# Full-Scale Testing of Self-Centering Steel Plate Shear Walls

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## ABSTRACT

This paper presents the results of a self-centering steel plate shear wall (SC-SPSW) experimental program conducted at the National Center for Research on Earthquake Engineering (NCREE) as part of a collaborative research endeavor. Two full-scale two-story SC-SPSW specimens were tested under pseudo-dynamic loading. The specimens investigated two different post-tensioned (PT) beam-to-column connection configurations—one using a PT connection detail where a gap forms in a connection as the beam rocks about its flanges, and one using a PT connection (called the NewZ-BREAKSS connection) where the beam in a connection always rocks about its top flanges, thus eliminating the problem of frame expansion.

The test specimens also incorporated a post-tensioned column base connection that allowed the column to rock about its flanges, relying on vertical post-tensioned rods anchored along the column height. The PT column base provides additional recentering capabilities, as well as eliminates the damage and residual plastic deformations that occur in the moment resisting base connections of SC-SPSWs. The results from this project will be used to validate numerical models and inform construction and design recommendations.

## INTRODUCTION

Recent experimental and analytical research has shown self-centering steel plate shear walls (SC-SPSWs) to be an effective lateral force resisting system for providing enhanced seismic performance (Dowden and Bruneau 2011, Dowden et al. 2012, Clayton et al. 2012a,b). Instead of moment-resting beam-to-column connections typically used in conventional steel plate shear walls (CSPSWs), SC-SPSWs utilize post-tensioned (PT) beam-to-column connections to provide frame recentering following an earthquake, while the thin steel web plates provide the primary lateral load resistance. This approach also eliminates boundary frame damage by concentrating energy dissipation to the web plates only, ultimately reducing the post-earthquake repair costs and loss of building functionality, while still retaining the strength and energy dissipating characteristics of SPSWs.

A performance-based seismic design (PBSD) methodology has been proposed for the new SC-SPSW system (Clayton et al. 2012a). The proposed performance objectives include:

1. *No repair* required after a 50% in 50 year event.
2. *Repair or web plates only* and recentering after a 10% in 50 year event.
3. *Collapse prevention* after a 2% in 50 year event.

Nonlinear response history analyses showed that the system was capable of achieving the proposed performance objectives (Clayton et al. 2012a). Quasi-static testing of large-scale subassemblies (Clayton et al. 2012b) and third-scale three-story specimens (Clayton et al. 2012c) have also shown good agreement with the cyclic response of simple nonlinear analyses. The test program presented here provides full-scale experimental verification of the system's seismic performance through pseudo-dynamic loading at the three hazard levels considered in the above performance objectives.

## EXPERIMENTAL PROGRAM

Full-scale, two-story SC-SPSW specimens were tested at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan. These tests were the first pseudo-dynamic tests and first full-scale system-level tests of the SC-SPSW system, and these were also the first SC-SPSW specimens to incorporate post-tensioned column base connection. Details of the test specimens and loading are provided below.

### Specimen Descriptions and Test Setup

The frame dimensions and member sizes of both specimens were identical with the only physical difference between the two specimens being the PT beam-to-column connections. The specimens had bay widths of 3.42m and beam centerline-to-centerline heights of 3.4m and 3.8m for the first and second stories, respectively. The web plates in both stories were 2.7mm thick low yield strength (LYS) steel. The web plates were welded to fish plates connected to the boundary frame, and radial corner cutouts were provided to reduce localized strain effects associated with connection gap opening at these locations. Only the top beam (TB) and middle beam (MB) were

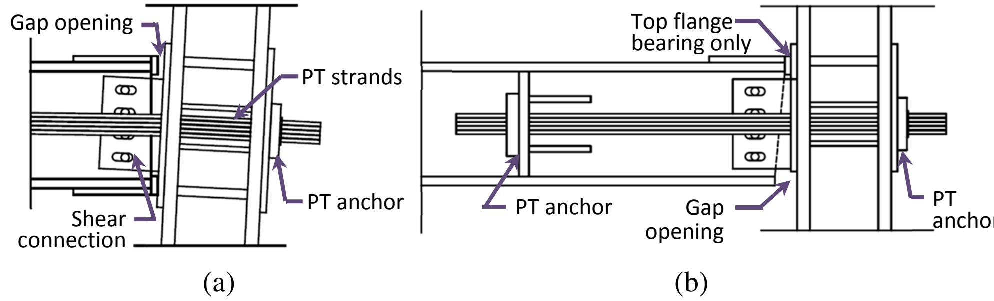



Figure 1: Schematic of (a) Flange Rocking and (b) NewZ-BREAKSS PT connections

post-tensioned, while the bottom beam (BB) was connected to the columns with bolted double-angle shear connections that provide a large rotation capacity without large moment demands on the beam.

The first specimen (Specimen FR) consists of PT beam-to-column connections that rock about both flanges as shown in Fig. 1(a). Here, the PT strands run along the full length of the beam and are anchored at the outside flanges of each column. The second specimen (Specimen NZ) consists of PT beam-to-column connections in which the beam rocks about its top flanges only as shown in Fig. 1(b). This connection, referred to as the NewZ-BREAKSS connection (Dowden and Bruneau 2011), essentially eliminates frame expansion, a phenomenon associated with traditional flange rocking PT connections and requiring special diaphragm detailing to alleviate restraint to this expansion (Garlock and Li 2007, Kim and Christopoulos 2008). To prevent flexural hinging at the column base and provide additional recentering capabilities, PT column base connections (Fig. 2) were used in both specimens.

The specimens were loaded with two 1000kN actuators attached to one column at the height of the top beam as shown in Fig. 3. A lateral bracing frame was erected on both sides of the specimen as shown in Fig. 3 to prevent out of plane deformation.

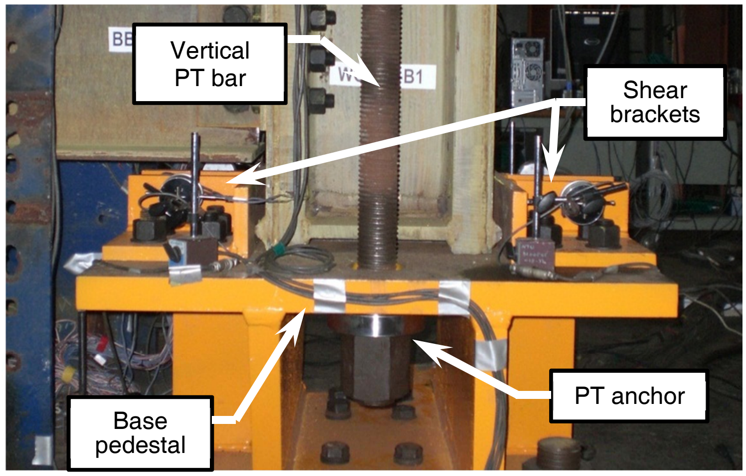



Figure 2: PT column base connection

**Prototype Building and Pseudo-dynamic Loading**

The prototype building for the specimens was a two-story adaptation of the three-story SAC building (Gupta and Krawinkler 1999) located in Los Angeles, California.Each specimen was subjected to pseudo-dynamic excitation at three seismic hazard levels—50%, 10%, and 2% probability of exceedence in 50 years (50/50, 10/50, and 2/50, respectively). The ground acceleration excitations were chosen from the SAC ground motion ensemble for Los Angeles (Somerville et al. 1997). The three ground acceleration excitation records are shown in Fig. 4.

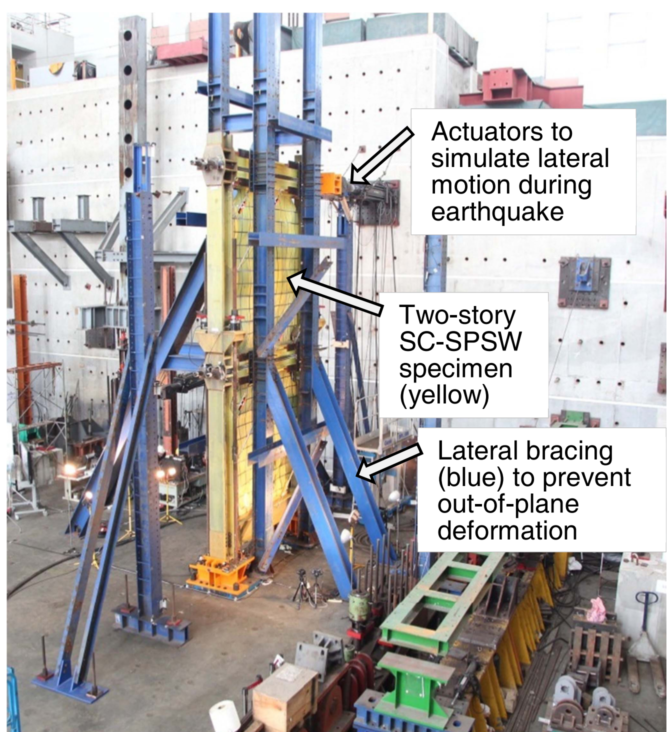



Figure 3: Test setup, shown here for Specimen FR.

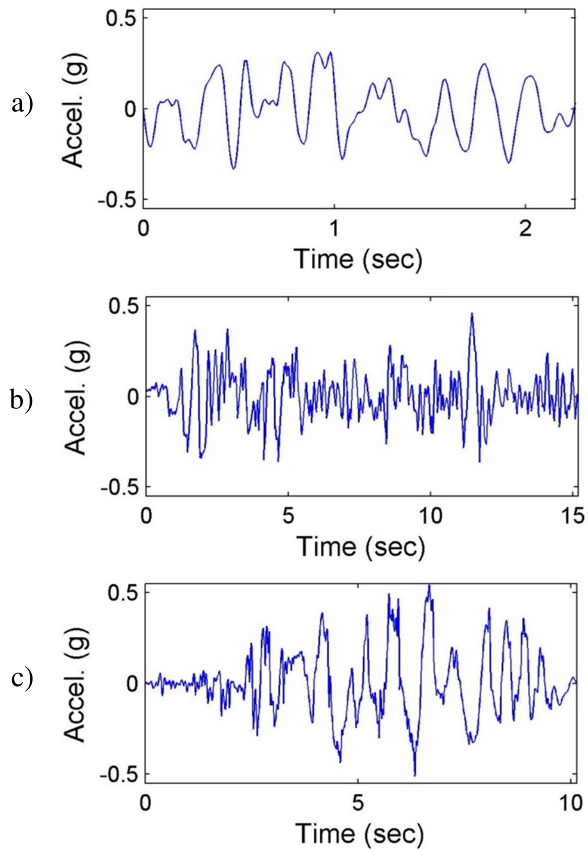
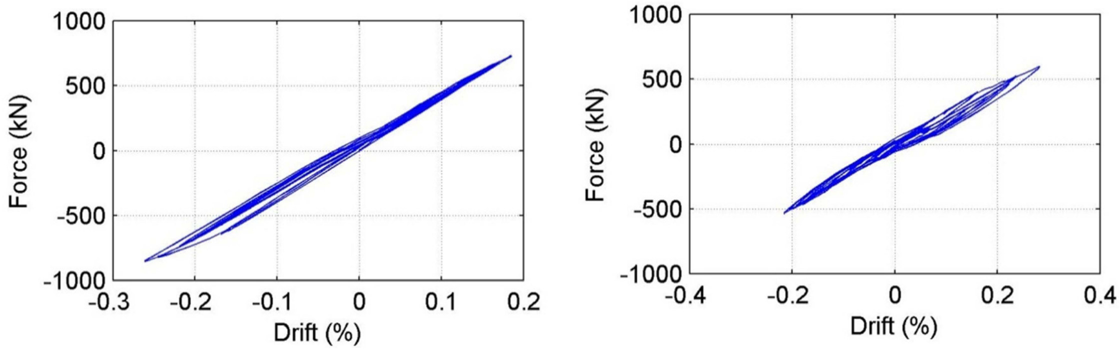



Figure 4: Excitation used for the (a) 50/50, (b) 10/50, and (c) 2/50 pseudo-dynamic tests

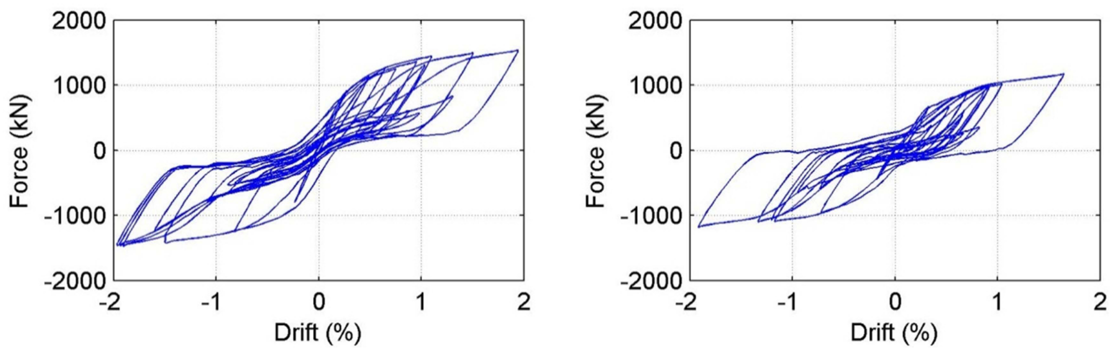
## TEST RESULTS

The preliminary results for each of the pseudo-dynamic tests are shown below. Fig. 5(a) and (b) show the force vs. drift responses of Specimens FR and NZ, respectively at the 50/50 hazard level. These response histories show nearly linear behavior, as desired.




(a) (b)

Figure 5: 50/50 force vs. drift response for (a) Specimen FR and (b) Specimen NZ




(a) (b)

Figure 6: 10/50 force vs. drift response for (a) Specimen FR and (b) Specimen NZ

Fig. 6 shows the force vs. drift response for both specimens during the 10/50 pseudo-dynamic test. Both specimens had peak drifts less than 2%, and residual drift of less than 0.2%, again meeting performance objectives.

The peak drifts in both specimens at the 2/50 year hazard level were less than 4.7%. No significant boundary frame yielding was observed, meeting the performance objective at this hazard level.

## CONCLUSIONS

Full scale pseudo-dynamic testing of a two-story single-bay SC-SPSW system was conducted. Two experiments were performed, Specimen FR and Specimen NZ. The two specimens were essentially identical with the exception of different PT beam-to-column rocking connections: Specimen FR using a PT connection detail where the beam is allowed to rock about both flanges; Specimen NZ using a PT connection detail where the beam rocks about its top flanges only. The pseudo-dynamic loading protocol consisted of 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 recentering after the 10/50 event, and collapse prevention after the 2/50 event.

## ACKNOWLEDGEMENTS

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