Experimental Investigation of Self-Centering Steel Plate Shear Walls

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ABSTRACT

A self-centering steel plate shear wall (SC-SPSW) system has been developed to achieve enhanced performance objectives following earthquakes, including recentering. The SC-SPSW consists of thin steel infill web panels as the primary lateral load resistance and energy dissipation of the system providing a high initial stiffness, where the moment resisting connections of conventional SPSW construction are replaced with post-tensioned (PT) beam-to-column connections that allow the beam to rock about its flanges to provide system recentering.

The system and component behavior of SC-SPSWs have been investigated experimentally through a series of quasi-static and shake table tests. Quasi-static subassembly tests at the University of Washington have been conducted to study the effects of various design parameters on overall cyclic response and component demands. The University at Buffalo experiments focus on third-scale 3-story SC-SPSWs subjected to quasi-static and shake table testing to investigate system behavior. These experiments consider three different PT rocking connection details: 1) connections that rock about the beam flanges, 2) connections that rock about the beam centerline, and 3) an innovative NewZ-BREAKSS connection that rocks about the top beam flange only. The latter two PT connections have been proposed as methods to essentially eliminate floor system damage due to frame expansion that occurs with typical PT connections where the beams rock about their flanges.

INTRODUCTION

Steel plate shear walls (SPSWs) are lateral force resisting systems that utilize thin steel infill plates, referred to as web plates, within a steel boundary frame to provide significant strength and stiffness through the development of tension field action. The web plates provide energy dissipation and substantial ductility through distributed yielding in the direction of the tension field. The low stiffness of thin web plate when unloaded after yielding makes the SPSW system ideal for being paired with self-centering technologies, such that smaller restoring forces are required to return the wall to essentially zero displacement after a seismic event.

A new self-centering SPSW (SC-SPSW) system (Fig. 1) has been developed by combining steel web plates with a steel boundary frame with post-tensioned (PT) beam-to-column connections (Dowden et at. 2012, Clayton et al. 2012). The post-tensioning in the connections is designed to remain elastic and elongates as the connection rotates relative to the column during lateral drift of the building (Fig. 1c), and with proper detailing the beams and columns, referred to as horizontal and vertical boundary elements (HBEs and VBEs), respectively, remain undamaged. This PT elongation provides the restoring forces necessary to recenter the building, which ultimately reduces the costs of repair and provides a more rapid return to occupancy following an earthquake.

SC-SPSW BEHAVIOR

In this research, three different PT HBE-to-VBE connections are being investigated to provide the recentering capabilities of the SC-SPSW system. The behavior of each connection type is discussed below. For purposes of general understanding of this new system, a simple approximation of the cyclic behavior of the SC-SPSW can be described by superimposing the response of the two key components of the system—

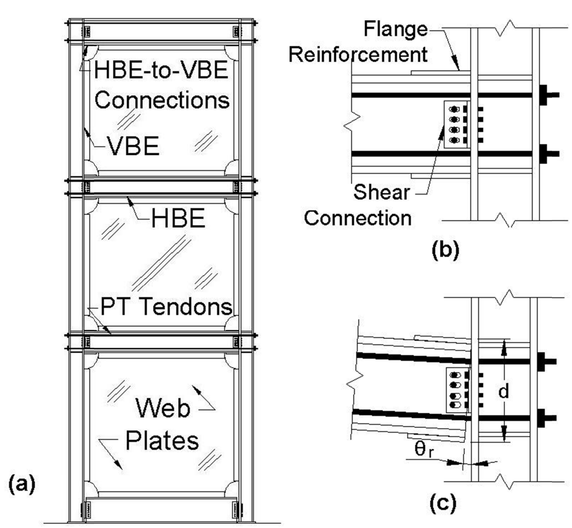


Figure 1. Schematics of (a) SC-SPSW and flange rocking PT HBE-to-VBE connection in its (b) undeformed and (c) deformed configuration.

the web plates and the PT boundary frame (Fig. 2). The idealized web plate has a pinched, tension-only cyclic response (Fig. 2a); actual web plate behavior is more complex than this idealization, and these key differences are discussed in later sections with respect to SC-SPSW experimental results. This is coupled with the elastic cyclic response of the PT frame (Fig. 2b), discussed below, to produce the flag-shaped hysteresis (Fig. 2c) that is characteristic of self-centering systems.

PT HBE-to-VBE Connections

The conventional PT connection as shown in Fig. 1b rocks about its flanges as shown in Fig. 1c. During lateral loading, the moment demand in the connection increases with a stiffness equivalent to that of a fully welded moment-resisting connection until a gap forms in the connection, referred to as the decompression moment, M_d. As the gap opens and the PT strands elongate, the connection responds with a reduced rotational stiffness. If the PT connection and its components remain elastic, the connection returns along the same bilinear path during unloading, resulting in the nonlinear elastic response shown for the flange rocking PT frame in Fig. 2b.

As a gap forms in the flange rocking PT connection, the columns are forced to spread apart, a phenomenon referred to as frame expansion (Garlock et al. 2007). Without careful detailing, this frame expansion can result in significant damage to the floor diaphragm system. Additionally, if frame expansion is not accommodated in the diaphragm detailing, the restraint to columns spreading provided by the slab can result in very large axial demands on the HBE (Garlock et al. 2007, Kim and Christopoulos 2008).

In this research, two new PT connection details have been proposed to eliminate frame expansion while still maintaining the recentering capabilities of the SC-SPSW. The first of these proposed connections is shown schematically in Fig. 3a. In this connection, the HBE-to-VBE joint rocks about a pin at the centerline of the HBE. Note that the PT strands must be terminated along the length of the HBE, otherwise the net elongation of the PT needed to generate recentering forces would be zero. Since the gap in the connection is present in its initial configuration and there is no decompression as with the flange rocking PT connection, as long as the PT remains elastic and does not fully relax, the connection responds in a linear, elastic manner as shown in Fig. 2b.

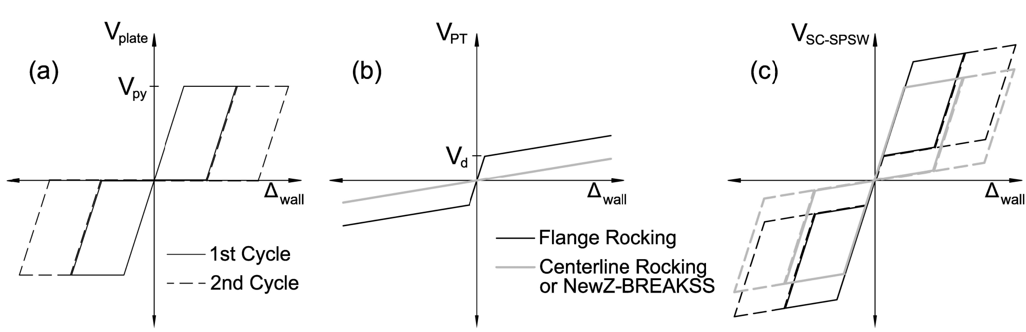


Figure 2. Idealized cyclic behavior of (a) web plate, (b) PT frame, (c) SC-SPSW.

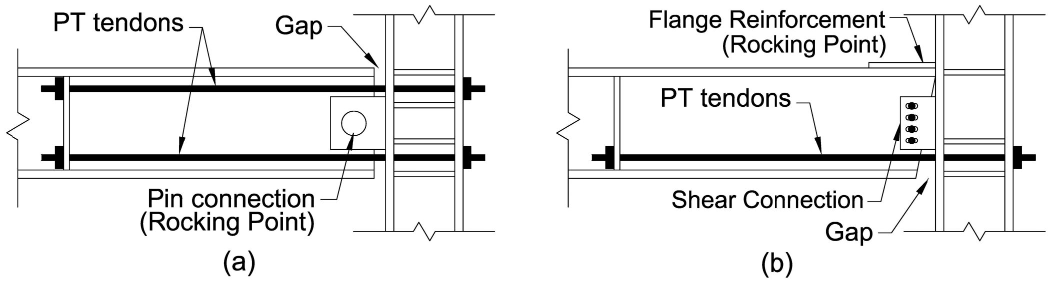


Figure 3. (a) Centerline rocking connection, (b) NewZ-BREAKSS connection.

Similarly, a new connection inspired by moment-resisting connections developed in New Zealand has been proposed, referred to as the NewZ-BREAKSS connection, and is schematically shown in Fig. 3b (Dowden and Bruneau 2011). This connection rocks about the top flanges of the HBE and also seeks to eliminate frame expansion thus mitigating damage to the floor slab. Again, the PT strands must be terminated along the length of the HBE in order to generate PT recentering forces. If the PT elements remain elastic and do not fully relax, then as with the centerline rocking connection, this results in a linear elastic PT frame response as shown in Fig. 2b.

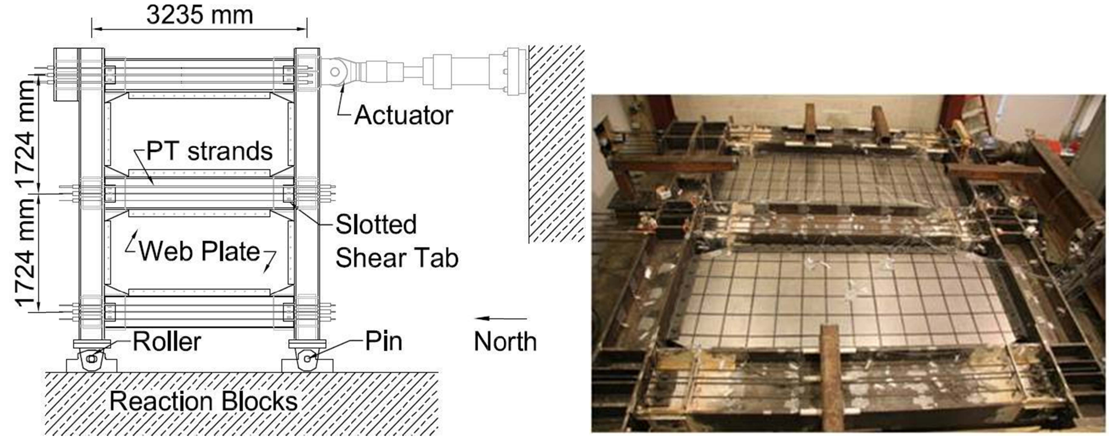
UNIVERSITY OF WASHINGTON EXPERIMENTAL TESTING

Large-scale SC-SPSW subassemblies have been tested at the University of Washington. 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 (Fig. 1b) as described previously.

Test Setup

A schematic of the test setup is shown in Fig. 4a. The 2-story configuration of the setup was used to simulate the boundary conditions for an intermediate HBE (middle HBE in Fig. 4), where the web plates above and below the HBE induce an effective post-tensioning in the HBE due to pull-in of the VBEs ($P_{HBE(VBE)}$). The SC-SPSW subassembly measures 3235 mm wide (centerline VBE dimension), with story heights (HBE centerline dimensions) of 1724 mm.

Frame expansion, discussed earlier, was accommodated in the physical model with a roller under the left VBE, allowing the frame to expand horizontally without imposing additional compressive forces on the middle HBE due to VBE restraint at its base. For similar purposes, the top and bottom anchor HBEs also had PT HBE-to-VBE connections, such that the gap opening, and thus the beam growth, at these levels were similar to the middle HBE.



(a) Schematic of test setup **(b) Specimen before testing**

Figure 4. UW SC-SPSW subassembly test setup

Shear forces at the PT HBE-to-VBE connections were transferred through slotted shear tab connections. Long slotted bolt holes were used in the shear tab to allow for connection rotation. The HBE flanges at the connections were reinforced to protect against local damage due to the large compressive forces acting on the flanges after decompression. Also, corner cutouts were provided in the web plates to prevent localized damage in the plate as a gap forms in the connection.

The boundary frame elements were of A992 steel and were designed to remain elastic during testing so that they could be reused for multiple tests. The PT strands were 13 mm diameter Grade 270 seven-wire strand with reusable barrel anchors at each end. The web plates were of ASTM A1008 steel with yield strengths of approximately 180 MPa and 240 MPa for the 20 and 16 gage plates (0.92mm and 1.52mm thick), respectively. In all but one of the specimens, the web plates were connected to the boundary elements via a bolted fishplate connection. The bolted web plate-to-fishplate connection allowed for the yielded web plates to be easily removed and replaced following each test. One specimen was tested with a more conventional welded web plate-to-fish plate connection to compare how the web plate connection affects specimen behavior. Further details on the test setup can be found in Winkley (2011).

Specimen Descriptions

The test program (Table 1) included variations in the web plate thicknesses, t_w, initial PT force at each HBE, T_o, and number of PT strands in each connection, N_s, to study the effects of web plate and PT connection strength and stiffness. The naming convention for the test specimens is the number of PT strands per HBE (e.g. “8s"), followed by the initial total PT force at each HBE in units of kips (e.g. “100k"), followed by the web plate gage thickness or thicknesses (e.g. “16Ga"), if applicable. All specimens utilized the bolted web plate-to-fishplate connection, with the exception of Specimen 8s10k20GaW, which utilized a welded web plate-to-fishplate connection as indicated by the “W” added to the specimen name.

Table 1. SC-SPSW subassembly specimens

Specimen Name	N_s	T_o (kN)	t_w(mm)		Web plate-to-fish plate conn. type	Load protocol
			1st story	2nd story		
8s100k	8	445	--	--	Bolted	LP-BF
6s75k	6	334	--	--	Bolted	LP-BF
8s100k20Ga	8	445	0.92	0.92	Bolted	LP1
8s100k16Ga	8	445	1.52	1.52	Bolted	LP1
6s75k20Ga	6	334	0.92	0.92	Bolted	LP1
6s75k16Ga	6	334	1.52	1.52	Bolted	LP1
8s100k20Ga-2	8	445	0.92	0.92	Bolted	LP2
8s100k16Ga20Ga	8	445	1.52	0.92	Bolted	LP2
8s100k20GaW	8	445	0.92	0.92	Welded	LP2

Instrumentation and Displacement History

Instrumentation was installed on the specimen to measure applied loads, global displacements, gap rotations, PT forces, and HBE and VBE strains. The cyclic displacement history for the tests (LP1) were a modification of ATC-24 (ATC 1992), similar to the history used in previous SPSW experiments by Vian et al. (2009). An alternate load protocol (LP2) was used for some of the later tests, as indicated in Table 1. This load protocol had fewer cycles at small drift levels. Since the specimens without web plates (8s100k and 6s75k) were expected to remain elastic during the entire test, a simplified load protocol (LP-BF) was used consisting of two cycles each at target peak drifts of 0.5%, 1%, and 2% and one cycle at 3% drift.

Experimental Results and Observations

Comparison of web plate thicknesses

As shown in Fig. 5, for specimens with the same number of PT strands and initial PT force, an increase in web plate thickness results in a proportional increase in specimen strength and energy dissipation as expected. When comparing the unloading portion of the hysteretic responses shown in Fig. 5, specimens with web plates (6s75k20Ga and 6s75k16Ga) have additional hysteresis below the unloading portion of the bare PT frame (6s75k) response. This additional hysteresis suggests that the web plate has some compressive strength that is not accounted for in the idealized tension-only behavior assumed in Fig. 2. This compressive strength increases as the web plate thickness increases, ranging from 10-20% of the web plate tension field strength (Clayton et al. 2011). Further research is being done to understand and better quantify this characteristic of web plate behavior. This additional hysteresis in the web plate during unloading also provides some resistance to recentering as suggested by the increase in residual drift at zero-load as the web plate thickness increases; however, with the exception of the negative loading direction of Specimen 6s75k16Ga, the specimen with the thickest web plates and lowest PT connection strength and stiffness, all test specimens were able to recenter with residual drifts less than 0.2% at zero-load (Clayton et al. 2011).

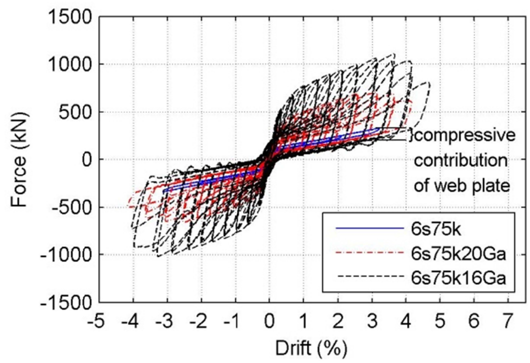


Figure 5. Comparison of specimens with different web plate thicknesses.

Comparison of PT connection designs

Fig. 6 shows a comparison of the responses of two specimens with the same web plate thicknesses but different number of PT strands and initial PT force. As expected, an increase in the total cross-sectional area of the PT strands results in a proportional increase in the recentering stiffness of the specimen during unloading, due to the increase in rotational stiffness of the decompressed PT connections (Clayton et al. 2011, 2012).

Comparison of web plate-to-fishplate connection types

The typical failure mode of specimens with the bolted web plate-to-fishplate connections was tearing of the web plate along the entire length of the clamping bar at the bottom of the first story (Fig. 7a). Tearing was typically initially observed between 2.5 to 3% drift. This tearing is believed to be due to the out-of-plane buckling of the web plate at this location as the tension field formed and re-formed during cyclic loading. However, at the end of testing, the specimen with the welded web plate-to-fishplate connection had tearing of the web plate along the entire length of the VBEs in both stories (Fig. 7b). Initial tearing was first observed at the toe of the weld near the rocking PT HBE-to-VBE connection and tearing propagated outside of the heat affected zone of the weld. The welded specimen (8s100k20GaW) did have a lower strength capacity, approximately 85% of the bolted specimen capacity, and earlier onset of strength degradation due to the initiation of tearing at lower drift demands; however, due to the slower propagation of tearing along the HBEs, the welded specimen did have a larger drift ductility.

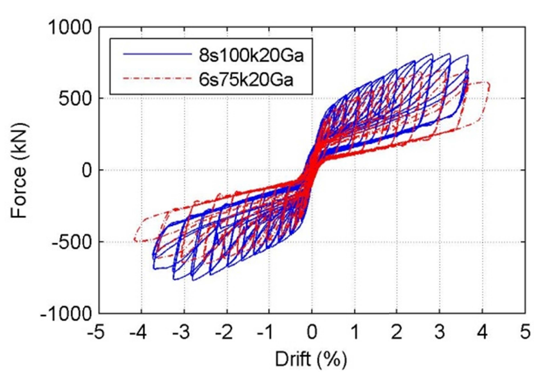


Figure 6. Comparison of specimens with different PT designs

(a) **(b)**

Figure 7. Web plate tearing along (a) bolted web plate connection of the bottom HBE at 4% drift and (b) welded web plate connections along VBEs at 5% drift.

Comparison with analytical models

Analytical nonlinear finite element models of the test specimens were created in OpenSees (Mazzoni et al. 2006). The web plates were modeled using the strip method and the rocking PT connections were modeled using a series of compression-only spring elements as described in Clayton et al. (2012). The cyclic behavior of the strip material was modeled using the idealized tension-only behavior, as suggested by the *AISC Design Guide 20* (Sabelli and Bruneau 2007), and also using a tension-only material coupled in parallel with an elastic-perfectly plastic, compression-only material with a compressive strength equivalent to 25% of the tension yield strength, as suggested by the experimental results. Both strip materials in OpenSees were modeled to have a backbone curve that matched the monotonic tension coupon tests of the actual web plate material.

Fig. 8 shows comparison of the experimental response of Specimen 8s100k16Ga with the OpenSees (OS) models using the tension-only and tension-and-compression strip materials. The OpenSees models shown here were only subjected to cycles at 1% and 2% drift demands for purposes of comparison. The OpenSees model utilizing the tension-and-compression strip material appears to more closely match the unloading and reloading path of the experimental hysteresis. As previously mentioned, further research is being done to better quantify this compressive contribution and develop methods of modeling this phenomenon.

Also both OpenSees models underestimate the ultimate strength of the experimental specimen. This is believed to be due to strain hardening of the web plate as it yields in alternating directions of the tension-field during cyclic loading in both directions. Further research is also being done to account for this accumulation of plastic strain during cyclic, bi-directional yielding of the plate in the strip model. Overall, the relatively simple OpenSees analytical models match well with the observed experimental response.

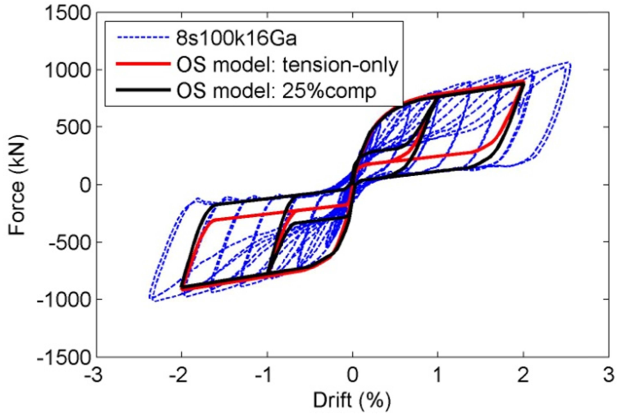
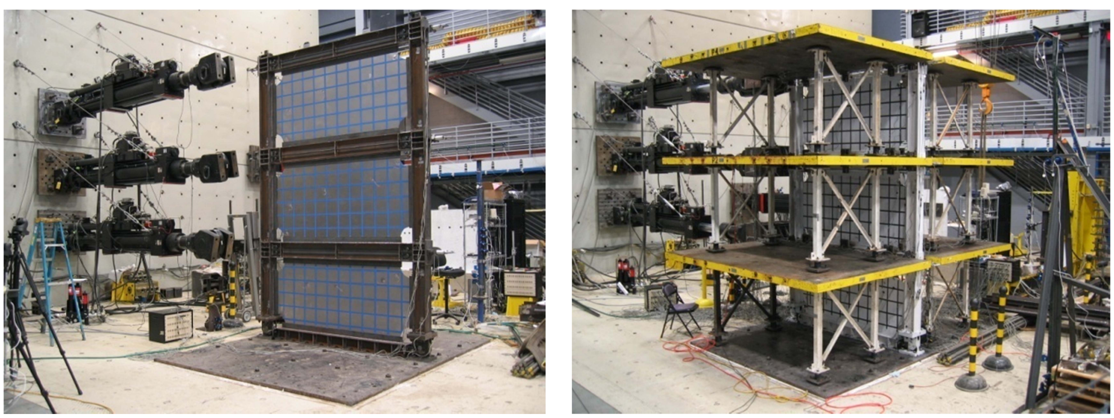


Figure 8. Comparison of experimental response and OpenSees analytical model response.

UNIVERSITY AT BUFFALO EXPERIMENTAL TESTING

Experimental testing of one-third scale single-bay three-story test specimens are currently underway at the University at Buffalo to investigate the system performance of SC-SPSWs. The full experimental program consists of quasi-static and shake-table testing to investigate SC-SPSW system performance with three different rocking joint configurations noted earlier. This paper presents preliminary quasi-static test results of an SC-SPSW system with rocking about the HBE flanges; which reflects the current level of test completion at the time of this paper submission. The test specimen and setup is shown in Fig. 9. Future testing will be done on specimens that employ the proposed centerline rocking and NewZ-BREAKSS connections previously described to eliminate frame expansion.



(a) Test Frame Before Whitewash **(b) Test Set-Up**

Figure 9. UB Test Specimen

The test specimen consists of a W8x18, W8x15, W8x18 (Grade A572) at level 3, 2, 1 respectively and W6x25 VBEs. Infill plate thickness consist of 26 GA, 24 GA, 22 GA (ASTM A1008) at level 3, 2, 1 respectively welded to steel fish plates along the boundary frame. Connection to the strong floor is provided by steel clevis & pin connection at the base of the VBEs to allow free rotation and a W6x20 HBE anchor beam bolted to the foundation plate. PT monostrands consisting of 13 mm (1/2 in.) diameter 1860 MPa (270 ksi) strands are provided at mid-depth of the HBE, one each side of the HBE web with an initial PT force of approximately 20% of the yield strength of the PT strands. The dimensions of the test specimen consist of HBE clear spans of 2134 mm (84 in.), level 1 HBE height of 1191 mm (46.875 in.) from centerline of foundation clevis connection and floor-to-floor HBE heights of 1289 mm (50.75 in.) at level 2 and 3. The test setup consists of (3) MTS 244.51 actuators one at each floor level and the use of a self-supporting gravity frame system (GFS) developed at UB that provides no in-plane resistance but provides out-of-plane stiffness to brace the test specimen. A displacement control loading based on a modified ATC 24 loading protocol was used up to 4% drift.

UB Experimental Preliminary Test Results

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 of the GFS 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.

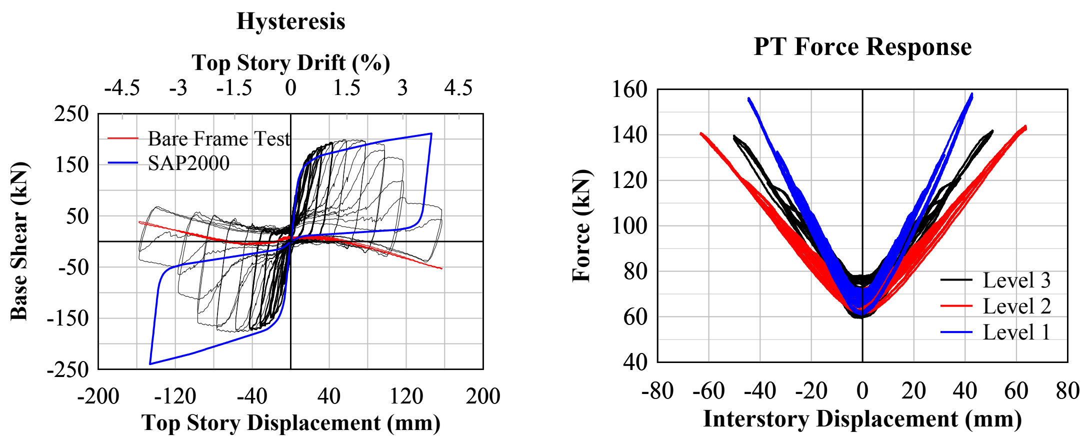


Figure 10. Experimental Results: (a) base shear and (b) PT force vs. displacement

From the hysteresis shown in Fig. 10a it observed that self-centering response is achieved. Separation of the infill plate from the boundary frame occurs at around 2% drift as indicated by the reduction of base shear capacity. With the exception of the negative stiffness of the experimental results and the compressive strength of the web plate at zero displacement noted earlier, the comparison to SAP2000 (using an idealized tension-only hysteretic model for the web plates) is comparable. Note that the negative stiffness observed is a consequence of the displacement shape imposed to the specimen, which has lead to undesirable actuator interaction across the stories. A forced controlled testing protocol will be used for the subsequent tests to eliminate this artifact. From observation of the PT force response (Fig. 10b), the PT strands remain elastic. Some PT force loss is observed which is attributed to anchor seating and strand relaxation. A typical test panel after testing is shown below in Fig. 11b.

The remainder of the quasi-static phase and the shake-table phase for the three different PT connection types is anticipated to be finished by summer 2012.

(a) Before Testing **(b) 4% Drift**

Figure 11. Level 2 North Elevation Infill Panel

CONCLUSIONS

The SC-SPSW is a lateral force resisting system that has been developed to reduce damage and repair costs following earthquakes by providing adequate strength stiffness, energy dissipation, and recentering capabilities. The SC-SPSW system is currently being investigated experimentally through large-scale subassembly tests at the University of Washington and third-scale three-story quasi-static and shake table tests at the University at Buffalo. The test program and preliminary results of these experiments were presented. The experimental results show that the SC-SPSW is capable of recentering and has cyclic behavior that matches well with that suggested by principles of mechanics and finite element models. Furthermore, two new PT connection details have been proposed to eliminate floor slab damage that is caused by typical PT connections rocking about their flanges. These new details will be tested experimentally in future tests at the University at Buffalo.

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