Journal of Constructional Steel Research 90 (2013) 85–97

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Performance-based plastic design of steel plate shear walls

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ARTICLE INFO

Article history:
Received 15 April 2013
Accepted 19 July 2013
Available online 25 August 2013

Keywords:
Steel plate shear wall
Performance-based design
Inelastic deformation capacity
Ductility-based design
P-Delta effects

ABSTRACT

The existing codes and design guidelines for steel plate shear walls (SPSWs) fail to utilise the excellent ductility capacity of SPSW systems to its fullest extent, because these methods do not consider the inelastic displacement demand or ductility demand as their design objective. A performance-based plastic design method for SPSW systems with rigid beam-to-column connections is proposed in this work, which sets a specific ductility demand and a preferred yield mechanism as its performance targets. The effectiveness of the proposed method in achieving these targets is illustrated through sample case studies of four- and eight-storey SPSW systems for varied design scenarios. A comparison with the existing AISC method for the same design scenario shows that the proposed method consistently performs better, in achieving these performance-based targets. The proposed method is modified to account for P-Delta effects, wherever necessary. This modified method is found to be more effective than the original proposal, whenever P-Delta effects are significant.

1. Existing design provisions for steel plate shear walls

During the 1980s and 1990s, a significant amount of research works, both ‘analytical’ and ‘experimental’, was conducted on the post-buckling behaviour of thin unstiffened steel plate shear wall (SPSW) systems [1]. These research works, conducted primarily in Canadian and U.S. universities (for example, [2–6]), resulted in the incorporation of design specifications for SPSW systems in design standards/codes. In 1994, the Canadian steel design standard [7] included design provisions for unstiffened thin SPSW, although only as an appendix to the main design code. The 2001 Canadian standard [8] incorporated mandatory clauses on the design of steel plate shear walls. This standard had provisions for both ‘limited ductility’ and ‘ductile’ steel plate shear walls. For the limited ductility SPSW, no special requirements were made for the beam-to-column connections and a response modification factor (R) of 2.0 was assigned for these systems. For the ductile SPSW, however, the beam-to-column connections had to be moment resisting and the response modification factor was higher ($R = 5.0$). In order to ensure a ductile failure mode for SPSW structures, this code recommended an indirect capacity design approach. In this approach, a factor B (ratio of the probable shear resistance at the base of the wall for a given plate thickness to the factored lateral force at the base of the wall, obtained from the calculated seismic load) was used to magnify the moments and axial forces in columns obtained from an elastic analysis. This magnification was not required if column forces and moments were obtained from a nonlinear pushover analysis. Further research on SPSW systems in the last decade, particularly the plastic analysis and design methods for SPSW [9], resulted in newer design provisions, for example, as in the AISC Seismic Provisions [10,11] and the Canadian standard CAN/CSA S16 [8,12].

The AISC SPSW specifications followed the load and resistance factor design (LRFD) format based on the limit state of collapse. The concept of capacity design was incorporated in this standard. For example, all edge/boundary elements (‘horizontal boundary elements/HBE’ and ‘vertical boundary elements/VBE’) were designed to resist the maximum forces that could be generated by fully yielded steel ‘infill panels’. These provisions also indicated to a preferred mechanism of failure through specifications, such as that the boundary elements were required to be proportioned in order to meet the ‘strong-column-weak-beam’ criterion, and that in boundary elements plastic hinging was permitted only at HBE ends. The recently published AISC Design Guide 20 for SPSW [13] developed the 2005 AISC Seismic Provisions into a complete design methodology. It included step-by-step design procedures as well as design examples for two types of steel plate shear walls: high-ductility SPSW (with $R = 7.0$) for high-seismic regions and low-ductility SPSW (with $R = 3.0$) for low seismic regions. This design guide was developed in accordance with the then existing relevant standards ASCE7-05 for minimum design loads in buildings [14], ANSI/AISC 360-05 for structural steel [15], and 2005 AISC Seismic Provisions [10].

Although elements of capacity design concepts were incorporated in the latest Canadian and U.S. steel design standards, there are a few limitations when assessed from a performance-based seismic design (PBSD) perspective

1. Significant inelastic deformation capacity (ductility) of SPSW systems cannot be fully utilised by these codes, as the design is primarily

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http://dx.doi.org/10.1016/j.jcsr.2013.07.029

based on an elastic force/strength-based approach where the inelastic behaviour is implicitly accounted for through a response modification factor, *R*.
2. These guides specify a desirable yield mechanism, however they do not provide specific design equations to attain this yield mechanism [16], especially for the VBE and HBE in the SPSW system.
3. These standards do not provide the designer any option to choose a specific yielding hierarchy or failure mechanism for the SPSW structure.

In more recent times, Berman and Bruneau [17] proposed a reasonably accurate and relatively effective capacity design method for SPSW columns (VBE). Their procedure combined a linear elastic model of SPSW and plastic analysis concepts. Research works by [18–21] provided capacity design provisions for boundary beams (HBE) in SPSW systems. These design equations, especially those for 'anchor beams' (beams at roof and ground level with infill panels only at one side) were derived considering local collapse mechanism ('beam mechanism') with plastic hinges forming at the ends of the HBE and close to the mid-span of the HBE. Vian et al. [19] also recommended the use of 'reduced beam section/RBS' at the ends of the HBE to ensure the preferred failure mechanism of the AISC Seismic Provisions.

Over the last decade, the performance-based seismic design philosophy has emerged as a promising and efficient seismic design approach. PBSD explicitly accounts for the inelastic behaviour of a structural system in the design process itself. PBSD approaches based on plastic analysis and design concepts called as performance-based plastic design (PBPD) methods were recently developed for different lateral load resisting systems (such as steel moment resisting frames, steel braced frames, etc.) in the University of Michigan [22,23]. In these design methods a pre-selected yield/failure mechanism and a uniform target drift (based on inelastic behaviour) were considered as performance objectives. The analytical validation of these methods showed that structures designed using these methods were very effective in achieving the pre-selected performance objectives. Details of these methods and step-by-step procedures were later compiled in a book by Goel and Chao [24]. Considering a gradual shift towards PBSD for seismic design methods in general, Ghosh et al. [25] proposed a displacement/ductility-based design methodology for steel plate shear wall systems with pin-connected boundary beams. Similar to the methods developed in the University of Michigan, they also considered the target displacement ductility ratio and a pre-selected yield mechanism as the design criterion; and an inelastic energy balance concept was used in the formulation of the design method. Ghosh et al. validated this method by designing a four-storey SPSW with pin-connected beams subjected to various ground motion scenarios and for different target ductility ratios. Gupta et al. [26] successfully applied the inelastic displacement ductility-based method proposed by Ghosh et al. using standard hot rolled-sections (for boundary elements) available in the U.S. [15] and in India [27]. More recently, while investigating for a suitable (height-wise) distribution of the design base shear for this method, [28] applied this method effectively to SPSW with pin-connected beams of various heights.

2. Objective

Considering that the existing U.S. and Canadian design standards/guides for 'ductile' SPSW recommend the use of only rigid beam-to-column connections, an inelastic displacement-based seismic design method similar to that proposed by Ghosh et al. [25] needs to be formulated for SPSW systems with rigid beam-to-column connections. The primary objective of the work presented here, thus, is to develop a PBPD method for SPSW systems with rigid beam-to-column connections, with the following performance goals:

1. achieving a target displacement ductility ratio demand considering the inelastic behaviour of the SPSW system, and
2. achieving a pre-selected yield/failure mechanism for this inelastic behaviour.

It must be mentioned here that in order to develop a full-fledged PBSD framework for any structural system, the first important task is to define acceptable performance levels in a specific quantitative manner in terms of structural, non-structural and component behaviours. The focus of this work, however, is on the structural design calculations once a performance level is selected and limits are defined in terms of displacement-based quantities. Before we begin with the proposal of a PBPD method for SPSW, the existing design method (based on AISC Design Guide 20) is reviewed through a sample design case and it is checked if this sample design meets the stated performance objectives (Section 3). Section 4 provides the fundamentals and the framework of the proposed PBPD method for SPSW with rigid beam-to-column connections. This method is validated in Section 5 through sample designs of low-rise (four-storey) and medium-rise (eight-storey) SPSW buildings, for different target ductility ratios, and subjected to various earthquake scenarios. Results of this validation are discussed in detail, along with a comparison with the sample design based on existing AISC guidelines. A modification of the proposed PBPD method – to account for P-Delta effects (which are predominant for medium- and high-rise SPSW systems with large displacement ductility demands) – is provided in Section 6. Section 7 presents the significant conclusions of this work and also discusses the limitations thereof. It should however, be noted that the work presented here does not address the issue of formulating the design method in a probabilistic framework, which is the most significant feature for a PBSD methodology, other than the explicit consideration of inelastic behaviour and damage in a structure. We are currently engaged in developing a reliability-based framework for the performance-based plastic design method, which will be reported in future.

3. Design of a SPSW system following AISC Design Guide 20, and its performance assessment

To assess the seismic performance of a steel plate shear wall structure, which is designed following provisions of AISC Design Guide 20 [13], a four-storey steel plate shear wall building is considered. The configuration of this four-storey building is illustrated in detail in Fig. 1. The building has a five bay by six bay plan, with one SPSW bay along each outer frame. All beams, except those in the SPSW bays, are pin-connected (shear-connected) to the frame, and therefore only the SPSW frames form the lateral load resisting system. The building is assumed to have seismic weights of 4690 kN per floor, except for the roof, where it is 5090 kN. For seismic force calculations, this study building is assumed to be located in downtown San Francisco, CA, USA. The building site is categorised as Site Class D for 'stiff soil' and its occupancy category is adopted as

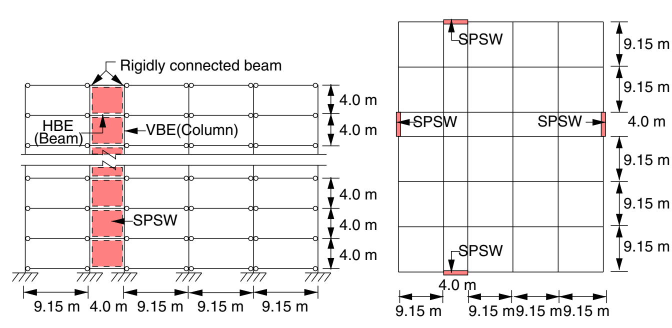

Fig. 1. Configuration of the hypothetical study building(s).