Steel Structures Research Update

Resilient Steel Plate Shear Walls

Second Quarter 2015

JUDY LIU

INTRODUCTION

Presented here are some highlights from a comprehensive, innovative and international study on resilient steel plate shear walls. The research capitalizes upon the high strength, elastic stiffness and energy dissipating capabilities of steel (a.k.a. special) plate shear walls, with steel web plates and boundary elements, to create more efficient, robust and economical systems. For example, the seismic force resisting system is reimagined as a recentering and easily repairable steel plate shear wall.

The research has also capitalized upon the expertise as well as computational and experimental capabilities of a team from Taiwan and across the United States. The research was conducted through the George E. Brown Network for Earthquake Engineering Simulation (NEES), funded by the National Science Foundation (NSF) with supplementary support from AISC. The research team is led by Professor Jeffrey Berman at University of Washington (UW). Key personnel from UW include Professor Laura Lowes, Dr. David Webster, now a Senior Associate at Thornton Tomasetti, and Dr. Patricia Clayton, now a professor at the University of Texas at Austin. Lead researchers from the University of Illinois at Urbana-Champaign (UIUC) are Professor Larry Fahnestock and Dr. Daniel Borello, now on the faculty at Oregon State University. Collaborators from the University at Buffalo (UB) include Professor Michel Bruneau and Dr. Daniel Dowden, now the Structural Engineer at the UB Structural Engineering and Earthquake Simulation Laboratory (SEESL). Professor Keh-Chyuan Tsai and Research Fellow Chao-Hsien Li have led the work at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan. The research team received extensive additional support from student research assistants and technical staff, and these contributions are acknowledged in the cited documents.

Steel plate shear wall (SPSW) research has been active for over 30 years, and progress toward more widespread implementation is being made (Berman, 2014). The stiff and ductile system relies on yielding of tension strips after buckling of the web plates and yielding at the beam ends and at the column bases. Seismic design provisions for special plate shear walls are in the ANSI/AISC 341-10, and documents such as the AISC *Design Guide 20* (Sabelli and Bruneau, 2006) provide a framework for ductile design and detailing. Notable projects in the United States include the U.S. Federal Courthouse in Seattle (Seilie and Hooper, 2005) and the 56-story L.A. Live Hotel & Residences, the first SPSW high-rise building in Los Angeles (AISC, 2008).

The recently completed collaborative research has contributed to the state of the art with deeper investigations into the complex behavior of the web plates and boundary elements of SPSWs, creation of more efficient and resilient SPSWs, and development of validated performance-based design guidelines for those new systems. Highlighted here are research on the SPSW web plate stress field, studies on coupled SPSWs, investigation of self-centering SPSWs, modeling of the web plates for self-centering SPSWs and the viability of web plates connected only to the beams in the self-centering SPSWs.

SPSW WEB PLATE STRESS FIELD

The angle of inclination of the tension field in the web plate may change with inelastic response. Designs following the current provisions utilize a tension field inclination angle equation derived from elastic analysis. A computational and experimental evaluation of SPSWs was undertaken to examine the web plate stress field and to evaluate the interaction with the boundary elements (Figure 1a and 1b) (Webster et al., 2014).

The experimental program, which was conducted in the Structural Research Laboratory at the University of Washington, included tests on web plates anchored to a pin-connected frame. Specimens were subjected to either a monotonically increasing load to 6% lateral drift or cyclic loading up to 4% drift. An OptoTrak optical measurement system was utilized to measure deformations, including out-of-plane deflections, of the web plate and boundary elements. OptoTrak measurements, as well as strain gage data,

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indicated for both types of loading that the tension field migrates from a relatively low angle of inclination (e.g., 37°) in the elastic range to an angle of 45° when inelastic and approaching 4% drift (Figure 1c and 1d).

The experimental results were confirmed with finite element analyses, and the finite element models were used in a parametric study on web plate inclination angle for a number of subassemblages of multi-story SPSWs. The frames used in the parametric study utilized various wide-flange horizontal boundary element (HBE) and vertical boundary element (VBE) sizes. At seismic drift levels, the angle ranged between 43° and 45°; the angle was independent of SPSW geometry and boundary element sizes. A constant angle of 45° is recommended for design, for simplicity and only slight conservatism with respect to demands on the VBE (Webster et al., 2014).

Additional work produced valuable information about the inelastic cyclic response of the web plates. One observation was that the compressive stresses are non-negligible and can affect load capacity and demands on the VBEs. A phenomenological material model developed by Webster (2013) for use in strip models of the plates captures this and other complex web plate behavior. The model has been put to good use in modeling for self-centering SPSWs, as summarized in a later section.

COUPLED SPSWs

A natural step in the research was to investigate the topic of coupled SPSWs, building upon the stiffness and energy dissipation of the SPSW and taking advantage of common architectural layouts that are well-suited for the coupled wall configuration. SPSWs are typically placed in pairs around passageways at the core of the building, so replacing the floor framing in between the walls with coupling beams to create an SPSW with coupling (SPSW-WC), shown in Figure 2, can increase the efficiency and effectiveness of the system.

The SPSW-WC study was comprised of a number of subtasks. Development of a design methodology, creation of validated component and subassembly models and nonlinear analysis of SPSW-WC models allowed for understanding of the behavior and design of SPSW-WCs. Parameters such as degree of coupling were studied computationally. The SPSW-WC study culminated in a large-scale experimental validation of the SPSW-WCs and the proposed design procedures.

The SPSW-WCs utilize the same capacity design methodology as in the AISC *Seismic Provisions* (AISC, 2010a). The behavior and strength of the system is largely governed by web plate buckling and development of tension field action. Aside from plastic hinges at the ends of the HBEs, the HBEs and VBEs are designed to remain elastic. The coupling

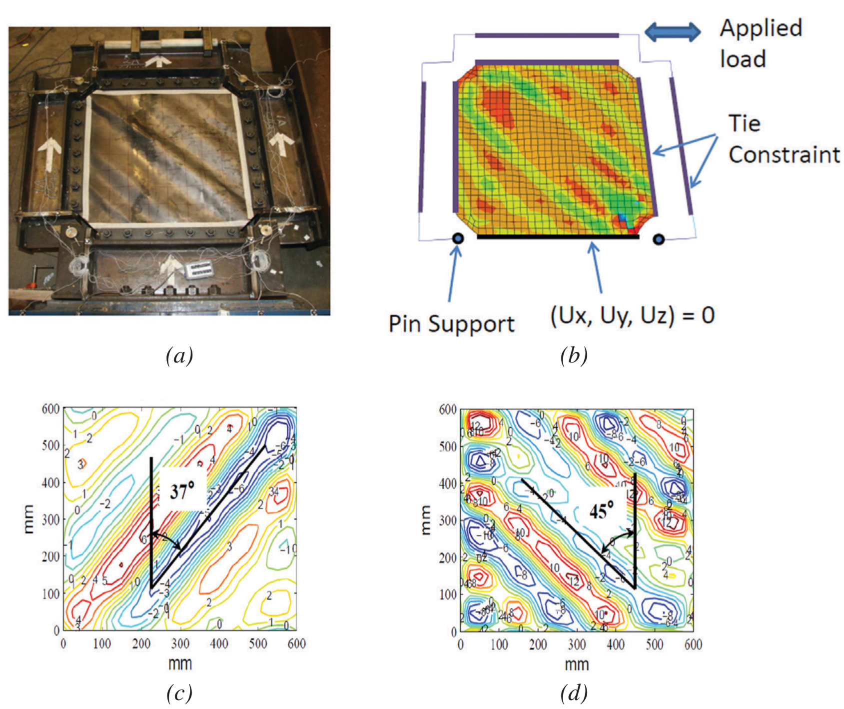


Fig. 1. Tension field inclination angle study: (a) typical test specimen, (b) finite element model, (c) inclination angle derived from Optotrak test data at 0.4% drift (d) inclination angle derived from Optotrak test data at 3.75% drift.

beams (CBs) can develop flexural or shear plastic hinges, or some combination. With the frame action provided by the CBs, the efficiency is improved relative to two independent SPSWs, and the web plate thicknesses and boundary element sizes can be reduced.

A number of 6- and 12-story prototype SPSW-WC office buildings were designed for Los Angeles, California, using both the equivalent lateral force (ELF) procedure and the inelastic lateral force (ILF) procedure (Chao et al., 2007; Ghosh et al., 2009). The square, five-bay buildings were based on plan dimensions of the SAC nine-story building (FEMA, 2000). Designs included single SPSWs (PLANAR), SPSW-WCs with intermediate flexural/shear yielding coupling beams (INT), SPSW-WCs with flexural yielding coupling beams (FLEX) and pairs of uncoupled SPSWs (UNCOUP). This resulted in eight combinations of configuration and design procedure for the 6-story prototypes and six combinations for the 12-story prototypes; the UNCOUP design was not feasible for the 12-story building (Borello and Fahnestock, 2013).

These prototype structures were evaluated using static and dynamic nonlinear analysis procedures. The models were validated against existing experimental data for assemblies such as a large-scale, four-story SPSW tested by Driver et al. (1997) and link beams tested by Lewis (2010). Tension strips were used to represent the web plates. Fiber elements were used to model the boundary elements and coupling beams. Details of the formulations and constitutive relationships are provided in Borello and Fahnestock (2013).

Nonlinear static pushover analyses demonstrated that all prototype configurations had comparable stiffness. The ultimate strengths of the PLANAR configurations were similar to those for the SPSW-WC configurations. The SPSW-WC ultimate strength is similar for different levels of coupling, and the values are slightly higher for the systems with the INT coupling beams as compared to the FLEX

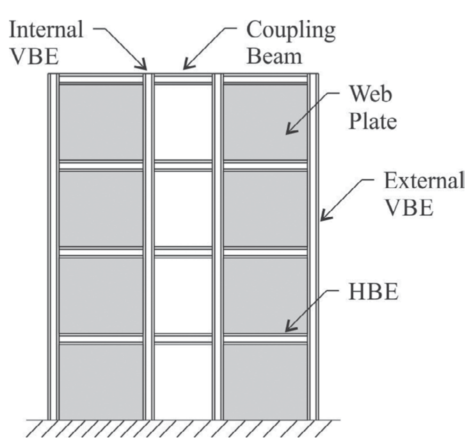


Fig. 2. Schematic of an SPSW-WC.

coupling beams. The higher degree of coupling also results in a lighter system. The UNCOUP prototypes exhibited the highest strength, but typically because of larger member sizes selected to satisfy lateral drift limits.

Nonlinear time history analyses revealed that the prototypes designed using ELF failed to satisfy lateral drift limits for the design-level ground motions (10% probability of exceedance in 50 years). Use of the ILF produced designs with better story drift performance. Regardless, the results also demonstrated that the more efficient (lighter) SPSW-WCs performed similarly to or better than the uncoupled systems. In addition, code-based seismic design parameters (R, Ω_0 and C_d) that are currently being used for the conventional uncoupled SPSW configuration (ASCE, 2010) appear to be appropriate for the SPSW-WC configuration.

The analyses also confirmed that the web plates in the SPSW-WCs have similar demands compared to SPSWs. Based on prior research, the SPSW-WCs are also expected to have similar levels of ductility and energy dissipation. Coupling beam rotation demands are also expected to be satisfied. Additional parametric studies of 6- and 12-story prototype structures were used to explore degree of coupling. Results demonstrated weight savings of as much as 40% for a 12-story SPSW-WC, as compared to an uncoupled pair of SPSWs. For the cases studied, the most efficient designs occurred within a range of degree of coupling (DC) from 0.4 to 0.6. A simple equation for determining DC for design was also developed (Borello and Fahnestock, 2012).

Important parameters for the experimental investigation were degree of coupling and coupling beam yield mechanism, either flexure or combined flexure and shear. Two approximately half-scale specimens, one FLEX (DC around 0.2) and one INT (DC around 0.4), were tested at UIUC (Borello et al., 2014). The HBEs had reduced beam section (RBS) connections. The coupling beams in the INT specimens were about twice as strong as those in the FLEX specimen, with 87 pounds additional coupling beam weight leading to 705 pounds of weight savings in the INT specimen VBEs.

The three-story specimens, which were tested in the NEES MUST-SIM facility at the University of Illinois at Urbana-Champaign, were anchored to the strong floor, braced at floor levels and secured to load and boundary condition box (LBCB) platens at the top (Figure 3). The specimen configurations and demands were based on the bottom three stories of the six-story prototype buildings. Therefore, vertical load and moment were applied in force control at the LBCBs, while increasing cycles of lateral displacement were applied in displacement control. The tests were used to confirm the expected global response, limit states, progression of yielding, design and detailing procedures for the SPSW-WCs.

The specimens performed well, with good energy dissipation and high initial stiffness. Buckling in the web plates was first observed in the FLEX specimen at 0.25% top drift. Some flaking of whitewash in the web plates and second-floor coupling beam occurred in the first cycle at 0.5% drift. The coupling beams developed flexural hinges, as well as minor flange local buckling and more significant web local buckling near the connections at 2.5% drift. Complete fracture through the second-floor coupling beam occurred in the first negative excursion to 4% drift. Subsequent cycles at 4% saw fracture between a VBE and base plate, causing a drop in load, and then complete fracture of the third-story coupling beam.

The INT specimen had elastic buckling in the web plates at 0.1% drift. Flexural hinges formed in the VBE bases at 1% drift. At 1.5% lateral drift, shear yielding and flexural hinges in the HBEs were apparent, with flange local buckling occurring after 2% drift. Fractures appeared at the HBE flange local buckling regions in the 3.5% drift cycles, but the HBEs remained intact, and there was no appreciable overall loss in strength. At 4% drift, after repeated cycling at this limit of the actuator stroke, there was fracture between a VBE and base plate. The coupling beams exhibited distributed shear yielding and remained intact with no signs of fracture initiation even after the demanding loading protocol.

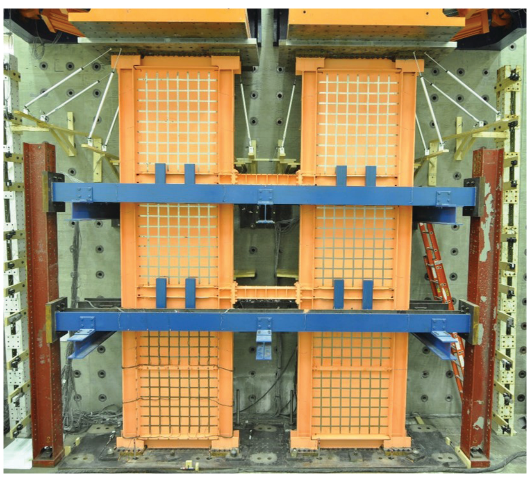
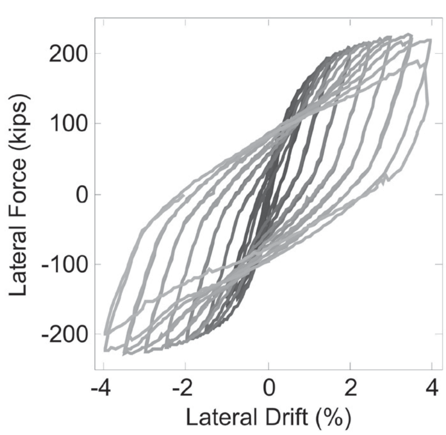


Fig. 3. SPSW-WC INT specimen before testing.

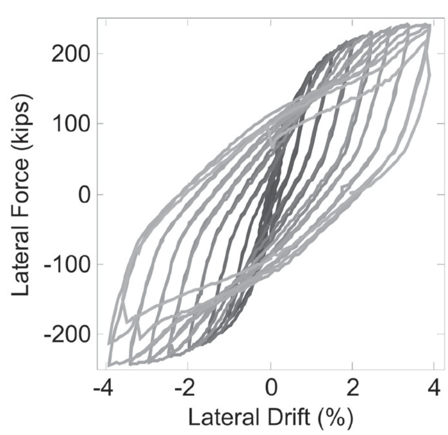
Although both specimens were designed for the same prototype building, the INT specimen was 17% lighter, initially 12% stiffer, and 10% stronger, with greater energy dissipation (Figure 4). Compared to that of the FLEX specimen, the INT specimen energy dissipation was slightly higher (in the range of 5% to 17% per cycle), but both specimens exhibited robust behavior with over 20% equivalent viscous damping in the 4% drift cycles. The experiments confirmed the viability of SPSW-WCs and demonstrated the importance of the coupling beam design for both seismic performance and economy. A SPSW-WC design with degree of coupling near the optimal and coupling beams dominated by shear yielding provides the lightest weight system with the most favorable cyclic behavior. In general, the SPSW-WC configuration was shown to provide excellent ductility and energy dissipation with only minor pinching, and it is a promising configuration that has the potential to significantly expand the range of application for SPSWs.

SELF-CENTERING SPSWs

Within this coordinated study, self-centering steel plate shear walls (SC-SPSWs) were envisioned as a more resilient and economical lateral force resisting system than even the ductile SPSWs. The SC-SPSWs would have recentering capability and yielding would be limited to the steel plates. The elimination of residual drift and the use of easily replaceable steel plates as seismic fuses would help to reduce repair costs after an earthquake.



(a)



(b)

Fig. 4. Force-drift for (a) FLEX and (b) INT specimens.

Performance objectives for SC-SPSWs were established such that no repair would be required after an earthquake with 50% probability of exceedance in 50 years (50/50). After a 10% in 50 year earthquake (10/50), the recentered SC-SPSWs would require repair only to the web plates. Collapse prevention performance would be achieved for a 2% in 50 year earthquake (2/50) (Clayton et al., 2012b).

For the performance objective of recentering after an earthquake, a residual drift limit of 0.2% was set. This drift level follows the AISC Code of Standard Practice and its limit for acceptable column out-of-plumbness in new construction (AISC, 2010b).

The SC-SPSW uses post-tensioned (PT) beam-column and column base connections. These connections provide recentering capability without yielding in the frame members. As in prior research on self-centering moment resisting frames (SC-MRFs) (e.g., Christopoulos et al., 2002; Garlock et al., 2005; Chi and Liu, 2012), the post-tensioned strands or bars provide an initial clamping force. Decompression rotation of the connection and elastic elongation of the strands provides softening behavior without yielding or damage. The connections rotate, or rock, about both flanges. In the SC-MRFs, rocking about the top or bottom beam flange results in expansion of the frame along the centerlines of the girders. This type of flange-rocking (FR) connection, was investigated as part of the SC-SPSW. The NewZ-BREAKSS (NZ) connection was also investigated. The NZ connection rocks always about the top flange and was developed to eliminate the frame expansion observed for the FR connections with the tradeoff being reduced connection strength and stiffness (Dowden and Bruneau, 2011).

A number of validation tests were conducted on the SC-SPSWs at UW and UB. These included quasi-static cyclic tests on subassembly and third-scale three-story specimens. A number of parameters were investigated, such as different connection types including the FR and NZ connections. Those tests demonstrated the SC-SPSW's ability to recenter while maintaining ductile yielding and energy dissipation through tension field action in the web plates (Dowden et al., 2012; Clayton et al., 2012a, 2012b). Shake table tests were also conducted on three-story specimens. Test specimens included full SC-SPSW as well as bare frames with the FR and NZ connections. The test results confirmed the viability of the SC-SPSW, with both connections, for resisting demands with recentering (Dowden and Bruneau, 2014).

Two full-scale two-story SC-SPSW specimens were tested pseudo-dynamically at NCREE. One specimen utilized the FR connection, and the other incorporated the NZ connection (Figure 5). Both were designed following the performance-based design procedures from Clayton et al. (2012b) and were based on a regular two-story prototype building located in Los Angeles, California.

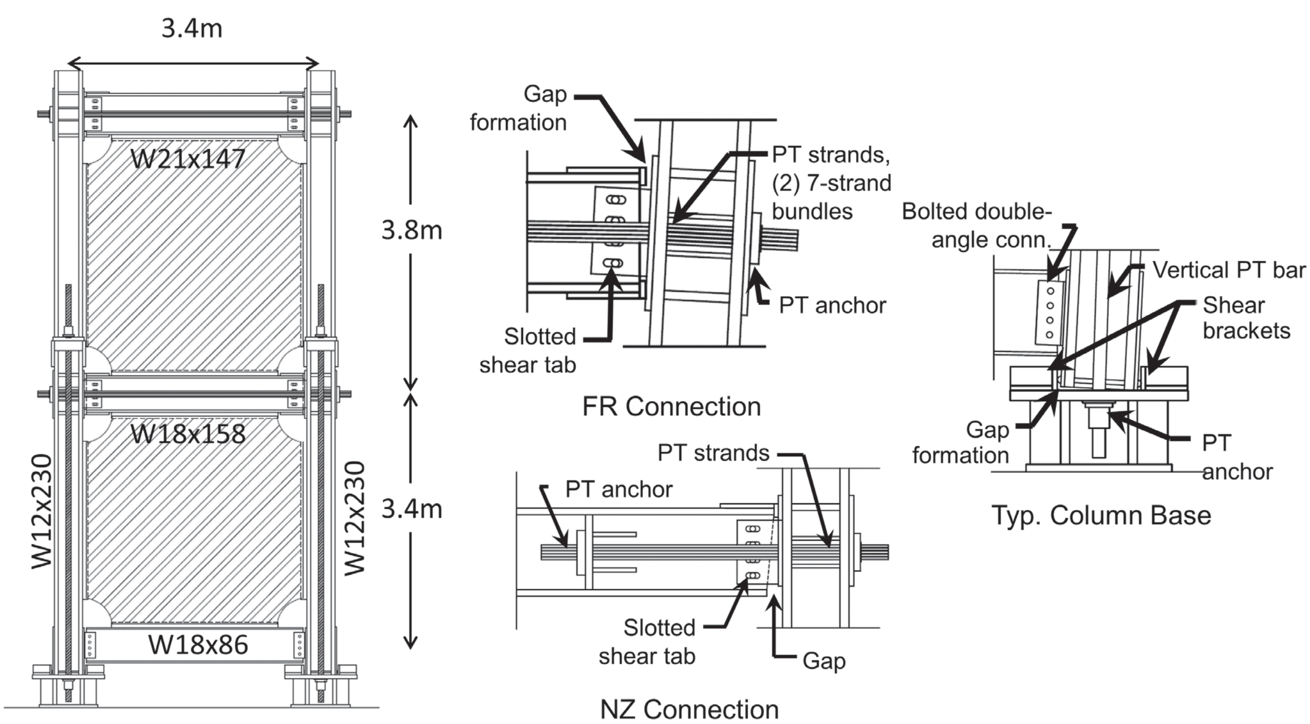


Fig. 5. SC-SPSW specimen drawing with FR, NZ and column base details.

The specimens were nominally the same, aside from the post-tensioned, beam-column connection details. At those connections, both specimens utilized shear tabs with slotted holes to accommodate the relative rotations. Bolted double-angle connections, detailed to also accommodate relative rotations, were used at the bottom beams. Web, or infill, plates with corner cut-outs were welded to fin plates at the boundary elements.

PT strands were used at the beam-column connections, and PT bars were used at the column bases. The PT strands were anchored outside of each column and ran along either side of the beam webs. The PT bars were anchored at the base and just above the middle beam connection. The PT strands and bars provided restoring forces to the connections and column bases. The PT bars also resisted column uplift. Shear resistance at the column bases was provided by bolted brackets.

The specimens were subjected to quasi-static cyclic and pseudo-dynamic (PSD) tests. PSD tests were used to evaluate the SC-SPSW response to ground motions at hazard levels of 50/50, 10/50 and 2/50. The PSD tests were followed by inelastic cyclic tests. The FR specimen was subjected to two cycles at 4.5% drift. The NZ specimen was subjected to increasing drift levels, with two cycles each at 2.5% and up to 4.5% in increments of 0.5% drift. It should be noted that no repairs were made to either specimen between tests. The specimens exhibited ductile response with recentering. Global system responses are shown in Figure 6.

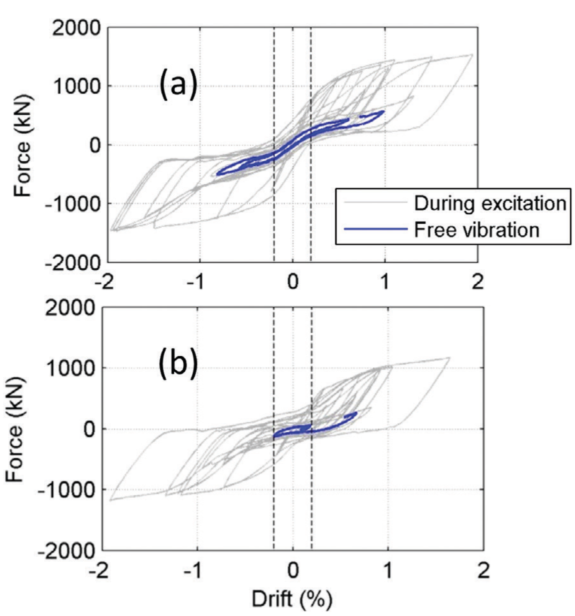


Fig. 6. Results from pseudo-dynamic testing using a ground motion representing the 10% in 50 year hazard for (a) specimen FR and (b) specimen NZ.

In the SC-SPSW specimens, the FR, NZ and PT column base connections behaved as expected. After the PSD and cyclic tests, the web plates were removed from the NZ specimen with the objective of evaluating the boundary frame. The PT frame was then subjected to quasi-static cyclic tests. The results confirmed that nearly all of the energy dissipation in the SC-SPSWs comes from the web plates. Meanwhile, about 30% of the SC-SPSW base shear resistance could be attributed to the PT boundary frame.

The SC-SPSW specimens were able to satisfy the performance objectives. Only minor web plate yielding was observed after the 50/50 hazard; therefore, no repair would be required. Some web plate tearing and minor yielding in the boundary elements (e.g., at the PT anchorage in the top beam of the NZ specimen) was observed for the 10/50 hazard. Residual drifts were less than the limit of 0.2%. Therefore, re-centering was achieved and only the web plates might need repair after the 10/50. The 2/50 event resulted in more tearing in the web plate, but boundary frames that remained essentially elastic. Recentering was also achieved, so the SC-SPSWs far exceeded the collapse prevention performance objective for the 2/50 hazard level.

WEB PLATE MODELING FOR SC-SPSWs

Investigation of the self-centering steel plate shear walls (SC-SPSWs) motivated improvements to the modeling of the web plates. The common tension strip model, a simple and generally effective method for idealizing the behavior of the web plate in conventional special plate shear walls, was shown to underestimate some important parameters. A simple modification of the tension strip model allowed for better representation of the complex web plate behavior and the seismic performance of the SC-SPSWs (Clayton, 2013).

Experimental and numerical research on SPSWs and SC-SPSWs has shown differences between the idealized tension strip behavior and web plates in pinned boundary frames (Clayton et al., 2012a; Clayton et al., 2013; Webster, 2013). For example, the web plate provides resistance during unloading as well as exhibiting strength and stiffness earlier in repeated cycles of loading than represented by the tension strip model. Figure 7 shows a comparison of one cycle (Exp) from a test of an SC-SPSW to the predicted force-drift curve from the tension strip, or tension-only, model (noted as TO in Figure 7). In SC-SPSWs, the web plates provide most of the energy dissipation in the system, so a model that could more accurately capture the web plate behavior would improve evaluation of seismic performance.

Modeling approaches for the web plate were investigated along with a couple of options for the post-tensioned boundary frame (PT-BF). Models of the two-story SC-SPSW specimen tested at NCREE were developed and analyzed. The web plate models included strip models (line elements) with tension-only or tension-compression capacity, or shell elements with isotropic or kinematic hardening. Shell elements were also capable of simulating web plate buckling. The PT-BF was modeled with either line elements or shell elements. The shell PT-BF models also included representation of components such as continuity plates, reinforcement plates and double-angle shear connections (simulated with springs in the shell models; modeled as pins in the line element models). Models were subjected to the displacement history measured during one of the pseudo-dynamic tests.

Shell elements for the PT-BF exhibited more strength and energy dissipation. However, as long as the PT-BFs remained elastic, the differences between the line and shell elements results were not significant. For the web plate shell elements, the measured web plate demands were bounded by the results for the different hardening rules. A combined hardening rule might best represent the web plate behavior.

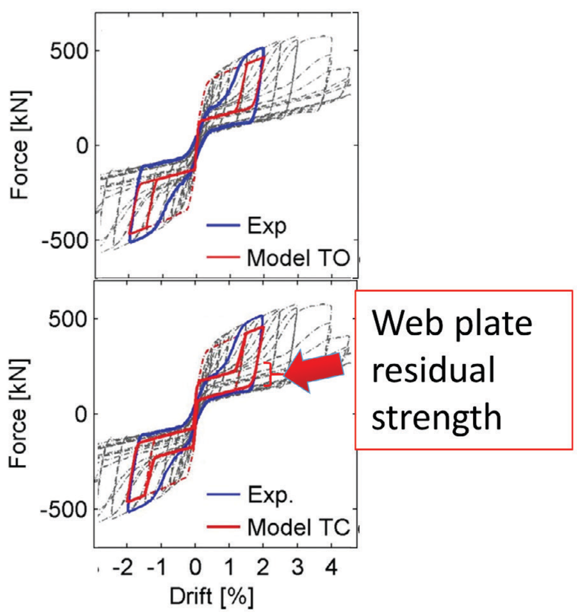


Fig. 7. Comparison of strip model hysteretic behaviors with experimental results for SC-SPSWs.

The results highlighted some benefits to using tension-compression strips. Compared to the tension-only strips, the tension-compression strips for the web plate provided better but still conservative estimates of energy dissipation, peak drift demands and residual drifts for the SC-SPSWs (see TC curve in Figure 7). The web plate strip models were also used in nonlinear response history analyses of three- and nine-story prototype SC-SPSWs for evaluation of effect on seismic performance. Use of the tension-compression strip models resulted in better performance than that predicted with the tension-only strips.

WEB PLATES CONNECTED TO BEAMS ONLY

Further investigation of the SC-SPSWs included the concept of connecting the web plates to the beams only. This change would eliminate the complex web plate demands on the columns, allowing for reduced column sizes. It would also improve energy dissipation in SC-SPSWs by delaying or preventing the web plate tearing that typically begins near the corners of the panel. Furthermore, for SC-SPSWs with FR connections, the PT frame expansion would no longer cause additional strains on the web plates. This expected behavior was validated by a two-story, large-scale specimen from quasi-static subassembly test program, and comparison to a fully-connected specimen (Figure 8; Clayton et al., 2013).

Cost-savings would be another benefit to using SC-SPSWs with web plates connected to the beams only. Although the web plates would need to be thicker than in their fully-connected counterparts, this increase in material could be offset by decreases in boundary frame member sizes. Furthermore, labor for installation of the web plates would be decreased.

The beam-only connected web plates were further investigated through nonlinear dynamic analysis. The tension-compression strip model described in the previous section was used. Three- and nine-story SC-SPSW prototype frames were designed for the performance levels defined by Clayton et al. (2012b) and used for the NCREE test specimens. The frames were computationally subjected to ground motions for 50/50, 10/50 and 2/50 hazard levels. Responses

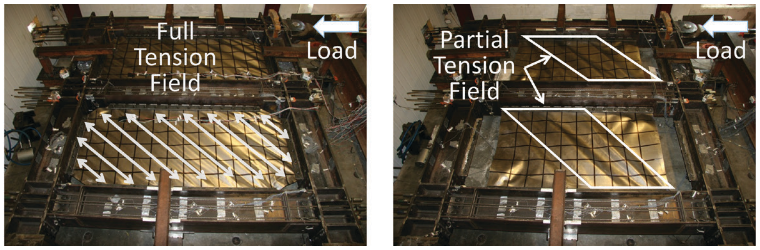


Fig. 8. Development of tension fields in a fully-connected (left) and beam-only (right) SC-SPSW.

of SC-SPSWs with beam-only and fully-connected web plates were compared. The results demonstrated that the beam-only SC-SPSWs were able to meet the performance objectives and are a viable alternative (Clayton et al., 2014).

FUTURE DIRECTIONS

Additional research is under way by the project team to:

1. Finalize a material model for use in OpenSees that is capable of representing complex web plate behavior including buckling, hardening, plastic contraction and other phenomena. The model will enable the most accurate representation of web plate behavior using strip models developed to date.

2. Finalize recommendations for considering web plate strain hardening in capacity design of SPSW beams and columns. These recommendations are based on observations from some of the experiments described above and extensive finite element modeling.

3. Explore the use of significantly smaller columns in SC-SPSWs using modified performance objectives and less conservative models of web plate strength and stiffness. Numerical analysis in OpenSees is being conducted to explore the performance of SC-SPSWs.

4. Finalize recommendations for SPSW-WC seismic design parameters (R, Ω_0 and C_d).

Related work includes research by Purba and Bruneau (2014) on seismic design parameters (R, Ω_0 and C_d) and different design approaches for SPSWs (Purba, 2014). Low and moderate seismic regions may also realize the benefits of ductile SPSWs based on research by Driver and Moghimi (2011). Modular, field-bolted SPSWs may provide economical, viable options for resisting the lower demands in these zones. As noted in Berman (2014), SPSW research has been active, and the technology is advancing. The results are some exciting possibilities for economical and resilient steel plate shear wall design.

ACKNOWLEDGMENTS

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