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Steel plate shear walls with outriggers. Part I: Plastic analysis and behavior

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ABSTRACT

Steel plate shear walls (SPSWs) are ductile and economical energy dissipating systems for buildings located in regions of high seismic risk. In spite of many advantages of SPSWs; however, their overturning stiffness is relatively low, especially when their width is narrow compared to the building height. Therefore, additional flexural stiffness must be provided to the system when designing narrow SPSWs. A logical solution that can be effectively used in SPSW systems is to rigidly connect the beams of adjacent bays to the columns of SPSWs (on both sides) forming an interacting system of SPSW and moment frame in which the adjacent beams act as outriggers resulting in an overall reduction of overturning in the SPSW. However, insufficient information exists on the behavior and efficiency of such structural systems, herein referred to as SPSW with outriggers (SPSW-O). This paper discusses four different potential SPSW-O options that can be used in mid- to high-rise buildings to enhance the flexural stiffness of the system. Plastic mechanisms, ultimate lateral load resistance and overturning stiffness of such systems are investigated, and key design parameters are identified through a combined analytical and numerical investigation. A parameter called the outrigger efficiency factor (OEF) is defined to quantify the contribution of the outrigger system to the overall overturning stiffness of a SPSW-O. Analytical expressions are derived for the lateral load resistance and OEF of the four SPSW-O options, and are then compared with numerical analysis results with reasonable agreement. Furthermore, parametric studies are performed to investigate the influence of a number of parameters on the overall behavior and characteristics of the SPSW-O systems. Parameters subject to investigation include height of the wall, outrigger beam and connection properties.

1. Introduction

Steel plate shear wall (SPSW) systems are one of the most efficient and economical seismic force resisting systems for buildings located in high-risk earthquake zones. A typical thin unstiffened SPSW resists lateral loads mainly through the formation of tension fields in its infill plates, which buckle in shear in transverse direction at low load levels. The boundary moment frame, which is designed to anchor the fully yielded infill plates according to the capacity design principles, provides additional resistance to the system by the moment-resisting action of the connections. In conventional SPSWs, the overturning moments resulting from lateral loads are essentially resisted through the couple formed by the axial forces in vertical boundary elements (VBEs) at each story. The axial demands imposed by overturning moments, which can become extremely large in taller walls, together with flexural demands resulting from plastic hinging of the beam ends and pull-in forces due to the tension field action can lead to unreasonably heavy VBEs [1]. On the other hand, the relatively low overturning stiffness of conventional SPSWs compared to that of reinforced concrete walls is an important factor reducing the desirability of the system, especially in mid- to high-rise buildings [1].

In taller buildings, where the wall flexure dominates over shear, the overturning stiffness of SPSWs can be improved using outrigger systems. In modern tall buildings, core-and-outrigger systems are commonly used to resist high lateral forces and overturning moments due to earthquake and wind [2]. In steel and composite constructions, the outriggers typically take the form of single- or multiple-story-tall trusses connecting the core (braced frame or shear wall) to perimeter frames where the axial stiffness of the outrigger columns is employed to enhance the flexural stiffness of the system [2]. However, even for relatively shorter SPSWs, the low overturning stiffness may result in undesirable system characteristics. Therefore, practical and cost-effective solutions are needed.

One practical option for improving the overturning stiffness of conventional SPSWs is to rigidly connect the beams of adjacent bays to the VBEs of SPSW at floor levels forming a dual structural system, herein referred to as steel plate shear wall with outriggers (SPSW-O). The moment-connected adjacent beams act as outriggers and work to reduce the bending in the SPSW by coupling it to the outrigger columns (OCs). Furthermore, since the axial demands on the VBEs stem primarily

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from overturning moments due to lateral loads, the reduced overturning in SPSW would consequently result in lighter VBE sections, thus improving the desirability of the system in taller walls. Another potential application of the SPSW-O configuration can be in buildings with large bay widths in which architectural constraints often do not allow the full width of the bay to be filled by a solid SPSW. In such cases, a narrower SPSW may be centrally placed within the bay to accommodate openings, and the adjacent beams may be designed as outriggers to improve the overturning stiffness of the narrow wall. As theoretically discussed above, the SPSW-O configuration can provide improved system performance as well as architectural flexibility for SPSWs to be more commonly used as lateral force resisting system in mid- to high-rise buildings. However, only limited work has been performed to investigate the efficiency and behavior of such structural systems. Gholipour et al. [3] investigated various arrangements of outrigger beam locations along the height of the SPSW. The researchers reported that the use of outrigger beams results in reduced VBE sizes and more uniform distribution of stiffness along the height of the system. However, the amount of VBE axial force reduction and the overturning stiffness provided by the outrigger elements depend highly on the level of interaction between SPSW and the outrigger system, which is a function of the outrigger beam (OB) properties (i.e., strength, stiffness and length) and the rigidity of their connections to the VBEs and outrigger columns.

On the other hand, the SPSW-O configuration is a dual system in which the outrigger elements provide substantial lateral resistance to the system through the moment-resisting action of the connections. The levels of overturning stiffness and lateral strength provided by the outrigger elements are two important factors that should be quantified to achieve an efficient design of the SPSW-O systems. This paper, along with a companion paper [4], undertakes this work through a combined analytical and numerical investigation aiming to provide a better understanding of the SPSW-O system behavior and design recommendations.

Several potential SPSW-O options are discussed and their characteristics particularly in terms of overturning stiffness and ultimate lateral strength are studied. A parameter called the outrigger efficiency factor (OEF) is defined to quantify the level of overturning stiffness provided by the outrigger system within a SPSW-O. The OEF represents the level of interaction between SPSW and the outrigger system, which allows for the comparison of different SPSW-O options on a consistent basis. Analytical expressions are derived for the OEF and ultimate lateral load resistance of the systems, and are verified using the results from numerical models. Sixty-four SPSW-O systems are designed to investigate the influence of various parameters on system behavior. Parameters subject to investigation include outrigger beam properties, the height of the system, and the types of the OB-to-OC and HBE-to-VBE connections.

2. SPSW-O system configurations and nomenclatures

In this paper, several SPSW-O options are considered that are designed specifically to improve the overturning stiffness of SPSWs. Fig. 1 schematically shows four potential SPSW-O options having different combinations of simple and rigid HBE-to-VBE and OB-to-OC connections. The main characteristic of all of these options is that they include moment-connected adjacent beams, which act as outriggers for the SPSW by connecting it to the outer (outrigger) columns (OCs). Fig. 1a shows the first SPSW-O option, herein referred to as SPSW-O (RR), in which all the connections in the system are rigid. In this option, while the outrigger system works to reduce the bending in the SPSW, it also provides significant lateral strength to the system due to moment-resisting action of the OB-to-OC and OB-to-VBE connections.

In the second option, named SPSW-O (RP), the outrigger beams are connected to the outrigger columns using pinned connections, and all other connections are moment resistant (Fig. 2b). Although the outrigger beams in this option transfer no moments to the outrigger columns, resulting in less interaction between the two systems, they effectively take part in restraining the rotation of the SPSW at floor levels. Therefore, they are expected to reduce the lateral drift corresponding to the flexural mode of deformation in the SPSW. The third option, called SPSW-O (PR), consists of a SPSW with pinned HBE-to-VBE connections and outrigger beams that are rigidly connected at both ends (Fig. 1c). While the American Institute of Steel Construction (AISC) Seismic Provisions [5] requires moment-resisting HBE-to-VBE connections for SPSWs, the Canadian Standards Associations (CSA) S16-14 [6] permits simple connections to be used in the limited ductility (Type LD Plate Wall) category of SPSWs. Although SPSWs with simple connections have been shown to exhibit a highly pinched hysteretic behavior, when they are used in conjunction with moment-connected outrigger beams, as shown in Fig. 1c, a dual system is formed in which the outrigger elements not only improve resistance to overturning but also provide complementary energy dissipation to the system.

Yet another option is the SPSW-O system with pinned HBE-to-VBE and OB-to-OC connections, as shown in Fig. 1d. This option, herein referred to as SPSW-O (PP), is intended to enhance the overturning stiffness of the system while reducing the fabrication costs associated with the high number of moment-resisting connections used in the previous options. In addition, the pinned HBE-to-VBE connections used in the SPSW-O (PR) and SPSW-O (PP) options are aimed at reducing the large demands on the VBEs by eliminating the portions of the axial and flexural demands that are imposed by the boundary frame moment-resisting action if rigid connections are used. Although the SPSW-O (PP) configuration would have lower redundancy and energy dissipation capacity compared to the previous options, it can be still considered an economical option for low to moderate, if not high, seismic areas. For the purpose of brevity, throughout this paper, the SPSW-O (RR), SPSW-O (RP), SPSW-O (PR) and SPSW-O (PP) options introduced above may be simply referred to as RR, RP, PR, and PP, respectively.

The level of overturning stiffness provided by the outrigger elements within a SPSW-O depends on various parameters such as the rigidity of OB-to-OC connections, outrigger beam properties and width of the outrigger bay. However, the lateral strength provided by these elements depends only on the first two parameters and is independent of the latter. In order to quantify the level of interaction between SPSW and the outrigger system, and to allow for the comparison of the four different SPSW-O options on a consistent basis, a simple parameter named the outrigger efficiency factor (OEF) is defined as the proportion of the overall overturning moment that is resisted by the outrigger system [7]:

$$\mathrm{OEF} = \frac{\mathrm{M_{Outrigger}}}{\mathrm{M_{Total}}} \quad (1)$$

3. Plastic analysis and mechanisms of SPSW-O systems

The plastic method of structural analysis is used in this paper to investigate behavior, mechanisms and efficiency of the four SPSW-O options discussed earlier. As previously mentioned, although the primary objective for using the SPSW-O configuration is to enhance the overturning stiffness of the conventional SPSW systems, the lateral strength arising from moment-resisting action of the connections is inevitable and must be accounted for in an efficient design. As such, the lateral load resistance and flexural stiffness provided by such systems under desired plastic mechanism are the basic building blocks used in understanding the behavior of SPSW-Os; they are thus helpful in developing design procedures for such systems.

3.1. Single-story SPSW-O

Statical and kinematic methods of plastic analysis are used in this section to derive the analytical expressions for ultimate lateral strength and outrigger efficiency factor of the SPSW-O systems introduced earlier. Although these parameters can be evaluated using nonlinear