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Effect of column stiffness on drift concentration in steel plate shear walls

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ABSTRACT

Steel plate shear walls (SPSWs) are a lateral force resisting system consisting of thin infill steel plates surrounded by boundary frame members. Hysteretic energy dissipation and lateral force resistance of the system are primarily achieved through the yielding of the infill steel plates. However, during an earthquake event, the infill plates at different building stories may not yield simultaneously due to many factors such as overstrength of some infill plates and the actual lateral force distribution which is different from the one assumed in design, possibly resulting in inter-story drift concentrations in the system. This paper investigates the effect of column stiffness on mitigating drift concentration in SPSWs. Based on an example two-story SPSW, mathematical models are derived to characterize the system behavior and quantify the effect of column stiffness on the mitigation of drift concentration. Nonlinear static pushover analyses using finite element models are performed to further validate the developed models. Finally, based on the developed models, parametric analyses are conducted to investigate the effect of column stiffness over a practical range of the considered parameters, followed by a discussion of the minimum SPSW column stiffness specified in North American codes. The results from this investigation show that column stiffness should be a design parameter to ensure a reasonably uniform drift distribution and hence a more uniform infill plate yielding along the height of SPSW buildings.

1. Introduction

Steel plate shear walls (SPSWs) are a lateral force resisting system which includes thin infill steel plates surrounded by boundary frame members. The infill steel plates are allowed to buckle in shear and subsequently form diagonal tension field actions during an earthquake event. Hysteretic energy dissipation and lateral force resistance of the system are primarily achieved through the yielding of the infill steel plates. Past experimental and analytical studies indicate that this system can behave in a ductile manner and have a high hysteretic energy dissipation capacity compared with conventional braced frames and concrete shear walls [1–18].

Seismic design codes in North America, including the American Institute of Steel Construction (AISC) Seismic Provisions for Structural Steel Buildings (ANSI/AISC 341) [19,20] and the Canadian Standards Association (CSA) S16-09, Design of Steel Structures [21], require SPSW columns be designed using a capacity design procedure. Such a design approach ensures SPSW columns to remain elastic when the infill plates are fully yielded during an earthquake event with the exception of plastic hinges at the column bases when the columns are fixed to ground.

In addition to capacity design requirements, ANSI/AISC 341-05 and CSA S16-09 [19,21] require a minimum moment of inertia, i.e., stiffness, for SPSW columns to avoid the column failures observed from prior experimental research [8]. Recent work by Qu and Bruneau [22] suggested that the column stiffness limit specified by the codes [19,21] is uncorrelated to satisfactory SPSW column performance. As a result, ANSI/AISC 341-10 [20] excludes the SPSW column stiffness requirement. While it has been a major stride to realize that there is no correlation between the column stiffness limit specified by the codes and the satisfactory SPSW column performance, it is unclear whether this limit is advantageous for other aspects of seismic performance of SPSWs. As such, Section F5 of the Commentary of ANSI/AISC 341-10 specifies that opportunity exists for future research to confirm or improve the applicability of the column stiffness requirement and the CSA S16-09 retains the minimum column stiffness requirement for SPSWs.

One potential advantage of using relatively stiff columns in a multi-story SPSW is that it may help minimize the detrimental effect of vertical irregularity by ensuring a more uniform infill plate yielding distribution and therefore reducing drift concentration along the height of the system during an earthquake event. Conceptually, if the SPSW columns are ideally rigid and pinned to ground, the infill plates at different stories will yield simultaneously during earthquake loading due to uniform inter-story drift imposed by the ideally rigid columns. If the SPSW columns become relatively flexible, infill plate

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yielding may first occur at a certain story and then progressively spread into the other stories, possibly resulting in drift concentration and premature failures at the initially yielded story before infill plate yielding occurs at all stories. The yielding sequence of infill panels in a multi-story SPSW depends on its column stiffness and other factors such as infill plate strength distribution and lateral force distribution along the height of the building.

This paper first reviews the code-specified minimum stiffness for SPSW columns. Then, an example two-story SPSW is selected to characterize the effect of column stiffness on system performance. Mathematical models quantifying the effect of column stiffness on the mitigation of drift concentration in the example SPSW are formulated and validated by results from nonlinear static pushover analyses using finite element (FE) models. Finally, based on the derived models, parametric analyses are conducted over a practical range of the considered parameters to further investigate the effect of column stiffness followed by a discussion of the minimum SPSW column stiffness specified in the codes.

2. Code requirement on SPSW column stiffness

The stiffness requirement of SPSW columns specified in CSA S16-09[21] and ANSI/AISC 341-05 [19] is intended to prevent excessive in-plane flexibility and buckling of SPSW columns observed in [8]. Such a stiffness limit was derived based on the plate girder flange flexibility factor, ω_h, developed in an early study of the elastic behavior of plate girders with thin metal webs subjected to transverse shear [23]. By analogy, some aspects of SPSWs are similar to those of plate girders; therefore, the SPSW column flexibility factor at each panel are obtained from the plate girder flange flexibility factor expressed below:

$$\omega_h = 0.7h\left(\frac{t}{2IL}\right)^{0.25} \tag{1}$$

where h represents the SPSW story height; L represents the length of infill plate measured as the center-to-center distance between columns; t is the infill plate thickness; and I is the moment of inertia of SPSW column. Incidentally, derivations of Eq. (1) are reviewed elsewhere[22].

Noting the facts that the previously tested SPSW specimens which exhibited undesirable column failures had flexibility factors of 3.35 and that all other known tested SPSWs that behaved in a ductile manner had flexibility factors of 2.5 or less [24], an upper bound of 2.5 on ω_h was empirically selected, which forms the current column stiffness requirement specified in CSA S16-09 [21].

Imposing the upper bound of 2.5 on Eq. (1) and solving for I leads to the following requirement implemented in ANSI/AISC 341-05[19]:

$$I \geq \frac{0.00307th^4}{L}. \tag{2}$$

3. Behavior and formulation of an example two-story SPSW

3.1. Description of the considered system

To formulate the mathematical models quantifying the effect of column stiffness, take the two-story SPSW shown in Fig. 1(a) as an example. Consistent with the current codes, assume boundary frame members of the wall are designed according to the capacity design approach, i.e., only the infill plates are allowed to develop inelastic behavior in the system under earthquake loading. For simplicity, make the following assumptions in the system: 1) the infill plates at both stories have the same yield strength and are elastic-perfectly-plastic; 2) story heights and column cross-section properties are constant over both stories; 3) the beam-to-column and column-to-ground connections are pinned; 4) the infill plate tension field orientation angles are the same at both stories and equal to 45° from the vertical. It is recognized that the orientation angle of the infill plate tension field action depends on infill plate height, length, and thickness, and property of the boundary frame members; the assumed value, 45°, is typically chosen for SPSW design and analysis [5,17]. Moreover, in an actual SPSW, the beam-to-column connections may be moment resisting; however, the plastic flexural strength of the connections can be significantly reduced due to the presence of combined shear force, axial compression, and vertical stress in the beam web caused by the infill plate tension field actions, resulting in significantly reduced moment resisting capacities of the beam-to-column connections [25]. For ease of derivation, the example SPSW shown in Fig. 1(a) is represented by analytical models described in the following section.

3.2. Analytical model of the considered system

Past research [26,27] has shown that performance of the example two-story SPSW shown in Fig. 1(a) can be equivalently considered by a model shown in Fig. 1(b), which includes a continuous column representing the contribution of the two original SPSW columns and connected by rigid links to a two-story frame with infill plates and pinned member-to-member connections. This prior research focused on the effect of column stiffness on the reduction of drift concentration in concentrically braced frames (CBFs) and on the derivations of the closed-form mathematical models for two-story and three-story CBFs.

Incorporating the strip model originally developed by Thorburn et al. [14], which models the infill plates as a series of discrete pin-ended strips inclined with the same orientation as the infill plate tension field action, the model shown in Fig. 1(b) can be further transformed into the one shown in Fig. 1(c). Incidentally, the strip model has been validated by results from experimental investigations [28]. Additionally, while less rigid beams and columns surrounding the plates may affect the uniformity of the tension field actions at low deformation levels, prior research [22] indicates that all strips will eventually yield upon the increase of lateral displacement of the structure if the beams and

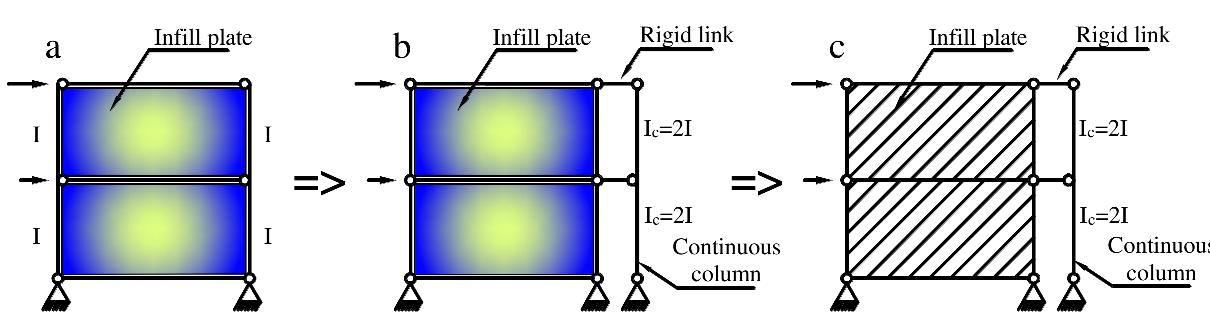

Fig. 1. Simplification of an example two-story SPSW: (a) actual system; (b) model with continuous column; and (c) strip model with continuous column.