A Closer Look at Steel Plate Shear Walls

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Addressed in AISC's *Seismic Provisions* and covered in AISC's *Design Guide 20*, special plate shear walls are a viable option for many high-seismic designs.

A SHEAR WALL MADE FROM STEEL PLATE MAY SEEM LIKE A NEW IDEA. However, the concept of the steel plate shear wall had been around for decades, and was used in a significant number of buildings, even before the existence of design provisions specifically addressing this structural system. It has been recognized by the National Building Code of Canada and Canadian Steel Design Standard since 1994. Similar provisions were included in FEMA 450 (*NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures*) in 2004. In 2005, the special plate shear wall was added to the AISC *Seismic Provisions for Structural Steel Buildings*, ANSI/AISC 341-05.

The recently published AISC *Design Guide 20*, *Steel Plate Shear Walls* develops the *Seismic Provisions* into a complete design methodology. The design guide discusses the history, research, and design requirements for steel plate shear walls used in both low- and high-seismic applications. This article will discuss the high-seismic applications, focusing on the design requirements and recommendations for the special plate shear wall (SPSW) system as found in the *Seismic Provisions* and the design guide. The term high-seismic, as used in this article, refers to structural systems that are expected to undergo significant inelastic deformations, designed to meet the requirements of the *Seismic Provisions*, and have a redundancy factor R greater than 3.

Terminology

The vertical steel plate connected to the columns and beams is referred to as the web plate. The columns in SPSW are referred to as vertical boundary elements (VBE) and the beams are referred to as horizontal boundary elements (HBE).

Mechanics and Behavior

The web plates in steel plate shear walls are categorized according to their ability to resist buckling. The web plates can be sufficiently stiffened to preclude buckling and allow the full shear strength of the web to be reached. Theses are known as "stiffened" web plates. While stiffening increases the effectiveness of a web plate, it is typically not as economical as the use of the "unstiffened" web plate in which buckling of the web plate is expected.

In typical designs (and as assumed by the *Seismic Provisions*) the webs of steel plate shear walls are unstiffened and slender. The webs are therefore capable of resisting large tension forces, but little or no compression. As lateral loads are imposed on the system, shear stresses develop in the web until the principal compression stresses (oriented at a 45° angle to the shear stress) exceed the compression strength of the plate. At this point, the web plate buckles and forms diagonal fold lines. The lateral loads are transferred through the plate by the principal tension stresses (parallel to the fold lines); the angle of the tension shifts from 45° to an angle α (discussed later).

In high-seismic design of SPSW, it is assumed that lateral loads will be sufficient to cause tension yielding of the web plate along its full height. Thus, the web plate forces are uniform, as shown in Figure 2 (in the elastic range, the web-plate tension stress is far from uniform). Ideally, the web plate at each level will reach its full tension yield simultaneously, or nearly so, and the yield mode of the system will be a multi-story shear mode. The axial yield of VBE (especially at the base), which corresponds to a flexural mode, should be avoided. Flexural yielding of the HBE at the ends (near the rigid connections to the VBE) is also expected as part of the shear mechanism.

Force Distribution

Figure 1 indicates the applied forces and base reactions for a one-story steel plate wall. Figure 2 indicates the internal forces of the elements of the wall system indicated in Figure 1. The forces shown are the result of the applied forces of Figure 1, assuming uniform tension yielding of the web plate. Figure 3 indicates the internal forces for an HBE at an intermediate floor of a multi-story wall system similar to the single-story system indicated in Figure 1. (Note that boundary element end moments are omitted from the illustrations for clarity.) Several interesting points are illustrated in these figures, including:

- The web tension forces on the HBE pull toward the plate. For a HBE at a typical intermediate floor level, the forces from the plate above balance much of the forces from the plate below. However, the HBE at the top level has no such balance of forces, creating significant flexure in this member. For this reason, the HBE at the top level is often much larger than HBE at other levels.
- At the base, the web tension forces (which pull upwards) must be resisted by the foundation. A steel or concrete grade beam with sufficient strength to anchor the tension in the web plate is typically provided.
- The web tension forces on the VBE also pull inward toward the web, creating significant flexure in these members. The VBE must have sufficient flexural strength and stiffness to resist these forces and permit the webs to develop their full tension strength along their entire depth.
- Inward flexure of the VBE is resisted by compression in the HBE at the top and bottom of the VBE segment (typically at each floor). Thus, the HBE are required to resist significant compression.
- Examine the forces at the base of the wall indicated in Figure 1.

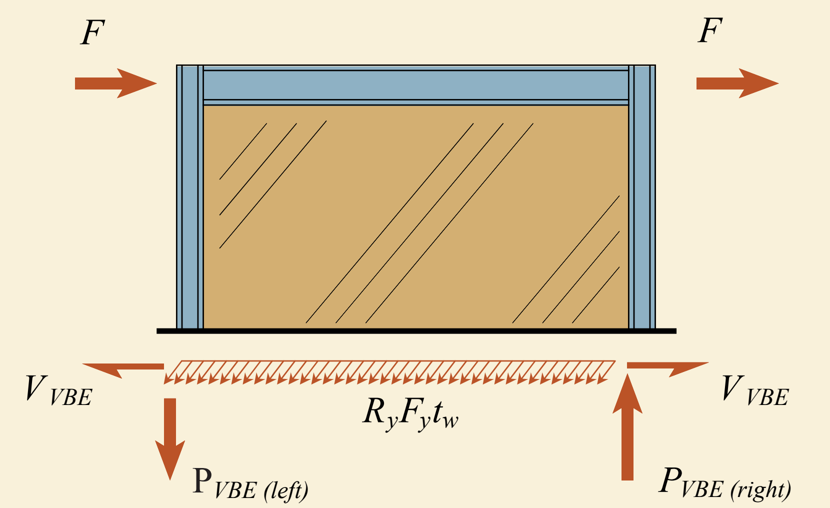


Figure 1. Applied forces and base reactions for a SPSW.

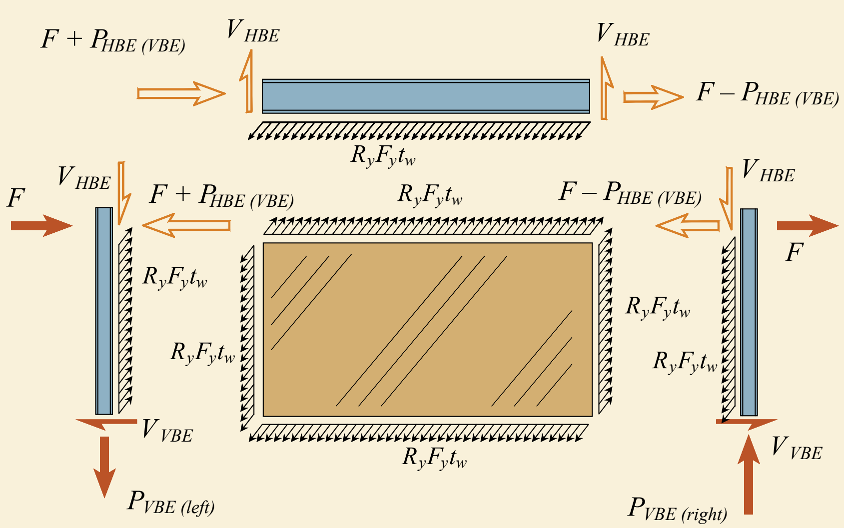


Figure 2. Free-body diagram of the web plate, boundary elements, and SPSW, based on applied forces from Figure 1.

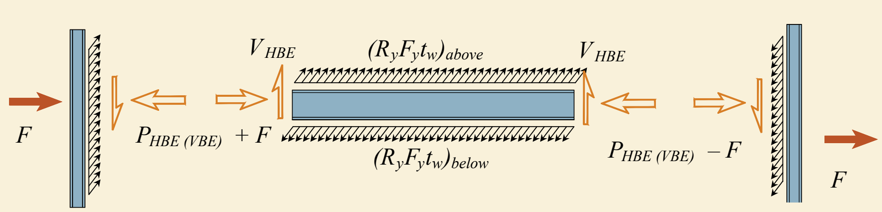


Figure 3. Free-body diagram of the boundary elements for intermediate HBE based on applied forces from Figure 1.

Notes

V_{HBE} = shear force in the vertical boundary element, kips (N)
F = collector force, kips (N)
$P_{HBE\ (VBE)}$ = axial force in the horizontal boundary element due to the vertical boundary element, kips (N)
R_y = ratio of the expected yield stress to the specified minimum yield stress, F_y
F_y = specified minimum yield stress of the type of steel to be used, ksi (MPa)
t_w = thickness of the web plate, in. (mm)
$P_{VBE\ (right\ or\ left)}$ = axial force in the vertical boundary element on the right or left side of the wall, kips (N)
V_{VBE} = shear force in the vertical boundary element, kips (N)

Compression at the base of the right-hand VBE is balanced by both tension at the left-hand VBE and in the web plate. This illustrates that the compression forces due to lateral loads in the VBE are greater than tension forces.

- The axial forces in the VBE to HBE connections at either end of the HBE are not symmetric. Examine Figure 2 or 3. At the right-hand connection, the axial force is the difference between two components: the collector force and the inward reaction from the VBE. (This axial force is usually compressive.) At the left-hand connection the axial force is compressive, with the two components adding.

AISC Requirements

Section 17 of the *Seismic Provisions* contains the requirements for the SPSW. Sections 1-8 and 18 contain the requirements for the seismic load resisting system in general. The requirements are summarized in Figure 4. The design guide has guidelines on how to apply the requirements and determine required forces. Generally speaking, the requirements are based on the following principles:

- The web plates are assumed to reach full tension yielding at angle α at each level. α is based on the wall geometry and the properties of the boundary elements and determined from equation 17-2.
- The webs are designed to meet the demand of the applied load with the shear strength as determined in equation 17-1.
- In order to ensure that the webs can reach their full tensile strength, the required strengths of the connections to the boundary elements are based on the fully yielded strength of the web, using the expected tension yield stress, R_yF_y. The web is welded or bolted to the boundary elements in the field by means of a "fish plate," which is welded in the shop to the HBE or VBE.
- The boundary elements are designed to remain essentially elastic (with the exception of the anticipated plastic hinging at the ends of the HBE) when the web reaches its expected tensile strength at angle α. Because the webs are assumed to fully yield in tension, the required strengths of the boundary elements and their connections are based on strength of web and the plastic moment strength of HBE, combined with gravity loads.
- The VBE-HBE moment ratio must meet the requirements of Section 9.6. Section

9 presents the requirements for special moment frames (SMF). This requirement is included to provide columns that are generally strong enough to force flexural yielding in beams in multiple levels of the frame, thereby achieving a higher level of energy dissipation.

- ➜ The width-thickness ratios of the boundary elements must meet the requirements of Section 8.2b, which is the same requirement as SMF. This requirement recognizes the significant part that frame action plays in the system and ensures that the moment frames elements (i.e., the boundary elements) are compact enough to undergo significant inelastic deformation.
- ➜ For the same reason, HBE have lateral bracing requirements consistent with the beams in SMF.
- ➜ The connections of the HBE to the VBE are expected to form plastic hinges, but they are not the main source of energy dissipation in this system. The SPSW is not expected to undergo as much drift as an SMF, therefore the requirements of an SMF moment connection are not necessary. Instead, the performance expected from an ordinary moment frame (OMF) connection is required (i.e. beam hinging rather than connection failure). In addition, rigid connections help prevent pinching of hysteretic behavior of the system.
- ➜ The stiffness of the VBE is critical to enabling the web to reach uniform tensile yielding in the entire web. Therefore, the VBE is required to have a minimum flexural stiffness in Section 17.4g.
- ➜ The panel zone requirements of Section17.4f for the VBE at the top and base HBE of the SPSW are the same as those for SMF (found in Section 9.3). These are generally large HBE and the VBE must be designed to resist the large forces the HBE may impose. Conversely, the intermediate HBE are expected to be small and connecting to sizable VBE. If this is not the case, or if there is an HBE on either side of the VBE, the engineer should use judgment as to whether the panel zone requirements should apply. The authors of the design guide recommend that the requirements of the *Seismic Provisions* Section 17.4f be applied to panel zones at all levels.

Analysis/Modeling

The SPSW system is modeled and analyzed to determine the forces in the elements of the system, determine the distribution of story shear between the web plates and VBE, and to estimate the lateral displacement of the frame (frame stiffness may be the governing criterion in some cases). Two modeling techniques are presented in the design guide as the most suitable for use by practicing structural engineers.

1. **Strip models.** The web plate is replaced by a series of diagonal and parallel tension-only members. This method is outlined in the Commentary to the *Seismic Provisions*. The strips are aligned at the angle α, as determined in equation 17-2, with area and spacing as determined in the Commentary, with a recommended minimum of 10 strips per panel. The authors of the design guide recommend that an average α be used (to simplify the model) wherever the calculated α is within 5° of the average angle. Research and other recommendations for the use of the strip model can be found in the design guide.
2. **Orthotropic membrane model.** The web plate is modeled by orthotropic (properties of the element depend on the axes) membrane elements to model the differing compression and tension resistance of the web plate. This method is recommended by the authors of the design guide for typical applications when software with this capability is available. The local axes of the elements are set to match the calculated angle of tension stress, α. The material properties in the axis aligned with α are the true material properties. The stiffness in the orthogonal direction should be assumed as zero so that the stresses calculated in the compression diagonal are essentially zero. Further recommendations for the use of the orthotropic membrane model can be found in the design guide.

Capacity Design Methods

Once the shear force in the web plates is determined from an analysis (as described above) the web plate can be designed. A capacity design is then required to determine the forces in the boundary elements and their connections based on the strength of the web plates. There are a number of analytical approaches to achieving a capacity design when determining the forces acting on the boundary elements.

The most direct method is to determine the forces associated with an earthquake by assuming the web plate has fully yielded, the HBE have formed plastic hinges, and the shear at the end of the VBE is as required by the *Seismic Provisions* Section 17.4b. This method is referred to as the direct capacity method in this article. Guidelines and recommendations on how to determine and apply these loads and combine them with gravity loads are found in the design guide. In essence, the forces determined from the full-tension yielding of the web are considered the earthquake effect, *E*, to be used in the load combinations of the applicable building code. Section 3.5.2.2 of the design guide covers HBE design. Section 3.5.2.3 covers VBE design.

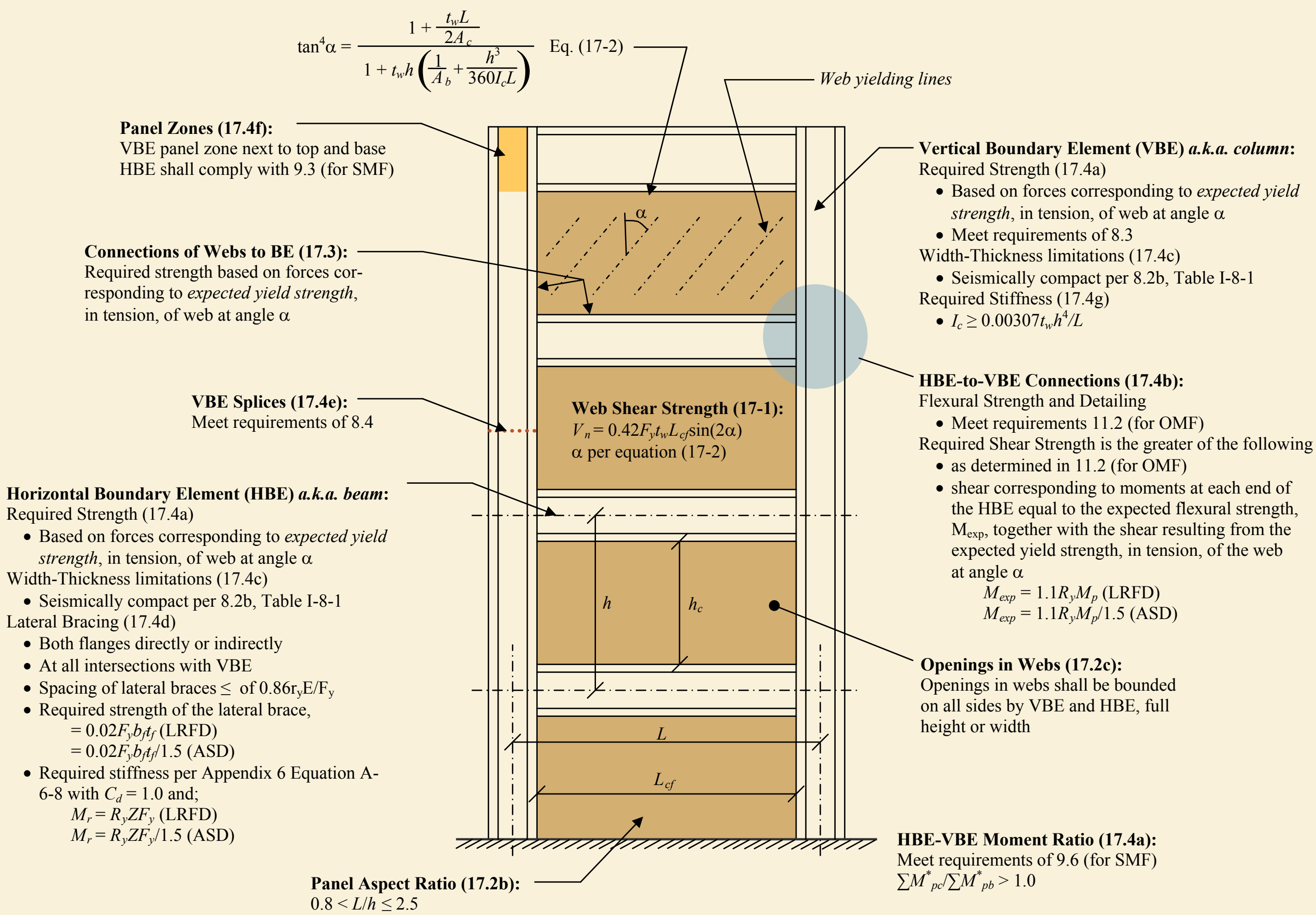
Axial forces in the VBE corresponding to web-plate yielding at all levels simultaneously (as assumed in the direct capacity method) can be extremely high. For this reason, alternative methods for estimating maximum forces corresponding to the expected mechanism have been proposed. Three of these are outlined in section C17.4a of the Commentary to the *Seismic Provisions*. They are:

- ➜ **Nonlinear push-over analysis (POA).** A standard push-over analysis is done with web elements having varying stiffness properties as yielding occurs. The forces in the boundary elements that correspond to web yielding are determined. This method is especially useful to reduce the overturning moment for taller structures (as compared to direct capacity method).
- ➜ **Combined linear elastic computer programs and capacity design concept (LE+CD).** This method involves the design of the VBE at a given level by applying loads from the expected strength of the connecting web plate and adding the overturning loads from levels above using the amplified seismic load.
- ➜ **Indirect capacity design approach (ICD).** In this method, loads in the VBE can be determined from the gravity loads combined with the seismic loads from a linear analysis increased by an amplification factor based on the overstrength of the web plate at the first level of the system.

Preliminary Design

For preliminary design, the web plates can be assumed to resist the entire shear in each frame, based on the following steps:

- ➜ The web plate thicknesses at each level can then be determined by meeting the shear strength requirements of the *Seismic Provisions* Equation 17-1, assuming a reasonable value for α. Typical designs show that the angle ranges from 30° to



Notes: All equation and section references (in parentheses) refer to the *AISC Seismic Provisions* unless noted otherwise. All symbols, except *hc*, are defined in the appropriate section of the Seismic Provisions. *hc* is the clear distance between adjacent HBE.

Figure 4. Summary of requirements for special plate shear walls.

55°. It is convenient to assume an angle of 45° (although 30° would be a more conservative estimate).

- ➜ Once web plates are selected, the preliminary selection of the VBE can be made based on the stiffness requirement given in the *Seismic Provisions* Section17.4g.
- ➜ For the preliminary design of the HBE, the forces imposed by the web plate can be derived from the same angle, α, as was assumed for the selection of the web plate. The selection of the HBE should be based on this load in combination with the gravity load effects.
- ➜ The preliminary sizes of the web plates and boundary elements can then be used in the analysis model as a starting point for iteration to the final design, which is based on the actual distribution of shear to the web and VBE, actual web plate thicknesses, and forces in the boundary elements based on the full yielding of the web plate.

Preliminary design is discussed in more detail in the design guide, section 3.4.1 and the Commentary to *Seismic Provisions* section C17.4a. A spreadsheet to automate many of these preliminary calculations is being developed through the AISC Steel Solutions Center and will be available as a Steel Tool from the AISC web site, **www.aisc.org**.

HBE-to-VBE moment connection

Consider two properties. First, the flexural force in the VBE due to HBE hinging is typically greater than that due to web-plate tension. In such cases, the flexure away from the connection does not govern the design of the VBE. Second, the required HBE flexural strength is governed by flexure in the mid-span due to web-plate tension (in combination with gravity loads), not at the ends. Based on these two properties, it is convenient to use a reduced beam section (RBS) connection in the HBE to limit the required flexural strength of the VBE. In addition, the RBS reduces the demand on the VBE when applying the HBE-VBE moment ratio requirements. The RBS is thus proposed for economy in the design of the VBE by the authors of the design guide. The connection only needs to meet the requirements of Section 11.2 (for OMF). The quality requirements of SMF are not applicable to the connection as these connections are not expected to undergo the same level of inelastic rotations as those expected for SMF.

Configuration

The design guide discusses the configuration options for a SPSW in section 3.5.2.5. Various configurations can be used to reduce the overturning of the system, which reduces the axial forces in the VBE as well as increases the lateral stiffness of the system. Additional web plates or moment-connected beams can be use as outriggers or as coupling beams between walls. Remember: Using walls in irregular configurations introduces vertical irregularities that must be addressed.

Mid-span Columns

HBE at the top and bottom of the SPSW have more severe loading from the web plate because there is a web plate on only one side of the HBE (as discussed earlier). A series of mid-span columns at each level can be used to reduce the required flexural strength of the HBE at the top and bottom levels. The mid-span column resists the upward force on the bottom HBE and carries the forces to the other HBE, and helps balance the downward force at the top HBE. The sections of the web bounded by the boundary elements and the mid-span column must meet the aspect ratio requirements of section 17.2b. Therefore, the columns can also help long walls meet the aspect ratio requirements.

Horizontal Struts

Horizontal struts at the mid-height of a story can also be used to brace the VBE against the inward flexure caused by the web-plate tension and help meet the minimum stiffness requirement for VBE of section 17.4g. The struts should be designed to carry the compressive axial load and should not have rigid moment connections to the boundary elements. The sections of the web bounded by the boundary elements and the struts must meet the aspect ratio requirements of section 17.2b. Therefore, the struts can also help tall walls meet the aspect ratio requirements.

Overstrength in the Web Plate

The web plate will have some overstrength due to the fact that plates are available in discrete thicknesses and yield strengths. (The design guide has a table of commonly produced thicknesses of materials suitable for web plates in SPSW.) This overstrength can have a significant effect on the design of the boundary elements and their connections due to the fact that all elements are designed based on the strength of the web plate. In addition, having stronger stories (relative to the demand) can concentrate the inelastic deformation in "weaker" stories. Thus, it is recommended to proportion the web plates to the story shear as closely as possible and not to provide unnecessary overstrength.

Low-seismic Design

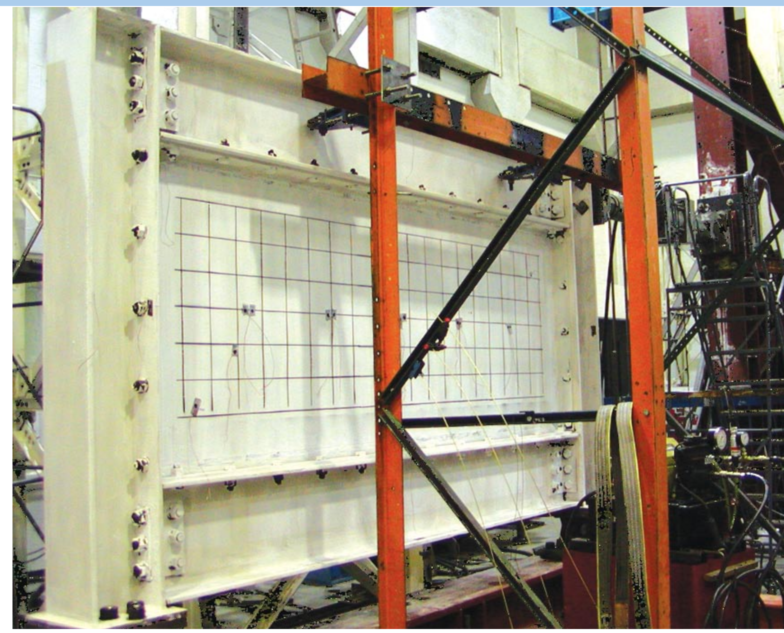
The term low-seismic, as used in this article, refers to structural systems that are not expected to undergo significant inelastic deformations, are not designed to meet the requirements of the *Seismic Provisions*, and have a redundancy factor *R* equal to 3. The general term for the system with steel boundary elements and web plates is the steel plate shear wall (SPW). The term special plate shear wall (SPSW) that is the main focus of this article is reserved for high-seismic applications. Low-seismic design of the system is based on the same mechanical principles as described here. However, the system is not proportioned to fully yield the web plate. Instead, the forces can come from one of two sources: Forces from the model can be used directly for sizing the web plate, HBE, and VBE; or design of those elements can be done assuming a uniform distribution of average stress in the web plate.

Resources

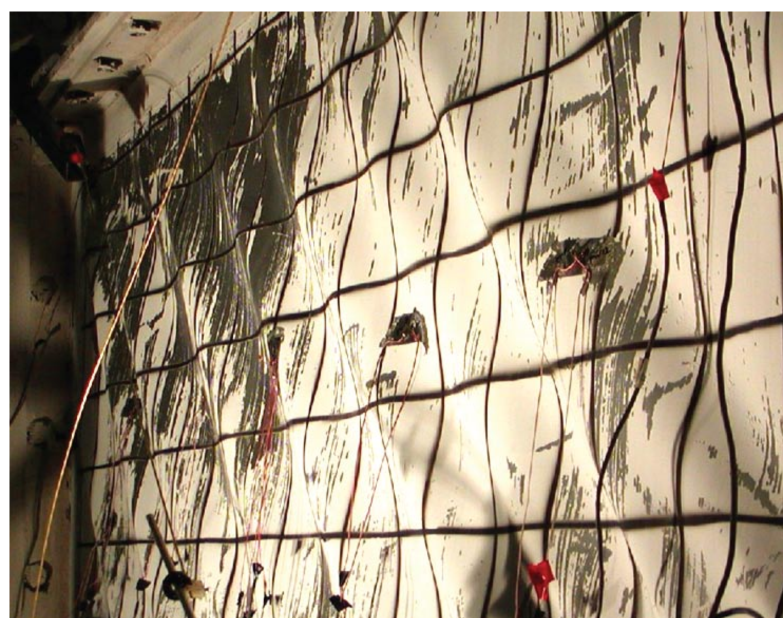
AISC *Design Guide 20, Steel Plate Shear Walls* has a complete discussion of the mechanics, research, and design requirements for low- and high-seismic applications, along with full design examples with preliminary and final designs. Visit **www.aisc.org/bookstore** to purchase the guide. AISC members can download the guide for free at **www.aisc.org/epubs**. The design guide also has a list of references that discusses the topics it covers in more detail.

AISC also offers a seminar on the design of steel plate shear walls for wind and seismic loading. Visit **www.aisc.org/seminars** for more information.

The spreadsheet discussed in the preliminary design section of this article will be available at a future date at **www.aisc.org/steel-tools** to help with preliminary design. MSC



Steel plate shear walls have been tested extensively. A shear wall specimen, above, is readied for testing. After testing, below, the diagonal fold lines of the buckled web are readily apparent.



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