Journal of Constructional Steel Research 117 (2016) 13–23

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Stability of buckling-restrained steel plate shear walls with inclined-slots: Theoretical analysis and design recommendations

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ARTICLE INFO

Article history:
Received 19 April 2015
Received in revised form 27 September 2015
Accepted 2 October 2015
Available online xxxx

Keywords:
Energy dissipation device
Steel plate shear wall (SPSW)
Buckling-restrained
Stability
Numerical analysis
Design

ABSTRACT

This paper presents a novel buckling-restrained steel plate shear wall with inclined slots called slotted SPSW to be used as an energy dissipation device for earthquake resistance. In the slotted SPSW, a steel plate with inclined slotted holes is sandwiched in between two external concrete panels which provide lateral restraint to achieve stable energy dissipation under cyclic reversal loading. Theoretical analysis and finite element monotonic push-over analyses are conducted to investigate the stability of slotted SPSWs. Global buckling and local buckling resistances of slotted SPSWs are determined. Some key parameters, such as the gap between steel plate and concrete panels, bolt spacing, width of steel strips, and steel panel slenderness, are investigated through numerical analyses. The shear force and lateral drift behavior of the slotted SPSW is found to be affected by the physical gap between the concrete panels and inner steel plate. The minimum concrete panel thickness for providing the effective lateral restraint to prevent buckling failure of the inner steel plate is determined based on the bolt spacing.

1. Introduction

Passive energy dissipation systems have been considered to be an attractive option for natural hazard mitigation. In particular, the structure consists of a main frame and some energy dissipation devices. The common design philosophy is that the yielding of energy dissipation devices has to occur earlier than other structural components in the main structure in order to trigger the energy dissipation mechanism and thus protect the main structure against the serious damage [1–3]. Among the frequently used energy dissipation devices, the steel plate shear wall (SPSW) is one of the cost-effective devices to be used in seismic prone regions [4] to dissipate energy and provide resistance against the lateral forces. In the early applications, relatively thick or heavily-stiffened infill plates have been employed to prevent out-of-plane buckling before shear yielding [5]. Since the early 1980s, unstiffened SPSWs, which resist lateral loads by the diagonal tension field action induced by shear buckling, have been investigated to reduce costs and improve constructability [6–8]. Although the unstiffened SPSW can provide high strength by relying on the tension field action, the out-of-plane displacement caused by shear buckling may result in damage to non-structural components under a small or moderate earthquake because shear buckling will happen at a low load level. To reduce the steel plate slenderness and to achieve shear yielding rather than shear buckling, plate-stiffeners are often welded to the steel plate leading to additional cost. Recently, precast concrete panels have been used to restrain the out-of-plane buckling of the steel plate, creating the composite steel plate shear wall [9,10].

For low-rise buildings, the required thickness of the steel plate is generally thinner than the minimum available thickness that can be handled and welded. Therefore, the used steel plate might be thicker than the design requirement. Based on the capacity design approach, thicker steel plates will produce excessive design forces in the surrounding frames, which increase the sizes of the adjacent columns and beams, and introduces additional construction cost. In fact, some improvements to avoid the excess forces induced by the thicker steel plate include: (a) providing a regular pattern of circular perforations on the steel plate [7,11], (b) providing vertical slits in the steel plate [12,13], (c) using light-gauge cold-formed corrugated steel plates [14], (d) using a low yielding steel plate [15,16], and (e) partially connecting the steel plates to the frame [17,18].

With reference to the above considerations, an innovative type of buckling restrained steel plate shear wall with inclined slots (slotted SPSW) has been proposed by the authors [19]. A slotted SPSW, as shown in Fig. 1, consists of boundary members and an inner steel plate with inclined slots sandwiched between two external concrete panels. The inner steel plate is fabricated by cutting a number of inclined

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http://dx.doi.org/10.1016/j.jcsr.2015.10.002
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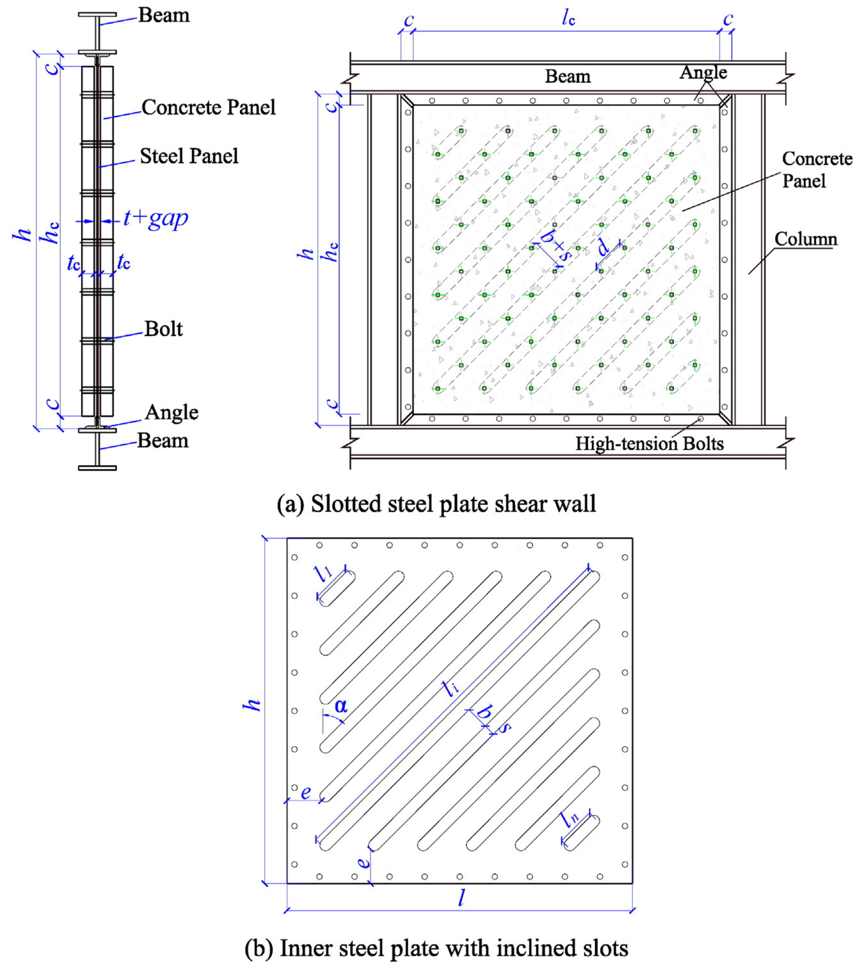

Fig. 1. Configuration of the slotted SPSW. (a) Slotted steel plate shear wall. (b) Inner steel plate with inclined slots.

slots with rounded ends, leaving a number of steel strips between inclined slots. The inner steel plate is inserted between a pair of angles and bolted to adjacent frame members by using high-strength bolts. Two precast reinforced concrete panels are bolted together on both sides of the inner steel plate through a number of holes in the concrete panels and inclined slots on the steel plate. These bolts are located along the inclined slotted holes to avoid restraining the deformability of steel strips. The compression buckling of the steel strips is restrained by precast concrete panels on both sides, which makes the inclined strips behave like a series of buckling-restrained braces. There are four distinct features of the proposed slotted SPSW:

1) The lateral resistance and stiffness can be adjusted by changing the number of inclined slots (n) and strip depth (b) for a fixed steel plate thickness. This will avoid excessive forces to be transferred to the adjacent frame members.
2) The yielding of the inclined steel strips can be controlled by changing the strip length (l_i), to dissipate earthquake-induced energy as early as possible to reduce damage to the main structure.
3) The inclined steel strips can yield in tension or compression. This enables high energy dissipation under reversal lateral loads.
4) Bolts are used for the connections. They can be installed rapidly at the site and replaced after severe earthquakes.

To avoid the occurrence of shear buckling failure of the slotted SPSW before the target drift ratio, two external concrete panels are used to provide the out-of-plane restraints to the inner steel plate. Theoretical studies and finite element pushover analyses are conducted to investigate the stability of slotted SPSW under shear force. Some key influential factors, such as the gap between steel plate and concrete panels, bolt spacing, width of steel strips and steel panel slenderness, are investigated through numerical analysis under monotonic horizontal load. Furthermore, the general behavior of the slotted SPSW under shear force is investigated and minimum concrete panel thickness is recommended for the purpose of design.

2. Theoretical analysis on stability of slotted SPSW

When the slotted SPSW is subjected to shear force, two external concrete panels can provide lateral restraint to the inner slotted plate to ensure that the steel strips yield both in tension and compression to provide the stable energy dissipation during earthquake. Since the precast concrete panels are connected to the inner steel plate by bolts, two types of buckling modes are possible. One is the global buckling mode as shown in Fig. 2(a), which will occur when the concrete panel thickness is too thin to provide adequate lateral restraints. The other is the local buckling mode as shown in Fig. 2(b), which will occur when the bolt spacing is too large to ensure that the concrete panels and inner steel plate work together. In the following analysis, these two types of buckling modes will be studied based on the theories of plate stability.

2.1. Global buckling of the slotted SPSW

When the global buckling occurs, the slotted SPSW will fail as shown in Fig. 2(a). Assuming that the concrete panels and steel plate work together without slippage, the equation of equilibrium for the slotted