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Pseudo-dynamic Testing of Self-centering Steel Plate Shear Walls

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ABSTRACT
The self-centering steel plate shear wall (SC-SPSW) has been developed as an effective lateral load resisting system that is capable of enhanced seismic performance including recentering after design-level earthquakes. Recent large-scale, pseudo-dynamic experimental research has been conducted at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan to better understand SC-SPSW behaviour and seismic performance. Pseudo-dynamic tests of two full-scale, two-story SC-SPSW specimens were conducted at NCREE to investigate the system performance in earthquake excitation representing events with 50%, 10%, and 2% probabilities of exceedence in 50 years. This test program was the first full-scale investigation of the SC-SPSW at the system-level and the first to incorporate PT column base details to improve column damage resistance and practical constructability. The specimens were physically identical with the exception of the PT beam-to-column connections: one using commonly-employed flange rocking connections, the other using a new PT connection designed to eliminate frame expansion. This paper will present the SC-SPSW pseudo-dynamic test program and its results.

KEYWORDS: *Post-tensioned, rocking connections, large-scale testing, pseudo-dynamic, steel plates*

1. INTRODUCTION

The self-centering steel plate shear wall (SC-SPSW) is a lateral force resisting system that leverages the recentering capabilities of post-tensioned steel frames with the strength and ductility of steel plate shear walls (SPSWs). Here, the SPSW infill plate, referred to as a web plate, provides the primary strength, stiffness, and energy dissipating capabilities. The welded moment-resisting connections of the conventional SPSW are replaced with post-tensioned (PT) steel connections to create the SC-SPSW. These PT connections provide recentering and, if designed properly, eliminate damage to the boundary frame, ultimately forming a more resilient structure and reducing post-earthquake economic impacts (Clayton et al. 2012a, Dowden et al. 2012).

The target performance objectives of the SC-SPSW system (Clayton et al. 2012a) include no repair following an event with a 50% probability of exceedance in 50 years (50% in 50 year, or 50/50), repair of web plates only and recentering following a 10% in 50 year (10/50) event, and collapse prevention in the 2% in 50 year (2/50) event. Previous nonlinear dynamic numerical simulations have shown that 3- and 9-story SC-SPSW buildings located in the Los Angeles, California area that were designed according to the proposed performance-based seismic design methodologies were able to achieve the target performance objectives (Clayton et al. 2012a). Nonlinear numerical simulations have also shown good agreement with previous quasi-static cyclic experimental investigations, including SC-SPSW subassembly (Clayton et al. 2012b) and third-scale three-story (Clayton et al. 2012c) specimens.

The test program described in this paper represents the first full-scale test of the SC-SPSW system, and the first SC-SPSW specimens incorporating PT column base connections to improve constructability and prevent damage at the column base. These full-scale specimens were also the first SC-SPSWs tested under pseudo-dynamic loading to investigate performance at various seismic hazard levels and to experimentally investigate the effects of load history on SC-SPSW response.

2. SPECIMEN DESCRIPTIONS

Two two-story full-scale SC-SPSW specimens were tested at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan. The specimens were physically identical with the exception of their PT beam-to-column connections. Descriptions and schematics of the PT connections and test specimen are provided in the following sections.

2.1. PT Connections

2.1.1. PT Beam-to-column Connections

The two specimens investigated SC-SPSW systems using two different PT beam-to-column connections. The first connection type is one that rocks about both flanges depending on the direction of sway (Figure 2.1(a)). The specimen employing these flange rocking PT beam-to-column connections was termed Specimen FR. The flange rocking connection is a commonly-employed PT connection type that has been used in numerous previous self-centering moment-resisting frame (SC-MRF) studies (e.g. Garlock et al. 2007, Kim and Chirstopoulos 2008, Lin et al. 2008, just to name a few). The connection behaviour is characterized by a high initial stiffness, equivalent to that of a welded moment-resisting connection, until the connection flexural demands reach what is referred to as the decompression moment. At connection decompression, the connection rocks open, forming a gap at either to top or bottom flange and response with a reduced flexural stiffness that depends primarily on the beam depth and the axial stiffness of all the PT elements in the connection. Also as the connection rocks open and gaps form at both ends of the beam, the column are forced to spread apart, a phenomenon referred to as frame expansion or beam growth. Typically, this frame expansion is accommodated by special diaphragm detailing (e.g. Garlock and Li 2007, Kim and Christopoulos 2008, Chou and Chen 2011).

The other specimen, referred to as Specimen NZ, utilized a recently developed PT connection termed the NewZ-BREAKSS connection (Dowden and Bruneau 2011). The NewZ-BREAKSS connection (Fig. 2.1(b)) was developed to eliminate the problems associated with beam growth. Here, the beam always rocks about its top flange, and the beam end is cut such that a gap is always present at the bottom flange. As the frame sways, the gap on one end of the beam closes, while the other end opens. In order to develop PT restoring forces the PT elements must be terminated along the length of the beam as there is no net elongation from column to column. As the connection is decompressed in their initial configuration (i.e. a gap is always present at the bottom flange), the connection flexural stiffness is similar to that of the decompressed flange rocking connection and is proportional to the axial stiffness of the PT elements and the distance from the top flange to the PT elements.

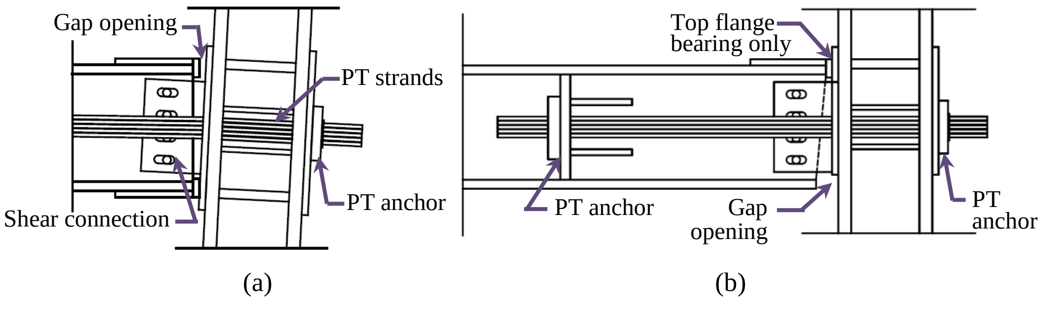


Figure 2.1: Schematic of (a) Flange Rocking and (b) NewZ-BREAKSS PT connections

The NewZ-BREAKSS connection is ideal for pairing with a tension-only or tension-dominant type of energy dissipating element such as the web plates in SC-SPSWs. With fully hysteretic energy dissipating devises, such as the energy dissipating bars in Christopoulos et al. (2002) or yielding angles in Garlock et al. (2007), the flange rocking PT connection decompression moment must be design to be sufficiently larger than the resistance of the yielding energy dissipation devises to ensure gap closure and recentering upon unloading. However, for the case of thin steel web plates, which are assumed to behave with a predominantly tension-only behaviour, the large decompression moments are not necessary to provide recentering capabilities. Although the NewZ-BREAKSS was developed as part of this SC-SPSW research program, it provides an alternative to typical flange rocking connections and the frame expansion problems that come along with them, and it can be further extended and implements in other resilient structural systems.

In each of the specimens, horizontally slotted shear tab connections were provided to transfer shear forces from the beam to the column while still allowing the connection to rotate. The PT beam-to-column connections contained two seven-strand bundles of 0.6” (15mm) diameter PT strands, one bundle located on each side of the beam web. The PT strands had an initial stress that was approximately 30% of the yield stress. Flange bearing plates were provided at each rocking flange (as seen in Fig. 2.1) to reinforce the flanges and provide an even bearing surface.

2.1.2. PT Column Connections

A PT flange-rocking connection was provided at the base of the columns to eliminate hinging at that location and to provide additional recentering. The PT connection (shown schematically in Fig. 2.2) consists of two 69mm diameter PT bars, one on each side of the column web, that are anchored below in the column pedestal and above within the height of the column (as shown in Fig. 2.3). The PT bars had an initial stress of approximately 25% and 13% of the yield stress for Specimens FR and NZ, respectively. The shear force in the column is transferred to the pedestal via slip-critical bolted shear brackets that allow the PT connection to rotate. The bottom beam is connected to the column with a double bolted-angle connection that allows the connection to rotate with minimal flexural resistance.

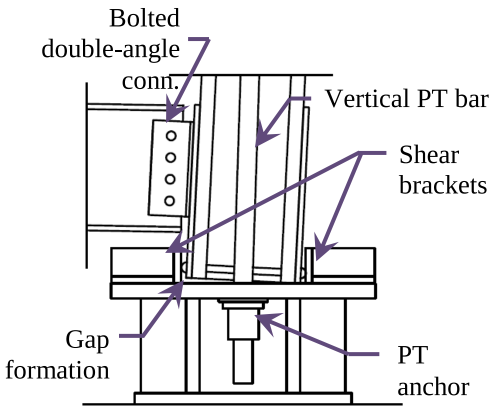


Figure 2.2: Schematic of PT column base connection

2.2. Test Setup

The test specimens both had centreline column-to-column dimensions of 3.42m and beam centreline heights of 3.4m and 3.8m for the first and second stories, respectfully. A schematic of the test setup is shown for Specimen FR in Fig. 2.3; however, the setup for Specimen NZ was identical with the exception of the PT beam-to-column connections. The web plates in each story were 2.7mm thick low yield strength (LYS) steel. The plates were connected to the boundary frame via a welded web plate-to-fishplate connection. Radial corner cutouts in the web plate were provided near to connections to reduce the large tensile strains associated with the gaps opening in the connections.

The specimens were both loaded with two 100kN actuators attached to the West Column at the top beam. PT beam-to column connections were only provided at the top beam (TB) and middle beam (MB), while the bottom beam (BB) has shear connections as described above. Lateral bracing (not shown in Fig. 2.3) was provided along the MB and TB to prevent out-of-plane motion of the boundary frame.

The specimen was instrumented with load cells to measure the PT bundle, PT bar, and actuator loads. String potentiometers and a Temposonic were used to measure the East and West column displacements. At each beam height. Displacement transducers were located at the top and bottom flange of each beam-to-column connection, as well as at each flange at the column base connections, to measure connection rotation. Strain gages were placed at critical sections along the beams and columns to estimate axial force and moment demands and localized strains near the connections. Displacement transducers were also placed diagonally within the boundary frame to estimate the axial strain in the web plate in the approximate tension field direction.

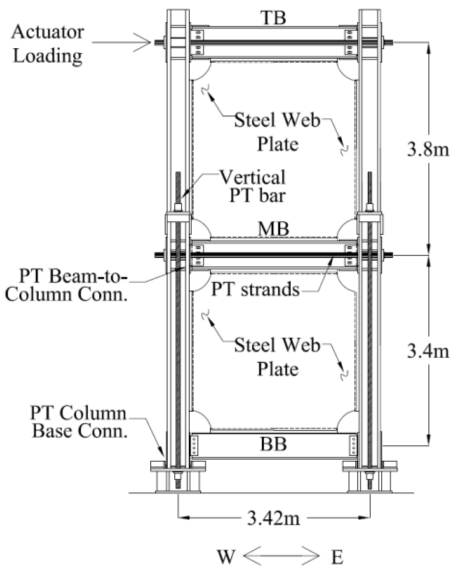


Figure 2.3: Schematic of test setup for Specimen FR

3. PSEUDO-DYNAMIC LOADING

Both specimens were loaded pseudo-dynamically with excitations representing a 50%, 10%, and 2% in 50 year event. The excitations were selected from the SAC ground motion ensembles for the Los Angeles area (Somerville et al. 1997) such that the peak predicted drift was similar to the median drift expected for that hazard level based on numerical studies from Clayton et al. (2012a). Only portions of the ground motions during strong shaking were selected to reduce the duration of testing, and preliminary numerical studies indicated that the selected ground motions truncations did not affect key performance parameters such as peak drift. Table 3.1 shows a summary of the excitations selected for each seismic hazard level. Note that the 2/50 excitation was scaled by 1.3 to achieve the desired peak drift based on preliminary numerical models. The excitations were also followed by period of free vibration to observe post-event response of each specimen.

Table 3.1 Summary of pseudo-dynamic excitations

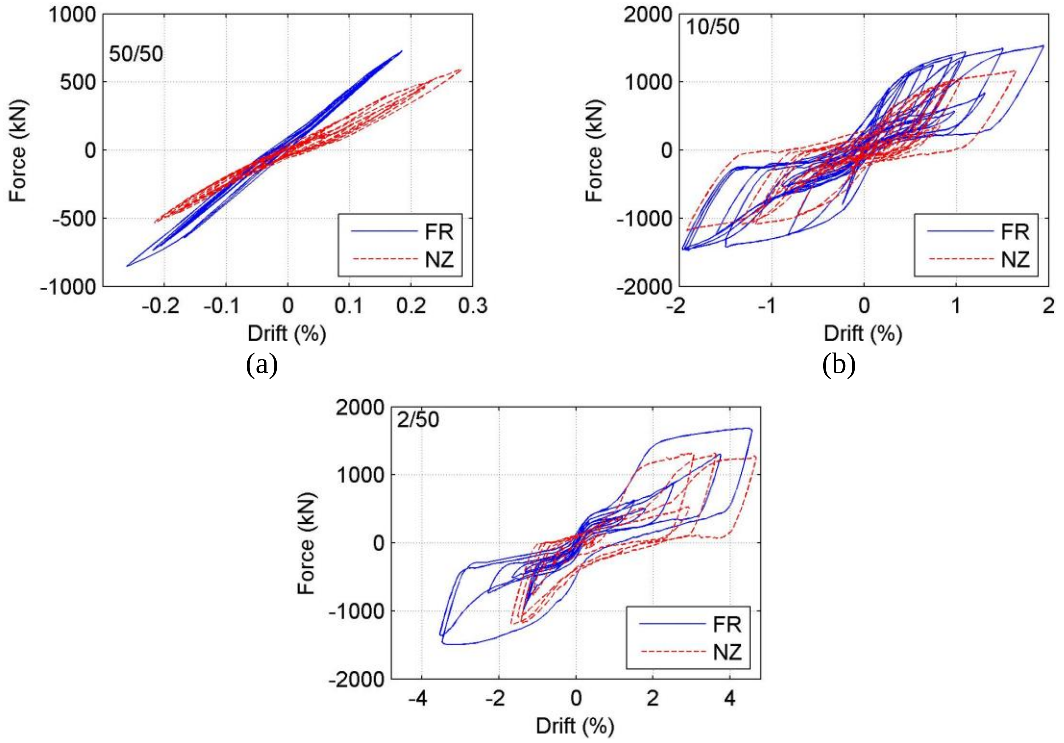
Hazard Level	SAC ground motion	Truncated length (sec)	Amplification factor	PGA (g)
50/50	LA42	2.26	1	0.33
10/50	LA01	15.18	1	0.46
2/50	LA23	10.13	1.3	0.54

The analytical seismic mass for each specimen was determined based on the prototype building which was a two-story adaptation of the three-story SAC building (Gupta and Krawinkler 1999) located in Los Angeles, California. The seismic mass of Specimen NZ was 75% of that of Specimen FR due to the reduced strength of the PT boundary frame resulting from the lack of connection decompression moment as described above in Section 1.

4. EXPERIMENTAL RESULTS

The force vs. roof drift responses for the 50/50, 10/50, and 2/50 tests are shown for both specimens in Fig. 4.1. Fig. 4.1(a) shows that both specimens remained essentially elastic during the 50/50 excitation, meaning that the web plates did not experience significant yielding. Thus, both specimens met the no repair performance objective at this hazard level. This figure also demonstrates the difference in the initial stiffness of Specimens NZ and FR. As previously described, the flange rocking connections of the Specimen FR boundary frame have a higher initial stiffness prior to connection decompression, while the NewZ-BREAKSS connections response with the reduced flexural stiffness of a decompressed connection upon initial loading.

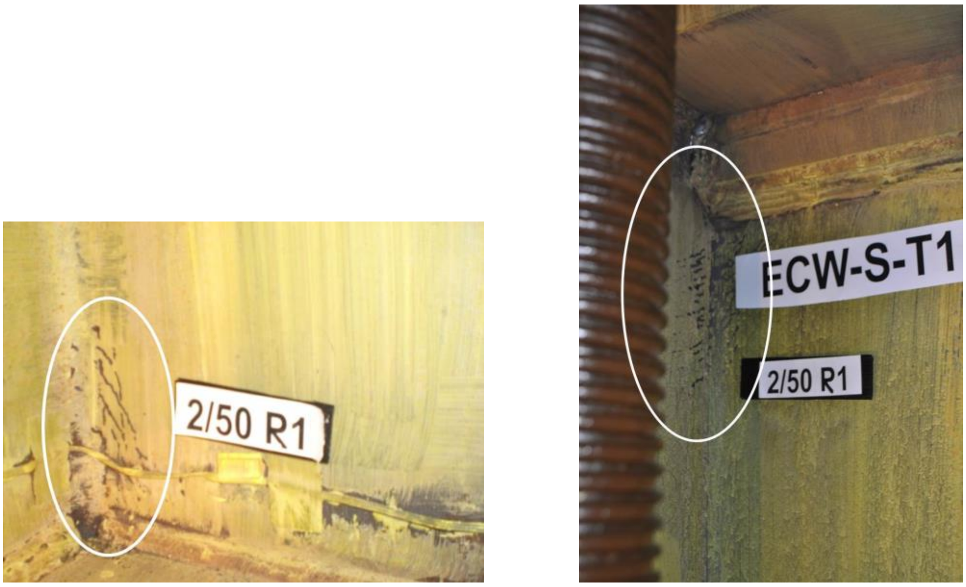
Fig. 4.1(b) shows that both specimens had peak drifts less than 2% during the 10/50 excitation. Since the 10/50 hazard level is assumed to approximate a design-level event for this prototype building, both specimens were able to meet the 2% code-based design level drift limit (ASCE 7-05). This figure also demonstrates the difference in specimen strength. As previously described, the strength of Specimen NZ is approximately 75% of Specimen FR due to the lack of the decompression moment in the initially decompressed NewZ-BREAKSS connections. During the free vibration following the 10/50 excitation both specimens had residual drifts less than 0.2%, indicating that they were both able to recenter at this hazard level. Although significant yielding was observed in the web plates at this hazard level, no significant yielding was observed in the boundary frames of either specimen.



(a) (b) (c)

Figure 4.1 Force vs. roof drift response for (a) 50/50, (b) 10/50, and (c) 2/50 tests

In the 2/50 excitation (Fig. 4.1(c)), both specimens had peak roof drift magnitudes less than 4.7%. It is important to note that no repairs or modifications were made to the specimens between the 10/50 and 2/50 tests; therefore, an actual SC-SPSW would be expected to have a lower peak drift during the 2/50 excitation as the web plates would be undamaged and have no previous yielding prior to the 2/50 event unlike the test specimen. Observations of yielding in the boundary frame at the 2/50 hazard level were very minor and were typically localized near the column web-flange intersection due to high stress concentrations associated with the shear lag effect in the rocking connections (as shown in Fig. 4.2). Both specimens had significant strength and energy dissipation in the 2/50 pseudo-dynamic test with minimal boundary frame damage and very small residual drifts, thus meeting, and even exceeding, the target performance objective at this hazard level.



(a) (b)

Figure 4.2 Observations of localized yielding in Specimen FR in the column webs during the 2/50 test near areas of high stress concentrations at (a) the base of the column and (b) at the middle beam PT connection

5. CONCLUSIONS

Pseudo-dynamic testing was conducted on two full-scale two-story SC-SPSW specimens. The two specimens were physically identical with the exception of the PT beam-to-column connections. Specimen FR utilized flange rocking connections, similar to those that have been used in previous self-centering moment-resisting frame research. Specimen NZ utilized a newly developed PT connection designed to eliminate frame expansion by only rocking about its top flanges. Both specimens incorporated PT column base connection to prevent hinging at the column bases and provide additional recentering capabilities.

The pseudo-dynamic loading simulated excitation at three hazard levels: 50%, 10%, and 2% probability of exceedance in 50 years. The tests indicated that both specimens were able to meet the proposed performance objectives of no repair, repair of web plates only and recentering, and collapse prevention at the 50/50, 10/50, and 2/50 hazard levels, respectively. The results of this large-scale experimental program will be used to validate numerical SC-SPSW models and will be used to inform future design recommendations.

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