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Seismic design and performance of SPSWs with beam-connected web plates

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A B S T R A C T

Steel plate shear walls with beam-connected web plates (B-SPSWs) are an alternative steel plate shear wall (SPSW) configuration in which the web plate edges are detached from the columns to avoid high flexural demands in the columns resulting from tension field action. Releasing the columns from the web plates results in development of a partial tension field instead of the full tension field observed in conventional SPSWs, which changes system behavior and member demands significantly. A numerical study is undertaken to assess the seismic performance of B-SPSWs designed for low-seismic regions. Equations for the web plate lateral strength and the beam axial force, shear force, and moment demands are provided. Following two design approaches, eighteen B-SPSWs possessing different geometric characteristics are designed based on the provided equations. Each B-SPSW is subjected to forty ground motions representing two seismic hazard levels. The seismic performance of these B-SPSWs is evaluated based on maximum interstory drifts, member demand-to-capacity ratios, and beam-column connection rotations. The results indicate that B-SPSWs show a promising seismic behavior and may be particularly attractive lateral force-resisting alternatives for regions of low and moderate seismicity.

1. Introduction and background

Experimental and numerical studies [1–7] have shown steel plate shear walls (SPSWs) to be a reliable earthquake-resistant system due to their high lateral stiffness, ductile behavior, and stable hysteresis characteristics. Web plates, which are typically connected to boundary elements (i.e., beams and columns) on all four sides, are the primary lateral-load-resisting elements of SPSWs, where thin web plates are capable of providing high lateral stiffness and strength after shear buckling due to a mechanism called tension field action (TFA) [8]. To develop TFA and to utilize the post-buckling lateral strength and stiffness of the web plates, the web plates must be anchored to properly designed boundary elements with sufficient strength and stiffness to resist the pull-in forces resulting from TFA.

While the *AISC Seismic Provisions* (AISC 341-10) [9] allow the formation of plastic hinges at the beam ends and column bases for special SPSWs, in-span hinges in the beams and columns must be avoided as they can result in excessive deformations that limit formation of TFA and reduces lateral strength capacity [10,11]. The flexural demands in the intermediate-story beams resulting from TFA are typically not as severe as those in the columns due to the fact that the web plates of the stories above and below pull the beams in opposite directions and reduce the flexural demands. As long as web plates with similar thicknesses are provided at adjacent stories, which is the case for typical designs, the beam flexural demands due to TFA are relatively small. Flexural demands on the columns due to TFA, however, can be significant since the columns are pulled in by the web plates on only one side. As the building height increases, the combined axial and flexural demands on the columns due to TFA and frame action can result in very large steel sections [12,13].

Over the past decades, several methods have been investigated to reduce the flexural demands in the columns of SPSWs. The methods can be categorized in three main groups: (1) reducing the flexural demands resulting from TFA by use of light gage web plates, low-yield-point web plate materials, and/or regular patterns of perforations in web plates [2,14–24]; (2) reducing the flexural demands resulting from frame action by introducing simple shear or partially-restrained moment connections at beam-column joints instead of fully-restrained moment connections and/or adopting reduced beam sections at the beam ends [3,10,11,25–32]; and (3) introducing an alternative SPSW configuration called SPSWs with beam-connected web plates (B-SPSW) where the web plates are connected to beams only and detached along column edges [1,28,29,33–36]. The focus of this study is on B-SPSWs with simple shear beam-column connections.

Past studies have been conducted to understand the behavior of B-SPSWs. Thorburn et al. [1] investigated the behavior of SPSWs with fully-connected web plates and the study was extended to SPSWs with infinitely flexible columns that show a similar behavior to

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B-SPSWs. Due to the limited or no restraint along the column edges in the plane of the web plate, the development of TFA was limited to some diagonal portion of the web plate between the top and bottom beams (Fig.1), resulting in a partial tension field (PTF). Thorburn et al. [1] developed equations to calculate the lateral load capacity of the web plate and the inclination angle of the PTF, θ, and proposed a simplified analytical model, called the strip model, where the web plate is represented by a series of inclined tension-only trusses.

Xue [29] conducted a numerical study to compare the behavior of SPSWs with different column-web plate connectivity (connected or detached) and different beam-column connections (partial or full moment-resisting). Xue [29] adopted a finite element software ADINA to perform pushover analyses of the different SPSWs in which the web plates were modeled using shell elements and boundary elements were represented by elastic line elements. The results of the monotonic loading suggested that B-SPSWs with partial moment-resisting beam-column connections showed the most desirable overall lateral behavior in terms of the proper utilization and effective participation of the web plates to the lateral strength and stiffness; however, further investigation of the performance under cyclic and dynamic loading was recommended. An empirical equation was proposed to estimate the lateral load capacity of web plates; however, the boundary element demands and the details of PTF such as the inclination angle and the extend of PTF were not discussed.

Guo et al. [34] tested two one-third scaled, one-story, one-bay B-SPSWs with true-pin beam-column connections. For one of the specimens, the free edges of the web plate were reinforced with stiffeners. The experimental study results suggested that B-SPSWs showed a ductile response with a large energy dissipation capacity. Although the stiffeners improved the energy dissipation capacity, there was no evident influence on the lateral load capacity and ductility. Numerical analyses were performed in a commercially-available finite element software ANSYS [37] in which the web plate, columns, and beams were modeled using shell elements. Based on the numerical study results, Guo et al. [34] proposed an empirical equation to estimate the lateral load capacity of web plates. Similar to Xue [29], Guo et al. [34] did not discuss the boundary frame member demands.

Vatansever and Yardimci [28] tested two one-third scaled SPSWs with partial moment-resisting beam-column connections. The web plate of the one of the specimens was connected to beams and columns while the web plate of the other specimen was free along the column edges, i.e., a beam-connected web plate. A unique connection was employed between the web plates and the boundary elements where the web plates were connected to the fish plates of the boundary elements with self-drilling screws. The results of the cyclic tests revealed that the B-SPSW had a lower lateral load capacity and less energy dissipation compared to the SPSW with fully-connected web plates of

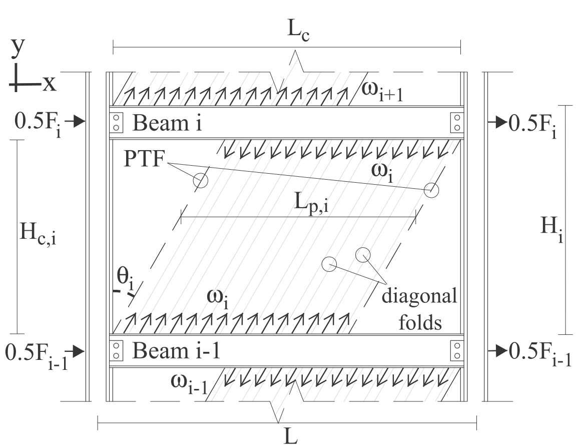

Fig. 1. Development of partial tension field.

the same thickness; therefore, the authors suggested that B-SPSWs would be a viable and economical option for retrofitting steel frames with inadequate stiffness and strength.

Clayton et al. [33,38–40] investigated self-centering SPSWs with post-tensioned moment-resisting beam-column connections (SC-SPSWs) and compared the behavior of SC-SPSWs with beam-connected and fully-connected web plates. The highlights of the experimental and analytical studies can be listed as follow: (1) Detaching the web plates along the column edges resulted in a delayed initiation and propagation of web plate tearing for this particular system. (2) For the same lateral load demand, SC-SPSWs with beam-connected web plates requires web plates from 1.5 to 2.5 times as thick as SC-SPWs with fully-connected web plates for typical aspect ratios. (3) Three- and nine-story SC-SPSWs designed with beam-connected web plates had lower total steel weight of the SPSW elements compared to SC-SPSWs with fully-connected web plates designed for the same lateral loads, and the reduction in steel weight was more prominent for taller SC-SPSWs.

Much of the past work on SPSWs, including the aforementioned work on B-SPSWs, has focused on high seismic applications. Unlike many other seismic force-resisting systems such as moment-resisting frames and concentrically-braced frames that have special, intermediate, and ordinary design options that offer varying levels of ductility and response modification factors used in design, only special (i.e. highly ductile) SPSWs are included in AISC 341-10 [9]. As per AISC 341-10 [9], special SPSWs are required to have fully-connected web plates, full moment-resisting beam-column connections, and boundary elements designed in accordance with the capacity design principles. Berman and Bruneau [41] reported that the capacity design of boundary elements might lead to overly conservative and uneconomical SPSW designs in low- and moderate-seismic regions that makes SPSWs less attractive. In contrast to AISC 341-10 [9], the Canadian provisions CSA S16-09 [42] provide a limited-ductility SPSW option (Type LD), permitting the use of simple beam-column connections instead of moment connections, in addition to high-ductility SPSW option (Type D); however, the web plates of Type LD SPSWs are still required to be attached to the boundary frames on all four sides of the web plates. Allowing the use of the simple beam-column connections is based on the experimental studies carried out by Timber and Kulak [43] and Tromposch and Kulak [27], which only included fully-connected web plates.

B-SPSWs are proposed here as a feasible SPSW alternative for moderate- and low-seismic regions. As the previous research suggested B-SPSWs with simple shear beam-column connections (hereafter referred to as B-SPSWs, unless otherwise stated) exhibit promising seismic performance despite (i) the reduction in the lateral load capacity, energy dissipation, and ductility due to the development of PTF instead of full TFA, and (ii) the reduced redundancy due to the lack of the moment frame action. In return for the beam-connected web plates and simple beam-column connections, the B-SPSW has the following benefits: (1) significant reduction of column flexural demands, (2) potential decrease in the total steel weight of the components, (3) elimination of costly detailing required for full moment-resisting connections, and (4) ease of construction due to the reduction in field welding required for beam-connected plates compared to fully-connected web plates.

This paper focuses on the seismic design and behavior of B-SPSWs designated for regions with low seismicity. The web plate lateral strength and boundary element demands are discussed and associated closed-form equations are provided. A series of three-, six-, and nine-story B-SPSWs adopting different design approaches are designed for a low-seismic site, and their seismic performance is assessed and compared using nonlinear response-history analyses.

2. Design of beam-connected web plates

The lateral resistance of beam-connected web plates has two components: shear buckling strength and the effects of partial tension