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Cyclic Testing of Light-Gauge Steel Plate Shear Walls

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Summary

This paper describes the prototype design, specimen design, experimental set-up, and experimental results of tests on three light-gauge steel plate shear wall (SPSW) concepts. Prototype light-gauge steel plate shear walls are designed as seismic retrofits for a hospital structure in an area of high seismicity and emphasis is placed on minimizing their impact on the existing framing. Three single story test specimens are designed using these prototypes as a basis, two specimens with flat infill plates (thicknesses of 0.9 mm) and a third using a corrugated infill plate (thickness of 0.7 mm). Connection of the infill plates to the boundary frames is achieved through the use of bolts in combination with industrial strength epoxy or welds, allowing for mobility of the infills if desired. Testing of the systems is done under quasi-static conditions. It is shown that one of the flat infill plate specimens, as well as the specimen utilizing a corrugated infill plate, achieve significant ductility and energy dissipation while minimizing the demands placed on the surrounding framing. Experimental results are compared to monotonic pushover predictions from computer analysis using a simple model and good agreement is observed.

Introduction

Light-gauge steel plate shear walls could provide engineers with an effective option for the seismic retrofit of older buildings. The concept is to create a system that is strong enough to resist the necessary seismic forces and yet light enough to avoid having to heavily reinforce existing framing due to the increased demands the retrofit strategy may place on it. Furthermore, an interest exists in creating systems that could be installed with minimum disruption to the function and occupants of an existing building, and, in the context of the seismic retrofit of hospitals, that could be modular to facilitate relocation of the light-gauge infills as floor plans are rearranged (something that often occurs in hospitals). This paper describes the design and quasi-static testing of three such light-gauge steel plate shear wall systems. Specimen design is based on accepted analytical representations for steel plate shear walls which, when allowed to buckle in shear and form a diagonal tension field, have been shown to be a useful seismic energy dissipation system. (Timler and Kulak, 1983, Driver et al., 1997, Elgaaly 1998, Rezai 1999, etc.)

Prototype Design

Two prototype light-gauge steel plate shear walls were designed as seismic retrofit options for a prototype demonstration hospital (Yang and Whittaker, 2002). This hospital is a four-story steel framed building with plan dimensions of 83.5 meters in the east-west direction and 17.2 meters in the north-south direction. The test specimens were designed to retrofit the north-south frames and they included the flexible web-angle beam-to-column connections. To minimize the forces applied to the existing framing by the yielding infill plates (i.e., to avoid having to strengthen the existing columns), it was decided that every line of gravity framing in the north-south direction would be retrofitted. The middle bay (between framing lines 3 and 4) was arbitrarily chosen as the location for the retrofit on each frame line.

The equivalent lateral force procedure of FEMA 302 (FEMA 1997) was used to calculate a design base shear. Tributary gravity loads for one bay of north-south framing were determined. These and a portion of the design live load were used as the active seismic weight for a single gravity frame line. The resulting seismic coefficient, C_s, was determined to be 0.58 and the corresponding base shear tributary to one of the gravity frames was approximately 1420 kN.

For the calculated design base shear, plate thicknesses for both flat and corrugated plate scenarios were found using the procedure described in Berman and Bruneau (2003a). This procedure is based on development of the plastic collapse mechanisms for the strip model, formulated by Timler and Kulak (1983), and implemented in a steel design standard (Figure 1). Minimum required plate thicknesses at the first floor level were found to be 22 Gauge (0.75 mm or 0.0295 in) for the corrugated infill plate (assuming a corrugation profile equal to that of Type B steel deck), and 20 Gauge (1.0 mm or 0.0396 in.) for the flat infill plates. A yield stress of 380 MPa (55 ksi) was assumed in both cases. Note that tension field action can only develop in the direction parallel to the corrugations, and that pairs of retrofitted bays (with corrugations oriented in opposite directions) are required to implement this system.

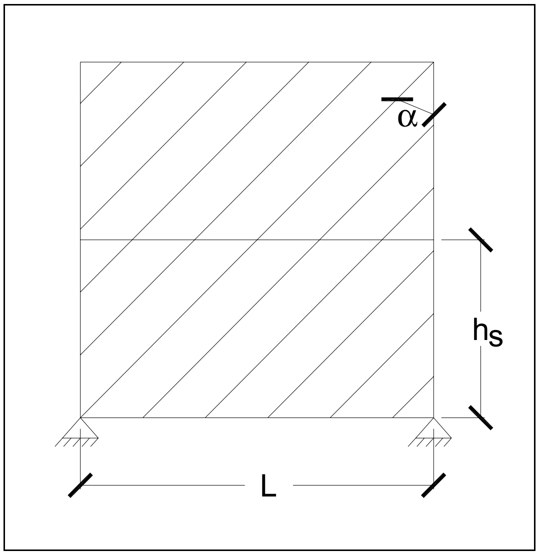

Figure 1. Example of Generic Strip model

Test Specimen Design

Using the prototype designs as a basis, three light-gauge steel plate shear wall specimens were designed for quasi-static testing in the Structural Engineering and Earthquake Simulation Laboratory

(SEESL) at the University at Buffalo (two flat infill plate specimens with different infill-to-boundary frame connections, and one corrugated specimen). The infill plate thicknesses for the specimens were selected to be identical to those for the prototype retrofits for the demonstration hospital. The 2:1 (L:h) aspect ratio of the prototype was also maintained for the specimens. The bay width and story height of the specimens were designed to be 3660 mm (12 ft.) and 1830 mm (6 ft.), respectively (i.e., approximately ½ scale from the prototypes).

Strip models of each specimen using a yield stress of 380 MPa for the infill material were developed and, using the results of pushover analyses, boundary frames for the infills were designed to remain elastic with a safety factor of 2.5, resulting in W 310 x 143 columns and W 460 x 128 beams. The beam-to-column connections using L 203 x 102 x 12.7 angles on both sides of the beam web were welded to the beam and bolted to the column flanges.

Connecting the infill plates to the surrounding frame members proved difficult and a number of different options were explored, some of which are detailed in Berman and Bruneau (2003b). In the case of the flat infills, two alternatives were developed which resulted in Specimens F1 and F2. To test the effectiveness of SPSW with corrugated infills, Specimen C1 was developed, in which the corrugated infill is connected to the boundary frame using the Hysol 9460 epoxy and intermediate L 152 x 102 x 19 angles. For more detailed information on the specimen design and infill connections used, see Berman and Bruneau (2003b).

The test setup is shown in Figure 2. Specimens are mounted on large clevises attached to a foundation beam, itself tensioned to the strong floor of the SEESL. Lateral load was applied at the top of the wall by a servo-controlled hydraulic actuator mounted between the specimen and a reaction frame. ATC 24 (ATC 1992) testing protocol was followed and Figures 3 and 4 show specimens F1 and C1 prior to testing.

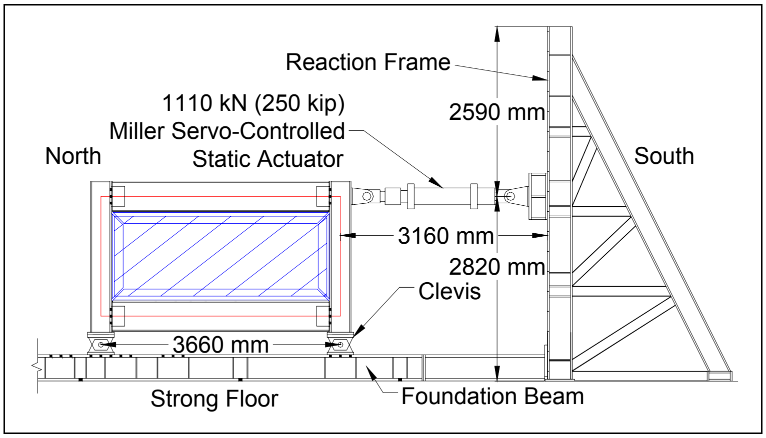

Figure 2. Test setup

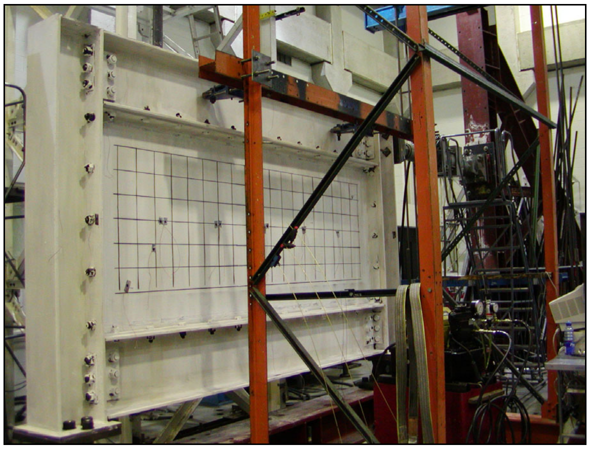

Figure 3. Specimen F1

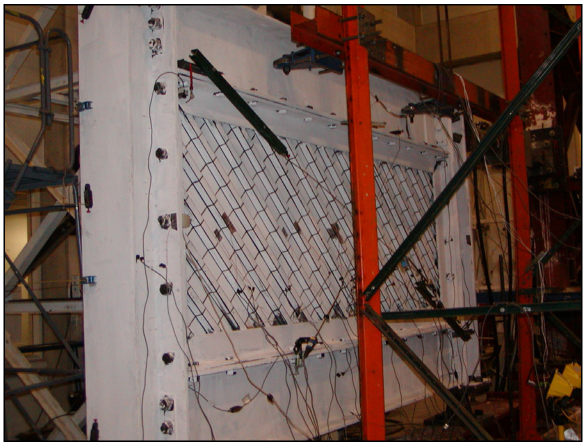

Figure 4. Specimen C1

Experimental Results

Despite the numerous ancillary tests that were performed to select an adequate connection configuration and epoxy, Specimen F1 suffered a premature failure of the epoxy during Cycle 7 at 0.25% drift while still exhibiting elastic behavior. The epoxy failed in the connection along the top beam of the specimen and the poor epoxy coverage is shown in Figure 5. Epoxy was directly applied to the infill plate only and not to the WT's, which could have contributed to cause this insufficient coverage. Qualitatively, this hypothesis was verified by the successful testing of Specimen C1, in which epoxy was applied to both the infill plate and intermediate angles.

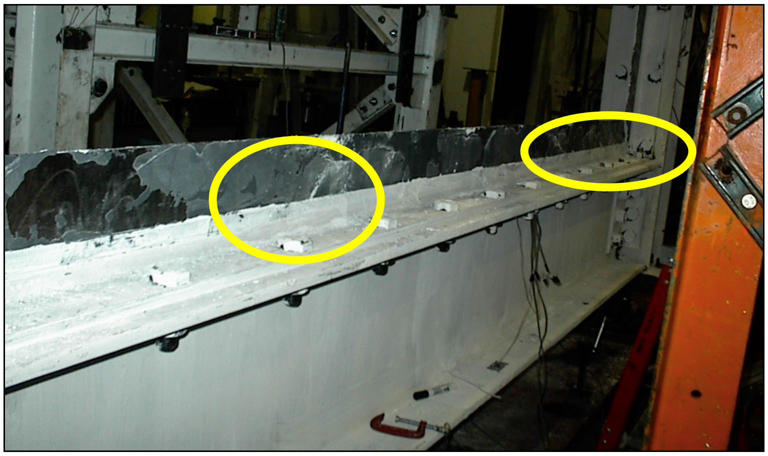

Figure 5. Poor epoxy coverage – Specimen F1

The hysteresis curves for Specimen C1 are shown in Figure 6 along with the monotonic pushover curve obtained from a strip model of the specimen using the measured material properties. Quantitative values of displacement ductility ratio, μ, and other key hysteretic response parameters are presented in Table 1. As shown, Specimen C1 reached a μ of 3 prior to losing substantial strength. Contribution of the infill to the total initial stiffness exceeded 90%. As expected, tension field action developed only in the direction parallel to the corrugations, resulting in unsymmetric hysteresis loops. Pinching of the hysteresis due to permanent plastic deformations of the infill is also apparent. This hysteretic behavior is similar to that of a braced frame with a single slender brace (Bruneau et al., 1997).

The epoxy connection of the infill plate to the boundary frame of specimen C1 cracked in some locations; however, according to strain gauge data, the entire plate yielded. This shows that epoxy connections are capable of developing yield forces in thin steel plates, although more research is needed to determine the reliability of such connections.

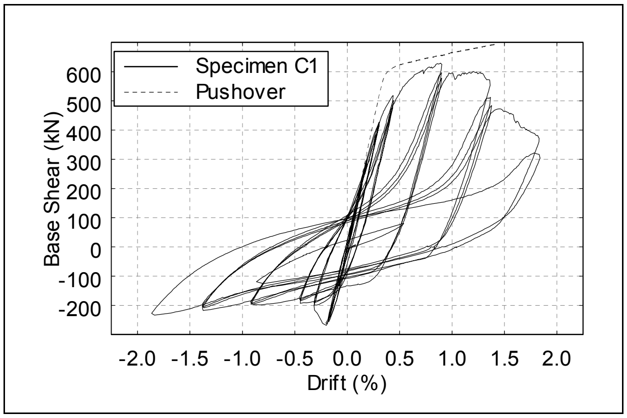

Figure 6. Specimen C1 hysteresis and pushover

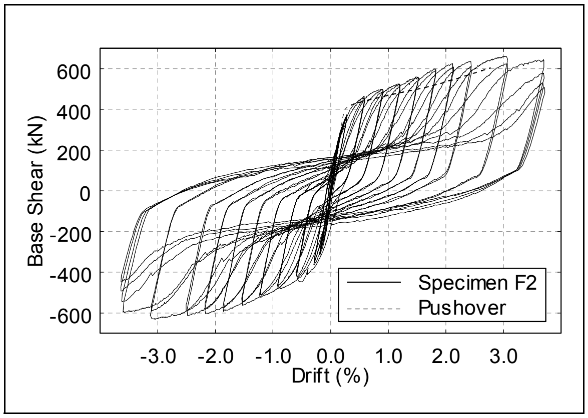

Figure 7. Specimen F2 hysteresis and pushover

Table 1. Hysteretic response values for all specimens

Specimen ID	Total Initial Stiffness [kN/mm]	Initial Stiffness w/o Boundary Frame [kN/mm]	Yield Base Shear [kN]	Yield Disp. [mm]	Max Drift [%]	μ	Total Energy Diss. [kN-m]	Energy Diss. Infill Only [kN-m]
F1	84	73	372	4.6	0.25	1	NA	NA
C1	93	86	518	8	1.4	3	73	50
F2	106	96	364	5.3	3.7	12	444	212

Stable and ductile behavior was observed in Specimen F2 as shown by the hysteresis loops of Figure 7. Also shown in Figure 7 is the monotonic pushover curve obtained from a strip model of the specimen. Reasonable agreement in terms of initial stiffness and yield base shear are evident. Specimen F2 reached a ductility ratio of 12 and drift of 3.7%, as shown in Table 1, prior to losing significant strength. Additionally, from the data presented in Table 1, the infill of Specimen F2 contributed approximately 90% of the initial stiffness of the system. The pinching exhibited by the hysteresis loops of Figure 7 is again due to the accumulation of non-recoverable plastic strains, a hysteretic behavior comparable to that of a concentrically braced frame having slender braces.

Conclusions

Three light-gauge steel plate shear wall specimens were designed and tested using quasi-static loading. Two of the specimens had flat infill plates, one with an epoxy connection to the boundary frame and one with a welded connection, while the third was designed with a corrugated infill plate and also utilized an epoxy connection to the boundary frame. Specimen design was based on prototype light-gauge steel plate shear walls, themselves designed as seismic retrofit options for a demonstration hospital. Two of the three specimens were shown to achieve the goals of increased stiffness, energy dissipation capability, and ductility of the existing framing, while using bolted connections detailed in a manner that provides a possibility to relocate the infills elsewhere in the building.

Though the hysteretic curves of the specimens were pinched, they were stable and provided significant energy dissipation in the cases of the specimens with the corrugated infill and the flat infill in which the welded connection was used (the former being significantly more ductile). Furthermore, the adequacy of the strip model in predicting the monotonic behavior of light-gauge steel plate shear walls into the nonlinear range was found to be acceptable through comparison with the experimental results. For more information, see Berman and Bruneau (2003b).

Acknowledgements

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