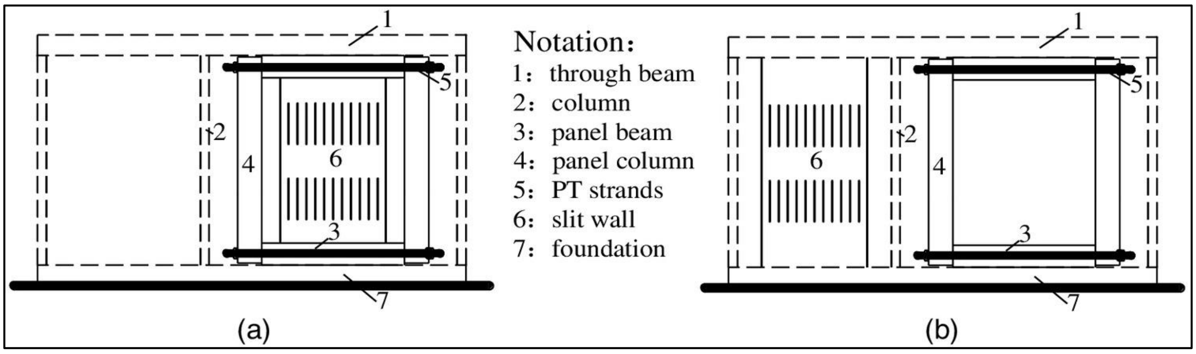

Fig. 8: An example of a SCMP-SW elevation arrangement [57]: (a) Assembled type. (b) Separated type

Ke and Chen [58] conducted a study aimed at crafting a feasible methodology for designing and evaluating steel frames featuring steel slit walls (SSWs). Their focus lay in enhancing structural resilience through damage control strategies. Their findings, which encompassed structural response observations and predictive analyses under specific ground motions, indicate that the suggested methodology holds promise for damage-control design and assessment with commendable accuracy. The energy-balance concept has been used to develop a multi-stage-based nonlinear static procedure (MNSP) by Ke *et al.*, [59]. This approach enables designers to assess seismic demands on steel moment-resisting frames (MRFs) equipped with special steel wall (SSW) systems that yield at various stages, as depicted in Fig. 9(a). Two prototype steel moment-resisting frames (MRFs) with slit steel walls (SSWs) were subsequently subjected to testing using the MNSP under both design basis earthquakes and maximum considered earthquakes. This method was examined by comparing the predictions by MNSP with those by nonlinear response history analysis (NL-RHA). In terms of ultimate response estimation for steel MRFs with multi-yielding SSWs, the proposed MNSP appears to be a promising tool. In addition to static pushovers and linear dynamics, abaqus software was also used for the analysis of nonlinear incremental dynamics and nonlinear linear dynamics by Aliakbari and Shariatmadar [60]. Numerical findings indicate that employing a moment resisting frame with steel slit panels yields overstrength, ductility, and response modification factors of 4.16, 1.91, and 8.11, respectively.

Jin and Bai [61] developed a buckling-restrained SPSW with inclined slits (see Fig. 9(c)). Inelastic axial deformation occurs when the steel strips between inclined slits undergo to cyclic loading like a series of buckling-restrained braces; thereby, dissipating the energy. It was proven that the slotted SPSW could withstand the targeted lateral drift ratio (2%) without compromising either shear force or energy dissipation capacity. It should also be noted that the specimens demonstrated stable fatigue hysteresis loops after 30 repetitions of the cyclic loadings at 1.5% peak lateral drift ratio. In another research [62], moment resisting steel frame (MRSF) structures were built with steel slit shear panels. The results of time history analysis indicate that the story displacement responses are reduced, but the floor accelerations are increased by the installation of the panels. The installation of low yield shear panels leads to a decrease in both the maximum and residual inter-story drift, as noted.

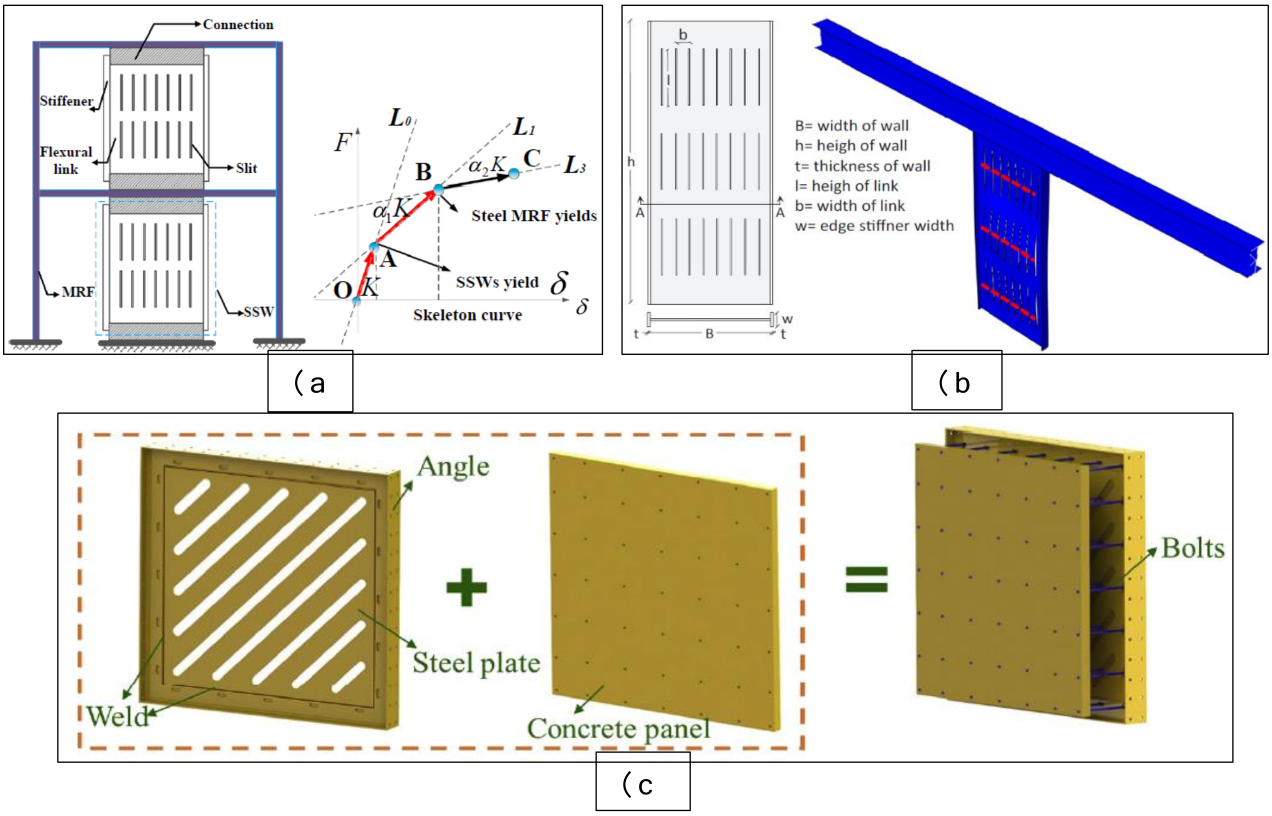

Fig. 9 : (a) Multi-yielding stages of a steel MRF outfitted with slit steel wall [59]. (b) Slit panel geometry with a vertical slit [60]. (c) SPSW configuration with inclined slots [61]

As mentioned earlier, the slit steel wall (SSW) serves as an efficient lateral force-resisting system. This system involves perforating a steel plate with slits. SSWs are typically installed in between floor beams. In order to focus the lateral deformation of the story into the slit steel wall, it is necessary to establish a rigid connection between the floor beam and SSW. This will enhance the plasticity of the slit ends to dissipate seismic energy. In order to develop this new method of connection, He and Khadka [63] experimentally and numerically tested an idea of using extended steel plates of the same thickness as SSWs. A greater width-depth ratio of the extended steel plate resulted in its primarily undergoing in-plane shear deformation, without being significantly constrained in the out-of-plane direction. When employing a width-depth ratio of 1.45, over 85% of the inter-story shear deformation was notably concentrated within the SSW. However, when the width-depth ratio decreased to 0.78, it became evident that out-of-plane buckling occurred. For a practical and economical approach to connecting the SSW to the beams, it is advisable to utilize an extended steel plate with a minimum width-to-depth ratio of 1.5. On the basis of experimental and numerical evidence obtained by Ahmadi *et al.*, [31], it has been proven that a frame structure outfitted with a SSW can withstand a drift of 6% without experiencing any notable damage. This level of ductility exceeds that anticipated from a special moment frame. Through an experimental numerical program, Kordzangeneh *et al.*, [1] investigated the effects of square openings on the SPSW, including the effects of the location and size of the opening. In their study, it was found that square openings reduced maximum shear capacities by 16%, 34%, and 38%, respectively, depending on the opening-to-panel area ratio of 4.00, 6.76, and 10.24%. The stiffness was also reduced by 12%, 15%, and 25%.

To analyze the causes of hysteresis in SSW, four specimens underwent cyclic loading, yielding four distinct shear hysteresis curves: plump, pinched, pinched without cyclic degradation, and combined [64]. Macro models were devised to replicate these hysteresis behaviors, aligning closely with experimental findings. Plump hysteresis was achieved using low yield steel in SSWs [64, 65], even with observable out-of-plane deformation, owing to the substantial strain hardening and ductility of low yield steel (refer to Fig. 10d). In mitigating maximum story displacement response, low yield steel and twisted SSWs performed similarly. During intense earthquakes, SSWs with twisted links sustained roughly twice the story shear force compared to other SSW types [64].

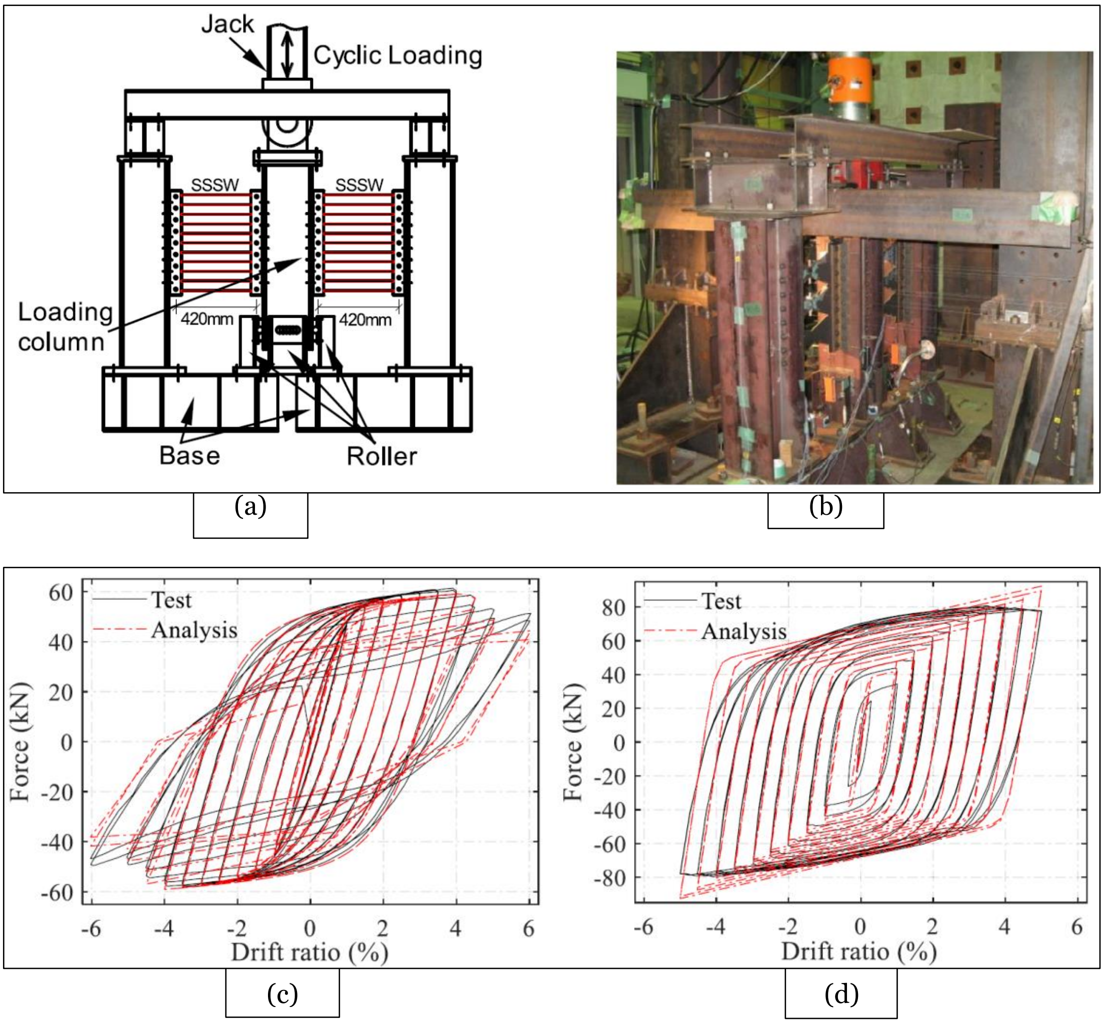

Fig. 10: (a) Illustration of test setup. (b) Test setup. (c) Test and simulation results for SSSW made of mild carbon steel. (d) Experimental and numerical results for SSSW made of low yield steel [64]

A subsequent study [66] uncovered that the width-to-thickness ratio of the links emerged as the predominant factor affecting out-of-plane buckling. This led to pinching in the hysteresis loop, consequently diminishing the energy dissipation capacity. Links with higher width-thickness ratios experienced earlier out-of-plane buckling, leading to decreased energy dissipation, while those with lower ratios exhibited the opposite behavior. An innovative method for evaluating the energy dissipation of SSWs, which takes into consideration out-of-plane buckling, was presented [66]. This method accurately predicted energy dissipation, aligning closely with experimental findings. Another variety of wall incorporating steel slit plates is the lightly reinforced concrete (LRC) walls. According to a study conducted by Maida *et al.*, [67], it was proposed to install the slit dampers to establish a controlled semi-rigid connection between LRC wall piers and RC frames in residential buildings. This connection is designed to improve the lateral strength and energy absorption of LRC wall piers while minimizing cracking. Compared to rigidly connected LRC wall piers, those with miniature steel dampers maintained moderate strength and remained intact up to a 1/200 story drift ratio. Dampers placed at mid-height, Fig. 11, exhibited approximately 60% more deformation compared to those at the bottom of the wall pier at the same story drift. To investigate how beam-through steel frames (BTSFs) with self-centering modular panels (SCMP) respond dynamically and how resilient they are, shake table tests were done on a 2-story SCMP-BTSF building model with SSWs [68]. Two different ground motion records were used at varying intensities. The SCMP-BTSF structure exhibited self-centering behavior and satisfactory seismic performance. Damage was limited to the SSWs, consistent with design expectations. The concrete floor slabs remained free from any cracks following the shake table tests [68].

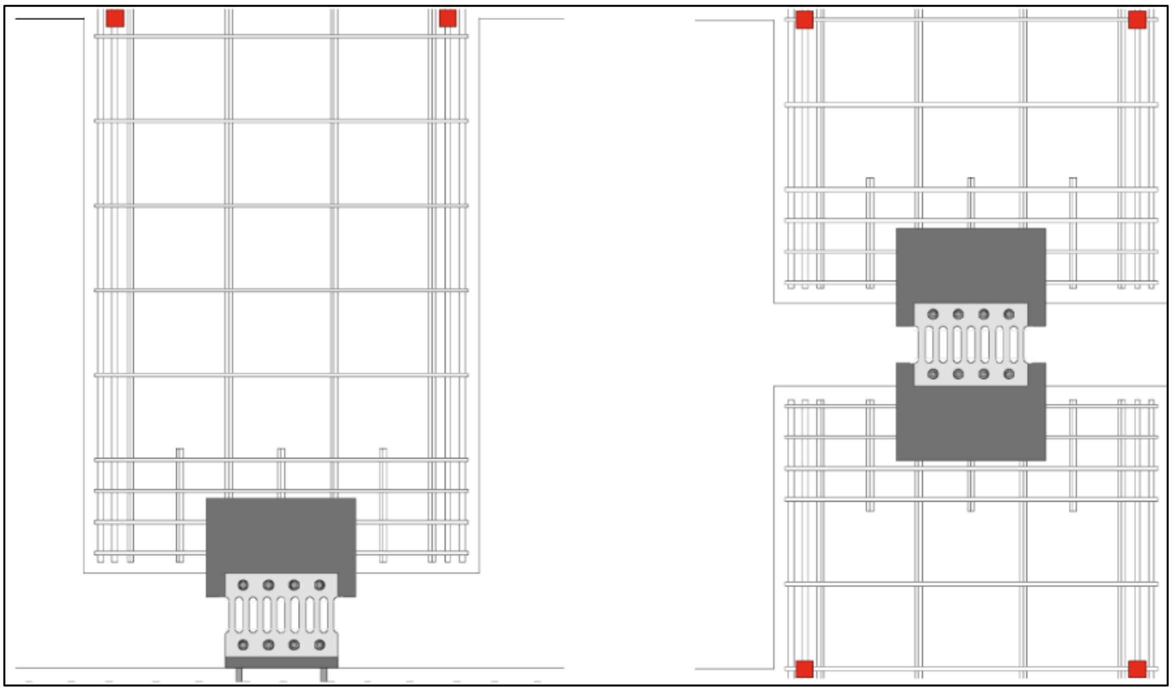
Fig. 11: Using Slit dampers in Lightly reinforced concrete (LRC) walls

Furthermore, a two-story self-centering SPSWs with slits (SC-SPSWS) was constructed and examined to assess the impact of varying geometric parameters [69]. Findings indicate that configurations featuring increased flexural link layers and thicker steel plates exhibit enhanced ultimate strngth and superior energy dissipation capabilities. However, this enhancement is accompanied by a weakening of the recentering capability [69]. Additionally, an innovative seismic force-resisting system called the self-centering post-tensioned concrete wall (PT-CW) was unveiled through the utilization of a Multi-Slit Device (MSD) [70]. Observations indicate that when subjected to earthquake forces, the PT-CW with MSD exhibits significantly reduced and more consistent story drift compared to PT-CW with conventional reinforcement bars (ED bars). The integration of a steel plate shear wall with slits (SPSWS) into a coupled system (see Fig. 12), referred to as C-SPSWS, demonstrated remarkable cyclic performance akin to traditional SPSWS setups [71]. The C-SPSWS specimen showcased enhanced resistance against lateral loads, thanks to the coupling beam's effect. This coupling mechanism notably bolstered the system's initial stiffness, strength, and ability to dissipate energy. Moreover, it alleviated the axial force exerted on the frame columns, especially those positioned within the interior of the frame.

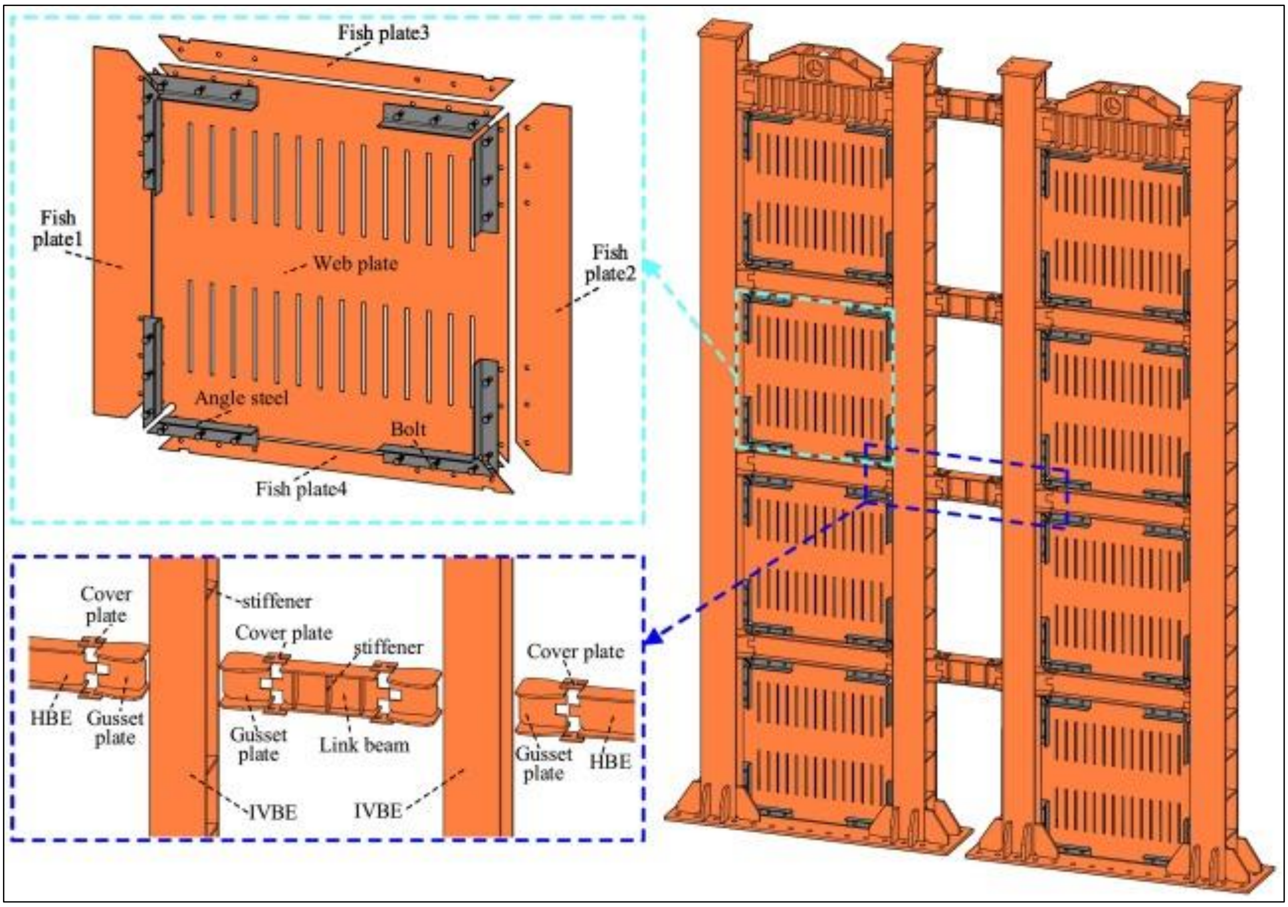

Fig. 12: C-SPSWS system [71]

5. CONCLUSION

Slit steel shear walls, also known as perforated steel shear walls or steel plate shear walls with slits, are innovative structural systems employed in building construction to enhance seismic resistance and lateral load-bearing capacity. These walls are composed of steel plates with strategically positioned slits or openings, which impart flexibility and ductility to the structure. This research primarily focused on examining the seismic behavior of slit steel shear walls, delving into their evolution and usage in buildings. From our analysis, we have derived the subsequent conclusions.

1. One of the main advantages of perforated steel shear walls is their light weight, which makes them easy to install and transport. They also offer flexibility in design, as the size and spacing of perforations can be customized to meet specific project requirements.
2. A further advantage of perforated steel shear walls is that they are stable in their hysteretic behavior and exhibit uniform force resistance in tension and compression.
3. In terms of performance, steel shear walls with holes have been shown to have good seismic resistance. This is due to their ability to dissipate energy through yielding of the steel panels and deformation of the perforations during an earthquake.
4. Research has shown that steel plate shear walls with slits can effectively absorb substantial amounts of energy and are highly proficient at dissipating energy through the yielding of the steel strips located between the slits.
5. Studies showed that using slit walls can help to keep drift to around 3% while minimizing any degradation in hysteresis.
6. The steel slit shear wall-equipped frame can withstand drifts of up to 6% without incurring notable damage. This level of ductility surpasses what is expected from a special moment frame.
7. Specimens with a single slit layer tended to experience torsional buckling of the flexural links, whereas specimens with multiple layers were more likely to undergo out-of-plane global buckling of the entire steel plate.

Conflict of Interest: The authors state that they do not have any conflicts of interest.

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