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CYCLIC AND DYNAMIC TESTING 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; namely system re-centering and concentration of energy dissipation in easily replaceable elements. The SC-SPSW consists of replaceable thin steel web panels as the primary lateral load resistance and energy dissipation elements of the system, whose replacement is facilitated by the presence of post-tensioned (PT) beam-to-column rocking connections that provide system recentering capabilities. The system behavior of SC-SPSWs have been investigated experimentally through a series of third-scale 3-story SC-SPSWs subjected to quasi-static cyclic and dynamic shake table tests at the University at Buffalo (UB). Typical test results performed at UB are presented for both static and dynamic tests. These experiments consider three different PT rocking connection details: 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. These experimental results presented are part of a collaborative research effort with the University of Washington (UW) on SC-SPSWs. The tests conducted at UB provide new knowledge about the cyclic and dynamic behavior of SC-SPSWs which provide key insight in the fundamental behavior and system performance of this type of innovative system.

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A self-centering steel plate shear wall (SC-SPSW) system has been developed to achieve enhanced performance objectives following earthquakes; namely system re-centering and concentration of energy dissipation in easily replaceable elements. The SC-SPSW consists of replaceable thin steel web panels as the primary lateral load resistance and energy dissipation elements of the system, whose replacement is facilitated by the presence of post-tensioned (PT) beam-to-column rocking connections that provide system recentering capabilities. The system behavior of SC-SPSWs have been investigated experimentally through a series of third-scale 3-story SC-SPSWs subjected to quasi-static cyclic and dynamic shake table tests at the University at Buffalo (UB). Typical test results performed at UB are presented for both static and dynamic tests. These experiments consider three different PT rocking connection details: 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. These experimental results presented are part of a collaborative research effort with the University of Washington (UW) on SC-SPSWs. The tests conducted at UB provide new knowledge about the cyclic and dynamic behavior of SC-SPSWs which provide key insight in the fundamental behavior and system performance of this type of innovative system.

Introduction

A Self-Centering Steel Plate Shear Wall (SC-SPSW) is a robust, ductile, and easily repairable system that will reduce life-cycle costs for buildings located in areas of high seismicity [1,2]. Tests of one-third scale single-bay three-story specimens have been conducted at the University at Buffalo (UB) to investigate the system performance of SC-SPSWs. The full experimental program consisted of quasi-static and shake-table testing to investigate SC-SPSW system performance with three different rocking joint configurations and two different infill plate configurations, shown in Fig.1 and Fig. 2 respectively. To address the issues related to post-tension (PT) boundary frame expansion (i.e. “beam growth”) in top and bottom Flange-Rocking self-centering systems [3,4], the Centerline and NewZ-BREAKSS [5] rocking joint connections are two new connections proposed to essentially eliminate beam growth.

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This paper presents selected key quasi-static and shake table test results of an SC-SPSW system as a sample of typical results conducted at UB.

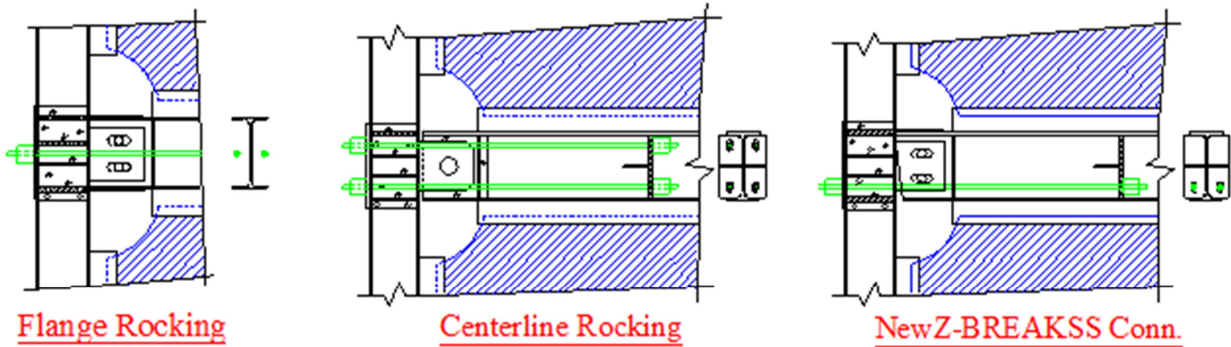


Figure 1. Test frame rocking joint configurations

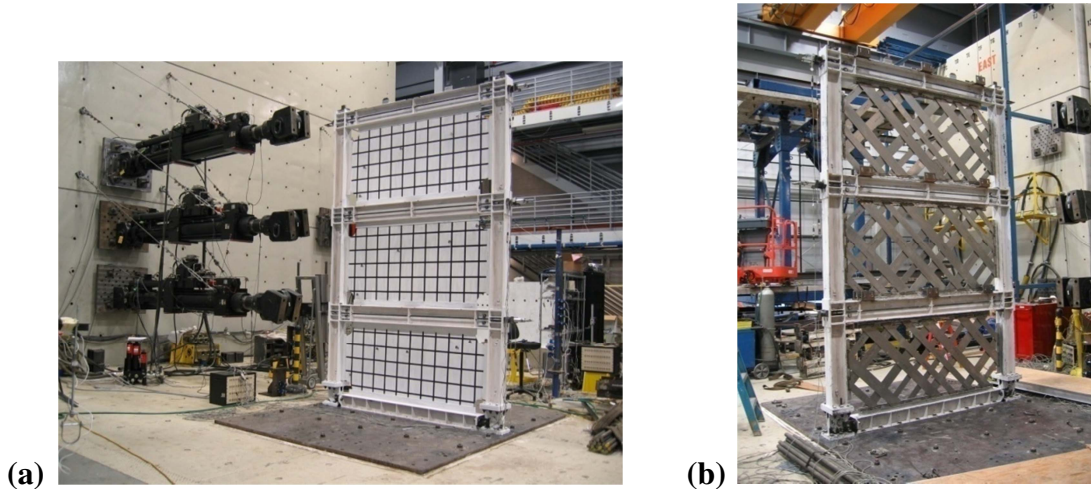


Figure 2. (a) Infill web plate; (b) Infill web strips

Quasi-Static Tests

The test specimen had W8x18, W8x15, W8x18 (Grade A992) horizontal boundary elements (HBEs) at level 3, 2, 1 respectively and W6x25 vertical boundary elements (VBEs). Infill web plate and strip thicknesses consisted of 26 GA, 24 GA, 22 GA (ASTM A1008) at level 3, 2, and 1, respectively, welded to steel fish plates along the boundary frame. Connection to the strong floor was provided by a steel clevis and pin connection at the base of each VBE to allow its 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 were provided, one on each side of the HBE web, with an initial PT force ranging between approximately 20% to 30% of the yield strength of the PT strands. The HBEs had clear spans of 2134 mm (84 in.). Level 1 had a height of 1089 mm (42.875 in.) from centerline of the foundation clevis connection to centerline of HBE, and floor-to-floor heights (measure from mid-depth of each HBEs) of 1289 mm (50.75 in.) at level 2 and 3. The quasi-static test setup consisted of three MTS 244.51 actuators (one at

each floor level) and a self-supporting gravity frame system (GFS) developed at UB that contributed no in-plane resistance but provided out-of-plane stiffness to laterally brace the test specimen (the GFS floor mass plates also served to provide inertia forces in the dynamic shake table tests). A top story displacement control loading protocol based on a modified ATC 24 [6] in conjunction with a slaved force control at the intermediate floor levels was used for the quasi-static tests.

Quasi-Static Experimental Key Results

Instrumentation was provided to record global and local responses. String pots were provided at each floor level of the GFS to determine global displacements. Strain gages and linear potentiometers were provided on the test specimen to determine local response. Load cells were provided at the PT anchorage locations to monitor PT forces. Actuator forces were recorded from the actuator load cells to determine story and base shears. A typical infill web plate panel after testing is shown in Fig. 3.

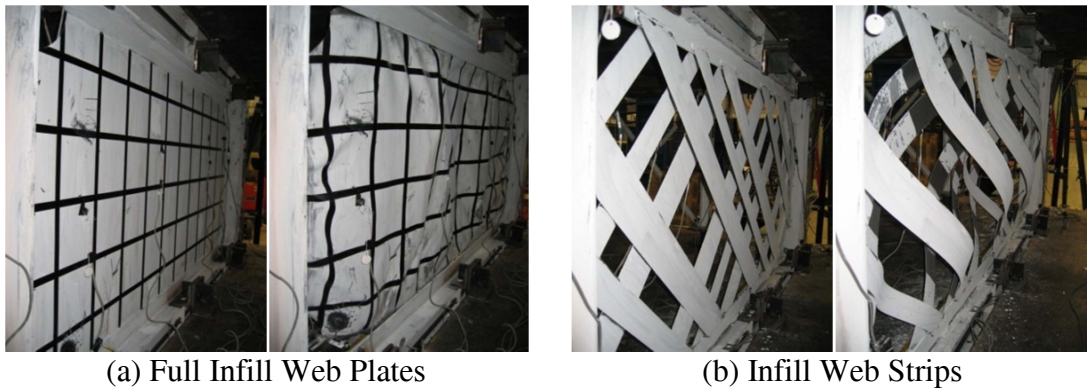


Figure 3. Level 2 north elevation infill panel.

Experimental hysteresis results are shown in Fig. 4 for the NewZ-BREAKSS test specimen with a full infill plate and an infill strip configuration along with the respective bare frame test. These show that some compression strength is developed by the infill web plates due to the random folding of the plate as it is pushed through the zero drift point after some cycles; this was observed to affect re-centering (which was not readily apparent at the time of design of the test specimens). This compression strength observed in the UB tests is observed to be approximately 25% to 30% of the yield strength of the infill plate (note that SC-SPSWs would be expected to “fully” re-center upon removal of infill web plate for replacement after an event regardless of residual drift levels). An investigation of this phenomenon was performed by [7]. To overcome this equivalent compression strength of the web plate, the PT boundary frame could be designed taking this into account. Alternatively, SPSW frames with infill strips could be used, as these behaved like the idealized tension-only behavior typically assumed for SPSWs. Note that for this alternative, some equivalent compression strength of the SPSW system was observed in the tests. However it was due to friction in the PT boundary frame and its connection to the steel mass plate diaphragm and not due to the infill web strips.

Infill web plate separation from boundary frame started to develop at approximately 2% drift, propagating from the plate corners; no separation occurred in the specimens with infill strips, tested up to 5% drift for the flange rocking frame, 6% for the NewZ-BREAKSS frame and 9% for the centerline rocking frame. Fig. 4 also shows that analytical results obtained with SAP2000 [8] matched well the experimental results.

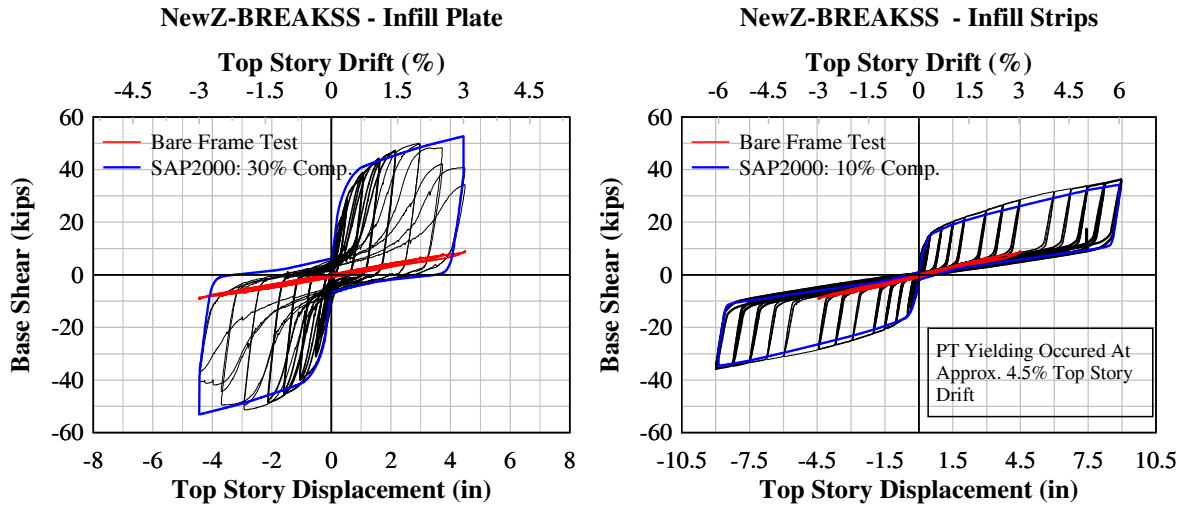


Figure 4. Quasi-static experimental hysteretic response

Shake Table Tests

The test setup for the shake-table tests (Fig. 5) using the gravity mass frame system was identical to that used for the quasi-static tests. Additionally, all design parameters remained unchanged from the quasi-static tests (boundary element frame members reused from static tests); only the lateral loading parameters were modified to reflect shake table testing. Moreover, the post-tension strand material and the light gage infill web plate material for the quasi-static and shake table tests were all ordered at the same time prior to commencement of the UB test phases to ensure continuity in material mechanical properties for both the quasi-static and shake table tests.

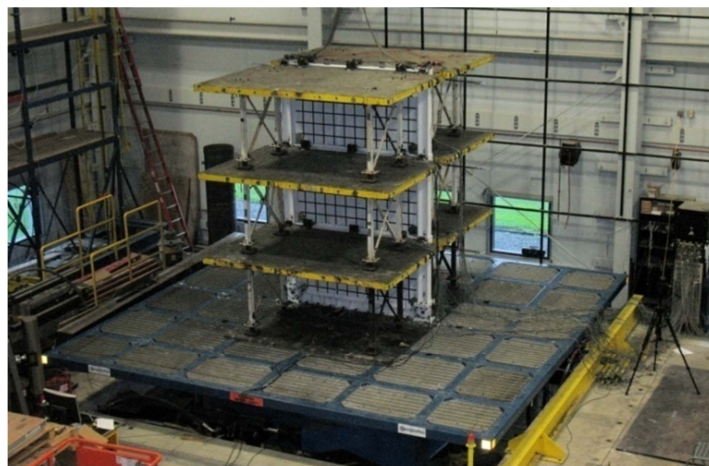


Figure 5. Shake table setup

In this case, of the three different test frames used in the quasi-static test phase, only two of the frames were tested, namely: the test frame with rocking connection about beam flanges, and the test frame with the NewZ-BREAKSS rocking connection. Each test frame consisted of three different test configurations: 1) full infill web plate, 2) bare frame and 3) infill web strips; similar to what was done with the quasi-static tests. A total of six tests were performed for the shake-table phase.

A spectra-compatible synthetic ground motion was used targeting a 10% in 50 year seismic hazard (Design Earthquake) ground motion for the Los Angeles, CA region. The ground motion was generated using the Target Acceleration Spectra Compatible Time Histories (TARSCTHS) code [9]. The target design spectrum is based on the 2009 NEHRP provisions for an assumed 5% damping and a building site with a soil Site Class D characteristics (stiff soil). The synthetic seed ground motion for use in the shake table tests was time compressed following similitude rules for the 1/3 scale test specimens. The loading protocol consisted of amplitude scaling the synthetic ground motion beginning with low level amplitude intensities followed by subsequent ground motions with increased scaled amplitudes. White noise identification tests were conducted at the start of each test, in between ground motion tests and at the conclusion of each test to obtain initial and changes in dynamic properties over the course of testing. Periodic pauses were performed from testing to monitor infill web plate damage and to make general observations of the test specimens. Testing continued up to the safe working limits of the shake table by monitoring the overturning moment and base shear demands of the test specimen response during each test. The loading protocol was modified as needed during the course of each test for safety reasons.

Shake-Table Experimental Key Results

Experimental hysteresis results showing the full loading history (i.e. cumulative infill web plate damage) for the NewZ-BREAKSS test frame is shown in Fig. 6. Of significance is that the test specimen fully recenter in all load cases where the recentering threshold is established at 0.2% drift (which is the accepted out-of-plumb construction tolerance accepted by current building code standards). From observation of the plots, similarly observed in the quasi-static tests, compression strength is developed by the infill web plates as the hysteresis plots do not have a fully pinched behavior. By observation of the quasi-static test results alone, this compression contribution of the infill web plate was thought to have a noticeable influence on the frame recentering stiffness. However, from the top story residual drift history shown; it is observed that recentering is still achieved. The compression stiffness of the infill web plate does not appear to have a significant influence on frame recentering. This may be due to the fact that the inertia forces that develop help to overcome the compression stiffening effect observed in the static tests, but also because of the many smaller cycles of excitations that follow large cycles and occur after the significant stage of the compression strut effect (which occur when the buckled plate develop a sort of “corrugated” shape upon reaching plastic deformations that exceed previous deformations reached). Similar results were observed with the Flange Rocking frame.

The test specimens with full infill plate performed as intended. Boundary frame remained elastic and recentering was achieved. Infill web plate separation from the boundary frame was observed to be minor. However the maximum drift for both test frames with the full

infill web plate configuration was approximately 2%. Further testing to reach larger drifts was not performed due to reaching the safe operating limits of the shake table.

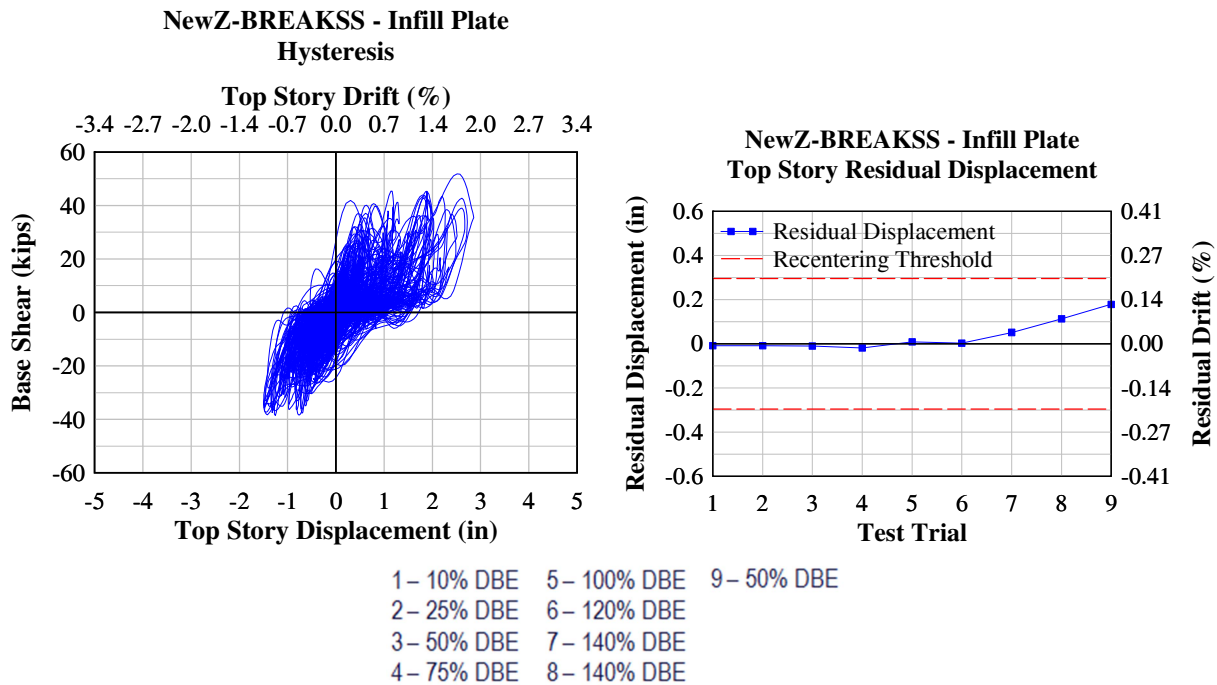


Figure 6. Global response – full loading history – infill web plates

Additionally, as was observed in the quasi-static tests, the test frames with the infill web strips essentially exhibit a tension-only behavior with essentially no compression stiffness effects. This was observed with the shake table tests by observation of a pinched hysteretic response (i.e., approximately zero base shear demand at the zero drift location). As anticipated for a tension-only system with PT rocking connections, recentering was achieved for all load cases. The test specimens with infill strips performed as intended. Boundary frame remained elastic and recentering was achieved. The maximum drift was approximately 6% and 3% for flange rocking and NewZ-BREAKSS frames respectively showing that at MCE level drifts the PT boundary frame performed well.

Conclusions

The UB experimental tests show that SC-SPSWs systems are a viable alternative lateral force resisting systems appropriate for buildings in regions of high seismicity. The quasi-static tests provided clear behavior differences between the infill web strip or infill web plate configurations, as well as with the response of the PT boundary frame by itself. The shake table tests conducted have provided key insights into the seismic response of SC-SPSW systems. In particular, the recentering stiffness was found to not be sensitive to the compression stiffening of the full infill web plate, contrary to what had been initially observed during the static tests. The experimental work performed at UB investigated three different PT rocking joint connections, two different infill plate configurations conducted under quasi-static and dynamic shake table testing to better understand and inform design on SC-SPSWs.

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