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Numerical investigation on ultimate shear strength of steel plate shear walls

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ABSTRACT

Ultimate shear strength of steel plate shear walls, SPSW, was conventionally computed as the sum of base shear supported by in-fill plate and boundary frame elements. The base shear supported by the in-fill plate was computed assuming that it was fully yielded after buckling whereas the base shear supported by the boundary frame elements was computed by plastic analysis assuming uniform yielding mechanism. In this paper the ultimate shear strength of SPSW was investigated by the finite element method. A detailed three-dimensional finite element model was established using ANSYS software at which the in-fill plate and the boundary frame elements were modeled using finite strain iso-parametric shell elements. The analysis included material and geometric non-linearities. Numerical results obtained from cyclic and pushover loading of SPSWs were verified by comparison to test results published in the literature. A comprehensive parametric analysis was conducted to assess the effect of geometric and material parameters of the wall on its ultimate shear strength. Discrepancies between numerical results and conventional theory were attributed to interaction of in-fill plate and boundary frame elements at ultimate load. When the flexural rigidity of boundary frame elements decreased, the in-fill plate did not achieve full yield strength. On the other hand, the base shear supported by boundary frame elements increased when thicker in-fill plates were utilized. Numerical results were used to update the theoretical expression of ultimate shear strength of SPSWs. The proposed expression was assessed by comparison to test results published in the literature.

1. Introduction

Previous research work on steel plate shear walls, SPSW, revealed that such a system was capable of resisting lateral loads effectively due to its adequate stiffness, ductility and large energy dissipation capacity [1–6]. A conventional SPSW (see Fig. 1) was composed of infill plate surrounded by beams and columns designated as boundary frame elements. In typical SPSW designs, the infill plate is un-stiffened and slender; thus principal compressive stresses due to shear cause the plate to buckle and form diagonal tension folds before failure.

Conventional theory and current code provisions [7,8] adopted an analytical approach to determine the ultimate shear strength of SPSWs based on the strip model developed by Thorburn et al. in 1983 [9]. In this model, the infill plate in each panel was replaced by a series of tension-only strips inclined by an angle α with the vertical to mimic tension field action in the plate after buckling. Timler et al. derived an expression for α using elastic strain energy formulation of an equivalent storey brace model assuming flexible boundary elements as follows [10]:

$$\tan^4(\alpha) = \frac{1 + (tL/2A_c)}{1 + th\left((1/A_b) + (h^3/360 I_c L)\right)} \quad (1)$$

where t is the infill plate thickness, L is the bay width, h is the infill plate height per floor (see Fig. 1), A_c and A_b are the cross-sectional area of column and beam surrounding the infill plate, respectively, and I_c is the in-plane moment of inertia of column cross section. For multistory SPSW with identical infill plate thickness in all floors, the base shear supported by in-fill plate, V_p, was determined by plastic analysis assuming that it was fully yielded as follows [4]:

$$V_p = \tfrac{1}{2} F_{yp} t L_p \sin(2\alpha) \quad (2)$$

where F_{yp} is the yield strength of infill plate. The ultimate shear strength of SPSW, V_s, was computed as the sum of V_p and base shear supported by boundary frame elements, V_f, as follows:

$$V_s = V_p + V_f \quad (3)$$

Boundary frame elements were conventionally designed to remain essentially elastic at ultimate load with the exception of plastic hinge formation at ends of beams and base connections of

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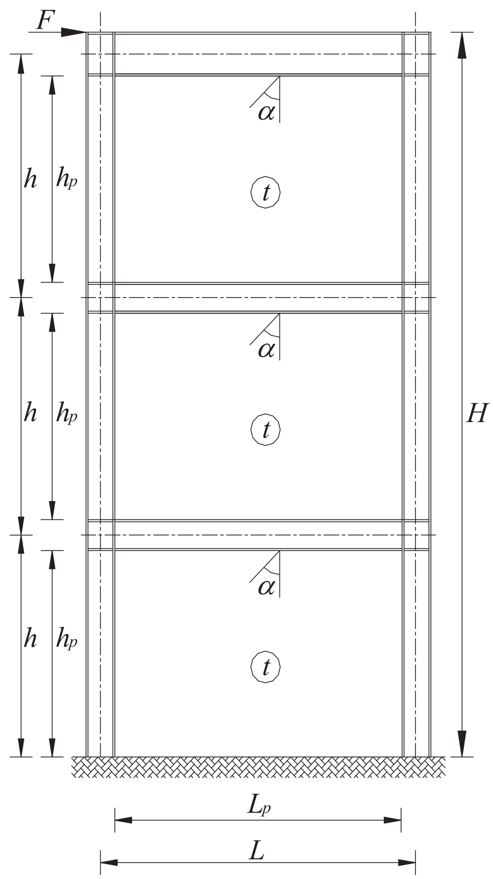

Fig. 1. Geometric configuration of three-story single bay SPSW.

columns. Therefore V_f of SPSWs with rigid beam-to-column connections and compact boundary elements was computed by plastic analysis assuming uniform yielding mechanism as follows [4]:

$$V_f = \frac{\sum M_p}{H} \tag{4}$$

where $\sum M_p$ is the sum of plastic moments at ends of beams and plastic moments at base connections of first storey columns, and H is the overall height of the wall (see Fig. 1). Eqs. (1)–(3) were adopted by the AISC 341-10 [7] and CSA S16-09 [8] to compute ultimate shear strength of SPSW after dividing Eq. (2) by an over-strength factor of 1.2. In order to achieve uniform stress field in the infill plate, it was recommended that it should be surrounded by rigid boundary elements. Therefore based on the Wagner flexibility parameter, an expression for minimum inertia of columns, I_{co}, was derived [11] and was later adopted by current codes [7,8] as follows:

$$I_{co} \geq 0.00307 \frac{th^4}{L} \tag{5}$$

Previous experimental research on SPSW was conducted to investigate the behavior and strength of the wall when subjected to pushover and/or cyclic loading. Park et al. [13] tested three storey-single bay SPSW at which the thickness of infill plate was varied as listed in Table 1. It was shown that ultimate shear strength, energy dissipation and stiffness of SPSW were progressively increased with the increase of t, and failure was caused by formation of plastic hinges in first and third-storey columns. The ultimate shear strength of SPSW obtained by test exceeded that predicted by theory by 10% on average. When weak columns were used, it was noticed that the ultimate shear strength and stiffness of the wall were not enhanced when thicker in-fill plate was used and failure was caused by local buckling of flanges and web of columns above the base connection.

Choi et al. [14,15] conducted tests on three stories-single bay SPSWs (see Table 1) subjected to cyclic loading. Test parameters included aspect ratio of in-fill plate, L_p/h_p, column inertia, I_c, type of connection of in-fill plate with boundary elements and openings in the infill plate. It was shown that the increase of L_p/h_p pronounced the ultimate shear strength and ductility of the wall since axial forces in columns caused by overturning were reduced and failure was caused by tearing of in-fill plate. Similar to the test results of Park et al. [13], it was shown that when I_c decreased, the ultimate shear strength and ductility of the wall were reduced and failure was caused by local buckling of column flanges and web above base connection. The ultimate shear strength obtained by test for FSPW1 and FSPW2 exceeded that predicted by theory by 5% on average. When the in-fill plate was detached from column, the ductility of the wall was not affected; however, the ultimate shear strength of the wall was reduced and failure took place by formation of plastic hinges at beam-to-column connections. It was shown that the presence of rectangular openings in the in-fill plate with width 500 mm extended through floor height reduced the ultimate shear strength of the wall dramatically since the in-fill plate was not fully yielded due to lack of stiff boundary elements on all boundaries of the plate; however, the ductility of the wall was not significantly affected. Chao et al. [16,17] conducted a full-scale testing program on two stories-single bay SPSWs (see Table 1) to monitor the behavior of narrow width SPSW and the effect of using horizontal columns restrainers. It was shown that the ultimate shear strength obtained by test was underestimated by theory (Eqs. (1)–(4)) by more than 20% [16,17]. On the other hand, the use of two column restrainers in each floor reduced inward deflection of columns between storey beams and increased the ultimate shear strength of SPSW by 10%.

Previous numerical research work on SPSWs was conducted using detailed and simplified finite element models. Elgaaly et al. [18] used a detailed finite element model where boundary elements and in-fill plate were modeled with shell elements. It was shown that when a coarse mesh was used, the numerical analysis overestimated the shear strength of SPSWs by 22% on average. Rezai et al. [19] modeled SPSWs with detailed and simplified finite element models. In the detailed model all boundary elements and in-fill plate were modeled with shell elements whereas in the simplified model, boundary elements were modeled with frame elements and the in-fill plate was modeled with tension-only link elements in the direction of diagonal tension forces. It was shown that both models over-predicted the elastic stiffness of test specimens. However, the yield strength and post-buckling capacity of test specimens were reasonably predicted using the detailed model. Bhowmick et al. [2] used ABAQUS/Explicit software to conduct the analysis of SPSWs subjected to pushover and cyclic loading using detailed and simplified finite element models. It was shown that the detailed model using shell elements predicted the initial stiffness of tested specimens very well, but slightly underestimated the ultimate shear strength of the wall by 7%. The simplified model was time efficient for both types of loading and provided results that agreed well with tests and the detailed model results. Botros et al. [3] successfully used ADINA software to model SPSW with flat and corrugated in-fill plate using a detailed finite element model. Shear wall components including beams, columns, and infill plates were modeled with shell element based on iso-parametric formulation considering large membrane strains and large rotations. A plastic-bilinear material model was adopted in the analysis. Qu et al. [20] used ABAQUS/Standard software to model SPSWs subjected to cyclic loading using dual strip model at which the in-fill plate was modeled with intersecting tension-only link elements in the