

## SELF-CENTERING STEEL PLATE SHEAR WALLS

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### ABSTRACT

A self-centering steel plate shear wall (SC-SPSW) consists of replaceable thin steel web panels as the primary lateral load resistance and energy dissipation elements, and post-tensioned (PT) beam-to-column rocking connections that provide system re-centering capabilities. The behavior of this new structural system has been analytically and experimentally investigated at the University at Buffalo and the University of Washington, in the USA, and at the National Center for Research in Earthquake Engineering, in Taiwan, as part of a collaborative research effort. The purpose of this paper is to provide a brief summary of some findings to date from this on-going research. References are provided to the publications available at the time of this writing. Reports to be published in 2013 (after completion of this project) will include recommended design procedure and design examples.

### Introduction

Steel plate shear wall (SPSW) systems are frames having steel plates (a.k.a. webs) connected between their beams and columns. SPSWs have been implemented in many buildings to provide ductile seismic resistance and their design is addressed by design specifications and standards (e.g. AISC 2010, CSA 2009). Comprehensive reviews of existing research on SPSWs, their seismic behavior, and their advantages compared to alternate lateral force resisting systems (LFRS) are available elsewhere (Sabelli and Bruneau 2007, Bruneau et al. 2011). During severe earthquakes, the unstiffened plates of SPSWs buckle in shear and yield by developing a diagonal tension field, together with plastic hinging of the beams at their ends. While SPSW systems are desirable for their significant stiffness, strength, and energy dissipation, the hysteretic energy dissipation of this system, like other traditional seismic-resistant systems that inherently relies on yielding of steel, results in some level of structural damage and the likelihood of significant residual drifts of the structure after severe earthquakes. As such, strategies to eliminate residual drifts and to localize structural damage only in easily replaceable structural elements are desirable in SPSWs (as in other systems).

In moment resisting steel frames, use of post-tension (PT) rocking moment connections was investigated to provide frame self-centering capability and to limit hysteretic damage to replaceable energy dissipating elements during earthquakes (e.g., Ricles et al. 2002; Christopoulos et al. 2002a, 2002b; Garlock et al. 2005; Rojas et al. 2005; to name a few), most notably building on the work of New Zealand researchers developed for pre-stressed concrete buildings (e.g., Priestley and Tao 1993, MacRae and Priestley 1994, to name a few) and others worldwide (e.g. Stanton 1993). Validation of performance for systems having this alternative type of moment resisting frame connection has been established based on analytical and experimental research and shows that these types of systems could be a viable alternative to conventional systems.

Building on this idea, Self-Centering Steel Plate Shear Walls (SC-SPSW) have been proposed, using similar post-tensioned rocking beam connections (Berman et al. 2010). In this proposed system, the SC-SPSW web plate is the replaceable energy dissipation element, and beam-plastic hinging is eliminated. The system combines the advantages of high lateral stiffness, a substantial energy dissipation capacity, and self-centering capability, at the expense of additional challenges to understanding the flow of forces within the structure compared to conventional SPSW (themselves, more complex than moment frames). Three

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different PT rocking connection details have been investigated: 1) connections that rock about the top and bottom beam flanges, 2) connections that rock about the beam centerline, and 3) an innovative NewZ-BREAKSS connection that rocks about the top beam flanges only. The latter two PT connections have been proposed as methods to essentially eliminate floor system damage due to frame expansion (a.k.a. beam growth) that occurs with typical PT rocking connections where the beams rock about both the top and bottom beam flanges.

This brief paper is intended to provide an overview of the work conducted so far as part of this collaborative research project, and to guide the reader to other references where additional information can be found. Note that at completion of this project (funded by the National Science Foundation) in late 2013, complete research reports as well as all experimental data will be freely available on the data repository of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) (<http://nees.org/warehouse/welcome>).

### Fundamental Behavior

A fundamental understanding of behavior and of how to calculate demands on the beams of SC-SPSWs is imperative to achieve effective designs. Detailed free-body-diagrams are essential and instructive in providing key insights for beam and system design. Such insights on SC-SPSW's beam and system fundamental behavior, through free-body-diagrams of individual beams, and push-over analysis of simple frames, was presented by Dowden et al. (2012), in terms of closed form equations for moment, shear, and axial forces along the HBE. These were validated by non-linear cyclic pushover analysis (typical hysteretic curves obtained from cyclic push-over analyses are shown in Fig. 1). These formulations and development of the free-body-diagrams not only provided insight on the behavior of a SC-SPSW system, but also provided a means to inform design. On the basis of that knowledge, a proposed HBE and PT connection design procedure was formulated and illustrated by a case study. The findings presented indicate that SC-SPSW systems could be a viable alternative to traditional lateral force resisting systems.

A companion paper by Clayton et al. (2012a) proposed a seismic design procedure aimed at achieving specified structural performance targets and analytical methods for modeling SC-SPSWs, which was used to design a series of 3-and 9-story prototype buildings located in a high seismic zone in California. Nonlinear, dynamic analyses performed for these prototype buildings, using ground motions representing three seismic hazard levels, showed that the systems achieved the desired performance objectives, including re-centering of the lateral system.

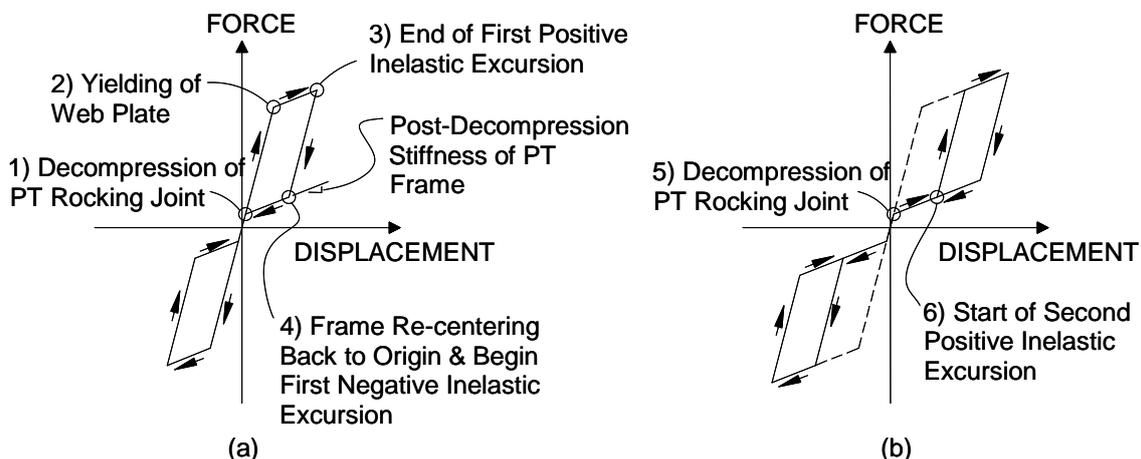


Figure 1: Idealized Hysteretic Response (Tension-Only Web Plate Behavior)

### Managing Beam Growth

It is well known that the use of rocking beam connection requires careful and non-conventional floor diaphragm detailing to account for interaction effects of the PT frame with the gravity system. In particular, issues with PT frame expansion (Garlock, 2003), often referred to as “beam growth”, arise associated with the opening of the rocking beam joint. Garlock and Li (2008) and Iyama et al. (2009) proposed some innovative floor slab diaphragm details for specific plan layouts to accommodate this beam growth that occurs in the PT frames relative to the other gravity frames in steel building structures, and more

challengingly when beam growth develops in both orthogonal plan directions. In addition to those floor slab issues, in taller frames having larger columns, because columns must flexurally deform to accommodate beam growth at subsequent stories, the large stiffness of these columns may become overwhelming and prevent beam-growth to the point where PT-RMC systems may not work properly (Greg MacRae, University of Canterbury, Research Directions and Priorities for Steel Structures Workshop, Christchurch, April 2010).

Therefore, to achieve self-centering without beam-growth, a type of rocking connection was proposed by Dowden and Bruneau (2011). Inspired by a moment-resisting connection developed and implemented in New Zealand (Clifton 1996 & 2005, MacRae et al. 2007, Clifton et al. 2007, MacRae 2008, MacRae et al. 2009), the proposed connection is called the “New Zealand-inspired – Buffalo Resilient Earthquake-resistant Auto-centering while Keeping Slab Sound (NewZ-BREAKSS) Rocking Connection”. This proposed rocking connection is shown in Fig. 2 for the particular detail that was used in a self-centering SPSW system (the detail shown is for a 1/3 scale frame tested).

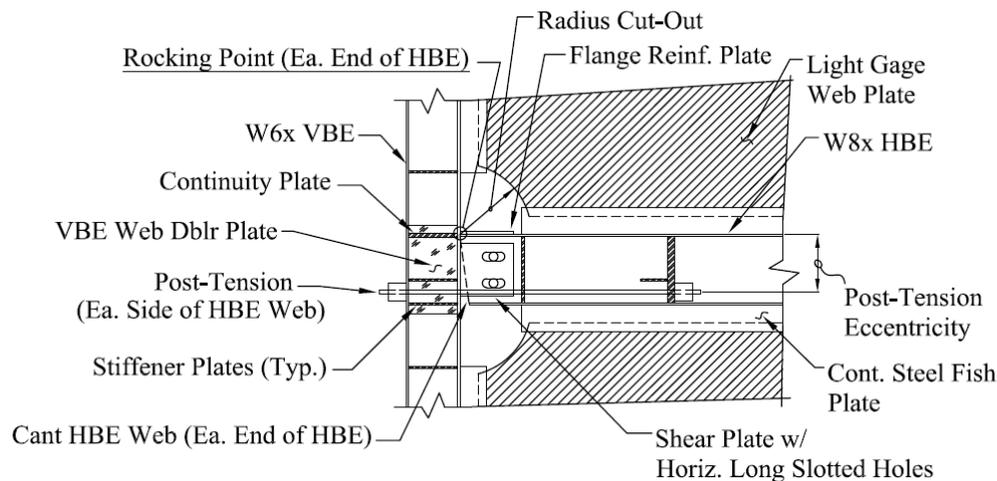


Figure 2 Self-Centering SPSW Rocking Connection

The proposed rocking connection essentially eliminates the beam growth typically encountered in the previously researched connections that rock about both of their beam flanges, by instead maintaining constant contact of the beam top flange with the column during lateral drift. Two PT elements need to be anchored independently along the length of the beam as shown in Fig. 2 to make self-centering possible (if a single PT element was used spanning across the entire beam and anchored only to the columns, its net elongation would be zero over the full length of the beam).

### Quasi-Static Tests

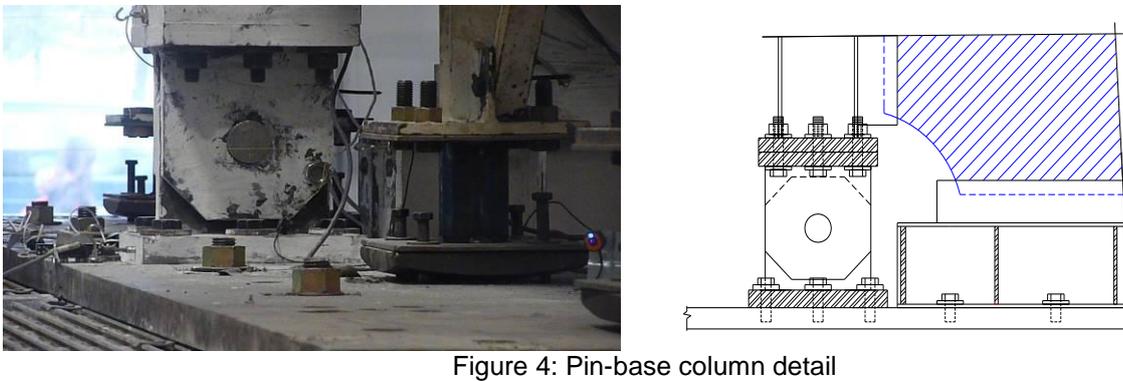
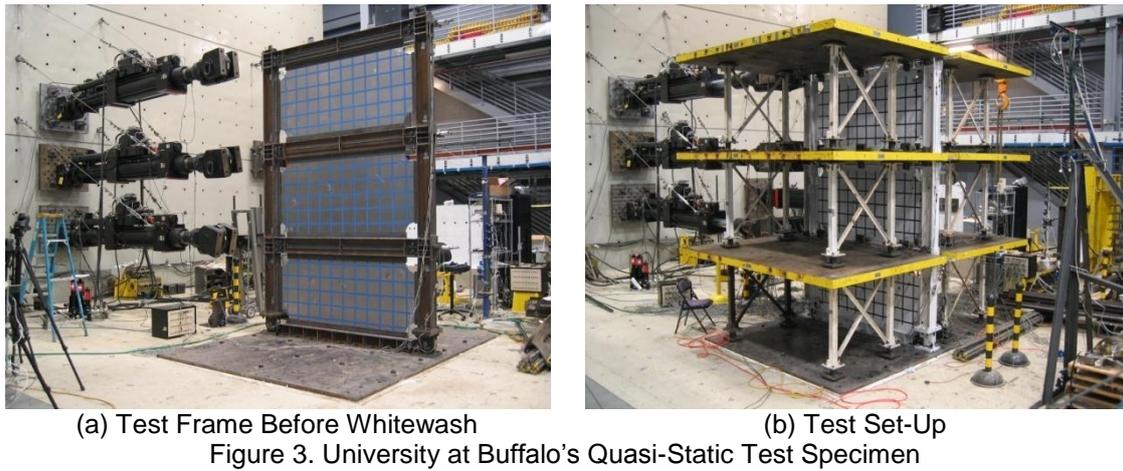
On the strength of these observations, an extensive experimental program of quasi-static tests was first undertaken to investigate the behavior of SC-SPSWs and their self-centering characteristics. These tests provided a better understanding of SC-SPSW cyclic behavior and provided much needed data to validate numerical modeling methods.

Large-scale SC-SPSW subassemblies were first tested at the University of Washington (Clayton et al. 2002b, Winkley 2011). The purpose of the SC-SPSW subassembly test program was to get a better understanding of SC-SPSW cyclic behavior, to capture the effects of the interaction of the PT and web plate forces acting on an intermediate HBE, and to validate numerical modeling methods. All of the specimens in this phase of testing utilized the flange rocking PT connection detail. These tests confirmed the re-centering capabilities of the SC-SPSW.

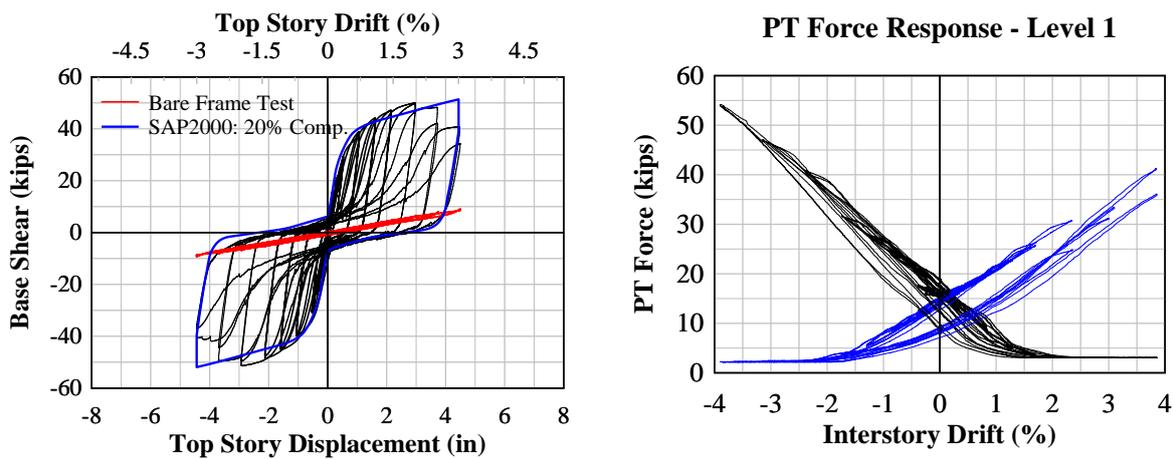
The experimentally-obtained hysteretic curves also revealed that the web plates had some compressive strength not accounted for in the typical idealized tension-only behavior assumed in SPSW analysis. This compressive strength increased as the web plate thickness increased (logically), ranging from 10-20% of the web plate tension field strength in some of the tested cases (Clayton et al. 2011). Further research allowed better understanding and quantifying this phenomenon (Webster et al. 2012). Fortunately, shake-table tests demonstrated this compression strength to be a transient condition that did not affect the re-centering capabilities of SC-SPSWs, as shown in a latter section.

Experimental quasi-static testing of one-third scale single-bay three-story test specimens were conducted at the University at Buffalo to investigate the system performance of SC-SPSWs. Three different rocking joint

configurations noted were considered. The test specimen and setup is shown in Fig. 3. A pin-based column base connection (Fig. 4) was used to prevent formation of a plastic hinge at the base of the column (which might have prevented re-centering).



Instrumentation was provided to record the response at strategic locations to monitor global and local responses. For the experimental results presented, string pots were provided at each floor level to determine displacements. Load cells were provided at the PT anchorage locations to monitor PT forces. Actuator forces were recorded from the actuator load cells.



From the hysteresis shown in Fig. 5a it is observed that self-centering response is achieved. Typical PT forces during cyclic testing are shown in Fig. 5b. Separation of the infill plate from the boundary frame occurred at around 2% drift as indicated by the reduction of base shear capacity. Analytical results obtained with SAP2000 compared reasonably well with the experimental ones.

## Specimens having Diagonal Strips

Specimens having diagonal strips instead of a full infill web plate were also tested (Fig. 6). These were initially intended to provide a point of comparison with the behavior of walls having solid infill plate, allowing to experimentally obtain data on behavior when the orientation of the infill plate diagonal stress field is perfectly known (forcing it to develop in a certain direction by using strips instead of a full infill plate). However, the idea of using strips instead of solid plates in actual implementations became quite appealing. First, because SC-SPSWs with strips did not exhibit the compression strength that had been observed in the quasi-static tests of SC-SPSWs with solid plates, second because the strips did not fractures at large drifts contrary to the solid infill plates, and third because, after an earthquake, the strips can be replaced one strip at the time, thus keeping most of the lateral-load resistance integrity of a given story in the process.

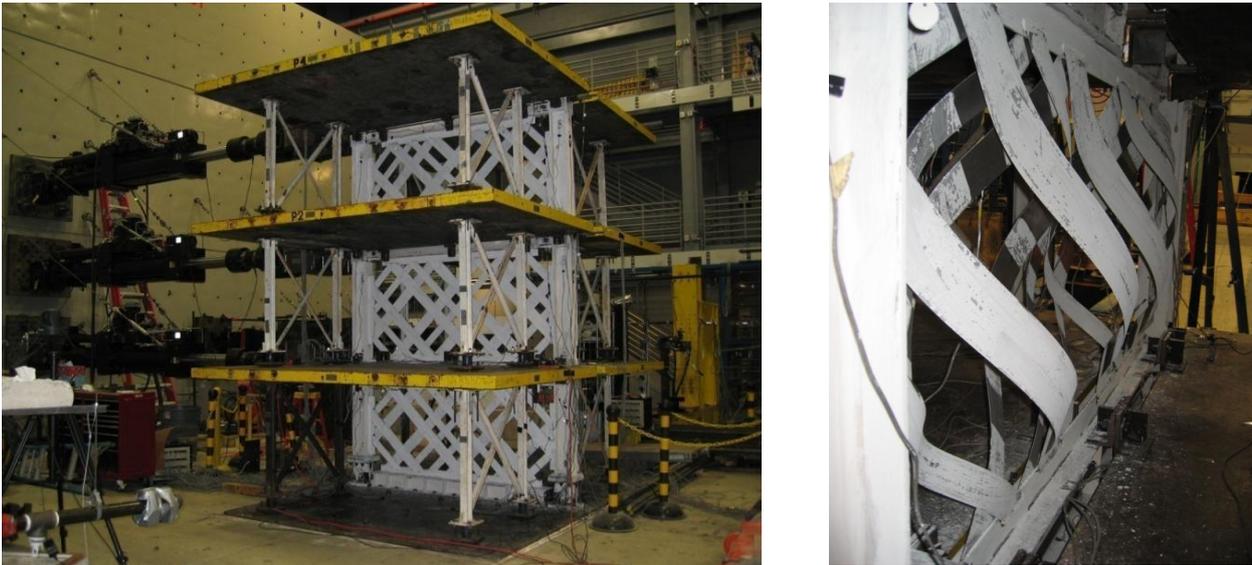


Figure 6: SPSW with strips: (a) Before testing; (b) Strip deformations at 5% Drift – Level 2 – North Elev.

## Pseudo-Dynamic Testing

Full scale pseudo-dynamic testing of a two-story single-bay SC-SPSW system was conducted. Test set-up is shown in Fig. 7. Two experiments were performed, with specimens identical except for the type of PT beam-to-column rocking connections: One specimen used a PT connection detail for which the beam rocked about both flanges, while another used the NewZ-BREAKSS type connection detail. Pseudo-dynamic testing was successively accomplished for simulating ground motions representing a 50%, 10%, and 2% in 50 year seismic hazard level. Both specimens were able to meet and even exceed the proposed performance objectives at all hazard levels, including no repair required after the 50/50 event, repair of the web plates only and re-centering after the 10/50 event, and collapse prevention after the 2/50 event.

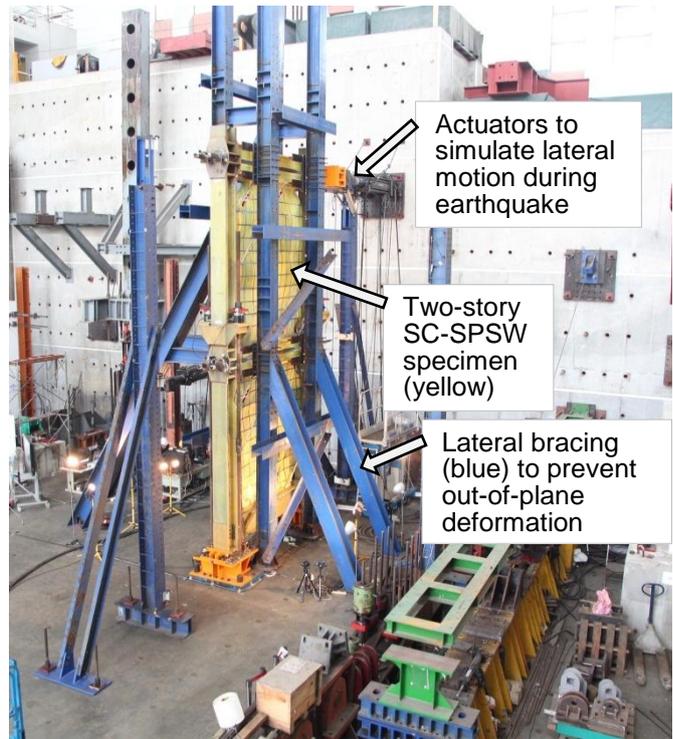


Figure 7: Pseudo-dynamic test: (a) Global view showing scale of specimen; (b) Parts of test set-up; (c) Rocking pre-tensioned column case, and; (d) Anchorage point of column pre-tension

### Shake Table Testing

Shake table testing was conducted at the University at Buffalo, using the same three-story specimen previously subjected to quasi-static testing (repaired to have new web plates). Specimens having beams rocking about their flanges and NewZ-BREAKSS frames were tested. For each of these configurations, a specimen having a full infill plate and one having an infill strip configuration were tested. The bare-frame corresponding to each of these configurations was also tested for reference.

Spectra-compatible ground motions were used, scaled to a design basis earthquake (DBE) level seismic hazard for a site located in Los Angeles. The wall was successively subjected to this ground motion, scaled in intensity, from 25% to 140% of the DBE. A specimen having diagonal strips instead of solid infill plate was even tested to 200% of the DBE. On each specimen, after the test at the maximum intensity of excitation, a final test was conducted to simulate a medium level aftershock.

System performance was excellent, with little to no tearing of the infill plates for frame configurations having full web plate (and of course no tearing for the frames having diagonal strips instead of infill plates). All tests fully re-centered (with less than 0.2% residual drift).

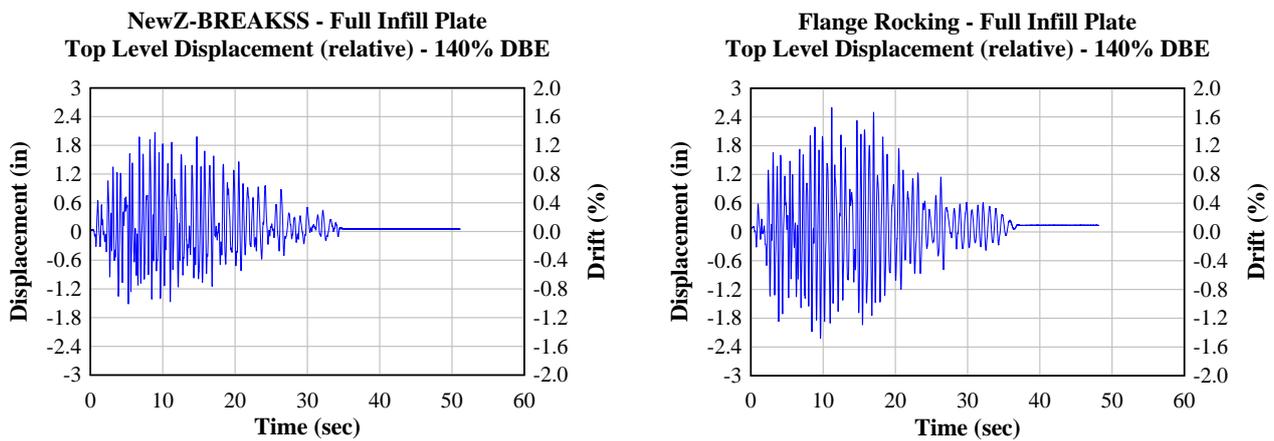


Figure 8: Roof displacement history at for base excitation at 140% of Design Basis Earthquake (DBE): (a) NewZ-BREAKSS specimen, and; (b) Flange rocking specimen

### Conclusions

Research has been conducted to develop practical details and design procedures for SC-SPSW, validated by extensive analysis and experimental work. A fundamental understand of the behavior of this new structural system has been acquired as a result of an extensive series of quasi-static, pseudo-dynamic, and shake table experiments, and analyses. SC-SPSW should be attractive in situations where high structural stiffness, strength, and system self re-centering after an earthquake are desired features. As such, it is an innovative technology worth the consideration of engineers interested in implementing damage-avoidance technology, with the understanding that yielding plates act as structural fuses that would need to be replaced following a large earthquake. Architectural finishes providing easy access to the SC-SPSW, without obstructions by difficulty to move non-structural components, should be designed to facilitate such replacement in those situations.

### Acknowledgments

Support was provided in part by the National Science Foundation as part of the George E. Brown Network for Earthquake Engineering Simulation under award number CMMI-0830294 and by the National Center for Research on Earthquake Engineering in Taiwan. P. Clayton was also supported by the NSF East Asia and Pacific Summer Institute program under award number OISE-1209569. The author also acknowledges material donations from the American Institute of Steel Construction.

Most importantly, this collaborative work has involved the following researchers:

- Jeff Berman, University of Washington (Principal Investigator)
- Michel Bruneau, University at Buffalo (Co-Principal Investigator)
- Laura Lowes, University of Washington (Co-Principal Investigator)
- Keh-Chuan Tsai, Dept. of Civil Engineering, National Taiwan University, Taiwan
- Patricia M. Clayton, University of Washington
- Daniel M. Dowden, University at Buffalo
- Chao-Hsien Li, National Center for Research on Earthquake Engineering Taiwan
- Ronny Purba, University at Buffalo
- David J. Webster, University of Washington
- Tyler Winkley, University of Washington

Any opinions, findings and conclusions presented in this paper are those of the writer and do not necessarily reflect the views of the sponsors.

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