SpeedCore: Seismic Advantages

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What to know when considering a SpeedCore system for its seismic properties.

SPEEDCORE'S MAIN ADVANTAGE, as its name suggests, is its ability to be erected quickly.

But it can also bring seismic advantages to a project.

The first article in this series on SpeedCore panels—"Core Value," which ran in the March 2021 issue and is available at **www.modernsteel.com**—provided a general overview of the system [SpeedCore's technical name is composite plate shear walls/concrete-filled (C-PSW/CF) or coupled composite plate shear walls/concrete-filled (CC-PSW/CF) for coupled systems]. Here, the focus is on design considerations for using the system in a seismic-governed region, specifically seismic response modification factors in both uncoupled and coupled SpeedCore installations.

Three seismic factors are at the core of all seismic design provisions:

- The seismic response reduction factor (R) accounts for system-level ductility and inelastic behavior. In a general sense, the seismic design forces calculated assuming elastic behavior are reduced by this seismic response reduction (R) factor, which accounts for the system level ductility and inelastic behavior. The higher the system-level ductility, the higher the R-factor; However, ASCE 7 limits the largest R-factor to 8.
- The overstrength factor Ω_o accounts for the overstrength in the system between the assumed onset of inelasticity and the formation of the complete plastic (failure) mechanism due to material overstrength, structural redundancy, and other contributing factors.
- The displacement amplification factor C_d accounts for the amplification of the calculated elastic story drift of the lateral force system due to inelastic behavior.

Representing these factors in terms of the base shear to story drift, they can be represented as shown in Figure 1. Values applicable to the C-PSW/CF system will be addressed after the following summary of the system's seismic performance.

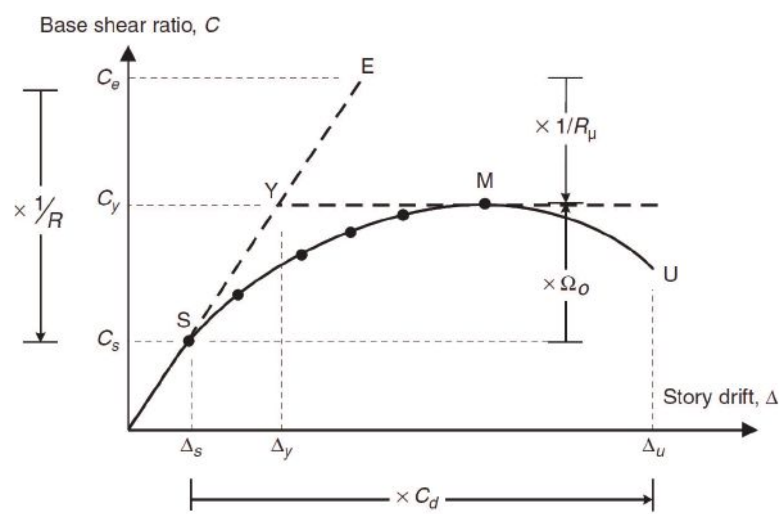

Fig. 1. Seismic response modification factors represented graphically.

Seismic Requirements: Basis of Design

Uncoupled or coupled C-PSW/CF systems can be used to resist lateral forces (wind or seismic forces) in buildings. Uncoupled systems consist of independent C-PSW/CF modules that are not tied together by specially detailed coupling beams, whereas coupled systems consist of C-PSW/CF modules that are connected at each story level using such composite or steel coupling beams. Composite walls can be planar, C-shaped, or I-shaped walls to resist seismic loads, as shown in Figure 2. These walls consist of two steel web plates (along the length) that are connected to each other using steel shapes or tie bars. Semicircular or circular concrete-filled steel tubes can be used as boundary elements. Alternatively, steel flange plates (closure plates) can be used at the ends of uncoupled walls. The individual linear segments in C-shaped or I-shaped walls are referred to as flange walls or web walls, depending on the direction of lateral loading. In each wall segment, the steel web plates have equal nominal thicknesses. The steel plates comprise at least 1%, but no more than 10% of the wall cross section. Walls without any boundary elements or closure plates are not permitted.

a. Planar rectangle wall with flange and tie bars

b. Planar wall with semi-circular boundary elements and tie bars

c. Planar wall with circular boundary elements and tie bars

d. C-shaped walls with flange (closure) plates and tie bars

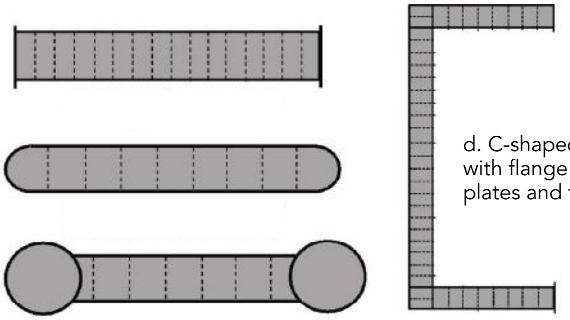

Fig. 2. Example cross-sections of C-PSW/CF walls (uncoupled).

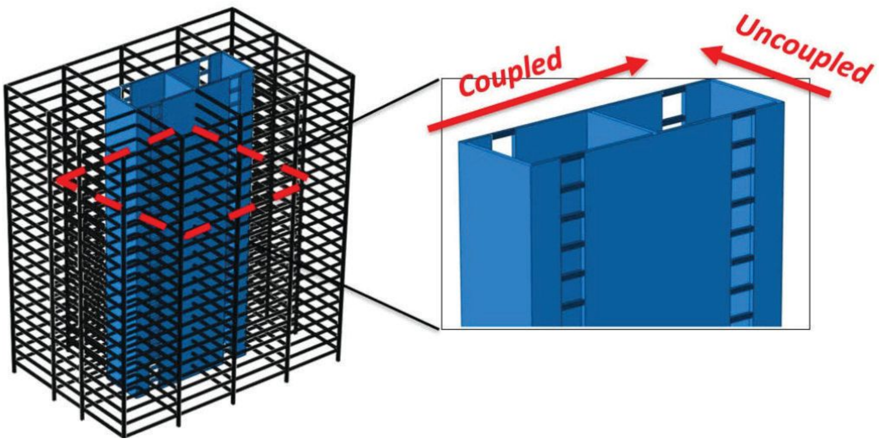

Fig. 3. Structural configuration of building with uncoupled and coupled C-PSW/CF systems in orthogonal directions.

Coupled C-PSW/CF systems are those systems in which the wall elements are tied together via ductile coupling beams, as shown in Figure 3. These coupled systems are structurally more efficient than pure planar walls and are generally used in taller buildings employing C-PSW/CF systems. They have similar design requirements to uncoupled wall systems but have slightly different seismic response modification factors (mainly the R factor).

Selection Seismic Response Modification Factors

ASCE 7-2016 defines the three mentioned seismic performance factors (R, Ω_o, and C_d) to represent the effects of inelastic behavior on the seismic response of the lateral force-resisting system. While values of these factors were empirically calibrated on past practice for legacy lateral load-resisting systems (such as ductile moment-resisting frames), the FEMA P-695 procedure was developed to verify the assumed values for new structural systems. This procedure is also used to evaluate and check the margin of collapse for the maximum considered earthquake (MCE) hazard and requires performing a large number of nonlinear earthquake analyses (i.e., incremental dynamic analysis; see Figure 4) for a significant set of strong earthquakes records. This procedure has been used to verify the proposed seismic performance factors for coupled C-PSW/CF walls when it was proposed to

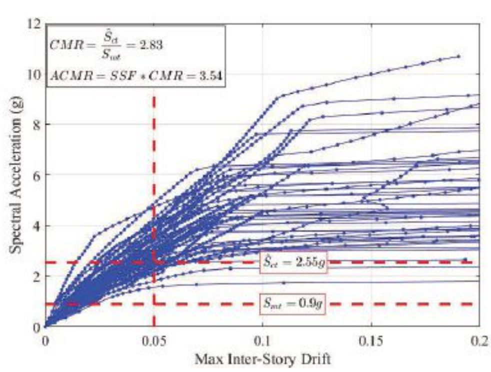

Fig. 4. Typical incremental dynamic analysis results from a FEMA P-695 procedure.

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Fig. 5. University at Buffalo test Specimen for a C-shaped wall configuration.

add this structural system to the list of lateral load-resisting systems covered by ASCE-7.

Incidentally, it was not necessary to use the FEMA P-695 methodology to develop similar factors for uncoupled walls because ASCE-7 already included such factors since its 2000 Edition. These factors were generically applicable to any composite plate shear walls, although the AISC *Seismic Provisions for Structural Steel Buildings* (ANSI/AISC 341, **aisc.org/specifications**) did not provide specific design and detailing requirements for SpeedCore walls at the time. The situation was partly remedied in the 2016 Edition, when specific requirements for SpeedCore panels were added in Section H7, separately from the existing requirements for composite plate shear walls/concrete-encased (C-PSW/CE) in Section H6. Both were designated as composite plate shear walls (C-PSW) in ASCE/SEI 7 Table 12.2-1. Recent studies, including at the University at Buffalo and Purdue University, independently verified the adequacy of these seismic performance factors for uncoupled walls.

Behavior and Capacity-Based Design Requirements for Uncoupled Walls

Comprehensive numerical investigations following the FEMA P-695 approach were conducted to verify the seismic response modification factors ($R = 6.5$, $\Omega W_o = 2.5$, and $C_d = 5.5$) for the uncoupled C-PSW/CF system. In addition to these numerical studies, there has been extensive research related to the cyclic lateral behavior, design, and analysis of uncoupled C-PSW/CF systems. In particular, experimental investigation of the cyclic lateral load behavior of planar C-PSW/CF with flange steel plates was performed at Purdue University, while experimental research on the cyclic lateral load behavior of C-shaped and T-shaped C-PSW/CF specimens was conducted at the University at Buffalo, as shown in Figure 5. Lastly, finite element models of C-PSW/CF were developed at Purdue University and the University at Buffalo to simulate the cyclic lateraling load behavior.

Note that seismic design of uncoupled C-PSW/CF systems can be conducted in accordance with the current 2016 or the upcoming 2022 version of the AISC *Seismic Provisions*, Section H7. The seismic response is governed by the inelastic behavior and formation of a plastic hinge at the base (or location of maximum moment) of the wall. This hinge develops the expected plastic flexural strength of the composite cross-section and has adequate energy dissipation and rotation capacity to warrant the seismic response modification factors (R, W_o, and C_d) specified in ASCE 7. The flexural capacity can be calculated using a plastic stress distribution method or fiber section analysis method. For seismic design, uncoupled C-PSW/CFs are required to be flexural critical, which can be achieved by restricting the wall height-to-length ratio to values greater than or equal to 3. The in-plane shear strength of C-PSW/CFs can be calculated using the composite contributions of the steel web plates and concrete infill. However, shear yielding of the steel web plates should not govern the behavior or design of uncoupled C-PSW/CFs.

Behavior and Capacity-Based Design Requirements of Coupled Walls

Coupled C-PSW/CF systems consist of two or more individual composite walls connected together by coupling beams. Planar, C-shaped, I-shaped, or L-shaped walls with composite coupling beams can be used to form coupled C-PSW/CF. Comprehensive research following the FEMA P-695 approach was conducted to verify the seismic response modification factors (R, Ω_0, and C_d) for the coupled C-PSW/CF system (a PDF of the research results can be downloaded from the Pankow Foundation's website at **tinyurl.com/coupledCPSWCF**). The seismic response modification factors of coupled C-PSW/CF of R=8, Ω_0=2.5, and C_d=5.5 were recommended as a result of this research.

Seismic design of coupled C-PSW/CF can be performed in accordance with the upcoming 2022 version of the AISC *Seismic Provisions* (Section H8). The seismic design criteria and procedure were developed based on capacity design principles. Coupled C-PSW/CF are expected to develop significant inelastic deformations during severe earthquakes. The coupled system is designed to develop flexural plastic hinges at the ends of coupling beams along the height of the structure and flexural plastic hinges at the base (or maximum moment locations) of the wall. Composite coupling beams and walls are sized considering the strong wall-weak coupling beam design approach, which favors the formation of plastic hinges in most coupling beams along the height of the structure before the formation of plastic hinges in the walls. Figure 6 illustrates the seismic response of an eight-story coupled C-PSW/CF structure subjected to a failure level earthquake inducing a maximum inter-story drift level of about 5%. The occurrence of various events along the time history response is marked and illustrated in the figure using plastic strain (PEEQ) contour plots from a 2D finite-element analysis of the structure. The response in Figure 6 illustrates the typical representative seismic response of a coupled C-PSW/CF structure designed according to capacity design procedures.

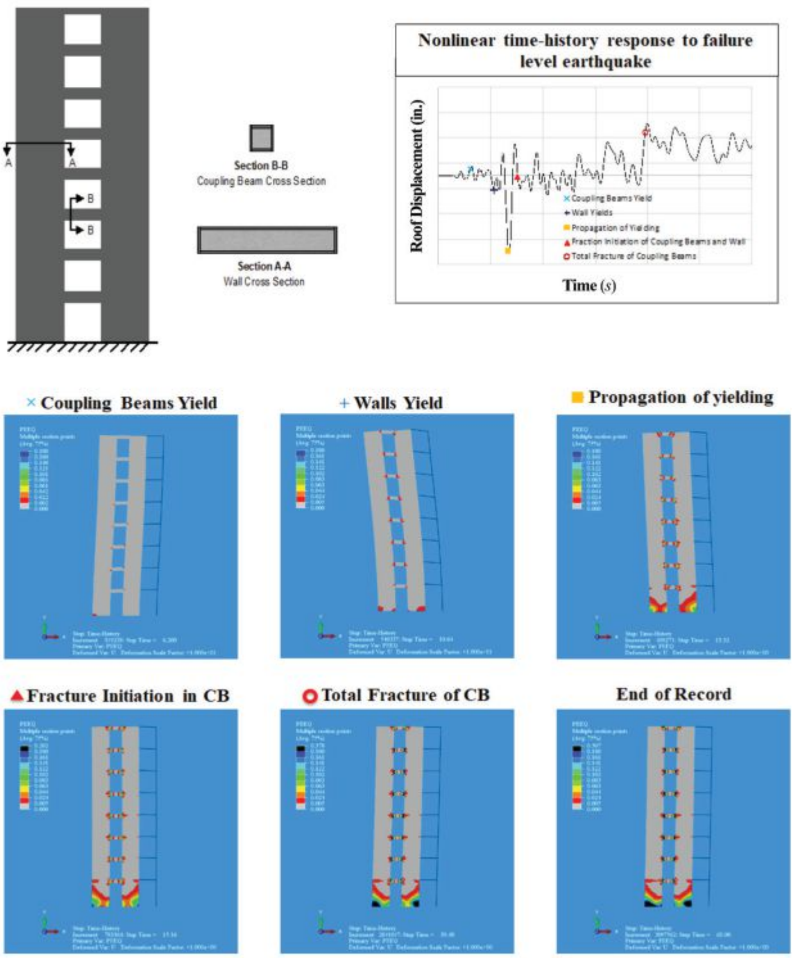

Fig. 6. Nonlinear time-history response of a coupled C-PSW system.

In addition to the design requirements for uncoupled C-PSW/CFs, coupled C-PSW/CFs are limited to walls with a height-to-length ratio greater than or equal to 4. The coupling beams are limited to length-to-depth ratios greater than or equal to 3 but less than or equal to 5. This is done to ensure flexure critical behavior in the composite walls and coupling beams because of the range of parameters and behavior considered using archetype structures in the FEMA P-695 studies.

NEHRP Implementation

ASCE 7-16 (2016) refers to the current AISC *Seismic Provisions* for specific requirements for the use of planar composite steel plate shear walls in seismic regions. However, ASCE-7-16 does not differentiate between coupled and non-coupled walls. As previously described, coupled C-PSW/CFs consist of two C-PSW/CFs linked together by ductile coupling beams at floor levels. Coupled systems are more ductile and have more redundancy, but ASCE-7-16 currently does not assign them higher R-factors. As indicated above, following the FEMA-P695 procedure, work was performed to determine the appropriate value for this structural system and to formalize the design and detailing procedure for these walls (this work was jointly funded by the Charles Pankow Foundation and AISC). In addition to the Project Advisory Group assigned to this project, a specific peer-review committee was established to oversee the steps and milestones explicitly spelled-out to require such oversight by the P-695 procedure itself.

In parallel, findings from the Pankow-AISC study were presented to the Building Seismic Safety Council (BSSC) expert Issue Team-4 (IT-4), which is a standing committee tasked with investigating issues related to the design of shear walls of reinforced concrete, steel, composite (steel-concrete), timber, and masonry and making recommendations to the National Earthquake Hazards Reduction Program (NEHRP) Provisions Update Committee (PUC). This technical committee of seismic experts is tasked with identifying and recommending the most advanced seismic technology available for possible adoptions in the *NEHRP Recommended Provisions for New Buildings and Other Structures*. (This document informs ASCE 7 of desirable updates to its seismic provisions.) As such, the BSSC IT-4 and PUC provided two additional expert peer-review panels of the proposed design provisions for C-PSW/CF walls and, by introducing the structural system into the 2020 Edition of the *NEHRP Recommended Provisions*, brought it up for consideration by ASCE-7-21.

ASCE 7-22 Implementation

As a first step following-up on the BSSC recommendations, a proposal to include coupled C-PSW/CFs with an *R*-factor of 8, as supported by the above research, as a new seismic force-resisting system in ASCE 7-22 received additional technical scrutiny by members of the ASCE-7 Technical Committee 6 (General Structural) and Main Committee. In addition, a complete set of detailing requirements was proposed for inclusion in Chapter 14 of ASCE-7-22. It has not been uncommon for ASCE-7 to include design and detailing requirements in Chapter 14 as interim measures until other provision documents (e.g., ACI and AISC) eventually integrated them. This was such an instance, given the strong interest of the practicing engineering community to implement the C-PSW/CF system in future projects within the umbrella of a soon-to-be-available code. Together, these two proposals introduce the design coefficients into ASCE 7-22 Table 12.2-1 and the detailing requirements into ASCE 7-22, Section 14.3.5. While the revisions to Table 12.2-1 adding the new structural system will remain through future editions of ASCE 7, it is intended that the detailing requirements of Section 14.3.5 will be replaced by similar requirements in the *Seismic Provisions*, with the remaining language in Section 14.3.3 of ASCE 7 redirecting the user to the *Seismic Provisions*.

Seismic Provisions Implementation

As indicated above, the inclusion of C-PSW/CF in the 2022 *Seismic Provisions* is already underway. Article H7 has been augmented to include new detailing requirements for uncoupled walls with closing plates instead of circular boundary elements, and a new Article H8 has been provided for coupled walls. Furthermore, all design requirements generally applicable to all coupled and uncoupled walls have been located in Chapter I of the AISC *Specification for Structural Steel Buildings* (ANSI/AISC 360, **aisc.org/specifications**) to equally facilitate implementation in buildings where wind instead of seismic governs C-PSW/CF design. These provisions have successfully passed the review of the AISC Technical Committee 5 on composite structures and are currently in the final stages of balloting for adoption in AISC 341-22, subsequently to the additional scrutiny of the Committee on Specifications and Public Reviews.

Benefiting from the compounding effects of all the above expert committee reviews, minor enhancements have been introduced in all steps of the process, starting from the design provision proposed during the FEMA P-695 process and culminating in the 2022 versions of the AISC *Seismic Provisions* and *Specification*. (In addition, an AISC Design Guide on C-PSW/CF is due to be published later this year.) However, the key provisions driving C-PSW/CF wall design have remained consistent throughout. These can be summarized as follows:

- A maximum plate slenderness requirement, to ensure that local buckling of the plates will not occur prior to their yielding, which is necessary to achieve ductile response.
- Equations to size the tie bars connecting the external steel plates.
- Limits on the minimum and maximum reinforcement ratio provided by the steel plates to the entire cross-section (namely 1% and 10%, respectively), to remain close to the largest values considered in past experiments.
- Limits on the minimum wall aspect ratio, to ensure flexurally dominant behavior, with ultimate strength governed by flexural hinging.
- For seismic applications, capacity design principles to design the parts of the structural system intended to remain elastic, such as to ensure the development of the intended ductile cyclic response mechanism for the wall.
- Seismic design requirements to ensure the presence of coupling beam providing energy dissipation by flexural hinging over at least 90% of the stories of the building and a requirement specifying that coupling beam-to-wall connection details must be able to develop a chord rotation capacity of 0.030 radians before flexural strength decreases to 80% of the flexural plastic strength of the beam.
- Commentaries documenting the purpose of the design requirements and providing references to substantiating documents.

Thanks to the rigorous set of peer reviews performed at all steps of the implementation process, robust design provisions are now available for engineers who wish to use the C-PSW/CF system as a lateral load-resisting system in projects with stringent seismic requirements. ■

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