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ADVANCES IN SELF-CENTERING STEEL PLATE SHEAR WALL TESTING AND DESIGN

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ABSTRACT

The self-centering steel plate shear wall (SC-SPSW) was developed as part of a NEESR-SG research project aimed at leveraging the benefits of self-centering post-tensioned steel frames with the strength and ductility of steel plate shear walls. Initial proof-of-concept numerical simulations showed that the SC-SPSW was capable of providing enhanced seismic performance, including recentering under design-level earthquakes. This paper will present recent advances in experimental testing of the new lateral force-resisting system, as well as, design recommendations that followed from these experiments and supporting finite element analyses. The extensive test program consisted of three major components: (i) large-scale quasi-static testing of SC-SPSW subassemblies, (ii) quasi-static and shake table testing of third-scale, three-story SC-SPSWs, and (iii) pseudo-dynamic testing of two full-scale, two-story SC-SPSW at multiple seismic hazard levels. Major outcomes of these experimental and numerical studies include: validation of seismic performance of various SC-SPSW configurations, development of a new post-tensioned (PT) beam-to-column connection to eliminate frame expansion that is typical of self-centering systems, incorporation of PT column base connections into the SC-SPSW performance-based seismic design procedure, and recommendations for SC-SPSW design, detailing, and modeling. The results of this research program can be used to inform designers and bring SC-SPSWs closer to implementation.

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Advances in Self-Centering Steel Plate Shear Wall Testing and Design

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Introduction

Significant advances have been made in research on steel plate shear wall (SPSW) lateral force-resisting systems as part of the NEES-SG project entitled "Smart and Resilient Steel Walls for Reducing Earthquake Impacts". This collaborative project comprised a team of researchers from the University of Washington (UW), University at Buffalo (UB), University of Illinois, and the National Center for Research in Earthquake Engineering (NCREE) in Taiwan. The primary goal for this research is to promote more widespread implementation of SPSW systems through developing performance-based design tools (e.g. fragility curves) for SPSWs, filling critical knowledge gap in SPSW design and behavior, specifically for coupled SPSWs, and developing a new resilient SPSW system for enhanced seismic performance. The latter research outcome, development of a resilient SPSW, is the topic of this paper.

The self-centering SPSW (SC-SPSW) system [1,2] combines the high strength, stiffness, and ductile energy dissipation of SPSW infill plates, referred to as web plates, [3,4] with the recentering and damage-mitigating capabilities of post-tensioned (PT) rocking connections [5,6] as shown schematically in Fig. 1. The research on the new SC-SPSW system has included experimental testing on large-scale subassemblies, scaled three-story systems, and full-scale two-story system, as well as analytical and numerical investigation into the system behavior and performance. As a culmination of this project, a summary of this multi-year research program will be presented in this paper to provide a complete picture of the work that has been done.

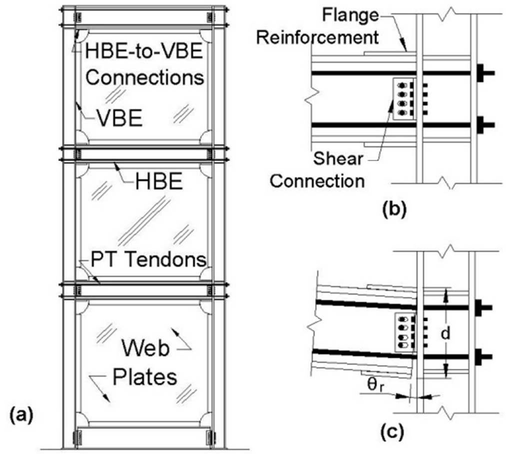


Figure 1. Schematic of a (a) SC-SPSW and flange rocking PT connection in its (b) undeformed and (c) deformed configuration.

References will be provided for additional, more in-depth discussions of each component of the research where necessary.

SC-SPSW Description

System Performance Objectives

The SC-SPSW system was developed to provide enhanced seismic performance. Performance objectives were proposed for earthquakes with a 50%, 10%, and 2% probability of exceedance in 50 years (denoted as 50/50, 10/50, 2/50 respectively). These performance objectives (POs) include [1]:

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.
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.
4. *Collapse prevention for the maximum credible earthquake* (2/50). Residual drifts and minor frame yielding may occur; however, soft-story mechanisms and significant PT and frame yielding should be avoided.

These performance objectives were incorporated into a performance-based seismic design (PBSD) procedure for the system [1]. Capacity design methodologies for design of the HBE components were provided in [2] to be used in conjunction with the system PBSD procedure.

PT Connection Types

In Fig. 1, the beams, also referred to as horizontal boundary elements (HBEs), and columns, also referred to as vertical boundary elements (VBEs), are connected via post-tensioning (PT) strands running horizontally from column to column, with horizontally slotted shear tabs to transfer shear forces. The PT HBE-to-VBE connection (based on [5,6]) rocks open during lateral sway as shown in Fig. 1(c), developing moment resistance as the PT strand elongate causing an increase in the compressive bearing flange force. If properly detailed, this rocking connection behavior eliminates the severe plastic deformation that occurs in the moment-resisting boundary frames of conventional SPSWs.

This PT connection, termed the flange-rocking (FR) connection, rocks about either the top or bottom flange depending on the direction of sway. As has been documented for other self-centering moment-resisting steel frame systems [7], the formation of gaps in the connections causes the columns spread apart, termed frame expansion, which must be accommodated via special diaphragm detailing [8,9]. As part of this research, two additional PT connections have been proposed to eliminate frame expansion while still providing recentering capabilities. These connections (shown schematically in Fig. 2) include one in which the beam rocks about its centerline via a pin, termed centerline (CL) connection, and on in which the beam rocks only about its top flange, termed NewZ-BREAKKS (NZ) connection [10]. In both of these connections because frame expansion is not present, the PT strands must be terminated along the length of the beam to develop restoring forces during sway.

To ensure system recentering and elimination of damage in the boundary frame, the column base connection should also be detailed in a way to prevent axial-flexural hinging in the column. This can be accomplished with pin-clevis-type connections for smaller column demands (as shown later in Fig. 5 for the third-scale system test) or with FR-type PT rocking connections at the column base (as shown later in Fig. 7 for the full-scale pseudo-dynamic test).

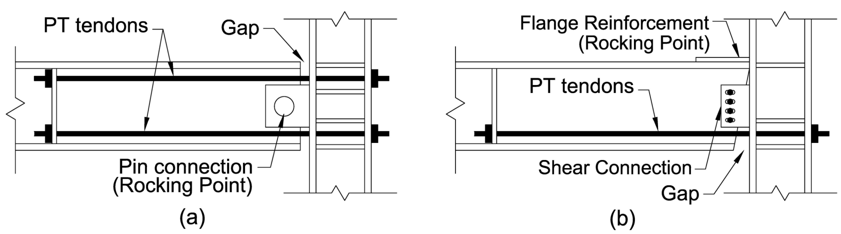


Figure 2. (a) Centerline rocking and (b) NewZ-BREAKSS PT connections

Experimental Programs

Subassembly Testing

The SC-SPSW subassembly tests (photo of a typical specimen shown in Fig. 3) [11,12] were conducted at UW. These tests aimed at investigating the influence of various design parameters on intermediate HBE (the middle HBE in Fig. 3) and PT connection demands and global behavior. To simulate appropriate boundary conditions, an approximately half-scale, two-story specimen (providing web plate demands above and below the intermediate HBE) with FR-type PT beam-to-column connections was loaded with a single actuator at the top HBE. To accommodate frame expansion (as would be present in an intermediate story of a SC-SPSW with FR-type connections), a horizontal roller was provided at the base of the unloaded column (left column in Fig. 3), and a pin was provided at the base of the loaded column.

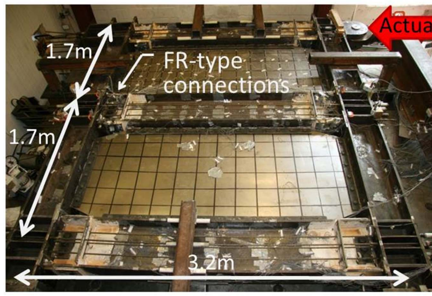


Figure 3. SC-SPSW subassembly test set-up

A total of fourteen subassembly tests were conducted under quasi-static cyclic loading with increasing drift amplitudes up to 4.5% to 5% (see [11,12] for further details on test set-up, load history, and results). These tests varied parameters such as web plate thickness, beam depth, number of PT strands per connection, initial PT force, methods of connecting web plate to boundary frame (welded vs. bolted), and web plate-to-frame connectivity configuration (connected to beams and columns vs. connected to beams only).

Fig. 4 shows examples of specimen force vs. drift responses comparing specimens with different number of PT strands (Fig. 4(a)) and different web plate thicknesses (Fig. 4(b)). The specimen naming scheme is as follows: beam depth (e.g. "W18" is a W18x106 wide-flange section), number of PT strands per connection (e.g. "6s" is six 13mm diameter Grade 270 seven-wire strands), initial PT force in units of kips (e.g. "100k" is equal to 445kN), followed by web plate gage thickness (e.g. "16Ga" is 1.52mm thick and "20Ga" is 0.91mm thick ASTM A1008 steel). These specimen response comparisons show that increasing the number of PT strands proportionally increases the unloading, or recentering stiffness, K_r, (Fig. 4(a)) and that increasing the web plate thickness increases the specimen strength and energy dissipation (Fig. 4(b)).

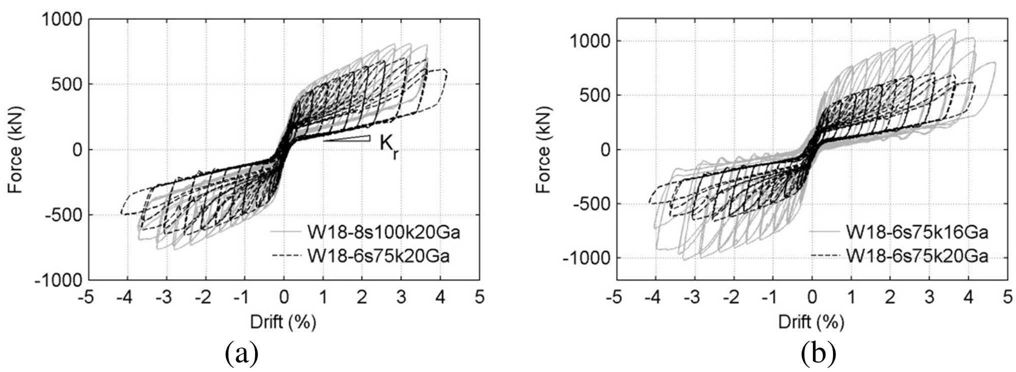


Figure 4. Subassembly force vs. drift responses comparing (a) number of PT strands and (b) web plate thickness.

Third-scale System Testing

Third-scale, three-story SC-SPSW specimens (Fig. 5) were tested under both cyclic (i.e. quasi-static) and shake table (i.e. dynamic) loading at UB. A total of fifteen specimens were tested (nine cyclic tests, six shake table tests) with specimens having variations in type of PT HBE-to-VBE connection (e.g. FR, CL, and NZ types) and variations in web plate infill. The variations in web plate infill included specimens with no web plate (i.e. bare PT frame), full infill plate (as shown in Fig. 6(a)), and infill strips (i.e. diagonally-oriented strips of steel of the same thickness as the full infill plate as shown in Fig. 6(b)). In each of these specimens, the column bases were connected to the foundation (e.g. strong floor or shaking table) via pin-clevis connections. Further details on this test program and results can be found in [13].

(a) Quasi-static test set-up (b) Full infill web plates (c) Infill web strips

Figure 5. Test set-up for quasi-static third-scale system tests.

Full-scale Pseudo-dynamic Testing

Two full-scale, two-story SC-SPSW specimens (Fig. 6) were tested under pseudo-dynamic loading at NCREE. The specimens both utilized PT column base connections (FR-type connections) and had PT HBE-to-VBE connections at the middle and top beams, MB and TB respectively (the bottom beam, BB, used double-angle shear connections). The PT HBE-to-VBE connections were different for each specimen—Specimen FR used FR-type connections, while Specimen NZ used NZ-type connections. Other than the PT connection types, the specimens were physically identical. The specimens were loaded with two 1000kN actuators at the top of the west column.

Both specimens were subjected to the same earthquake excitation representing seismic hazard levels with 50%, 10%, and 2% probability of exceedence in 50 years (50/50, 1050, and 2/50 respectively). Each of the ground motions were selected from those developed for the SAC steel project [14] for the Los Angeles site. The ground motion, truncated length, scale factor, and peak ground acceleration (PGA) for each excitation is provided in Table 1. Each ground motion was followed by a period of free vibration to investigate post-event response.

Table 1. Summary of pseudo-dynamic excitations

Hazard Level	SAC ground motion	Truncated length (sec)	Amplification factor	PGA (g)
50/50	LA42	2.26	1	0.33
10/50	LA01	15.18	1	0.46
2/50	LA23	10.13	1.3	0.54

The prototype building for the test specimens was a two-story adaptation of the three-story SAC building [15] in Los Angeles. The seismic mass for Specimen FR was taken as one-fourth of the building's total seismic mass based on a reasonable yet less conservative design methodology (i.e. the specimen's design strength was estimated as the strength of the PT frame in addition to the strength of the web plate, whereas conventional SPSW and SC-SPSW design methodologies typically consider only the web plate lateral strength in design [1]). The seismic mass of Specimen NZ was taken as 75% of that of Specimen FR due to the reduction in PT frame strength resulting from the initially decompressed NZ-type connections.

The force vs. drift responses for Specimens FR and NZ during the 50/50, 10/50, and 2/50 pseudo-dynamic tests are shown in Fig. 7. Fig. 7(a) shows that during the 50/50 excitation, both specimens remained essentially elastic meeting the "no repair" performance objective (PO 2) described above. Fig. 7(b) shows that both specimens had peak drifts less than the 2% code-based limit in the 10/50 event. During free vibration following the 10/50 excitation, the residual drifts of both specimens were less than 0.2%, indicating that each specimen was able to recenter and meet the "web plate repair only" performance objective (PO 3) described above.

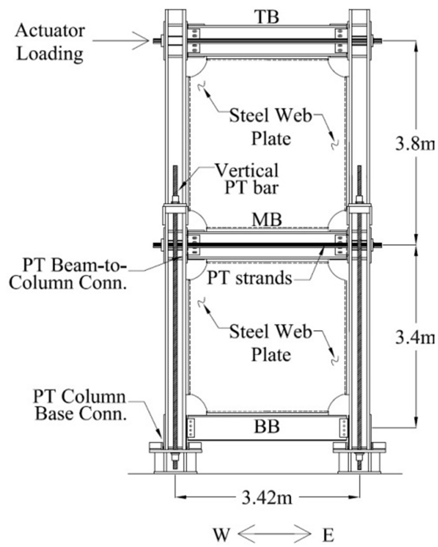


Figure 6. Schematic of full-scale test set-up (shown here for Specimen FR).

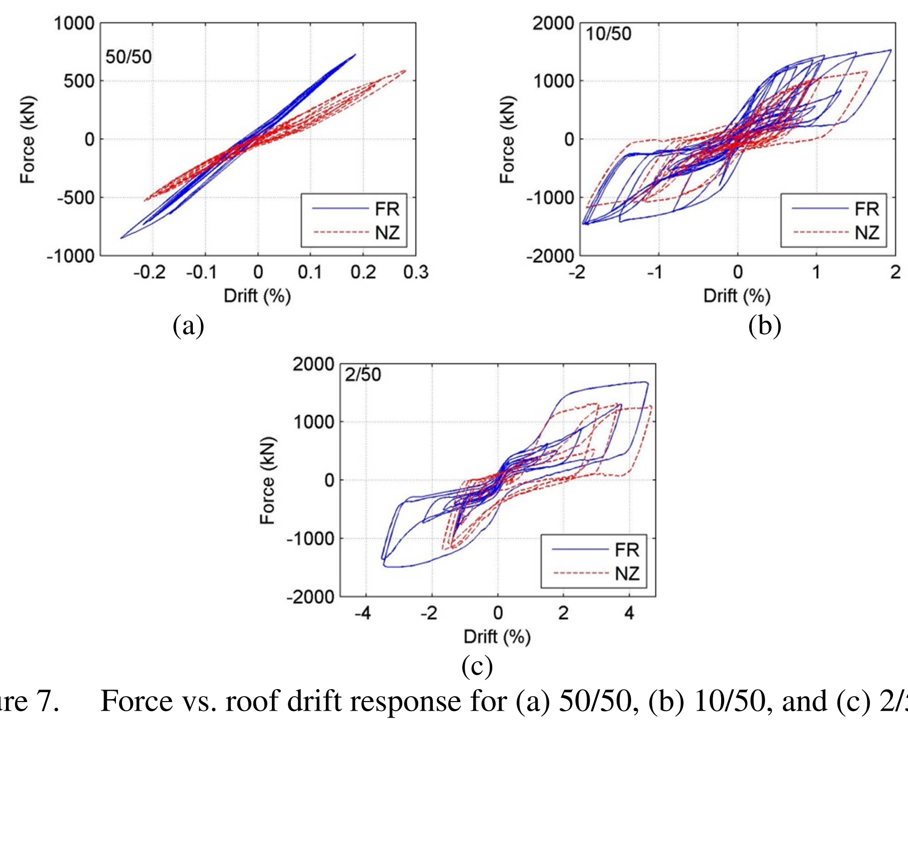


Figure 7. Force vs. roof drift response for (a) 50/50, (b) 10/50, and (c) 2/50 tests.

During the 2/50 excitation shown in Fig. 7(c), both specimens had peak roof drifts less than 4.7%. At the end of the 2/50 test for both specimens, only very minor localized yielding was observed in the boundary frame near areas of stress concentrations in the PT connections. Thus, both specimens were able to meet the "collapse prevention" performance objective (PO 4) at this hazard level. In this test, the web plates were not repaired or replaced following the 10/50 test prior to the 2/50 test; therefore, the drift demands in the 2/50 are more severe than would be expected in an actual 2/50 level earthquake where the SC-SPSW web plates would initially be undamaged and elastic.

Numerical Studies

Comparison of Web Plate Models

The results of the SC-SPSW experimental programs demonstrated some of the complex web plate behavior that is typically ignored in conventional SPSWs. Most significantly is the phenomenon of the web plate unloading, or residual, strength. Typical SPSW web plates are assumed to behave with a tension-only (TO) response [1,2,4]—after unloading and before reloading in the opposite direction, the thin plate buckles in shear and is assumed to have negligible strength. This web plate residual strength has been suggested in previous conventional SPSW studies [4], although the unloading strength and hysteretic energy dissipation of the welded moment-resisting boundary frame is typically larger such that the web plate unloading strength can be ignored. However, in SC-SPSW the PT boundary frame strength is relatively small, and large web plate residual strengths may impact recentering capabilities, thus the phenomenon cannot be ignored in this application.

In the subassembly and third-scale system cyclic tests however, the web plates were observed to have a non-negligible strength upon unloading (as indicated by the difference in web plate loading and unloading strength in Fig. 4). These tests also suggested that this web plate residual strength is constant, as indicated by the constant unloading strength of the specimens in Fig. 4. However, in the pseudo-dynamic tests, the magnitude of the web plate residual strength appeared to decrease during the smaller cycles of loading at the end of the excitation (e.g. during free vibration) as can be seen in Fig. 7.

Based on these observations, a simple modification of the tension-only behavior was proposed to model web plates for SC-SPSW application. Here, the modified tension-compression (TC) behavior includes a constant compressive strength to simulate the web plate residual strength. The compressive strength is taken as a portion of the web plate yield strength (typically between 25-30% of yield) based on a web plate behavior studies conducted by Webster in [16]. For web plates that are modeled using the strip method with diagonal truss elements oriented in both directions of the tension field (as shown in Fig. 8), the tension strength of the TC strip must be reduced such that the additional lateral resistance of the compressive strips in the direction opposite the tension field result in lateral web plate strengths equal to the TO model. An example stress vs. strain response for a single strip in the TO and TC model is shown in Fig. 9, along with the corresponding web plate monotonic coupon data for reference.

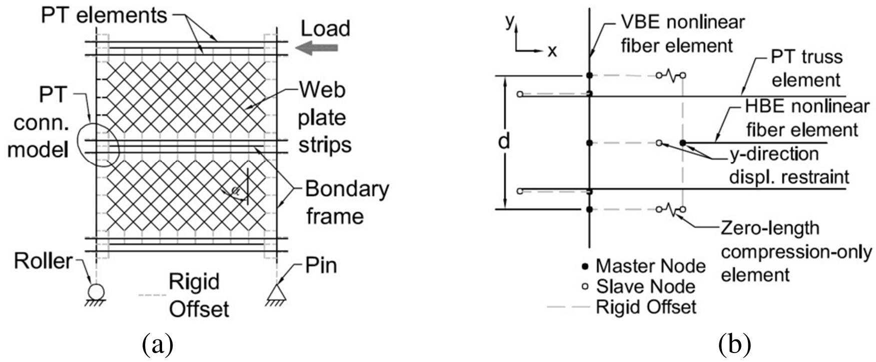


Figure 8. Schematic of (a) SC-SPSW strip model (shown for the subassembly test set-up) and (b) FR-type PT connection model.

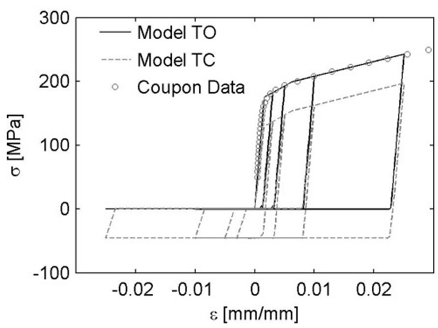
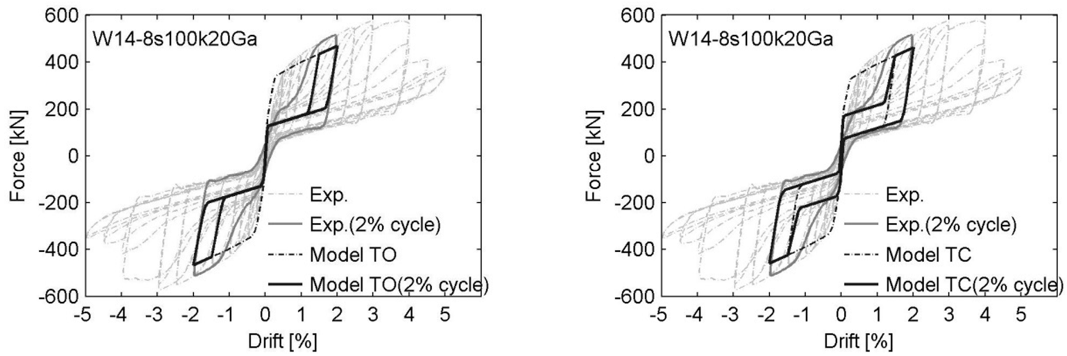


Figure 9. Stress vs. strain response of single strips for TO and TC web plate models.

Fig. 10 shows a comparison of the TO and TC web plate models with the experimental response of one of the SC-SPSW subassembly specimens (the 2% drift cycles are highlighted for easier single-cycle response comparison). These figures show that that TO model (Fig. 10(a)) significantly underestimates web plate energy dissipation. The TC model (Fig. 10(b)) is able to reasonably approximate the web plate residual strength and provides a better estimation of web plate energy dissipation (although still an underestimation). Although the TC model does not account for the diminishing web plate residual strength during free vibration as observed in the pseudo-dynamic tests, the constant residual strength is thought to provide a conservative approximation (i.e. overestimation) of SC-SPSW residual strength while still providing a conservative approximation (i.e. underestimation) of energy dissipation during strong shaking.

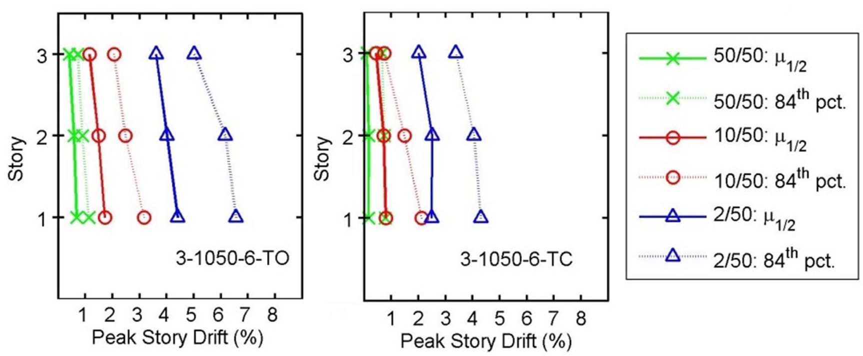
SC-SPSW Building Response

The TO and TC models were implemented in nonlinear response history analyses of various three- and nine-story SC-SPSWs [1,17]. The results of these numerical studies showed that although the SC-SPSWs modeled using the TO web plate model were able to meet the proposed performance objectives, implementing the TC model resulted in an approximately 50% reduction in peak story drift demands at all hazard levels (50/50, 10/50, 2/50 from the SAC Los Angeles ground motion ensemble [14]) as shown in Fig. 11 for a typical three-story SC-SPSW. The reduction in demands due to consideration of additional web plate energy dissipation and residual strength indicates that the proposed design procedure can be revised to consider lower target drift demands, which will result in smaller and more economical boundary frame member sizes without a significant impact on performance.



(a) (b)

Figure 10. Comparison of SC-SPSW subassembly test specimen response with (a) TO and (b) TC web plate models.



(a) (b)

Figure 11. Comparison of peak story drift responses for typical three-story SC-SPSW using (a) TO and (b) TC web plate models.

Conclusions

Experimental and numerical investigations have been conducted and multiple institutions in the US and in Taiwan to better understand the behavior and seismic performance of the SC-SPSW behavior. Subassembly cyclic tests investigated the impact of varying design parameters, third-scale cycle and dynamic system tests investigated the impact of different PT connect types and web plate infill types, and full-scale pseudo-dynamic tests investigated seismic performance of SC-SPSWs utilizing two PT connection types that performed well in the previous scaled tests. Simple numerical models match well with the response of the test specimens. A modification of the common tension strip web plate model was employed to conservatively simulate the effects of web plate residual strength. Nonlinear dynamic response histories suggest that considering the additional energy dissipated provided by the non-ideal web plate can result in significantly reduced peak drift demands. These finding suggest that SC-SPSW system economy may be further improved by revising the target design target drifts to account for these reduced demands.

Acknowledgments

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