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RESEARCH ARTICLE

Self-centering steel plate shear walls for improving seismic resilience

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ABSTRACT As part of a Network for Earthquake Engineering Simulation research project led by researchers at the University of Washington with collaborators at University at Buffalo, and Taiwan National Center for Research on Earthquake Engineering, a self-centering steel plate shear wall (SC-SPSW) system has been developed to achieve enhanced seismic performance objectives, including recentering. The SC-SPSW consists of thin steel infill panels, referred to as web plates that serve as the primary lateral load-resisting and energy dissipating element of the system. Post-tensioned (PT) beam-to-column connections provide system recentering capabilities. A performance-based design procedure has been developed for the SC-SPSW, and a series of nonlinear response history analyses have been conducted to verify intended seismic performance at multiple hazard levels. Quasi-static subassembly tests, quasi-static and shake table tests of scaled three-story specimens, and pseudo-dynamic tests of two full-scale two-story SC-SPSWs have been conducted. As a culmination of this multi-year, multi-institutional project, this paper will present an overview of the SC-SPSW numerical and experimental research programs. This paper will also discuss innovative PT connection and web plate designs that were investigated to improve constructability, resilience, and seismic performance and that can be applied to other self-centering and steel plate shear wall systems.

KEYWORDS self-centering, steel plate shear walls, large-scale experiment, post-tensioned connections, performance-based design

1 Introduction

Steel plate shear walls (SPSWs) are lateral load resisting systems that are desirable for use in high seismic areas for their high strength and initial stiffness, energy dissipating qualities, ductility, and architectural flexibility [1]. SPSWs are made up of a steel boundary frame, consisting of beams and columns that are typically connected via moment-resisting (MR) or reduced beam section (RBS) connections. The boundary frame is infilled by a thin steel web plate. The web plate buckles in shear at low loads resulting in development of a diagonal tension field, the primary lateral load resisting mechanism.

The MR and RBS connections in conventional SPSWs are intended to provide strength and energy dissipation through the development of axial-flexural hinges in the beam-column connection region; however, inelastic behavior in the boundary frame can result in residual drifts and costly repairs in a building after an earthquake. A new self-centering SPSW (SC-SPSW) system has been proposed to provide building recentering and reduce damage to the boundary frame, ultimately reducing repair costs and loss of functionality in a building after an earthquake.

The self-centering capabilities of the SC-SPSW are

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provided by flange-rocking (FR) post-tensioned (PT) beam-to-column connections (Fig. 1(a)). Here, post-tensioned elements run along the length of the beam and are anchored at the outside flanges of the columns. During lateral sway, the beam rocks about its flanges, forming a gap between the beam end and column face, known as decompression. The formation of the gap causes the PT strands to elongate, which provide the restoring forces necessary to close the gap and bring the building back to its original configuration. The tension-only behavior and low stiffness of the web plate after unloading is ideal for being paired with self-centering technologies as lower restoring forces are required for recentering.

As the HBE rocks about its flanges, the VBEs are forced to spread apart, a phenomenon referred to as frame expansion and is typical of most post-tensioned self-centering systems [2]. This frame expansion can cause significant damage to the floor slab. If not properly detailed, restraint from the slab as the gap forms also results in increased axial demands in the beams, and thus an increased susceptibility to axial hinging and damage in the beams [2,3], a damage state not desirable in self-centering systems.

To address the issues surrounding frame expansion in self-centering systems, a new PT beam-to-column connection has been proposed. The proposed connection is inspired by moment-resisting connections developed in New Zealand, referred to as the NewZ-BREAKSS connection [4] (Fig. 1(b)). In the NewZ-BREAKSS connection, the beam rocks about its top flanges only. The PT strands must be terminated along the length of the beam in order to produce lateral sway-induced restoring forces. This connection eliminates frame expansion and could be extended to use in other self-centering applications.

2 Performance-based seismic design

A performance-based seismic design (PBSD) approach has been developed for the SC-SPSW [5]. The performance objectives proposed in the design procedure include earthquakes with a 50%, 10%, and 2% probability of exceedence in 50 years (denoted as 50/50, 10/50, 2/50, respectively), representing frequent, design-level, and maximum credible earthquakes, respectively. The proposed performance objectives include:

1) No connection decompression under wind or gravity loading.

2) System recenters and no repair required under frequent (50/50) earthquake demands. Recentering is assessed using a residual drift limit of 0.2%, corresponding to out-of-plumb limits in construction. The no repair limit state requires that the web plate remain essentially elastic and is assessed using a peak story drift limit of 0.5%, the median drift at which web plate repair is required in conventional SPSW experimental studies [6].

3) System recenters and only web plate repair required under design (10/50) earthquake demands. The web plate may have significant yielding; however, the boundary frame and PT elements should remain elastic and the system should recenter. The damaged web plate can be replaced relatively quickly and simply, resulting in a more rapid return to occupancy following an earthquake [7].

4) Collapse prevention for the maximum credible earthquake (2/10). Residual drifts and minor frame yielding may occur; however, soft-story mechanisms and significant PT and frame yielding should be avoided. A target drift limit of this performance objective was assumed to be 4%, based on engineering judgment and the drift at which significant strength loss was observed in conventional SPSW experimental studies [6].

Since the no repair performance in the 50/50 earthquake can result in uneconomical and overly conservative designs in regions where the 50/50 seismic forces are significant, this performance objective is proposed as optional. When assessing the adequacy of the proposed design procedure (to be discussed below), buildings with and without this design objective were considered. Further

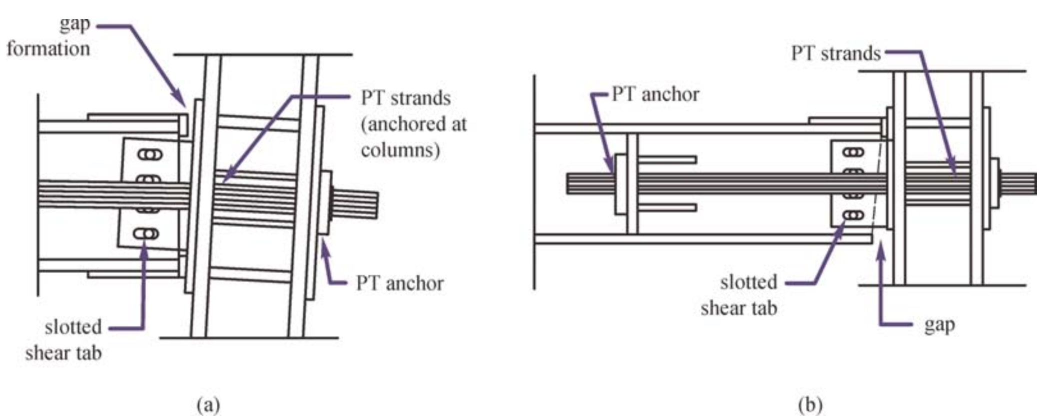


Fig. 1 (a) FR and (b) NewZ-BREAKSS PT connections

details on the PBSD procedure can be found in Ref. [5], while equations necessary for capacity design of the beams with FR and NewZ-BREAKSS PT connections can be found in and capacity design of the beam and PT components can be found in Refs. [4,8], respectively.

3 Experimental studies

Behavior and seismic performance of SC-SPSWs were investigated in three different experimental programs conducted at the University of Washington (UW), at the University at Buffalo (UB), and at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan. Summaries and key results from these test programs are provided below.

3.1 UW subassembly quasi-static tests

Quasi-static subassembly tests were conducted at UW to investigate the impact of design parameters on SC-SPSW response and beam demands. In this test program, only FR connections were considered. The design parameters that were investigated included: web plate thickness, number of PT strands, initial PT force, beam depth, and web plate-to-boundary frame connection detail (welded *vs.* bolted connection) and connection configuration (connected to the beams and columns *vs.* connected to the beams only). To simulate the boundary conditions on an intermediate beam in a SC-SPSW, a two-story specimen was used (Fig. 2). The specimen was approximately half-scale with a pin and roller boundary condition at the bottom of each column to allow for frame expansion that would be present in intermediate stories of SC-SPSWs. The specimens were loaded cyclically with increasing displacement amplitudes via an actuator attached to the top of one column as shown in Fig. 2(a). More details on this test program can be found in Refs. [9,10].

Key results from the UW subassembly test program include:

1) Comparison of the global response of the PT boundary frame with and without web plates showed that the web plates hysteretic behavior deviates from the idealized tension-only response that is commonly assumed in two distinct ways: 1) the web plate is able to resist load prior to reaching the peak plastic strain from previous cycles, which increased the energy dissipation and post-yield reloading stiffness provided by the web plate, and 2) the web plate has non-negligible resistance, termed web plate residual strength, during unloading, which may impact SC-SPSW recentering capabilities (Fig. 2(b)).

2) Most specimens were able to reach drifts of at least 4.5% to 5.0% before web plate tearing propagated along an entire edge. Even after significant web plate tearing at these drift levels, the specimens retained a large percentage of their peak strength (often more than 80% of the peak strength).

3) The bolted web-plate-to-boundary frame connection, consisting of the web plate sandwiched between clamping bars via slip-critical bolts, was able to adequately transfer web plate forces and may facilitate rapid post-earthquake repair of web plates. One specimen was tested with a welded web plate-to-boundary frame connection. Web plate tearing was first observed at a smaller drift in this specimen compared with the specimen with bolted web plate connections; however, this observation may be due to the lower quality of welding in such thin web plates that would not be present in typical web plate thicknesses used in full-scale building applications.

4) Connecting the web plates to the beams only (compared to typical web plates connected to both the beams and the columns) resulted in lower lateral strength for a given web plate thickness due to the development of a partial tension filed. The specimen with web plates connected to the beams only also exhibited delayed onset and propagation of web plate tearing due to the elimination of 1) the net horizontal strain in the web plate due to frame expansion and 2) the localized tensile strains in the corner of the web plate near the opening PT connections. SC-SPSWs with web plates connected to the beams only may

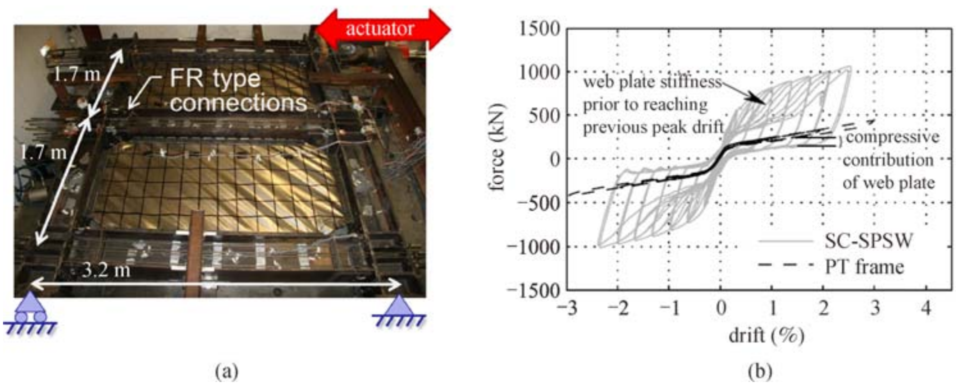


Fig. 2 UW Subassembly test (a) test set-up and (b) sample results (adapted from Ref. [9])

be a viable option for a lateral load-resisting system and warrant further investigation.

3.2 UB scaled three-story quasi-static and shake table tests

One-third scale, three-story SC-SPSW specimens were tested under quasi-static and dynamic loading at UB. The specimens investigated the influence of PT connection type and idealized vs. non-idealized web plate behavior. The PT connection types included FR and NewZ-BREAKSS connections, as well as another connection type that rocked about the beam centerline, which is not discussed in this paper. Idealized tension-only web plate behavior was simulated in the specimen by using diagonal strips of infill material as shown in Fig. 3(a). Full infill web plates (Fig. 3 (b)) were used to simulate more realistic, non-idealized web plate behavior. For all of the specimens in this test program, the pin-and-clevis connections were provided at the base of the columns.

(a) (b)

Fig. 3 UB third-scale specimens with (a) strip infill and (b) full infill web plates

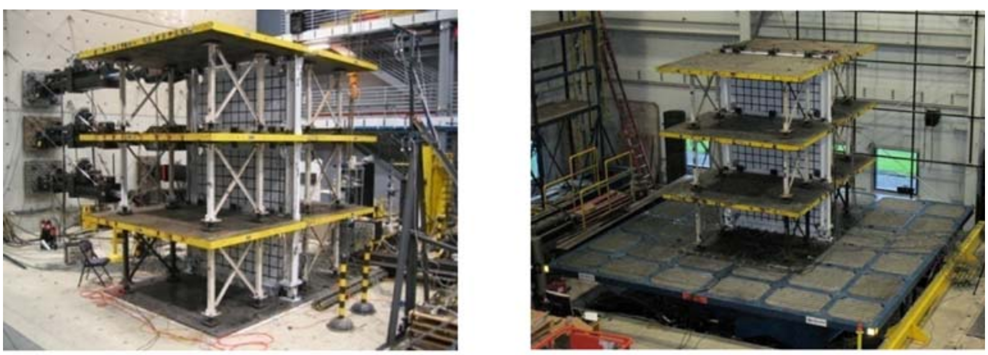
The beams of the SC-SPSW specimens were attached to a self-supporting gravity mass frame (GMF) as shown in Fig. 4. For the quasi-static tests (Fig. 4(a)), actuators at each floor level were attached to the GMF to transfer the load to the specimen, where the top actuator was loaded under displacement control, and the other actuators were loaded under force control with the force slaved to a fraction of the top actuator force. For the shake table tests (Fig. 4(b)), the GMF provided the inertial mass to be excited during ground shaking. In the shake table test, a spectra-compatible synthetic ground motion was used to simulate design-basis earthquake (DBE) spectrum at a location in Los Angeles, California. A series of shaking tests were conducted on each specimen ranging from 10% to 140% of the DBE. The GMF provides out-of-plane lateral restraint, imposes no additional gravity load on the SC-SPSW specimens, and provides negligible lateral resistance. Further details on the UB test program can be found in Refs. [11,12].

Key results from the UB quasi-static and shake table test program include:

1) The full infill plate exhibited non-negligible compressive strength during unloading in the quasi-static tests (example results shown in Fig. 5(a)), as was observed in the UW subassembly tests; however, the compressive resistance of the web plates during unloading does not appear to adversely impact recentering during dynamic loading since all the specimens were all able to recenter following ground motion shaking. Further details on earthquake loading can be found in Ref. [13].

2) The strip infill web plate configuration does exhibit the idealized tension-only web plate response as intended (example results shown in Fig. 5(b)), where the web plate has negligible resistance during unloading and does not resist load until reaching the peak plastic strain from previous cycles. Infill strips were able to sustain larger drift demands without tearing compared with full infill plates, and may be beneficial in retrofit or repair applications where it is difficult to bring large infill plates into occupied buildings.

3) SC-SPSWs with the NewZ-BREAKSS connections were able to eliminate frame expansion while still providing recentering capabilities. This PT connection



(a) (b)

Fig. 4 UB test set-up for (a) quasi-static and (b) shake table tests [11]

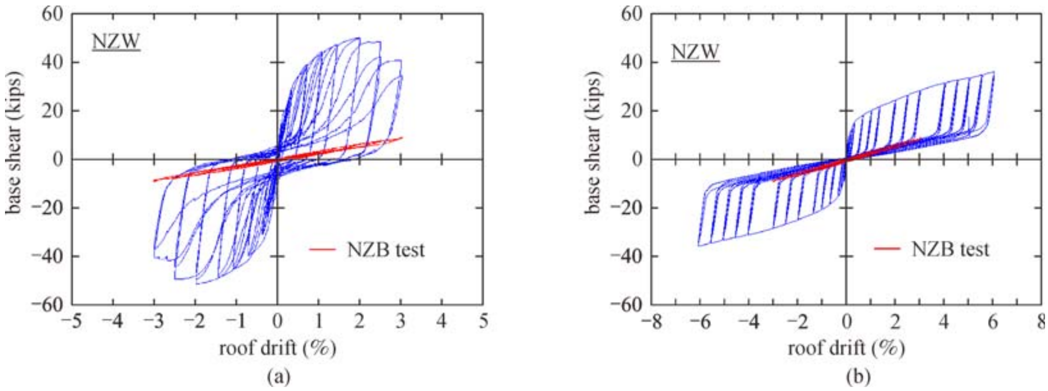


Fig. 5 Results from quasi-static testing of SC-SPSW specimens employing NZ-type connections with (a) full infill web plate and (b) strip infill plates

type is a viable alternative to the FR connection for self-centering systems.

4) In all tests, the PT boundary frame remained essentially elastic, and only the web plates were replaced between tests, verifying the rapid repairability of the SC-SPSW system. Response of the PT boundary frame without infill web plates and with NewZ-BREAKSS connections is indicated by the red lines (denoted "NZB test") in Fig. 5.

3.3 NCREE full-scale two-story pseudo-dynamic tests

Two full-scale, two-story specimens were tested under pseudo-dynamic loading at NCREE. One specimen employed FR beam-to-column connections (Specimen FR), while the other employed NewZ-BREAKSS beam-to-column connections (Specimen NZ). All other physical aspects of the specimens were identical apart from the PT beam-to-column connections used. This test program was also the first to employ post-tensioned column base connections in the SC-SPSWs. These PT column base connections behaved like a flange-rocking connection, where vertical PT bars were provided on both sides of the column web and were anchored within the height of the columns, and shear forces at the base of the column were transferred to the foundation vie reinforced angles attached to the foundation pedestal to allow for the column base connection to uplift and rotate. Lateral bracing (shown in blue in Fig. 6) prevented out-of-plane deformation of the specimen (shown in yellow in Fig. 6), and two actuators were placed at the top of one of the column to load the specimen.

Each specimen was pseudo-dynamically subjected to ground motions representing three seismic hazard levels (50/50, 10/50, and 2/50) for a Los Angeles, California location. These ground motions were selected from the suite of ground motions developed for this site as part of the SAC Steel Project [14]. Each ground motion was followed by a period of free vibration to assess recentering characteristics, and no repair was done to the web plates between ground motions, even though significant web plate yielding was observed, as expected, during the 10/50 excitation. Further details on the NCREE test program can be found in Refs. [12,15,16].

Key results from the NCREE pseudo-dynamic test program include:

1) Both the FR and NZ were able to recenter following the 10/50 excitation (as shown in Fig. 7), and had very small residual drifts following the 2/50 excitation. This observation supported findings of the UB test program that the web plate residual strength does not appear to adversely impact recentering capabilities. These pseudo-dynamic tests showed that the magnitude of the compressive unloading resistance provided by the web plate decreases with decreasing amplitude of oscillation following larger peak drift demands. For example, the web plate unloading

Fig. 6 NCREE full-scale test set-up

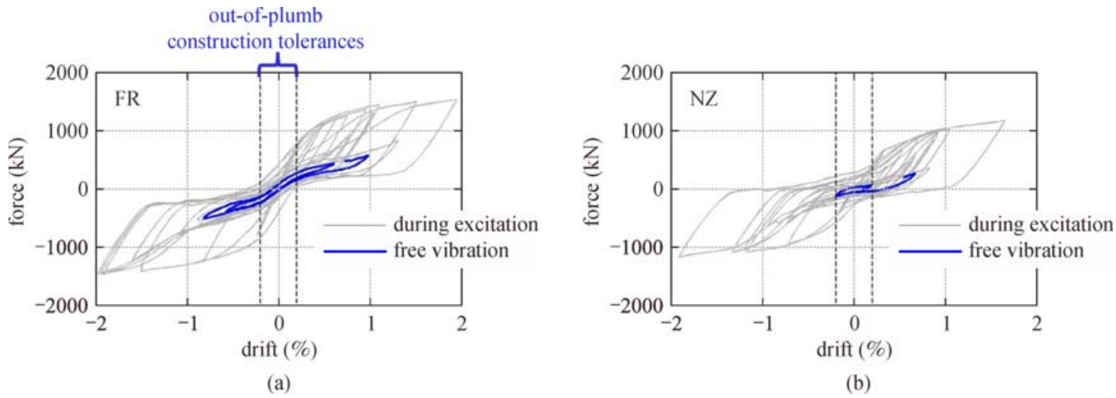


Fig. 7 Results from 10/50 excitation for specimens (a) FR and (b) NZ

resistance is largest after a large peak drift when the web plate must overcome the compressive resistance of the essentially corrugated (due to the diagonal buckles of the tension field), strain hardened web plate. During smaller cycles of loading after a large cycle, the buckled tension field does not fully develop in the plastically elongated web plate, thus the web plate, which has a residual out-of-plane deformation, does not provide as much compressive resistance upon unloading.

2) The PT column base connections performed as intended. The PT column base connection can be used instead of moment-resisting base connection to prevent hinging in the column at that location, and it provides additional recentering capabilities compared with a pin-clevis column base connection.

4 Numerical Studies

Numerical models have been developed to simulate SC-SPSW behavior. These models vary in complexity, ranging from simple tension-only diagonal strip models (shown in Fig. 8(a)) to simulate the idealized tension-only web plate response (results shown in Fig. 8(a)), a modified tension-compression strip model to simulate the non-negligible unloading resistance of the web plate (results shown in Fig. 9(b)), and shell element models (model shown in Fig. 8(b), results shown in Fig. 9(c)) to explicitly simulate the web plate tension field hysteretic behavior. These models were employed in cyclic pushover and nonlinear response history analyses (NRHA). Details of the various web plate and PT connection modeling approaches and analysis results can be found in Refs. [10,12,16].

Key results of the numerical studies include:

1) Nonlinear response history analyses of various three- and nine-story SC-SPSWs designs for a Los Angeles, CA prototype building indicate that the system is able to meet all intended performance objectives and that consideration of the non-negligible web plate residual strength results in improved seismic performance (e.g., lower peak drift demands) compared to the assumed tension-only behavior when used in NRHA. Examples of the median ($\mu_{1/2}$) and 84th percentile peak story drifts from each seismic hazard level for one of the three-story designs is shown in Fig. 10. The results from models labeled 3-1050-6-TO and 3-1050-6-TC25 (Figs. 10(a) and (b), respectively) indicate results from the tension-only and the modified tension-compression strip models, respectively. All other aspects of the design and modeling are the same. Notice that the peak story drifts are significantly reduced when the non-

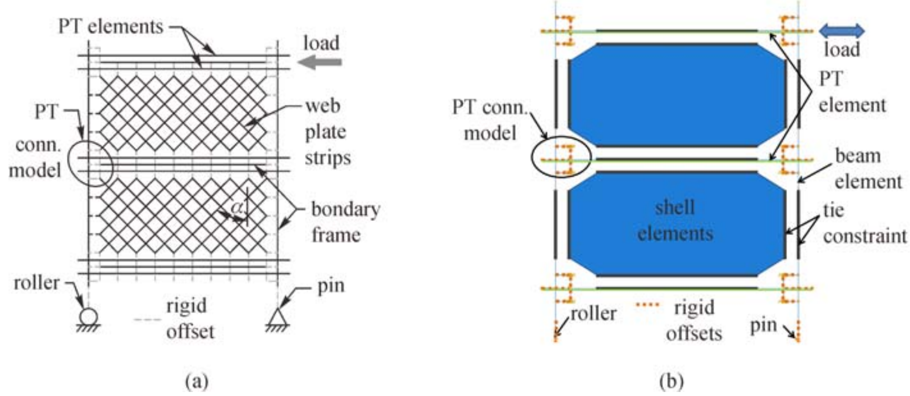


Fig. 8 Example of (a) strip model [10] and (b) shell element web plate model for a UW subassembly test

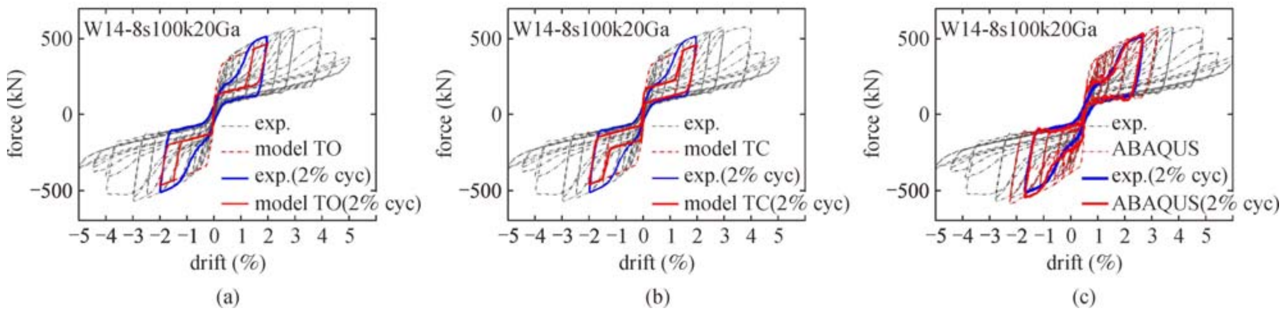


Fig. 9 Example of comparison between a typical UW subassembly specimen with the following web plate numerical models: (a) Strip model with tension-only material behavior (adapted from Ref. [10]), (b) strip model with compressive capacity equal to 25% of yield (adapted from Ref. [10]), and (c) shell element web plate model

negligible compressive strength is considered in the NRHA.

2) SC-SPSWs designed to have web plates connected to the beams only (as were tested in the UW subassembly experiments discussed in Section 3.1) were designed to have the same strength as SC-SPSWs with web plates connected to the beams and columns. These SC-SPSWs were modeled using a modified strip model where only the strips connected to the beams were included. Details of this modeling approach and the resulting SC-SPSW designs are presented in Ref. [17]. Results from NRHAs of these designs showed that although SC-SPSWs with beam-connected web plates did exhibit larger peak drift demands than SC-SPSWs with fully-connected web plates of comparable strength, they were still able to meet all proposed performance objectives. Peak drift demand statistics for a three-story SC-SPSW with beam-connected web plates are shown in Fig. 10(c). This SC-SPSW was designed to have the same lateral strength as the fully-connected web plate designed, and the web plates were modeled using the tension-compression strip model.

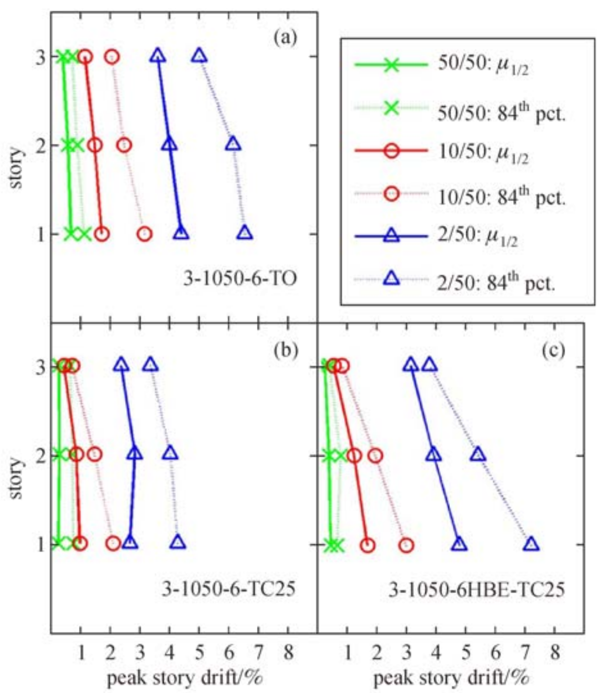


Fig. 10 Results from NRHA of 3-story SC-SPSWs (based on results presented in Refs. [5] and [17]) including SC-SPSWs with web plates fully connected to beams and columns but modeled using a (a) tension-only and (b) tension-compression strip model, and (c) a comparable SC-SPSW with web plates connected to the beams only modeled using a tension-compression strip model

3) Shell element models of the web plate are able to accurately simulate its complex hysteretic behavior (Fig. 9(c)), including the decreasing amplitude of web plate unloading resistance with smaller oscillations of loading as was observed in the NCREE pseudo-dynamic tests; however, this accuracy comes at the cost of increased computational demands, which may not be appropriate for numerous NRHAs.

5 Conclusions

A new SC-SPSW lateral force-resisting system that has been developed as part of a five-year, multi-institute, international NEES research program. This paper serves as the culmination and relatively brief summary of this large body of work, directing the reader to other publications for further details on particular aspects of the research program. This research utilizes some of the world's premiere experimental research laboratories to conduct testing at various scales (half-scale, one-third scale, and full-scale) and under different loading (quasi-static cyclic loading at multiple floors, pseudo-dynamic loading under multiple seismic hazard levels, and shake table testing at various ground motion intensities), and specimens were design to investigate a variety of aspects of SC-SPSW behavior and design, including variations in web plate configurations and variations in beam-to-column and column base connection details. Significant results of this research program include development of and validation of the seismic performance of a new lateral force-resisting system with the potential to reduce economic impact of earthquakes and development of a new PT connection that eliminates frame expansion that occurs in several self-centering systems.

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