Journal of Constructional Steel Research 99 (2014) 72–84

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Behavioral characteristics of code designed steel plate shear wall systems

S.A.A. Hosseinzadeh [a,*], Mohsen Tehranizadeh [b,1]

[a] Department of Civil Engineering, Faculty of Engineering, Golestan University, Al-Ghadir Ave, Golestan 49188-88369, Iran
[b] Department of Civil Engineering, Amirkabir University of Technology, 424 Hafez Ave, Tehran 15875-4413, Iran

ARTICLE INFO

Article history:
Received 10 June 2013
Accepted 2 April 2014
Available online xxxx

Keywords:
Shear walls
Wall–frame contribution
Interaction
Strength
Ductility
Stiffness

ABSTRACT

A series of code designed steel plate shear walls (SPSWs) with different aspect ratios and number of stories are numerically analyzed to investigate different aspects of the behavior of such SPSWs, particularly with regard to the wall/frame contributions. Results show that frames contribute effectively in resisting story shear only at a few of lower stories and infill plates absorb substantial part of story shear at the remaining stories. About 70–80% of the compressive column axial force comes from plate tension fields. The tensile column is found to be more effective in resisting base shear than the compressive one and it contributes about 55–95% of the total shear force of the frame column bases at the ultimate state. Up to 32% reduction in the overall stiffness of SPSWs due to early buckling of their infill plates is observed. The first yield points in the infill walls and in the boundary frames of different SPSWs occur at about 25–45% and 70–85% of their strength, respectively. As a result of the current design procedure that neglects the boundary frame moment resisting action, the stiffness and ductility of SPSWs having almost the same design lateral loads but different aspect ratios can be quite different.

1. Introduction

Steel plate shear wall (SPSW) systems are one of the most promising lateral load resisting systems currently available to structural engineers. The SPSW system comprises a steel frame with thin steel infill plates that are allowed to buckle in shear and develop tension field action under lateral loading. Past studies have shown that SPSWs can exhibit exemplary seismic performance. In comparison with conventional lateral load resisting systems, such as reinforced concrete shear walls, various types of braced frames and moment resisting frames, SPSWs have fewer costly detailing requirements, facilitate fast construction, and have high strength and ductility that allow for fewer bays of lateral load resisting framing. With these advantages, this system has attracted many research activities throughout the world. Many researchers have focused their research on the discovery of the behavior of SPSWs [1–5], while others have proposed the use of light-gauge [6] or low yield point (LYP) SPSWs [7,8], SPSWs with slits [9] or special metal shear panels as dampers [10–12], as alternatives to conventional SPSWs to improve the dissipation capacity of the system. However, more recent studies have worked on new types of SPSW systems, such as semi-supported [13,14] and self-centering [15] steel shear walls, to further increase the efficiency of the system.

Design clauses for design of SPSWs were provided first in CAN/CSA 16-01 [16] and then in FEMA 450 [17], AISC 341 [18] and AISC Design Guide 20 [19]. To ensure a ductile and desirable behavior, the current codes require capacity design of SPSWs. Capacity design implies that the horizontal boundary elements (HBEs) must be designed to resist demands resulting from tension field yielding of the infill plates, and the vertical boundary elements (VBEs) must be designed to resist demands resulting from both tension field yielding of the infill plates and flexural yielding of the HBE ends. Although, the suggested design procedures can be an iterative and time-consuming process (due in part to the dependence of the angle of the tension fields on the cross-sectional properties of the surrounding members and the infill plate thickness), results of recent research have shown that if the SPSWs are designed according to the code recommendations, the desired sequence of yielding will be achieved [20] and maximum interstory drift requirements considering design level earthquakes will be satisfied [21]. Note that most of the experimental and analytical research studies performed on SPSWs in the past, particularly before the existence of codified design requirements for SPSWs, dealt with systems not meeting the capacity design requirements and therefore not necessarily having a desirable mode of failure. Hence, the findings from those studies, although valuable, are not necessarily valid for all SPSW systems, especially for those designed per design code.

In general, for a given panel geometry, infill plate thickness and material properties, the behavior of a SPSW system depending on the

* Corresponding author. Tel.: +98 171 444 1002; fax: +98 171 444 1003.
E-mail addresses: ahosseinzade@gmail.com (S.A.A. Hosseinzadeh), dtehz@yahoo.com (M. Tehranizadeh).
[1] Tel.: +98 21 6454 3030; fax: +98 21 6454 3037.

http://dx.doi.org/10.1016/j.jcsr.2014.04.004
0143-974X/

cross-sectional properties of its boundary members can be controlled by two general types of failure mechanisms, namely brittle and ductile. A list of possible failure mechanisms of typical SPSWs in the order of their desirability was provided by Astaneh-Asl [5]. It is generally accepted that the tension yielding in the infill plate, occurring under the action of story shear, should be considered as the primary mode of energy dissipation of SPSWs. Again, for the full-tension yielding of the infill plates, the boundary frame members should have adequate strength and stiffness. However, if the frame member sections are selected from weaker profiles, the system behavior is primarily governed by an undesirable or less desirable failure mode rather than a ductile or desirable one and the full-tension yielding of infill plates would not be realized even at the ultimate state. Several experimental investigations have confirmed the above discussion [3,22–24]. In some of those tests excessive deformation, premature yielding and/or buckling of boundary elements limited the strength and ductility of the SPSW systems.

The overall behavior of a SPSW comprises the contributions of the infill wall and boundary frame actions. Hence, separation of the contributions of infill wall tension field action and boundary frame moment resisting action to the overall behavior, in addition to studying the overall behavior of the system, provides a better insight into the system behavior. It is to be noted that there is an interaction effect between the infill wall and the boundary frame, which is too complicated to be defined by a closed form solution. Nevertheless, in order to accurately predict the overall behavior of the SPSW based on the discrete behaviors of the infill wall and the frame, or to separate the wall and frame responses from the overall response of the SPSW, the effect of the interaction must be taken into account somehow.

The purpose of this research is to investigate different aspects of the behavior of code designed SPSWs, particularly with regard to the relative or respective contributions of their infill walls and boundary frames to the overall behavior. To accomplish this, a series of SPSWs with different aspect ratios and number of stories, designed per design code [18, 19], are analyzed using the finite element method and the obtained results are utilized to investigate: (a) wall–frame contribution shares of story shears, (b) wall–frame contribution shares of the VBE axial forces, (c) comparison of the VBE axial and shear forces, (d) overall stiffness and ductility, and the contributions from infill walls and frames, (e) base shear levels associated with the first yielding of walls and frames, and (f) influence of the SPSW aspect ratio and number of story on the above.

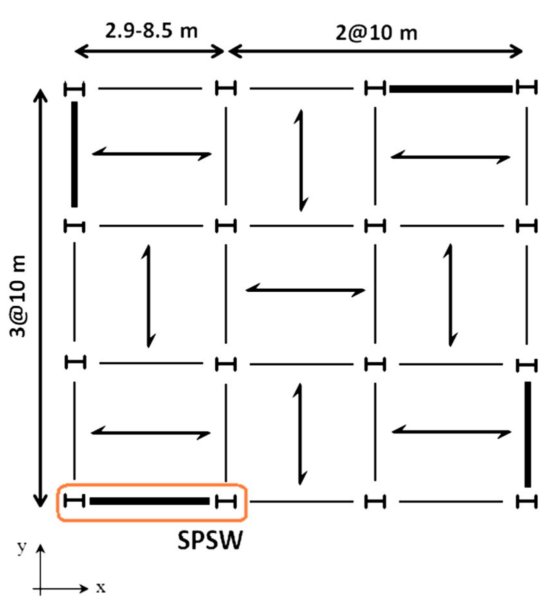

Fig. 1. Typical plan and considered SPSW.

2. Method of the study

2.1. Design of models

A number of SPSW systems having different aspect ratios and number of stories are considered for this research. SPSWs are designed for a typical building plan (Fig. 1). The buildings considered are 1, 2, 4, 6, 8, 10, 12 and 15 stories tall and have uniform story heights of 3.40 m. SPSWs are designed according to the recommendations given in AISC Seismic Provisions [18] and AISC Design Guide 20 [19]. The perimeter gravity frames without shear walls are assumed to have pinned beam to column connections and therefore, they are not incorporated in design and analysis. However, gravity loads transmitted by perimeter frame beams to SPSW beam–column connections, are considered in the design and analysis.

All models have beam-to-column connection details that include reduced beam sections (RBS) at each end, as recommended by the AISC Design Guide 20 [19], to ensure inelastic beam action at the desired locations. Also, the use of the RBS is reasonable considering the following two properties. First, the flexural force in the VBE due to HBE hinging is typically greater than that due to plate tension. In such cases, the flexure away from the connection does not govern the design of the VBE. Second, the required HBE flexural strength is governed by flexure in the mid-span due to plate tension (in combination with gravity load effects, if any), not at the ends. Based on these two properties, it is convenient to use a RBS in the HBE to limit the required flexural strength of the VBE. Moreover, the RBS reduces the demand on the VBE when applying the "strong column–weak beam" requirement. However, special concern must be paid to the design of HBEs, particularly for intermediate ones having RBS connections, since recent research [25] has shown that the current design approach does not necessarily lead to a HBE with the expected performance. To reliably achieve capacity design, analytical models for estimating the design forces for intermediate HBEs have been proposed by researchers [26].

A dead load of 4.6 kPa is used for each floor and 3.2 kPa for the roof. Live loads are taken equal to 2.4 kPa for each floor and 0.96 kPa for the roof. According to the code-compliant range of aspect ratios, the bay widths (L), measured from center to center of VBEs, are assumed to vary from 2.9 to 8.5 m (i.e. $L/h = 0.85$, 1.4, 2 and 2.5). Infill plate thicknesses are designed to resist the entire story shear per [18]. Plate thicknesses are selected from those available in ASTM A36 steel [19]. During the design, the minimum practical infill plate thickness required for handling and welding considerations is considered to be 3.18 mm (1/8 in.). Note that the infill plate, however, will often have some overstrength (i.e. the specified plate thickness will be thicker than required by design) not only due to the consideration of the minimum practical plate thickness but also due the fact that steel plates are available in discrete thicknesses on the market. The boundary frame members are designed using the capacity design principles to resist the forces from infill plate yielding. The resulting plate thicknesses and member sizes are shown in Table 1. Table 2 presents the RBS connection dimensions (see Fig. 2) for different HBE profiles per AISC 358-05 [27]. Throughout the article, each model will be identified by the value of SPSW aspect ratio (L/h) and number of story (n).

Finally, in order to check that drift requirements are met, the designed SPSW systems in Table 1 are numerically analyzed under the design level earthquake forces as determined by ASCE 7-05 [28]. Table 3 presents the design base shears and the corresponding maximum interstory drift ratios for different SPSWs. The results show that in all designs, the maximum interstory drifts are relatively low (lower than 0.01 h). This indicates that all designs are governed by strength and not by drift limitations. However, as can be inferred from the results