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Seismic performance of self-centering steel plate shear walls with beam-only-connected web plates

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ABSTRACT

In the self-centering steel plate shear wall (SC-SPSW) system, thin steel web plates provide the primary lateral strength and energy dissipation, while post-tensioned connections in the boundary frame provide recentering and mitigate frame damage. In most steel plate shear walls (SPSWs), web plates are connected to the beams and columns; however, connecting the web plates to the beams only has been proposed as a means of reducing boundary frame demands and mitigating web plate damage. This paper investigates the impact of using beam-only-connected web plates on SC-SPSW design and seismic performance. Expressions for determining beam demands for purposes of design are developed. Three- and nine-story prototype SC-SPSWs are designed using beam-only-connected web plates and are compared with equivalent SC-SPSWs designs with fully-connected web plates. To evaluate the potential for material savings, the weight of steel required for each system is compared. The seismic performance of the SC-SPSWs with beam-only-connected and fully-connected web plates is compared using results of nonlinear response history analyses in which relatively simple, yet conservative, modeling techniques are employed.

1. Introduction

The self-centering steel plate shear wall (SC-SPSW) is a lateral force-resisting system that is capable of withstanding moderate to severe seismic events with full recentering capabilities and with damage concentrated in easily replaced thin steel infill plates, referred to as web plates [1,2]. The SC-SPSW utilizes web plates to provide the energy dissipation and primary lateral strength of the system, while the boundary frame employs post-tensioned (PT) beam-to-column connections to provide recentering and mitigate frame damage. Under lateral loading, beams rock about their flanges at the PT connection to form a gap (θ_r in Fig. 1) between the decompressed beam flange and the column. The formation of this gap eliminates the plastic rotation that would have otherwise been present in a welded moment-resisting connection. Analytical design expressions and performance-based design methodologies have been developed to facilitate SC-SPSW design at the component and system level [1,2]. The seismic performance of the SC-SPSW has been validated with nonlinear response history analyses of several prototype buildings [1] and with subassemblage and full-scale experiments [3–5]. These studies demonstrate the system's potential for reducing post-earthquake downtime and repair costs due to structural damage.

As with conventional steel plate shear walls (SPSWs), which employ web plates with boundary frames with welded moment-resisting connections, the web plates in SC-SPSWs resist lateral load through the development of tension field action (TFA) [6]. Under lateral loading, V, the TFA present in the web plate results in the distributed diagonal loads, ω, acting on the boundary frame members at and angle α, imposing both axial and lateral distributed loadings on the beams and columns (Fig. 1). When columns are capacity designed to resist the expected yield strength of the web plate (as is suggested for conventional SPSWs [7] and for SC-SPSWs [1]), the required column sizes can be substantial. Potential methods for reducing column demands in SPSWs have been proposed, including offsetting web plates at each story [6], using outriggers or coupling beams to reduce overturning forces [6,8], perforating web plates to reduce overstrength [9], and releasing the web plates from the columns [10,11]. The latter option is of particular interest in SC-SPSW applications as discussed below.

Experimental and numerical investigations of single-story SPSWs with web plates connected to the beams only, referred to as beam-only-connected web plates, have shown the system to have significant lateral resistance, energy dissipation, and ductility [10–12]. Beam-only-connected web plates are particularly appealing for application in SC-SPSWs due to the phenomena of gap opening and frame expansion, which are particular to PT moment-resisting frames. As the PT connections rock open during lateral sway, the columns (with an original centerline spacing of L) are pushed apart due to

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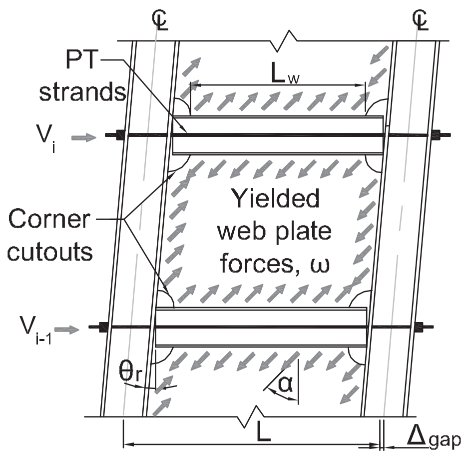

Fig. 1. Schematic of forces in SC-SPSW with fully-connected web plates.

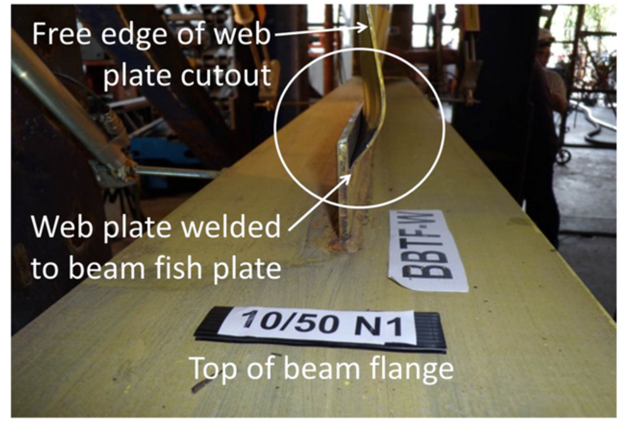

Fig. 2. Example of out-of-plane deformation along web plate corner cutout prior to web plate tearing.

the formation of the gap (Δ_{gap} in Fig. 1). As a result, web plates in SC-SPSWs have two additional demands that are not present in conventional SPSWs where gap opening and frame expansion do not occur: (1) an additional net horizontal strain due to frame expansion and (2) localized strains near the rocking PT connections.

In SC-SPSWs, gap opening in the connections increases localized tensile strains in the web plate where the gap forms. Although corner cutouts are suggested (shown in Fig. 1) to accommodate gap opening and prevent web plate tensile rupture, the increased tensile strains in this region result in increased plastic elongation along the cutout. As the gap closes, the plastically elongated plate near the cutout must buckle out-of-plane. The out-of-plane deformation along the free edge produces large curvature demands at the edge of the bolted or welded web plate-to-boundary frame connection as shown in Fig. 2 for a full-scale SC-SPSW specimen with a welded web plate connection detail [5]. Experimental observations suggest that these localized out-of-plane deformations at the edge of the corner cutout are the primary cause of initiation of web plate tearing for tests with welded and bolted web plate-to-boundary frame connection details [4]. Note that this out-of-plane deformation is not typically present in conventional SPSWs, as the web plates are connected to the boundary frame along their entire edge and there is no beam-to-column connection rocking.

When the web plate is released from the columns, the additional horizontal strain associated with frame expansion is eliminated, as are the localized tensile strains near the opening PT connection (Fig. 2). The free edge of the beam-only-connected web plate will still deform out-of-plane due to shear buckling; however, the localized web plate curvature at the end of the bolted or welded web plate connection is significantly reduced. As a part of the large-scale two-story SC-SPSW subassembly test program presented in Clayton et al. [4], one specimen (W14-8s100k20GaHBE) employing beam-only-connected web plates was tested (shown in Fig. 2). When compared with a similar specimen (i.e., having the same web plate thickness, number of PT strands, initial PT force, and load protocol) with fully-connected web plates (i.e., connected to the beams and columns), the beam-only-connected web plate specimen achieved a significantly larger drift prior to the onset of web plate tearing and noteably less tearing at the end of testing at 5% drift [4].

Although beam-only-connected web plates offer the potential benefits of mitigating web plate damage and reducing column demands in SC-SPSWs, a possible drawback is their reduced lateral load capacity compared with fully-connected web plates. Because the columns do not restrain the tension field in the entire web plate, beam-only-connected web plates develop only a partial tension field (Fig. 3) over the diagonal portion of the plate restrained by both boundary beams. The partial tension field (PTF) results in reduced lateral strength for a given web plate thickness and geometry compared with fully-connected web plates. To develop lateral strength comparable to a fully-connected SC-SPSW, a SC-SPSW with beam-only-connected web plates must have thicker plates, wider or more numerous SC-SPSW bays, or a combination of these. The associated increase in material may impact the potential steel savings hoped to gain by using beam-only-connected web plates to reduce column demands; this is investigated as part of the current study.

This paper discusses design considerations for SC-SPSWs employing beam-only-connected web plates. A series of three- and nine-story prototype SC-SPSWs employing beam-only-connected web plates with design strengths comparable to that of the SC-SPSWs with fully-connected web plates presented in [1] are presented, and the potential for column size and overall material reduction is assessed. Methods for modeling beam-only-connected web plates in SC-SPSWs are discussed and used to conduct nonlinear response history analyses of the prototype buildings to assess the impact of beam-only-connected web plates on SC-SPSW seismic response.

2. Beam demands

Beams are a critical component in SC-SPSWs as they must resist complex distributions of axial forces, shear forces, and moment resulting from combined PT and web plate forces. Dowden et al. [2] presented a capacity design procedure for SC-SPSW beams with fully-connected web plates. Similar design methodologies can be used for SC-SPSW beams with beam-only-connected web plates; however, demands will differ due to the development of a PTF. Beam-only-connected web plates may be assumed to have a constant web plate stress acting only along the portion of the beam where the PTF occurs; for fully-connected web plates, a constant stress is assumed to act along the entire length of the beam. In actuality, the web plate forces are not constant and vary slightly in magnitude and orientation; however, these variations are typically neglected in steel plate shear wall design.

Additionally, the angle of orientation of the PTF (θ in Fig. 2) is different than that of the tension field orientation for a fully-connected web plate (α in Fig. 1). The PTF angle of inclination, θ, can be calculated from the following equation:

$$\tan(2\theta) = \frac{L_w}{h_c} \quad (1)$$

where, L_w is the length of the web plate along the beam and h_c is the clear height of the web plate [13,14]. Thus, the length of the PTF along the beam, L_{PTF}, can be determined as a function of web plate geometry:

$$L_{PTF} = L_w - h_c \tan\theta. \quad (2)$$