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Steel plate shear walls with outriggers. Part II: Seismic design and performance

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ABSTRACT

Having investigated the plastic behavior and mechanisms of steel plate shear walls with outriggers (SPSW-O) introduced in Part I, it was shown that such systems are considerably effective in improving the flexural stiffness of conventional SPSWs. This paper describes procedures for the efficient design of SPSW-Os employing the principles of plastic analysis and capacity design. While the primary motivation behind the use of SPSW-O configuration is to enhance the overturning stiffness of SPSWs and provide architectural flexibility, the rigidly connected outrigger beams introduce additional lateral force resistance to the system due to the frame action, which must be taken into account for an efficient design. As such, this part of the analytical investigation focuses on quantifying the contributions of the tension field action of the infill panels and moment-resisting action of the SPSW boundary frame and/or outrigger frames in the global strength of the four SPSW-O options discussed in part I. The proposed approach together with the knowledge generated in part I are utilized in developing design procedures to achieve an optimum design of the SPSW-O systems. Then, the proposed procedures are used to design 12- and 20-story case study buildings having four different SPSW-O options as their seismic force resisting systems. Additionally, two SPSWs without outriggers, herein referred to as free-standing SPSWs, were also designed for comparison purposes. The seismic performances of the prototype SPSW-Os are evaluated using nonlinear static and response history analyses, and are compared with those of the free-standing SPSWs.

1. Extension to the Analytical Study.

In Part I of the research, analytical studies were performed to investigate the behavior and efficiency of SPSW-Os, focusing on system configurations, plastic mechanisms, plastic strength and overturning stiffness [1]. An attempt was made to quantify the contribution of the outrigger elements to the overall overturning stiffness of the system by defining a simple parameter, called the outrigger efficiency factor (OEF), which allows for the comparison of the four different SPSW-O options on a consistent basis. Some valuable knowledge has been generated in part I covering a relatively wide range of parameters influencing the behavior and efficiency of such systems; this was useful in the development of the proposed design procedure that is presented in part II. As demonstrated by the analytical studies presented in Part I, the lateral load resistance of a SPSW-O is provided by three components, namely: (1) the tension field action of the infill panels; (2) the moment-resisting action of the boundary frame; and (3) the moment-resisting action of the outrigger frames. It is recalled that the boundary frame in a SPSW-O with ideally pinned HBE-to-VBE connections (i.e., PR and PP systems) obviously does not contribute to the lateral strength of the system. In Part II, analytical studies are extended to quantify the relative contributions of these components to the overall strength of the four SPSW-O options introduced in Part I, with the primary aim of achieving efficient designs for such systems. Procedures developed for the seismic design of SPSW-Os are described; numerical studies investigating the seismic behavior of such systems designed using the proposed approach are then presented.

2. Optimum Design for Lateral Load Resistance

In the conventional design of SPSWs in North America [2,3], the infill plate at every story is designed to resist 100% of the factored story shear force; hence, the lateral strength of the boundary moment frame, which substantially contributes to the overall lateral load resistance of the system, is neglected. Qu and Bruneau [4] investigated the relative and respective contributions of these components to the overall strength of the conventional SPSWs and showed that the overstrength due to the boundary frame action can be significant. As discussed in Part I, the outrigger frames within a SPSW-O add even more strength to the system, especially in cases where the outrigger beams are moment-

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connected at both ends (i.e., RR and PR systems). As such, it would be overly conservative to neglect the lateral strength of the outrigger frames and the boundary frame, and design the infill plates for the full lateral design loads. Therefore, in order to achieve material efficient designs for each of the four SPSW-O options discussed in this research, procedures are needed to quantify the contribution of each component (i.e., the tension field action and frame action) to the overall lateral load resistance of the systems. Such procedures are studied in the following sections by employing the principles of plastic analysis and capacity design. Both single-story and multi-story systems are considered for this purpose. Based on this study, a design procedure is developed for SPSW-Os by extending the conventional capacity design procedures used for SPSWs, while attempting to optimize material efficiency.

2.1. Single-story SPSW-O systems

To better understand the concepts and procedures presented in this section, the expressions are first developed for the case of single-story SPSW-Os, and are then extended to the more complex case of multi-story systems in the next section. The principles of plastic analysis and capacity design are employed to investigate the relative contributions of the tension field action and frame action to the global lateral strength of the four different SPSW-O options discussed in this research. Moreover, procedures are developed to achieve an efficient design approach for each of these options by minimizing their structural overstrength.

2.1.1. Single-story SPSW-O (RR)

The single-story SPSW-O with rigid HBE-to-VBE and OB-to-OC connections, shown in Fig. 1, is assumed to be pinned to the ground. This simplifying assumption is made to reduce the complexity of the expressions developed next. Since the plastic strength of the VBE bases are greatly reduced due to the presence of significant axial loads in these elements, they contribute very little to the global strength of multi-story SPSW-O systems with a high degree of redundancy. On the other hand, since the SPSW-O configuration is intended to improve the flexural stiffness of the system primarily through the couple formed by the axial forces of the outrigger columns, these elements can be connected to the ground using pinned connections. In order to design the infill panel within the SPSW-O system shown in Fig. 1a, it is assumed that a fraction of the total lateral design load ($\kappa_{RR}F_D$) is resisted by this element through the formation of tension field. Considering the plastic mechanism shown in Fig. 1.c, this portion of the design load is resisted by the horizontal component of the tension field in the fully yielded infill panel. Note that the flexural rigidities of the OB-to-OC, OB-to-HBE and HBE-to-VBE connections in Fig. 1b are removed; therefore, the required thickness of the infill panel can be calculated using Eq. (1) [4]:

$$\kappa_{RR}F_D = \frac{1}{2}F_yLt\ \sin 2\alpha \tag{1}$$

where, t and F_y are the thickness and yield strength of the infill panels, respectively; L is the SPSW bay width and α is the tension field inclination angle estimated using the following eq. [5]:

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

where $A_b$and A_c are the cross-sectional areas of the HBE and VBE, respectively; h is the story height; L is the SPSW bay width, and I_c is the moment of inertia of the VBE.

The vertical and horizontal components of the distributed force along the HBE due to the yielding of the infill panel are given by Eqs. (5.3) and (5.4), respectively, and are related to each other through Eq. (5) [6]:

$$\omega_v = F_yt\ \cos^2\alpha \tag{3}$$

$$\omega_h = \frac{1}{2}F_yt\ \sin 2\alpha \tag{4}$$

$$\omega_v = \omega_h \cot\alpha \tag{5}$$

Substituting Eq. (5.4) into Eq. (5.1) results in the following [4]:

$$\kappa_{RR}F_D = \omega_hL \tag{6}$$

On the other hand, equating internal and external work and assuming the desirable yield mechanism shown in Fig. 1c, the plastic lateral strength of the system can be expressed as:

$$F_pH = \omega_hLH + 2M_{HBE} + 4M_{OB} \tag{7}$$

where M_{OB} and M_{HBE} are the plastic flexural strengths of the outrigger beams and HBE, respectively. For preliminary design purposes, it is assumed that the outrigger beams are proportioned based on the size of HBE, and the parameter λ is defined as follows:

$$\lambda = \frac{Z_{OB}}{Z_{HBE}} = \frac{M_{OB}}{M_{HBE}} \tag{8}$$

where Z_{OB} and Z_{HBE} are the plastic section moduli of the outrigger beams and HBEs, respectively. Substituting λ in Eq. (7), the expression for the plastic strength of the system takes the following format:

$$F_pH = \omega_hLH + 2M_{HBE}(1+2\lambda) \tag{9}$$

On the other hand, as discussed by Vian and Bruneau [7], in order to prevent in-span plastic hinging of the HBEs, which results in an undesirable plastic mechanism for the system, these elements must be proportioned for a minimum plastic section modulus given by Eq. (10).

$$Z_x = \frac{1}{4F_y}\omega_vL^2\frac{1}{1+\sqrt{1-\beta^2}} \tag{10}$$

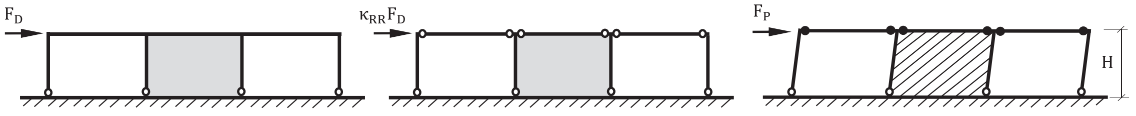
In this equation, β is the plastic section modulus reduction ratio in cases where reduced-beam section (RBS) HBE-to-VBE connections are used, and is defined as the ratio of the plastic section modulus of the reduced section to that of the full section (i.e., $\beta = Z_{RBS}/Z_x$). Assuming that no RBS connections are used (i.e., $\beta = 1$), the required plastic flexural strength of the HBE can be calculated as:

$$M_{HBE} = \frac{1}{4}\omega_vL^2 \tag{11}$$

Substituting Eq. (11) into Eq. (9), the plastic strength of the system is given by:

$$F_p = \omega_hL + (1+2\lambda)\frac{\omega_vL^2}{2H} \tag{12}$$

Considering the relationship between the horizontal and vertical components of the tension field given by Eq. (5), the ultimate strength of the system can be rewritten as:



(a) (b) (c)

Fig. 1. Single-story SPSW-O (RR): (a) system subjected to full lateral design load; (b) assigning a portion of the design load to the infill panel; (c) lateral force needed to develop plastic mechanism of the system.