Research Needs and Future Directions for Steel Plate Shear Walls

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ABSTRACT

Steel plate shear walls (SPSWs) are one of the most economical and under-utilized lateral load resisting systems currently available to structural engineers. In comparison with traditional lateral load systems, such as steel braced frames, reinforced concrete walls and moment resisting frames, SPSWs have fewer costly detailing requirements, require less stringent construction tolerances, allow for rapid construction, and result in fewer bays of lateral load resisting framing. Past studies have also shown that SPSWs can exhibit exemplary seismic performance. Despite these advantages, SPSWs are not widely used because: i) traditional SPSW configurations result in large column dimensions and prohibit the use of narrow walls, thereby reducing the system's economy, ii) numerical models used to analyze SPSW systems are cumbersome and overly time consuming for engineers, iii) SPSW system behavior is not well understood, leading to conservative design requirements and further reduction in economy, and iv) SPSWs have a lower flexural stiffness relative to concrete walls, making their use in taller buildings more challenging. Further, SPSW systems must be studied in the context of performance-based design as this will result in reliable and robust systems.

This paper will discusses the issues above, with specific examples and propose solutions for developing the next-generation of steel plate shear walls. These solutions will allow SPSWs to be economically implemented by providing new configurations, new modeling techniques, and a more complete understanding of system behavior. Development of these solutions and performance-based criteria for their design will require a significant, coordinated research initiative. As such, research needs are identified and discussed.

INTRODUCTION

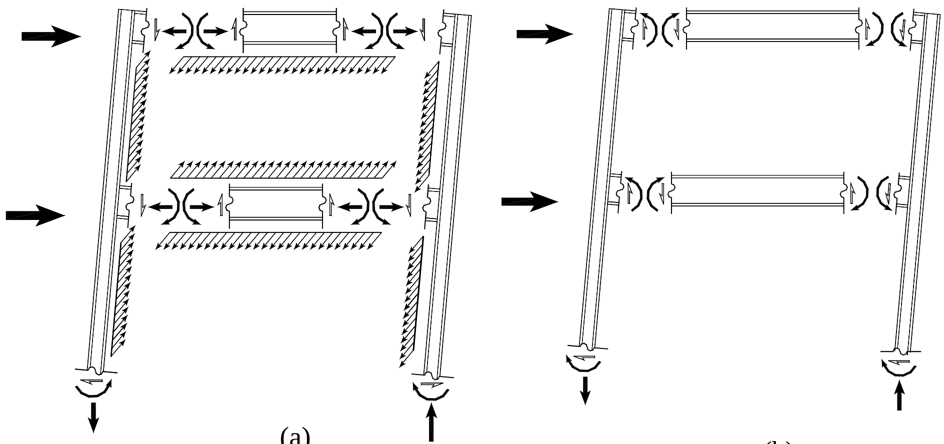
Many steel buildings are constructed in areas of moderate to high seismicity, requiring the use of ductile lateral load resisting systems. These systems are often the most complicated, time-consuming, and costly components of the structural framing. Substantial economic benefits are possible by using SPSW systems that provide the strength and ductility required for seismic resistance as well as reduced construction cost [Timler and Ventura 1999] and accelerated construction time [Seilie and Hooper 2005].

In comparison with traditional systems, SPSWs offer the potential for comparable, if not superior, seismic performance at a possibly reduced construction cost. SPSWs have high strength that allows for fewer bays of lateral load resisting framing, they utilize moment resisting beam-to-column connections that must only qualify for ordinary moment resisting frames and thus have fewer restrictions and limitations than special moment resisting frames, and they employ infill connection details using simple fillet welds that can accommodate traditional erection tolerances. Erection of SPSWs in multi-story lifts is also possible and therefore the system has the potential to enable rapid construction.

Despite the benefits of SPSWs, they are not widely used. The limited implementation of SPSWs is a direct result of: i) traditional SPSW configurations result in large column dimensions and prohibit the use of narrow walls, thereby reducing the system's economy, ii) numerical models used to analyze SPSW systems are cumbersome and overly time consuming for engineers, iii) SPSW system behavior is not well understood, leading to conservative design requirements and further reduction in economy, and iv) SPSWs have a lower flexural stiffness relative to concrete walls, making their use in taller buildings more challenging. Further, SPSW systems must be studied in the context of performance-based design as this will result in reliable and robust systems. Performance objectives must be identified and a procedure for reliably achieving those objectives for various levels of seismic hazard must be developed. This paper reviews current literature regarding these problems and indicate areas in need of research to advance the use and practicality of SPSWs. This is not an exhaustive list of research needs, but rather ones the authors have identified through their experience and in discussions with practicing engineers.

COLUMN DEMANDS IN SPSW

Many previous experimental and analytical studies have shown that the column demands in a SPSW are both complex and, for typical systems, extremely large. Column flexural demands result from the development of the tension field in the infill panel (i.e., the horizontal components of tension field action (pull-in forces)) and from the frame action of the boundary moment frame. Column axial demands result primarily from resisting the overturning moment and can be large for multi-story SPSWs (Fig. 1). These significant demands on SPSW columns can result in column failures. For example, Driver et al. [1998] tested a large-scale 4-story specimen that exhibited first story drifts of over 4.2% at roof drifts of 2.2%. These large first-story drifts were due, in part, to excessive deformation, including plastic hinge development and ultimately local buckling, in the first story columns (Fig 2a). It should be noted that stable system response was observed up to the point of column buckling, however. Similar behavior of first story columns was observed in testing of a three-story SPSW by Behbahanifard et al. [2003] as shown in Fig. 2b. From these studies, it is clear that column behavior is critical in SPSWs and that in conventional configurations the demands on the columns may result in poor system performance, which has appropriately resulted in conservative column design requirements.



(a) (b)

FIGURE 1 - (a) MEMBER FORCES IN A SPSW (b) MEMBER FORCES IN A MOMENT FRAME

Berman and Bruneau [2007] have developed a procedure for capacity design of columns in SPSWs. That procedure conservatively assumes that the infill plates are yielding at every level and that all beams are forming plastic hinges. It then uses a plastic collapse mechanism to approximate the lateral loading that caused the yielding to occur and develops column demands from a complete column free-body diagram. The procedure ensures that yielding occurs in the infill plate and beams before the columns; however, it may be overly conservative to assume full yielding at all stories, especially for mid-to-high rise SPSWs.

(a) (b)

FIGURE 2 - (a) COLUMN BUCKLING FROM DRIVER ET AL. [1998] (b) COLUMN BUCKLING FROM BEHBAHANIFARD ET AL. [2003].

To reduce column demands in SPSWs researchers have investigated the use of low yield-point steels for the infills, reduced beam sections at beam-to-column connections, and strategic placement of holes in the infill panels [Vian and Bruneau 2005]. While these strategies lower the column demands resulting from pull-in and frame action, they may not be as effective at limiting the axial demands resulting from global overturning moment, especially for taller wall systems. Further, the study regarding strategic hole placement was limited to placing them such that the strips of infill panel that remained were at an orientation near that of the expected tension field orientation. It is conceivable that this could be modified to force a tension field to occur at a different angle which could have added benefits for reducing column demands. Tsai and Li

[2008] have performed the first tests using a pin-ended horizontal strut at mid-height of the columns at each story in a SPSW (a schematic of the concept is shown in Fig. 3). This strut helps resist the pull-in forces and reduces the flexural demands in the columns. Such a solution will be effective in making low-rise SPSW more practical. In practice, to address large column demands in SPSWs in mid-to-high rise buildings (i.e., those over eight stories), engineers have employed large concrete-filled tube columns [Seilie and Hooper 2005] or large steel column sections [Monnier and Harasimowicz 2007]. Experimental work on the use of concrete filled tubular columns [Asteneh-Asl and Zhou 2001] and composite columns [Deng et al. 2008] are important advances in providing solutions to resist the large column demands and provide increased stiffness for overturning. However, there may be other means of reducing the column design loads by evaluating the extent of expected yielding of infill plates and beams throughout the height of a SPSW or by using a SPSW configuration that inherently reduces those demands.

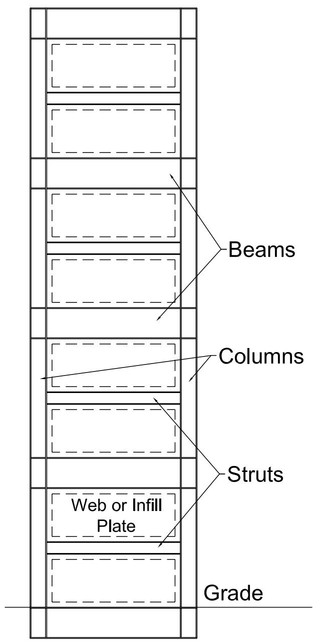


FIGURE 3 – SPSW WITH INTERMEDIATE STRUTS.

Research Needs

Research is needed to develop SPSW systems that reduce column demands. As noted above, some systems have already been tested in a "proof-of-concept" manner (i.e., the use of low yield point steel, strategic holes in the infill, horizontal struts, and the use of composite columns to resist the large demands). Additional approaches that merit investigation include:

- SPSWs with adjacent outrigger beams where the shear forces in the outriggers work to reduce the column demands (Fig. 4a).
- SPSWs with adjacent outrigger beams and released beams within the SPSW, as shown in Fig. 4b. Such systems would still have the full hysteresis loops resulting from the flexural yielding of the coupling or outrigger beams and the shear strength of the infill plate, but the shear forces and moment in the beams within the SPSW would be reduced, resulting in smaller column demands.

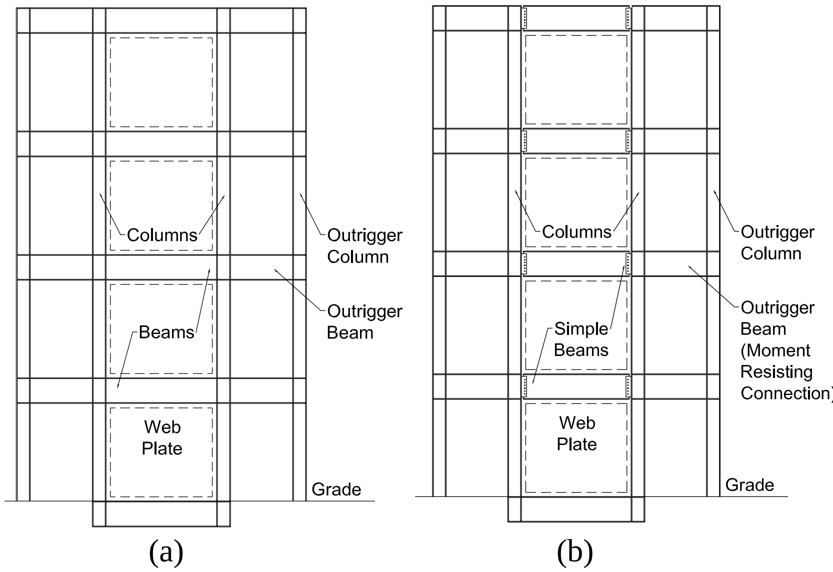


FIGURE 4 - (a) SPSW WITH OUTRIGGERS (b) SPSW WITH OUTRIGGERS AND SIMPLE BEAMS (c) SPSW WITH ADJACENT WEB PLATES.

Combinations of these systems and the previously tested systems could lead to the most practical means of reducing column demands. In all of these cases, research is needed to determine the impact of these changes on the orientation of the diagonal tension field, the influence of the various component properties on system behavior, and to develop appropriate design recommendations.

In addition to developing new systems, experiments and analyses are needed to determine the extent of infill yielding that can be expected for a wide-range of SPSW designs. The conservative column design philosophy used now can then be revised based on those results. In buildings over a few stories it is unlikely that full infill yielding over the entire SPSW height will occur. A significant savings in column size, and an improvement in the economy of the system, is possible if the likely extent of yielding can be quantified.

ANALYTICAL MODELS FOR SPSW DESIGN

Determining demands on columns, coupling beams and other SPSW components resulting from local and global response mechanisms requires accurate numerical models. Because SPSW infill panels buckle under minimal loads, these models cannot be simple linear elastic models defined by gross section geometries and elastic moduli. To address these modeling needs, Timler and Kulak [1983] developed the strip model in which the infill is represented by a series of pin-ended tension-only elements (Fig. 5). Subsequent research by several groups [Elgaaly et al. 1993, Rezai 1999] has advanced the original strip model using additional experimental data, shown that the model accurately represents the inelastic behavior of SPSWs, and shown that it can over-predict initial stiffness due to an over-prediction of the average initial angle of inclination of the panel tension field. While the strip model is appropriate for use in design to determine the response of SPSWs, time consuming and may not be considered practical for use in design of all but low-rise buildings [Hooper 2006].

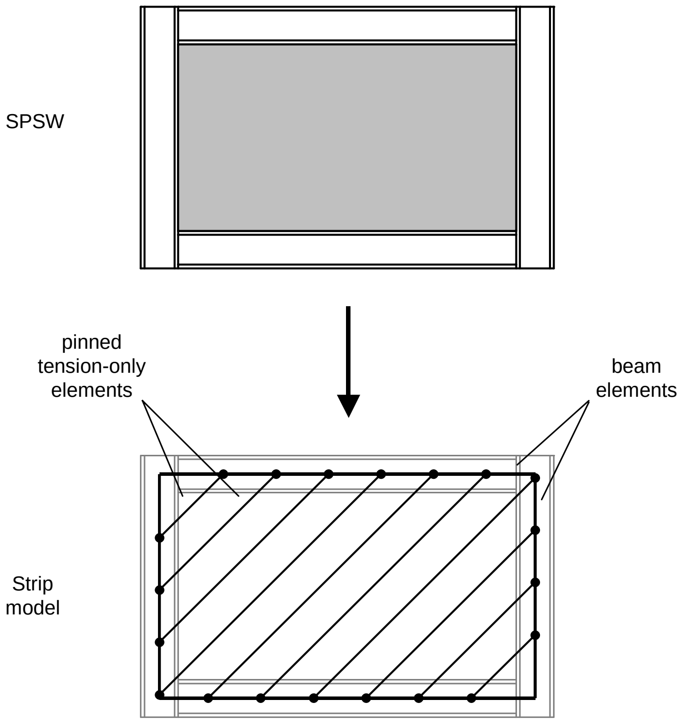


FIGURE 5 – STRIP MODEL (FROM SABELLI AND BRUNEAU [2006]).

In addition to the strip model, researchers have used continuum-type finite element analysis to determine and investigate local response mechanisms in SPSWs. Asteneh-Asl and Zhou [2002] employed orthotropic plate elements to simulate the response of infill panels. This approach has also been used in the design of SPSW buildings [Seilie and Hooper 2005] and is discussed along with the strip model in Sabelli and Bruneau [2006]. While practical, orthotropic plate models are limited to elastic behavior and thus can only be used in the equivalent lateral force or elastic time history analysis procedures. Vian and Bruneau [2005] and others have used a refined mesh of nonlinear shell elements to simulate the response of infill panels in SPSW sub-assemblages. This type of highly detailed nonlinear finite element analysis, while an excellent tool for investigating local behavior, is not cost-effective for use in design or for parametric analyses of complete SPSW systems.

Research Needs

A new modeling technique is necessary to enable more efficient design of SPSWs. Possibilities include the development of: "super elements" that merge an entire panel of strips into one element with a certain number of nodes along each edge, elements based on a tension membrane formulation, and the separation of the analyses into macro and micro models (i.e., entire walls versus individual panels) where strut or shell elements are used for macro behavior while the strip model is used to determine local effects. In all cases, the element formulations should be aimed at satisfying the primary objectives of 1) accurate simulation of the global response of SPSW infill panels under the range of cyclic load histories that develop in typical SPSWs, 2) efficient model-building, including objective procedures for calibration that are based on panel geometric, material and design properties, 3) a simple model formulation, and 4) portability to commercial software for nonlinear analysis of structural systems.

FLEXURAL STIFFNESS FOR MID-TO-HIGH RISE SPSW

As Seilie and Hooper [2005] noted, the flexural (i.e., overturning) stiffness of SPSWs can be a significant detraction to the system's use in mid-to-high rise buildings. Concrete shear walls use their entire width to resist overturning and when used in a core wall configuration they benefit from tub behavior. In contrast, SPSWs use only the boundary columns to resist overturning, thus they are much more flexible in cases when wall flexure dominates over shear. A similar problem exists with braced frames and in high-rise buildings the need for outrigger systems is clear. This is commonly done in high-rise structures at mechanical levels using large outrigger trusses. However, mid-rise SPSWs are also rather flexible with regards to overturning and practical solutions are needed.

Research Needs

Approaches for improving the overturning stiffness of SPSWs are needed. Systems such as those in Fig. 4a and 4b provide reasonable alternatives but there is little information on how such systems will perform. Parametric analyses and carefully designed experiments will be necessary to determine the behavior of those systems and develop design recommendations. Splitting a SPSW into two coupled SPSWs, as shown in Fig. 6 may also improve the overturning stiffness but there is little information available regarding how coupling beams should be designed within such a system. Important factors that must be researched include the required strengths and stiffnesses of coupling beams, the distribution of coupling beam strength and stiffness over the height of the SPSW, the magnitude of coupling beam rotation demands, and the impact of coupling beam behavior on the overturning stiffness of SPSWs.

Other approaches to improving the flexural stiffness of SPSWs involve adding web plates in various locations to act as story-tall coupling beams or outriggers (Fig. 7). Such approaches are discussed conceptually by Sabelli and Bruneau [2006] but there has been no research performed on these configurations. Of particular importance for such situations is the prevention of soft-stories which would severely impact the SPSWs performance.

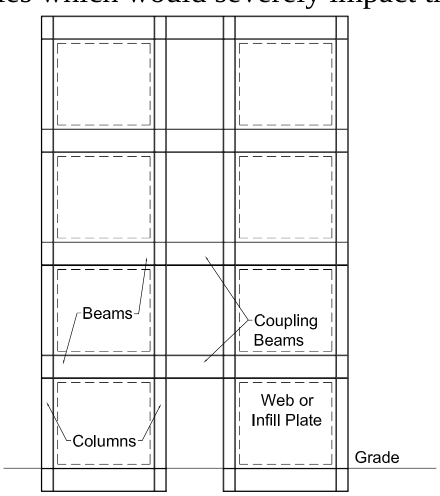
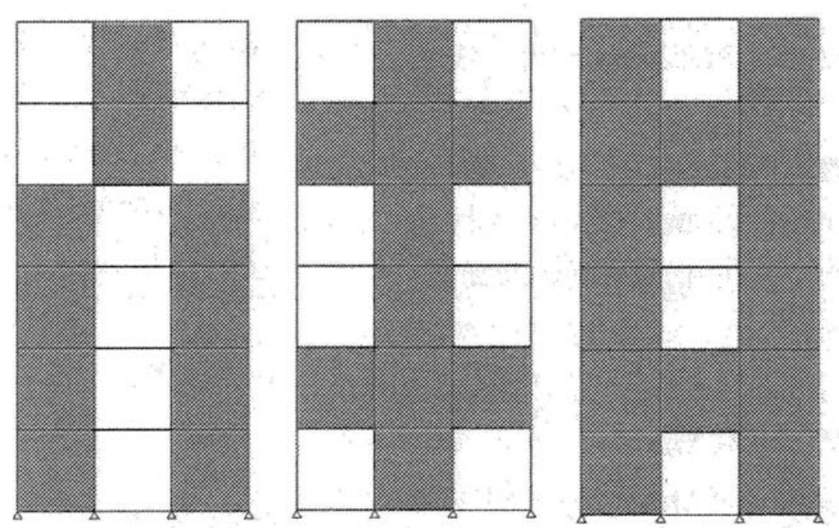


FIGURE 6 – COUPLED SPSW.



(a) (b) (c)

FIGURE 7 - SPSW CONFIGURATIONS THAT MAY IMPROVE OVERTURNING STIFFNESS (FROM SABELLI AND BRUNEAU [2006]).

PERFORMANCE-BASED DESIGN OF SPSWS

The structural engineering community must have performance-based design procedures for SPSWs to ensure that they can meet multiple performance objectives in an efficient and economical manner. Since SPSW systems are inherently dual systems (infill plates within moment resisting frames) it is conceivable that yielding in different elements can be used as performance objectives for various levels of seismic demand. Although the particular performance objectives would be different for some of the modified configurations discussed above (i.e., in a coupled wall yielding of coupling beams may be the performance objective for lower seismic hazard levels), the concept is similar.

The approach for SPSWs should be similar to what has been done for moment resisting frames through the SAC project [FEMA 2000, Roeder 2002]. First, a full account of failure modes for conventional and innovative SPSW configurations must be taken. Then the design approach must establish a yielding hierarchy and balance the more desirable yielding mechanisms while restricting undesirable mechanism from forming. The current AISC Seismic Provisions [AISC 2005] establish a yielding hierarchy (web plates, then beams, then columns) but the approach is not balanced and it is unclear when different yielding mechanisms will occur. Further, it is not clear that all yielding mechanisms will occur prior to more undesirable failure modes such as beam buckling, plate tearing, etc. A current project is developing performance based design recommendations for special concentrically braced frames [Roeder and Lehman 2007]. That work utilizes different balance factors that apply to various limit states to ensure their strength relative to the brace yield strength. Such an approach is able to allow the more desirable yielding mechanisms to occur gradually while preventing more undesirable failure modes.

Significant research is needed to develop performance-based design guidelines for SPSWs. Databases of tests results and failure modes for systems and components must be developed and additional testing will be needed. Extensive analytical modeling must also be undertaken to determine variations in component demands with respect to changes in input motions. Once these data are collected, the hierarchy of yielding can be established and statistical calibration of balance factors can be performed.

CONCLUSIONS

This paper has identified areas where research is necessary to further the implementation of SPSW in seismic regions. Certainly the research needs described above do not constitute an exhaustive list. They do, however, identify high impact areas that would make this promising seismic load resisting system easier to design (through the development of new modeling techniques), more economical (largely by reducing column demands), and structurally more efficient (by increasing overturning stiffness). The authors hope this paper will provide a basis and rationale for future research directions with respect to SPSWs. Ideally, a large-scale comprehensive research project aimed at advancing these promising systems and developing performance-based design recommendations will be supported in the future.

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