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Experimental study of ring-shaped steel plate shear walls

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ABSTRACT

A new type of steel plate shear wall (SPSW) has been developed which resists out-of-plane buckling. The ring-shaped steel plate shear wall (RS-SPSW) includes a steel web plate that is cut with a pattern of holes leaving ring-shaped portions of steel connected by diagonal links. The ring shape resists out-of-plane buckling through the mechanics of how a circular ring deforms into an ellipse. It is shown that the ring's compression diagonal will shorten a similar amount as the tension diagonal elongates, essentially eliminating the slack in the direction perpendicular to the tension field. Because of the unique features of the ring's mode of distortion, the load-deformation response of the resulting RS-SPSW system can exhibit full hysteretic behavior and possess greatly improved stiffness relative to thin unstiffened SPSW. The concept has been validated through testing on seven approximately 1 m × 1 m RS-SPSW panels and compared to the experimental response of a solid plate panel. General conclusions about the influence of different geometric parameters on plate behavior are made including limits on geometry that produce desirable hysteretic response.

1. Introduction

Steel plate shear walls (SPSW) are an attractive option for earthquake engineering design for a variety of reasons including reduced cost, less invasive construction, and small architectural wall thickness relative to concrete shear walls as well as increased speed of construction and efficient use of slender wall elements (see [1] for a summary). In the past few decades, a significant number of computational and experimental research programs have been conducted on SPSW and they have been implemented in buildings located in the USA, Canada, Japan and elsewhere. Even though SPSWs have been used in practice, there are several challenges associated with the design, construction, and behavior of SPSW that limit their use.

The key components of a typical SPSW (see Fig. 1a) are a thin web plate, beams which are referred to as horizontal boundary elements, and columns also referred to as vertical boundary elements. The web plate resists horizontal story shear through tension field action of the web plate and dissipates seismic energy as the web plate yields along the inclined tension field direction (e.g. [2]). Although SPSW can develop significant post-buckling shear capacity, the web plate buckles at small shear force which may even occur during large wind loads. Buckling of the SPSW leads to significant loss of stiffness and a pinched hysteretic behavior (e.g. [3]). To mitigate the negative effects associated with SPSW web plate buckling, a surrounding moment frame is required in the U.S. building codes [4].

The ring-shaped steel plate shear wall (RS-SPSW) (see Fig. 1b) includes a unique pattern of cutouts leaving ring shapes that can mitigate plate buckling by the mechanics of how a circle deforms into an ellipse. The mechanics of the system were explored by Maurya et al. [5] including computational simulation of a set of RS-SPSW panels [6]. It was found that the RS-SPSW system has substantially improved stiffness and energy dissipation characteristics as compared to conventional SPSW.

The objective of this paper is to verify the RS-SPSW theoretical concepts through an experimental program. Furthermore, different configurations including plate thickness, number of rings, and ring geometry were chosen to study the effect of design variables on RS-SPSW behavior, identify potential buckling modes, provide data for validation/calibration of computational models by others, compare measured shear capacity with theoretical strength predications, and to explore which combinations of design variables produce desirable hysteretic response.

To serve these goals, eight specimens were designed, fabricated and subjected to reversed cyclic shear deformations. This paper describes the basic concepts related to the RS-SPSW system, the experimental setup and displacement protocol, as well as presenting the results and analyzing the implications of the results for use of this system in practice.

2. Background and RS-SPSW concept

A large number of small and large scale experiments have been performed on steel plate shear wall panels (see [1] for a summary). Of

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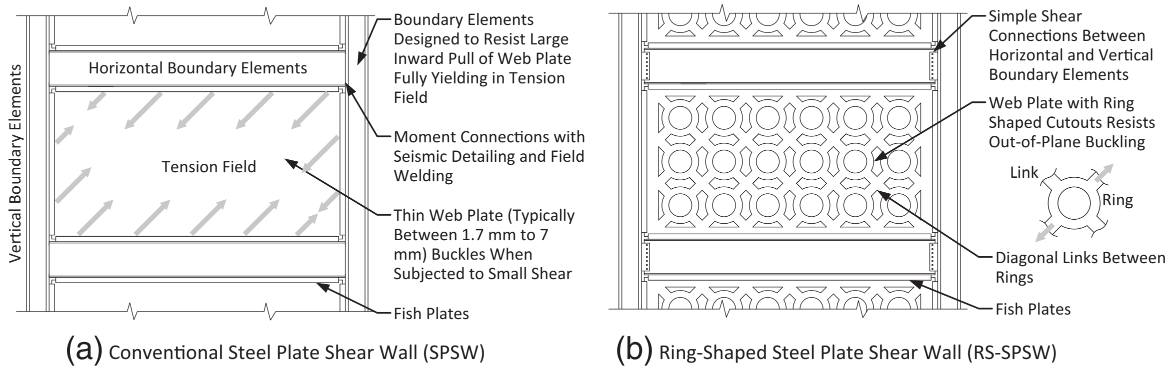

Fig. 1. Conventional and ring-shaped steel plate shear walls.

particular interest are tests on specimens with thin web plates, such as the web plates as thin as 1.6 mm suggested for upper floors in design examples [1]. It has been shown in tests that thin 1.0 mm web plates act similar to 25 mm x 50 mm tension only braces with negligible lateral resistance provided by the web plate during load reversal [7]. There have been a number of attempts to improve the performance of SPSW including use of low yield strength steel [8], corrugated steel panels (e.g. [9]), and perforated steel plate shear walls [8]. The perforated SPSW include a regular pattern of circular holes cut in the web plate and are allowed in current U.S. building codes [4]. However, perforated SPSW also develop early buckling and have limited design flexibility because the ductile mechanism still depends on tension field action and yielding of the web plate along tension diagonals.

On the other hand, ring shapes have been used in seismic systems to dissipate seismic energy without buckling. Tyler [10] describes tests on a yielding frame that dissipates energy through the yielding of round bars that are oriented in a circular or rectangular shape and connected to the four corners of a steel frame with diagonal braces. When the steel frame was subjected to lateral loading, this device deformed in such a way as to eliminate slack in the braces and thus exhibited significant energy dissipation, even during load reversal. Ciampi et al. [11] proposed a similar class of hysteretic devices with rectangular geometry suspended in a steel frame with diagonal tension braces to the four corners. A modified version of the device was incorporated in one of the buildings of the Laboratories of the National Research Council in Frascati, Italy [11].

The RS-SPSW system proposed herein also uses the ring shape to resist buckling. To demonstrate this concept, a single ring is considered as shown in Fig. 2a. The perimeter of the ring, P_{circle}, is given in Eq. (1) where r is the centerline radius of the ring.

$$P_{circle} = 2\pi r \tag{1}$$

The application of a diagonal tension force transforms the circle into an ellipse as shown in Fig. 2a. The perimeter of the ellipse is approximately given by Eq (2) as a function of the elongation of the circle in the longitudinal tension direction, δ_1, and its shortening in the transverse direction, δ_2. A relationship between δ_1 and δ_2 can then be found by setting the perimeter of the circle equal to the perimeter of the ellipse as given in Eq. (3) assuming the circle does not undergo any axial stretching.

$$P_{ellipse} \approx 2\pi\sqrt{\frac{(r+\delta_1)^2+(r-\delta_2)^2}{2}} \tag{2}$$

$$\delta_2 = r - \frac{1}{2}\sqrt{4r^2 - 4\delta_1^2 - 8r\delta_1} \tag{3}$$

A plot of the relationship between the longitudinal elongation, δ_1, and the transverse shortening, δ_2 is shown in Fig. 2c for an arbitrary value of the ring radius. It is shown in Fig. 2c that the longitudinal elongation and transverse shortening are approximately equal for values of deformation that are small relative to the ring radius. Conversely, a solid square steel cube undergoing small uniaxial elongation will contract in the transverse directions, δ_2, by an amount equal to the Poisson's ratio (0.3 for steel) multiplied by the longitudinal elongation, δ_1. In the inelastic range, this ratio increases toward 0.5 for constant volume deformation. If shear buckling of a thin unstiffened SPSW is conceptually viewed as occurring when there is excess material along the compression diagonal, then the shaded region of Fig. 2c represents configurations prone to buckling. Unlike the solid plate, the ring shape removes the slack in the compression diagonal direction and therefore reduces out-of-plane buckling.

A finite element (FE) computational study was previously conducted to study the RS-SPSW concept [6]. Shell element models were used with

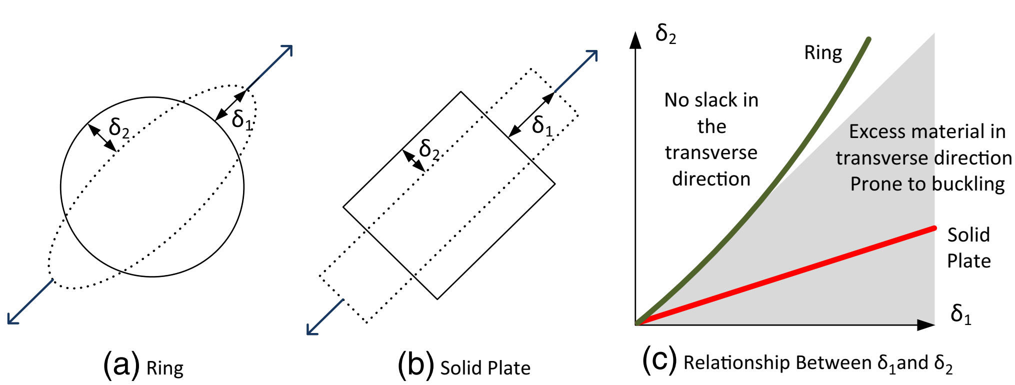

Fig. 2. Mechanics of ring shape resistance to buckling.