BEHAVIOR OF STEEL PLATE SHEAR WALLS WITH IN-SPAN PLASTIC HINGES

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ABSTRACT

Research was conducted to investigate the seismic behavior of steel plate shear walls with in-span plastic hinges. Results show that the development of in-span plastic hinges has detrimental impacts on the behavior of the structure through inducing: (1) significant vertical and residual deformations on the HBEs (i.e. shakedown phenomenon); (2) only partial yielding of the infill plates; (3) lower global plastic strength compared to the values predicted by code equations; and (4) total HBE rotations greater than 0.03 radians after the structure was pushed cyclically up to a maximum lateral drift of 3%. Nonlinear time history analyses also demonstrated that the severity of the ground excitations accentuated the shakedown phenomenon.

INTRODUCTION

There have been numerous experimental and analytical studies investigating the behavior of unstiffened Steel Plate Shear Walls (SPSW) in the past thirty years. An extensive summary of that research has been presented in Sabelli and Bruneau (2007). Much of that research has focused on designing and modeling of the SPSW web plates, analysis methods, and validation of satisfactory cyclic inelastic and seismic performance. Few have focused on alternative ways to analyze and design SPSW horizontal and vertical boundary elements (HBEs and VBEs). Xue and Lu (1994) suggested means to reduce demand on VBEs, including connecting the infill panel to only the HBEs. Berman and Bruneau (2008) developed an analytical procedure to obtain correct forces in the VBEs. Lopez-Garcia and Bruneau (2006) and Qu *et al.* (2008) investigated possible inadequate performance of HBEs, building on the work of Vian and Bruneau (2005).

This paper presents the results of an analytical investigation on the seismic behavior of steel plate shear walls having HBEs designed to have different plastic collapse mechanisms. In the first SPSW, formation of in-span plastic hinges on HBEs is possible, whereas in the second SPSW, plastic hinges can only occur at the ends of HBEs. Results and observations from pushover analyses and time-history analyses are used to assess the relative performance of the two SPSWs.

STRUCTURE DESCRIPTION & ANALYTICAL MODEL DEVELOPMENT

As a case study to investigate the possible significance of in-span HBE plastic hinges, a three-story single-bay SPSW was selected. Bay width and typical story height were arbitrarily chosen equal to 20 and 10 ft, respectively, resulting in an infill plate aspect ratio of 2.0. It was also assumed that the structure is located on Class D soil in downtown San Francisco, California and designed for an office building. Total weight of the structure W_t is 1085 kips, distributed as 352 kips on the first two stories and 381 kips on the roof. The total base shear V resisted by the structure was 176 kips, distributed as lateral loads along the height of the building of 92 kips, 56 kips, and 28 kips from the third to the first floor. Two design procedures were applied to design the boundary elements: (1) the Indirect Capacity Design approach (AISC 2010) and (2) the capacity design approach which combines the procedure proposed by Vian and Bruneau (2005) for HBEs and that proposed by Berman and Bruneau (2008) for VBEs. The resulting sizes of VBEs and HBEs obtained by the two different design procedures are compared in Figure 1. For SPSW designed by the capacity approach (SPSW-CD), all the HBE demand-capacity ratios exceed 0.98, except one at 0.95. For SPSW designed by the indirect capacity approach (SPSW-ID), the HBE ratios varied from 0.88 to 0.99; but this slight difference from the second SPSW case will not violate the conclusions reached by this study as will be shown later.

To investigate the behavior of both SPSW-ID and SPSW-CD, two analytical models were developed in SAP2000 program: (1) a strip model for monotonic pushover analysis and (2) a dual strip model for cyclic pushover analysis and time history analyses. In this study, twelve strips were provided at every floor to model the infill plates of the two 3-story SPSWs. The *Axial-P Hinge* (set to exhibit correct hysteretic tension-only behavior, per Purba and Bruneau 2010) was chosen to define the inelastic behavior of the strips. The *Fiber P-M2-M3 Hinge* was chosen to define plastic hinges in the VBEs and HBEs, which automatically accounts for the interaction between the axial loads and moments that can occur in the HBEs and VBEs.

NONLINEAR STATIC ANALYSIS (PUSHOVER ANALYSIS)

A monotonic pushover analysis was conducted for both SPSW-ID and SPSW-CD until each structure reached a 4% lateral drift. At 4% drift, the base shears are 311 and 477 kips for the respective structures; for comparison, their respective theoretical

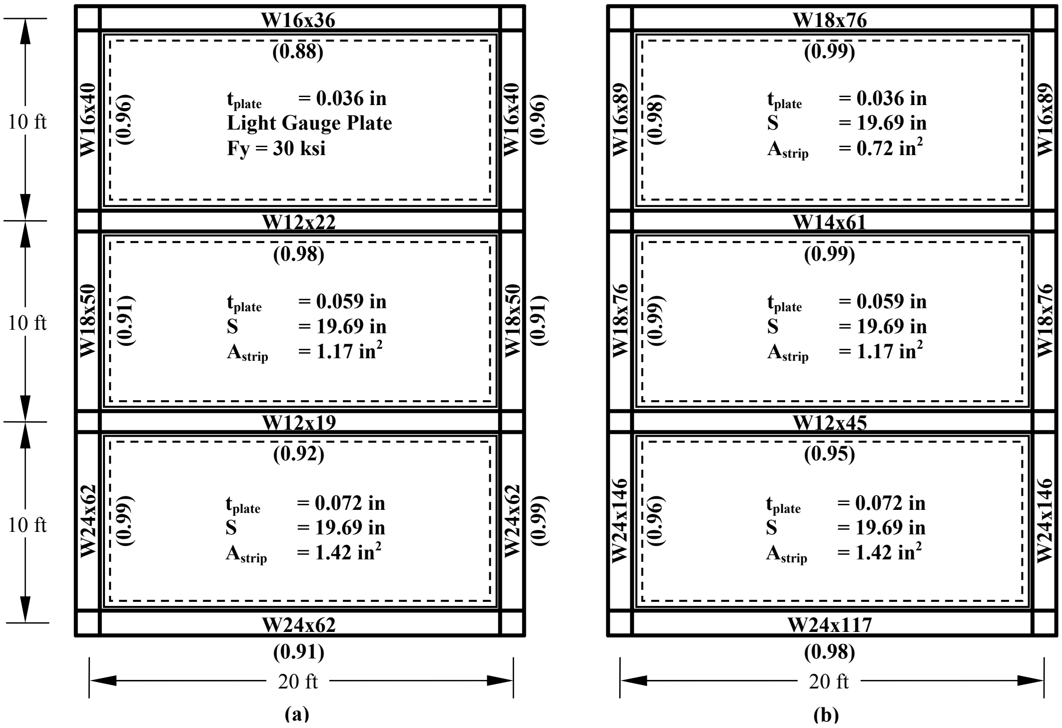
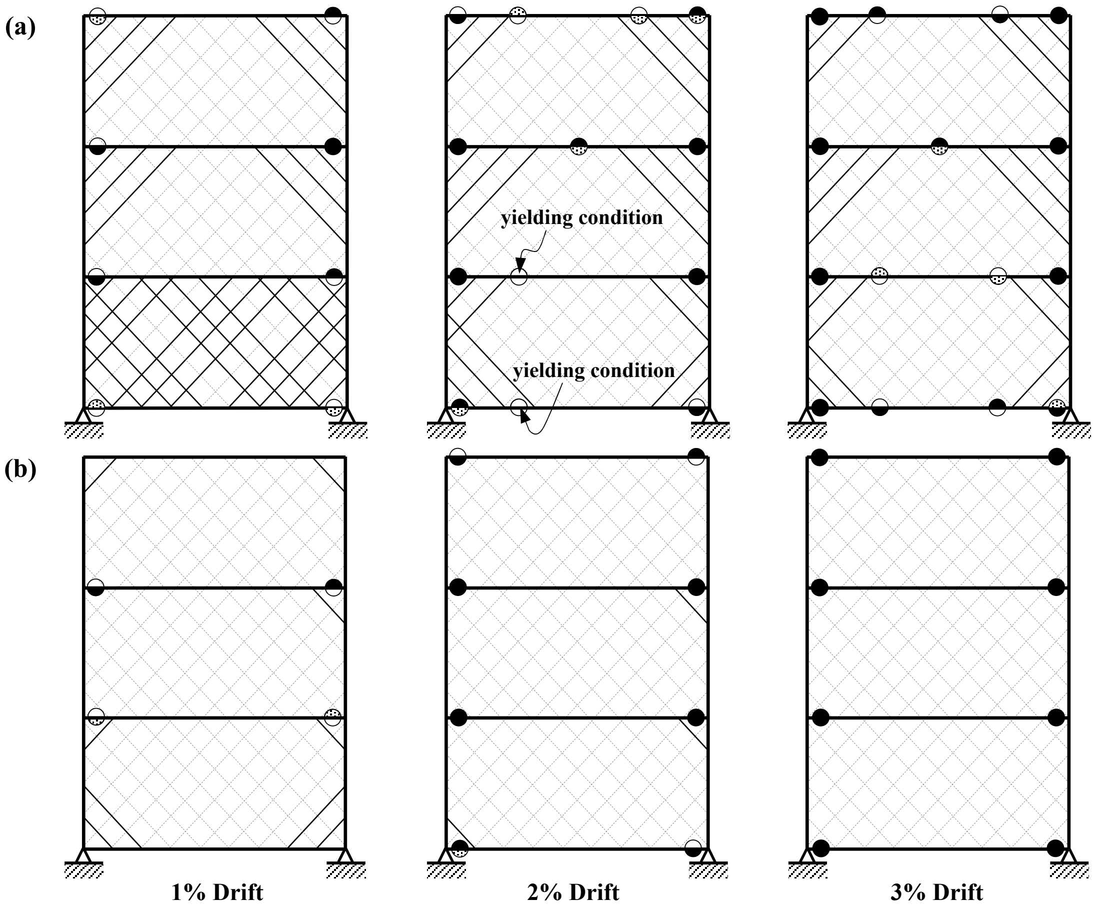


Figure 1. VBE and HBE Sizes (a) SPSW-ID; (b) SPSW-CD

values are 351 and 488 kips, obtained using the plastic analysis equations for uniform plastic collapse mechanism (Berman and Bruneau 2003). For SPSW-CD, the two values are in a good agreement with only a 2.3% difference. However for SPSW-ID, the theoretical base shear is 13% more than obtained from the monotonic pushover analysis. This because SPSW-ID did not follow the uniform plastic collapse sway-mechanism but rather consists of a 'sway' and 'beam' combined mechanism. Four in-span plastic hinges have developed on the HBEs of SPSW-ID and significant vertical deformations were observed along the HBEs spans of SPSW-ID.

In a seismic excitation environment, when a structure experiences cyclic loading, plastic hinging along an HBE span could lead to an unbounded progressively increasing deformation. This detrimental impact on a structure is called a "shakedown phenomenon". To investigate whether this phenomenon develops in the HBEs of SPSW-ID and SPSW-CD, and whether it may detrimentally affect structural performance, cyclic pushover analysis was conducted. A progressively increasing cyclic displacement history of up to 3% drift (in increment of 0.5%) was applied to the top floor of the structure for this purpose.

Figure 2(a) shows the plastic hinge and strip yielding distributions on SPSW-ID. When the structure experienced +1% lateral drift, a total of four plastic hinges (1 partial plastification and 3 fully plastic) occurred at the HBE ends; and somewhat the same distributions occurred at the reversed excursion of −1% lateral drift. In addition, three strips (the right-leaning or left-leaning strips for the positive or negative direction, respectively) on the second and the third floor remained elastic and only two strips on the first floor had yielded. Though more strips yielded as the



Legend:
◍|◓ = partial plastification | fully plastic in **positive** drift
◍|◒ = partial plastification | fully plastic in **negative** drift
◍|● = partial plastification | fully plastic in both directions
○ = yielding condition (yielding remains within HBE flanges)
┈ = strip yielding ($P = P_y$)

Yielding condition : Mp = 0.88 – 0.91 Mp
Partial plastification : Mp = 0.88 – 0.97 Mp
Fully plastic : Mp ≥ 0.97 Mp

Figure 2. Plastic Hinge and Strip Yielding Distributions on (a) SPSW-ID; (b) SPSW-CD

pushover displacement increased, some strips remained elastic. Moreover for the plastic hinge distribution, beyond the plastic hinges that occurred at the HBE ends, three locations of in-span plastic hinges were also observed on HBE2 and HBE3 at the end of 2% drift cycle; and the yielding condition occurred along the span of HBE0 and HBE1. At the end of the 3% drift cyclic, in-span plastic hinges on the HBEs occurred at 4 locations for both positive and negative drift excursions. In contrast with SPSW-CD [presented in Figure 2(b)], most of the strips had yielded at the end of the 1% drift cycle and only four right-leaning strips and five left-leaning strips in total had remained elastic. All strips have completely yielded at the end of the 3% drift cycle. In addition, all plastic hinges have developed at the HBE ends of SPSW-CD and no in-span plastic hinge developed.

A most significant phenomenon observed is the HBE vertical downward deformation of SPSW-ID, progressively increasing and of significant magnitude as the lateral drift increased, as one example is shown in Figure 3. This figure compares vertical displacement history at the mid-span of the top HBE for both SPSWs. The backbone-displacement slope (i.e., displacement at maximum drift) of SPSW-ID is stiffer than that of SPSW-CD. This implies that the HBE vertical downward displacement for SPSW-ID increases faster than that for SPSW-CD. In other words, the shakedown phenomenon due to cyclic pushover displacement detrimentally affects the structural performance of SPSW-ID. The same trend was also exhibited with the residual displacements (i.e., displacement when the structure returns to its original position at 0% drift). Moreover, note that the shakedown phenomenon on SPSW-ID would be even worse if a smaller W-section had been used for the top HBE such that its demand-to-capacity ratio was closer to 1.0; recall that a value of 0.88 (as shown in Figure 1) was obtained for that top HBE in the SPSW-ID case, compared to the corresponding 0.99 value at the top HBE of SPSW-CD. If anything, this discrepancy reinforces the conclusions reached by this case study.

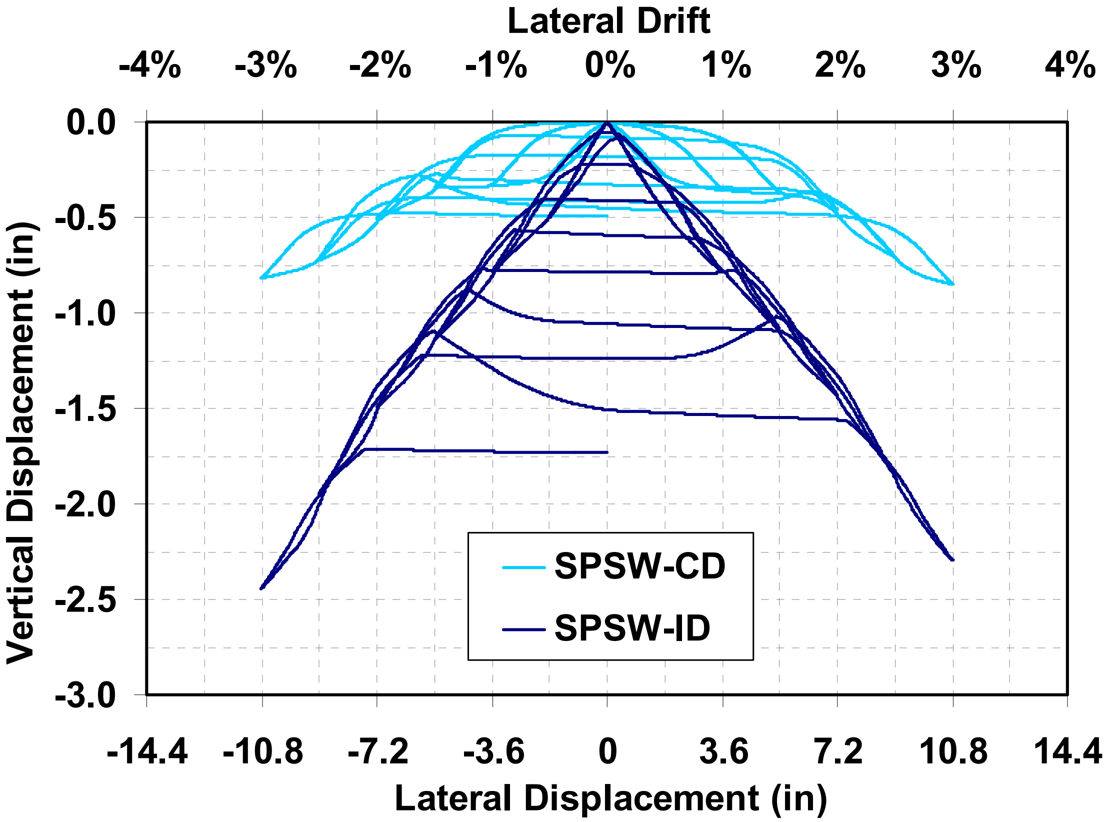


Figure 3. History of HBE3 Vertical Displacement (Cyclic Pushover)

Another approach that can be used to examine the behavior of the two SPSWs is by comparing the moment-rotation hysteresis of their HBEs, as done in Figure 4, which plots the normalized moment-rotation hysteresis of HBE2 (as an example) obtained during the cyclic pushover displacements. Interestingly, the moment-resisting ends of the HBEs of SPSW-ID developed a cross-section rotation greater than 0.03 radians after the structure was pushed cyclically up to a maximum lateral drift of 3%. Such a significantly high cyclic rotation demand would be difficult to achieve using the type of moment resisting connections used in SPSW (the AISC 2010 Seismic Specifications only require that Ordinary-type connections be used in SPSW). In fact, it might also be difficult to achieve with special moment resisting frame (SMRF) beam-to-column connections approved by AISC 2010, which are experimentally verified to perform well up to +/–0.04 radians total rotations, or +/–0.03 radians plastic rotations. By comparison for SPSW-CD, all HBE total rotations obtained were less than or equal to 0.03 radians under the same cyclic pushover displacements up to 3% drift.

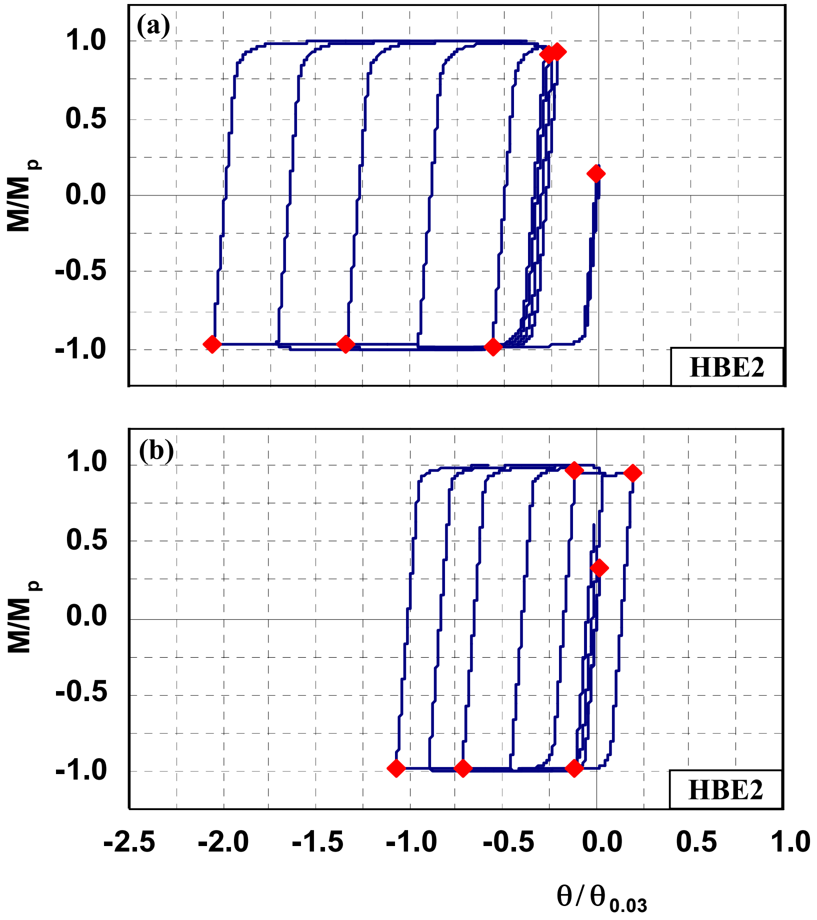


Figure 4. Normalized Moment Rotation Hysteresis at HBE Left End for (a) SPSW-ID; (b) SPSW-CD

NONLINEAR TIME HISTORY ANALYSIS

While several key seismic behaviors of steel plate shear walls having HBEs designed to have different plastic collapse mechanisms have been discovered through the incrementally cyclic pushover analysis, conducting nonlinear time history analysis remains necessary to investigate whether those previous results would be replicated during earthquakes excitations and whether additional seismic behaviors for the aforementioned SPSW systems would emerge as a consequence of the random nature of earthquake records. Three synthetic time histories of ground acceleration were generated for this purpose

The nonlinear time history results show that the shakedown phenomenon is still observed, with maximum and residual vertical deformations more apparent on SPSW-ID than on SPSW-CD. HBE3 vertical downward displacement for SPSW-ID increased faster than that for SPSW-CD as the lateral drift increased. For example, when SPSW-CD reached a lateral drift of 1% for the first time, the largest HBE3 vertical displacement at the same drift for SPSW-ID was 2.25 larger; and became 4 times larger as the ground excitation increased and caused a 2% lateral drift on both structures.

The nonlinear time history analyses were then extended to investigate the performance of both SPSWs under the more severe Maximum Considered Earthquake (MCE). It was observed that as the severity of the synthetic ground motions increased (consequently generating higher lateral drifts on both SPSWs), HBE vertical deformations of SPSW-ID especially at the top two floors significantly increased compared to the corresponding magnitudes in the DBE case. By comparison for SPSW-CD, only minor changes of HBE vertical deformations occurred. Hence, when formation of in-span plastic hinges on HBEs is possible, such as in the case of SPSW-ID, the more severe the ground excitations, the worse the shakedown phenomenon.

CONCLUSIONS

An analytical investigation on the seismic behavior of steel plate shear walls having boundary elements designed by two different philosophies was conducted. It was demonstrated that plastification along HBE spans (i.e., in SPSW-ID) has detrimental impacts on the behavior of the structure. Nonlinear time history analysis also demonstrated that the severity of the ground excitations accentuated the shakedown phenomenon on SPSW-ID, while this was not the case for SPSW-CD. These conclusions on the behavior of the SPSW-ID are equally applicable to SPSWs designed by any method for which in-span hinges is not explicitly prevented.

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