Steel Plate Shear Walls:

Practical Design and Construction

By Ignasius F. Seilie, P.E. and John D. Hooper, P.E.

Used for more than three decades as a primary lateral force resisting system, steel plate shear walls are a good choice for a variety of building applications.

Steel plate shear walls (SPSW) have been used, to a limited extent, as the primary lateral force resisting system in buildings for more than three decades. There have been numerous SPSW research programs in this timeframe in the United States, Canada, and Japan to help foster a better understanding of the system's behavior, particularly as it relates to earthquake-resistant design. Some major building projects that utilized SPSW as the primary lateral force resisting system include the following:

- United States Federal Courthouse, Seattle, WA— 23-story building (350′)
- Sylmar Hospital, Los Angeles, CA— six-story building
- Canam-Manac Headquarters Expansion, St. George, Quebec— six-story building
- Hyatt Regency Hotel at Reunion, Dallas, TX— 50-story building (562′)
- The Century, San Francisco, CA— 46-story building (465′; the project was cancelled after the completion of design and permit)
- Nippon Steel Building, Tokyo, Japan— 20-story building
- Shinjuku Nomura Building, Tokyo, Japan— 51-story building (693′)
- Kobe Office Building, Kobe, Japan— 35-story building (425′)

The SPSW systems in the Kobe Office Building and Sylmar Hospital have been "tested," having withstood fairly significant earthquakes. The Sylmar Hospital went through the Northridge Earthquake in 1994 and survived without any structural damage; however, there was

U.S. Federal Courthouse, Seattle (left) and The Century, San Francisco (right).

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Planar SPSW (Canam HQ). See the September 2001 issue of *MSC* at **www.modernsteel.com**.

wide-ranging non-structural damage (Astaneh & Zhao, 2002). The Kobe Office Building survived the Kobe Earthquake in 1995 with minor damage (Astaneh & Zhao, 2002).

There are three different SPSW systems:

1. Un-stiffened, thin SPSW
2. Stiffened SPSW
3. Composite concrete SPSW

This paper will focus on the un-stiffened, thin SPSW system, which is commonly used in North America.

Why Steel Plate Shear Walls?

SPSW systems have been researched since the early 1970s. The most common research and application of SPSW in North America is the un-stiffened, thin SPSW system. In Japan, the stiffened SPSW system is more common. Regardless of which system is used, the determination of whether a SPSW system is the right application in general is important. The advantages and disadvantages of SPSW systems depend on the type of building being considered, as indicated below.

Advantages of SPSW

Wall Thickness. SPSW allow for less structural wall thickness in comparison to the thickness of concrete shear walls. A study performed for The Century project indicated an average wall thickness, including the furring, of 18″ as opposed to a concrete shear wall thickness with an average of 28″ (refer to Figure 2). This resulted in a savings of approximately 2% in gross square footage.

Building Weight. SPSW result in a lesser building weight in comparison to buildings that use concrete shear walls. A study performed for The Century project indicated that the total weight of the building as designed using SPSW was approximately 18% less than that of the building designed using a concrete shear wall core system, which results in a reduction of foundation loads due to gravity and overall building seismic loads.

Fast Construction. The use of a SPSW system reduces construction time. Not only is it fast to erect, but there also is no curing period. A scheduling study performed by a contractor for The Century project indicated a one-month reduction in construction time. The steel erector for the U.S. Federal Courthouse indicated that the erection of the SPSW was much easier than that of the special concentrically braced frames.

Ductility. A relatively thin steel plate has excellent post-buckling capacity. Research performed on the SPSW system indicates that the system can survive up to 4% drift without experiencing significant damage, even though most of the tests showed damage outside the steel plate panel. There was some pinching and tearing close to the corners of the panel due to bending. However, this tearing did not reduce the plate capacity and stiffness (Astaneh & Zhao, 2002).

Tested System. At least two buildings that use SPSW as their primary lateral force resisting system have undergone significant earthquake ground shaking. Both buildings survived with insignificant structural damage (Astaneh & Zhao, 2002). The system also has been tested since the 1970s. The system has been recognized in the National Building Code of Canada (NBCC) since 1994 and will be included in the American Institute of Steel Construction (AISC) *Seismic Provisions* in 2005.

Disadvantages of SPSW

Stiffness. SPSW systems are usually more flexible in comparison to concrete shear walls, primarily due to their flexural flexibility. Therefore, when using SPSW in tall buildings, the engineer must provide additional flexural stiffness. In both The Century and the U.S. Federal Courthouse projects, large composite concrete infill steel pipe columns were used at all corners of the core wall to improve the system's flexural stiffness as well as its overturning capacity.

Construction Sequence. Excessive initial compressive force in the steel plate panel may delay the development of the tension-field action. It is important that the construction sequence be designed to avoid excessive compression in the panel. In the U.S. Federal Courthouse project, the welding of the plate splice connections was delayed until most of the dead load deformation occurred in order to relieve the pre-compression within the steel plate shear wall panel.

New System. Due to unfamiliarity with the system, a contractor will typically estimate a relatively high erected cost. This may be solved by engaging the contractor early in the design phase.

Steel Plate Shear Wall Configuration

There are two distinct SPSW configurations: core systems and planar systems. Depending on the building layout, size, and height, one type may be more advantageous than the other.

SPSW core systems are best suited for medium- to high-rise buildings. This configuration provides better torsional and overturning stiffness and capacity.

Multiple planar SPSW are more suitable for low-rise buildings and also for rehabilitating existing buildings. These walls will provide sufficient shear capacity with somewhat limited overturning moment capacity.

Analysis and Design Approach

The typical SPSW system is comprised of steel plate panels, vertical boundary elements, and horizontal boundary elements.

The general procedure in the design of the SPSW system is as follows:

Gravity Framing

The building frames, including the SPSW boundary elements, should be designed to carry gravity loadings while neglecting the contribution of the SPSW panels. This is an important factor, done to ensure that the building frames have sufficient capacity to support the gravity loads during seismic events, during which the plate experiences buckling due to the development of its tension-field action.

Steel Plate Panel

The steel plate panel is designed to handle both wind and seismic loads. All lateral shear loads in the SPSW panel are resisted by the steel plate, utilizing tension-field action. There are many different approaches that can be used to analyze the plate. The most common approach is the tension-field strut model, oriented in the direction of the tension field "a." Plate elements with orthotropic properties oriented in the a direction may be used in the lateral model as a substitute for the struts. These tension struts are designed as tension members. This approach is represented by the following equation:

$$\tan^4 \alpha = \frac{\dfrac{2}{wL} + \dfrac{1}{A_c}}{\dfrac{2}{wL} + \dfrac{2h}{A_b L} + \dfrac{h^4}{180 I_c L^2}}$$

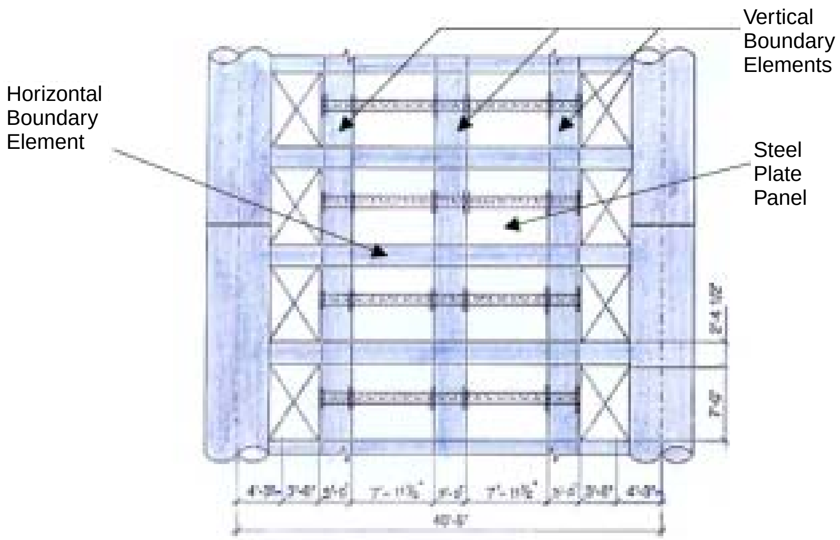
Where:

L = steel plate panel length
h = steel plate panel height
w = steel plate thickness
A_c, I_c = vertical boundary element member area and moment of inertia
A_b = horizontal boundary element member area

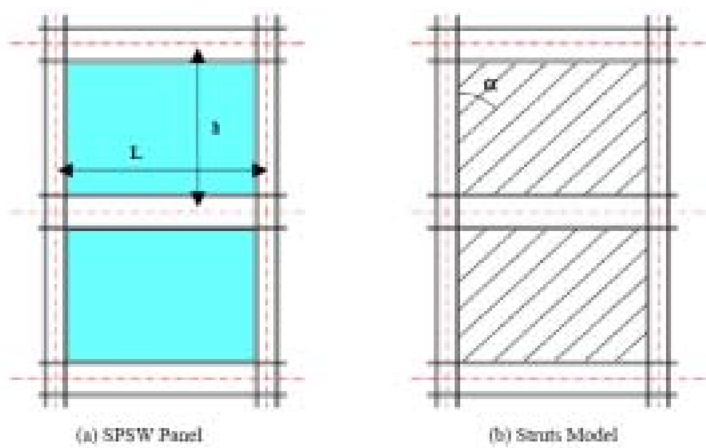
The suggested maximum height/length aspect ratio (h/L) is 1. A large height/length ratio means the vertical boundary elements' stiffness and capacity will have more influence on the system quality. The suggested minimum length/thickness ratio is 180. Thicker plates will delay the development of tension-field action.

Boundary Elements

The boundary elements are very



SPSW panel assemblage (The Century, San Francisco).



Gravity framing analysis, The Century, San Francisco.

important to the proper performance of SPSW systems. For boundary elements with plate walls on one side only (edge boundary elements), the boundary element should be designed based on the capacity of the steel plate wall. This demand is based on the panel's aspect ratio, the steel plate's thickness, and the steel plate's expected strength.

The vertical boundary elements, whether built-up or comprised of standard "W" shapes, should meet the AISC compactness criteria.

Hinging Sequence

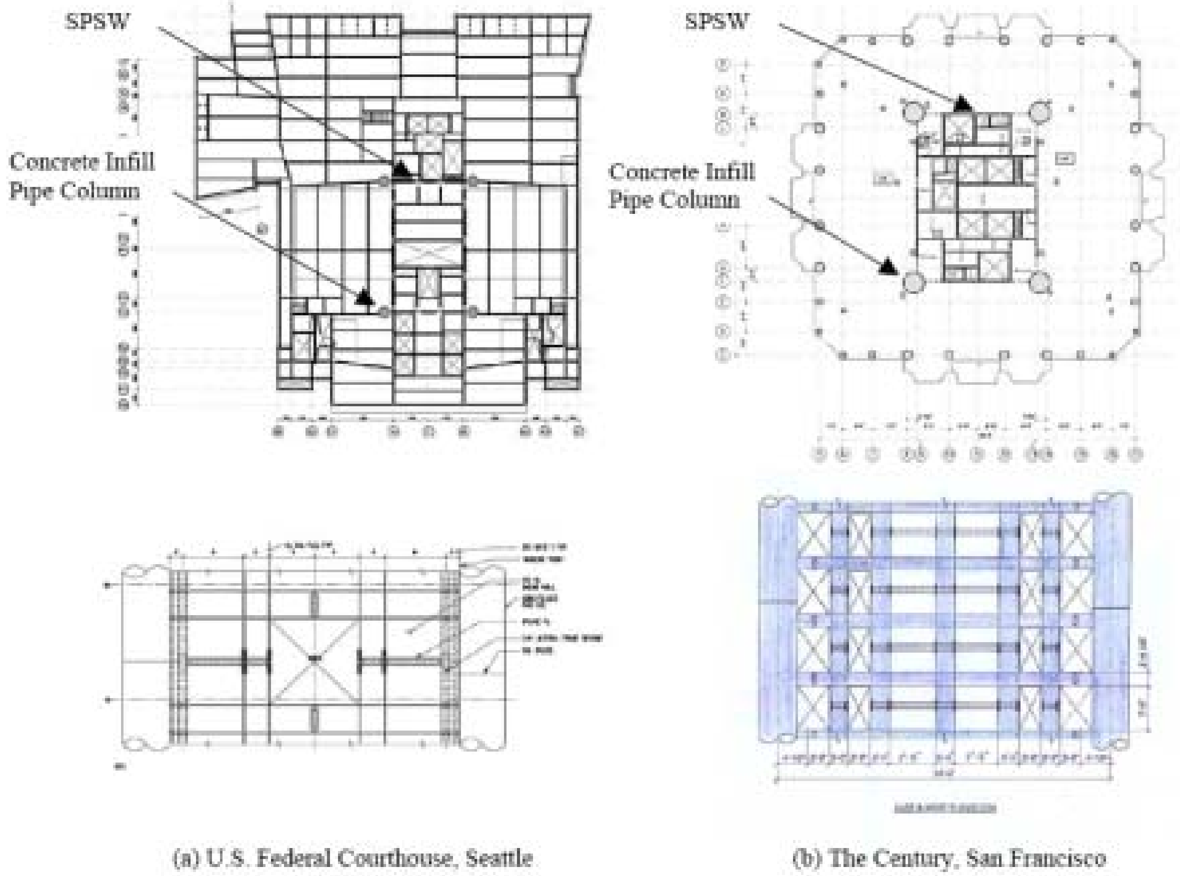
The desirable hinging sequence for the SPSW system is as follows:

1. Steel plate walls
2. Coupling beams
3. Horizontal boundary elements
4. Vertical boundary elements

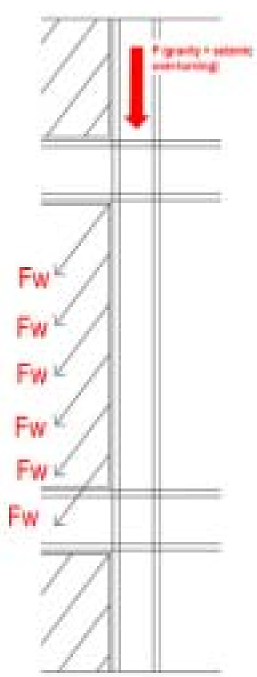
Alternative Modeling Techniques

Comparative studies between actual physical SPSW tests at the University of California, Berkeley (Astaneh & Zhao, 2002), tension-field strut models, and elastic orthotropic plate element models indicate that both modeling techniques are suitable for use. The NBCC suggests the use of the tension-field strut model, with a minimum of ten struts per panel oriented in the "a" direction. However, for high-rise building design, this approach can be very tedious. The use of elastic orthotropic plate elements simplifies the analysis for high-rise buildings.

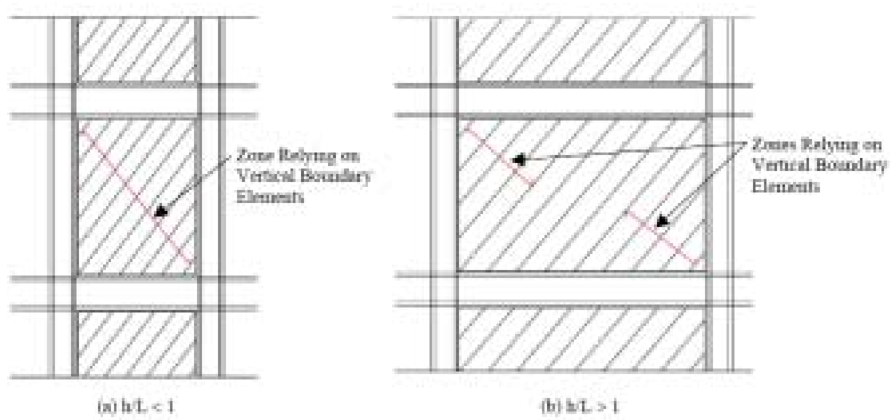
The stiffness property in the direction of the tension-field should be the full steel stiffness property, while the stiffness property in the perpendicular direction to the tension-field should be a fraction



Core walls with composite concrete infill steel pipe columns.



Forces supported by vertical boundary element.



Height/length aspect ratio.

of the steel stiffness in order to represent limited steel stiffness under compression.

Construction Considerations

There are several important factors that need to be considered by the engineer in order to produce good SPSW behavior and an efficient construction process.

SPSW Fabricated Panel Size and Details. SPSW panels can consist of large steel panels with low out-of-plane stiffness, which can create difficulties for stick building/erection of the system. The engineer should plan the panel segment size and details to mitigate this construction issue. Sufficient out-of-plane stiffness should be provided.

Careful Construction Sequence Plan. The engineer, with assistance from the contractor, should plan the construction sequence to alleviate gravity-load induced axial compression in the steel plate panels. Axial pre-compression in the steel plate wall may delay the development of the tension-field action. One approach to overcome this is to delay the tightening/fixing of the steel plate splice connection. This will allow shortening of the vertical elements prior to fixing the steel plate splice.

Stability During Construction. One of the advantages of using the SPSW system is speed of construction. The engineer needs to make sure that the assembled system has sufficient out-of-plane stiffness during construction. The SPSW has less out-of-plane stiffness in comparison to a concrete wall.

Summary

SPSW systems have been used, to a limited extent, as the primary lateral force resisting system in buildings for more than three decades. Their recent good performance in major earthquakes, their robust performance in the laboratory, and their recent inclusion in codes and standards suggest that SPSW systems are here to stay. ★

This paper has been edited for space considerations. To learn more about practical design and construction of steel plate shear walls, read the complete text online at www.modernsteel.com or in the 2005 NASCC Proceedings.

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