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SEIMSIC EVALUATION OF WOOD HOUSE OVER GARAGE

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ABSTRACT: This study presents results from shake table and pseudo-dynamic tests of a wood building conducted at the University of California, Berkeley. A 13.5-ft×19.5-ft two-story wood building representing San Francisco 1940's design of residential house with a garage space on the first story (house-over-garage) was tested. The test building was subjected to scaled ground motion from Loma Prieta 1989 earthquake scaled to match design spectra of a site in Richmond district of San Francisco. The test results from conventional instrumentation and high-definition laser scanning techniques demonstrated the seismic vulnerability of the test building due to soft story mechanism and significant twisting when shaken in two horizontal directions. A brief discussion of pseudo-dynamic testing conducted on a substructure from the first story of the building is presented with comparison between the findings from the pseudo-dynamic and shake table tests.

KEYWORDS: House-over-garage, Laser scan, Pseudo-dynamic, Shake table, Soft story, Wood

1. INTRODUCTION

Wood structures, especially low-rise residential buildings, represent 80% of the USA market. Wood buildings with open front due to tuck-under garages behaved poorly during the 1994 Northridge earthquake [1]. Such buildings are characterized by a soft (or weak) first story and an asymmetric configuration causing twisting when subjected to ground motion. In this study, shake table (ST) experiments were conducted on a typical San Francisco residential wood building to provide data and observations on the seismic vulnerability of this type of commonly constructed houses in urban California and other parts of US. Moreover, the data were utilized in the development and verification of novel pseudo-dynamic or hybrid simulation (HS) techniques [2].

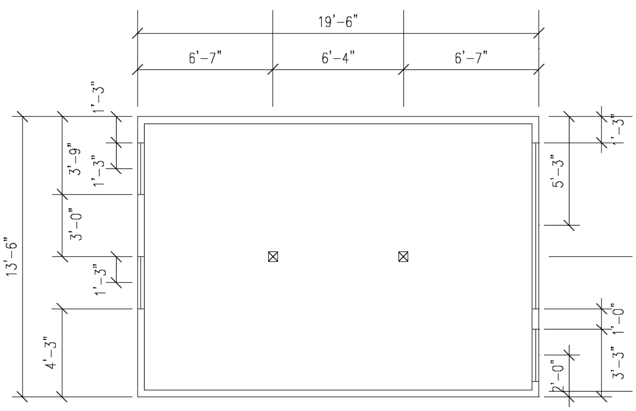
In addition to conventional discrete acceleration and displacement instrumentation, high-definition laser scanning technology was employed to assess global and local displacement measurements. In this technology, millions or even billions of points are captured on an object resulting in the so called "3D point cloud" which is subsequently analyzed for graphical representation. This technology has been extensively used for damage assessment of test structures subjected to earthquake loads at the University of California, Berkeley [3].

2. DESCRIPTION OF TEST BUILDING AND SHAKE TABLE MOTION

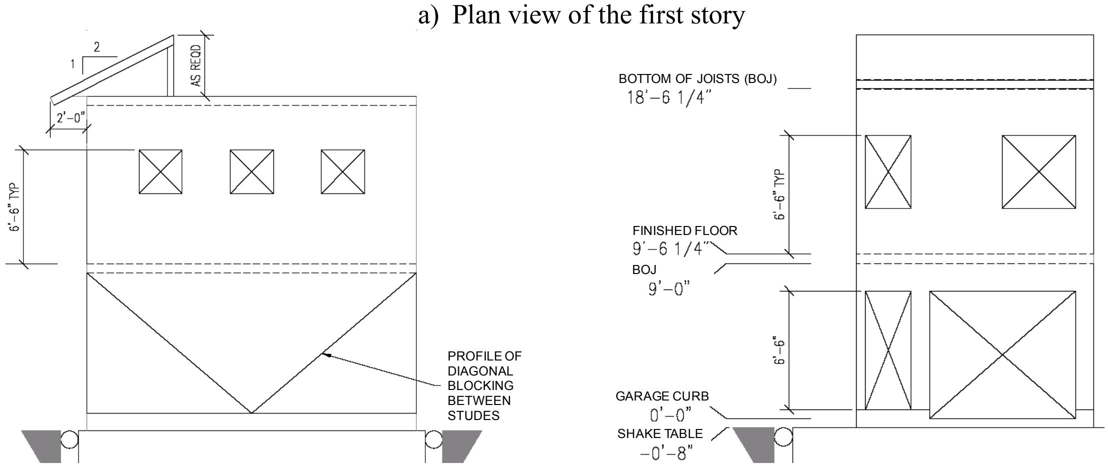
The test building is a hypothetical two-story single-family "house-over-garage" representing the plethora of houses in San Francisco, California constructed in 1940's, Figure 1a. Due to the size of the shake table, the constructed plan dimensions of the test building were limited to 19' 6"×13' 6". The total height was 18' 6" and roof partially covered by a parapet of height 2' 10", Figures 1 and 2. Several configurations with various levels of retrofitting of the building were tested. This paper focuses on the performance of the as-built structure. The second story comprised the living space where the floor was divided into three rooms and one corridor by two partitions walls attached to the south solid wall. Second story walls and ceiling were internally covered by gypsum boards. Siding consisted of ship laps connected to the frame by three 8d common nails per stud crossing. No exterior finishes were applied consistent with the 1940's construction techniques. A summary of the used material for the main structural elements is given in Table 1. Moisture content (MC) for the different structural elements was monitored and it ranged from 13% for sill plates to 21% for the 2×8 joists with the majority of the studs at about 15% to 17% MC. The first floor and roof diaphragms were made of Douglas Fir joists covered with plywood.

a) House in San Francisco b) Test building – east c) Test building – northwest

Figure 1 Similarity between a typical San Francisco house and the test building



a) Plan view of the first story



b) Elevation view of north wall (Longitudinal) c) Elevation view of east wall (transverse)

Figure 2 Geometry of the wood-frame test building

Weight of the test building was 18.3 kips in addition to added roof weight of 8.2 kips to match the weight of a typical house, i.e. total weight of the test building was 26.5 kips. Although the test building was constructed using modern techniques, details observed in typical 1940's construction were preserved. Finally, the second story was furnished as an office and a living room. Commercially available straps were used to restrain the furniture.

Table 1 Construction materials of the test building

Walls	First floor	Roof	Post & footing	Nonstructural
• 1×12 ship lap siding • 2×4 studs at 16" OC with 2-16d end common nails to two 2×4 top plates & 2-16d toe nails to 3×6 sill plate • 2 studs at opening sides • V-shaped 2×4 diagonal blocking between studs (2-16d toe common nails) for lateral capacity • 1/2" gypsum board on second story wall interior and ceiling	• 2×6 joists at 16" OC with 2 joists beneath partition walls • 3/4" PS1-95 CD plywood • 4×8 beam in longitudinal direction in the middle of the floor supported on two posts • Carpet flooring	• 2×8 joists at 16" OC with double joists beneath the parapet • 3/4" PS1-95 CD veneer plywood over entire roof • Blocking between joists at mid-span • 2× blocking at 16" OC over partition walls • Parapet roofing	• Two 6×6 posts on the first story • Sill plate connected by 1/2"×12" anchor bolts at 4' spacing with 1.5" cut washers and square nuts to the RC footings	• Two 9-ft long partition walls connected to the first floor south wall • Similar to the shear walls, framing members of partitions are 2×4 studs at 16" on center

The used time histories were spectrally matched to the fault normal (FN) and fault parallel (FP) spectra for the design basis earthquake (DBE) and the upper-bound earthquake (UBE), 10% probability of exceedance in 50 and 100 years, respectively. The records from Loma Prieta, CA, 1989 earthquake, Los Gatos station, were adopted assuming a stiff soil site. FN component was applied in the north-south (NS) or transverse direction and FP component was applied in the east-west (EW) or longitudinal direction, except for level 5 as noted in Table 2. Five levels of shaking were applied with 38 runs in three phases. Phase I included 7 runs for levels 1 and 2 (both in EW, NS, and bidirectional) to check instruments and capture elastic response. Level 3 EW was the last run in phase I. Subsequently, the weak first story east and west walls were braced by two 2×6 NS diagonals for phase II to investigate the building contents. This phase included 10 runs for levels 1 and 2 (both bidirectional), levels 3 and 4 (both in EW, NS, and bidirectional (runs 12 and 15)), and level 5 bidirectional applied twice with and without furniture straps. Finally, NS braces were removed and phase III started with 21 runs for levels 1, 2, and 3 (all in EW, NS, and bidirectional) followed by level 2 bidirectional and by 7 runs of level 3 as follows: EW, NS, bidirectional, NS, EW, bidirectional (run 33), and NS. These repeated runs of level 3 aimed to investigate different scenarios of adding brackets and holdowns to strengthen the garage door for lateral resistance to the first story east wall and reducing building twist. Level 4 is then applied in NS, EW, and bidirectional (run 37) followed by level 5 bidirectional (run 38). This paper mainly discusses results of runs 33, 37, and 38, which are underlined above.

Table 2 Levels of shaking for the shake table tests and maximum FN quantities

Level	Scaling	Description	Acc. [g]	Vel. [in/sec]	Disp. [in]
1	0.10×UBE	Initiation	0.05	2.54	0.51
2	0.25×UBE	Elastic	0.12	6.36	1.27
3	0.50×UBE	Damage onset	0.23	12.72	2.53
4	1.00×DBE	DBE	0.42	21.09	3.77
5†	1.00×UBE	UBE	0.46	25.43	5.06

†Bidirectional motion: FN (EW)-FP (NS) followed by FP (NS)-FN (EW)

3. PRELIMNARY TESTS AND DAMPING PROPERTIES

Two series of snap back tests were realized in the longitudinal and transverse directions. The test building was loaded from the roof where 2 kips force was applied in one direction at a time and then released abruptly to obtain a Heavyside unload. Three tests were performed in both NS and EW directions and acceleration records from the center of each diaphragm were used to determine the modal properties with average results in Table 3.

During the shake table tests, the damping ratio varied from one test run to the other depending on the intensity of the motion, elements resisting shear, and previous damage. Using energy equivalent mean damping ratio [4] obtained from the hysteretic plot of the lateral displacement of the first floor versus the base shear of the building, Figure 3 summarizes the findings. One distinguishes two average values of the damping ratio, before (5% as used in HS [2]) and after severe shaking (2%), i.e. level 5 in runs 16 and 17. This reduction in the damping ratio is attributed to less energy dissipative mechanisms after the building experienced major damage with increased tendency to twist after runs 16 and 17. The largest damping ratio of 6.62% (~13% less than value in Table 3) was estimated at run 7. Finally, the damping ratios for the same input level were significantly higher (up to 10 times) in the EW than the NS due to limited energy dissipation mechanisms in the NS direction.

Table 3 Snap back test results

Direction	Frequency [Hz]	Period [sec]	Damping ratio [%]
NS (transverse)	2.288	0.437	7.92
EW (longitudinal)	3.774	0.265	7.60

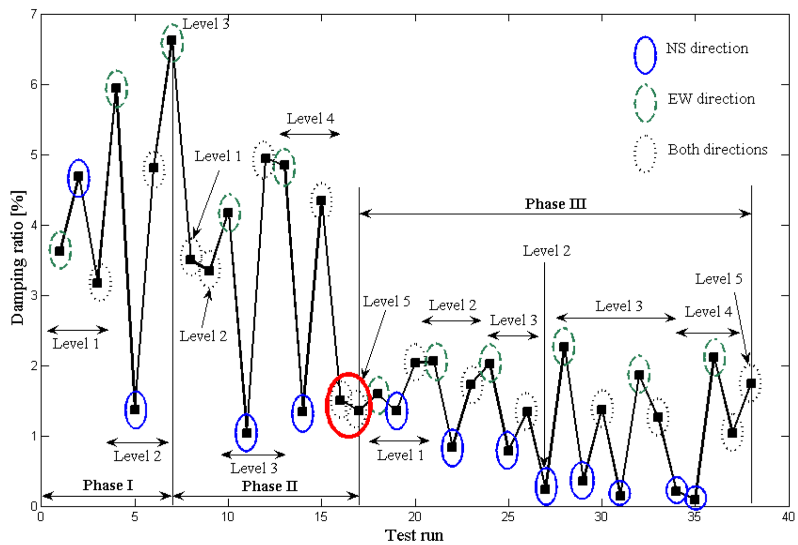


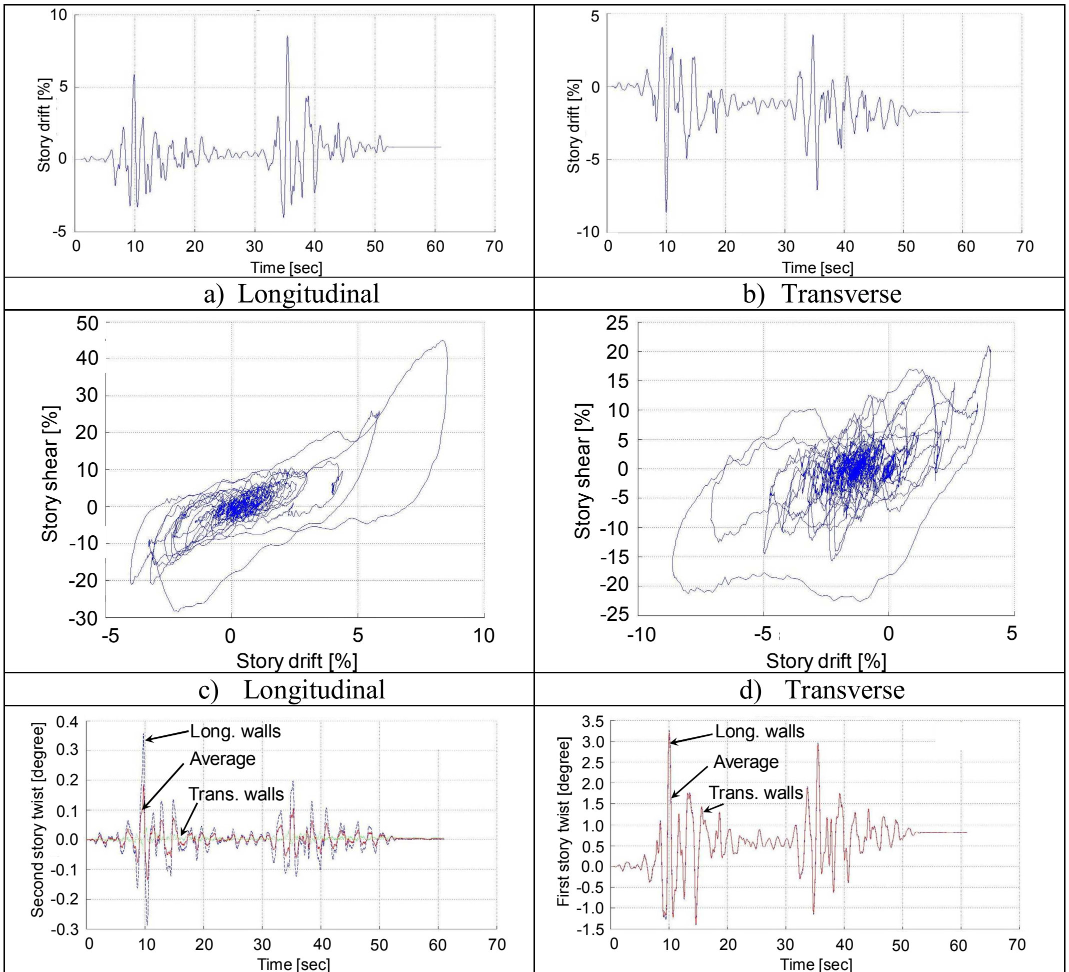
Figure 3 Variation of the energy equivalent mean damping ratio in the EW (longitudinal) direction

4. OBJECTIVES AND RESULTS OF THE SHAKE TABLE TESTS

The shake table runs of the test building had the following major objectives:
1) Demonstrate vulnerability of building contents with and without available straps (phases I and II).
2) Demonstrate effectiveness of several simple garage door retrofits (phases II and III).
3) Demonstrate structural vulnerability in the transverse direction by increasing levels of shaking runs (phase III).

The results in this paper focus on the third objective. The structural vulnerability is due to lack of shear resistance of the transverse wall and twist caused by asymmetric first story plan. The following observations can be made:

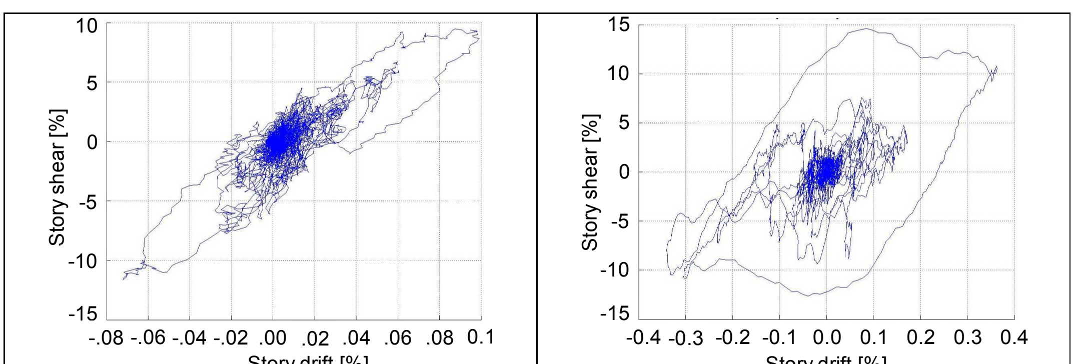
1) Up to run 33 (50% UBE), negligible residual deformations were obtained.
2) Slight residual deformations were observed at run 37 (100% DBE).
3) Significant residual deformations in the EW (~0.9% first story drift) and in the NS (~1.8% first story drift) were observed after completion of all test runs, Figures 4a and b, i.e. after run 38 (100% UBE).
4) The first story hysteretic response in the longitudinal direction had clear pinching behavior, Figure 4c, due to sliding of the ship lap siding of the longitudinal walls. The complexity caused by the large openings in the east wall made the hysteretic response in the transverse direction very complicated, Figure 4d.
5) Compared to the first story, the twisting of the second story was much smaller (~6% at the peak of run 38), Figures 4e and f, and the residual twist of the second story was negligible (~0.8^{o} after all runs), Figure 4f.
6) The twist angle of the second story was much larger from the EW walls than the NS walls due to the large in-plane displacement of the transverse walls, Figure 4e. The twist angle of the first story was comparable from the NS and EW walls, Figure 4f, making averaging the twist angles more accurate for the first story.



a) Longitudinal | b) Transverse | c) Longitudinal | d) Transverse | e) Twisting of second story | f) Twisting of first story

Figure 4 Time histories and force-deformation relationships for run 38

The second story experienced much less damage than the first story, remaining essentially elastic in the longitudinal direction, Figure 5a. The transverse direction in the second story experienced significant reduction of the average (between east and west walls) secant stiffness, Figure 5b, due to accumulation of damage in the junction between the first and second stories. For the transverse direction, the secant stiffness values, Table 4, are based on peak-to-peak story shear (initial) and on peak-to-peak story drift (final) with 7.08 reduction factor.



a) Longitudinal | b) Transverse

Figure 5 Force-deformation relationships of second story for run 33

Table 4 Peak-to-peak secant stiffness for second story from run 33

Direction	Longitudinal	Transverse (initial)	Transverse (final)
Stiffness [kip/in]	29.91	51.27	7.24

The stiffness in the first story longitudinal walls was not affected by the inclusion of the diagonal bracing in the transverse direction. However, this stiffness was affected by the levels of shaking. Table 5 compares the average secant stiffness (peak-to-peak story shear) for levels 3 (run 12) and 4 (run 15) in phase II to those of the same levels, i.e. level 3 (run 33) and level 4 (run 37), in phase III. It is concluded that the first story longitudinal walls were partially damaged due to nail pull out and sliding of the ship lap boards. Moreover, comparing results in Tables 4 and 5 for run 33, the stiffness in the longitudinal direction is much smaller (only 4.25%) in the first story than that of the second story suggesting a concentration of damage in the first story of the shake table test building. Therefore, the HS study of the longitudinal walls in [2] focused on the first story walls.

Table 5 Reduction of first story longitudinal stiffness after application of severe shaking (level 5)

Run	12	33	15	37
Stiffness [kip/in]	8.61	1.27	5.38	1.37
Ratio	6.78		3.93	

The accumulation of the permanent deformations of the test building from all test runs is given in Figure 6 by subtracting the mean of the first 0.5 sec of the data from that of the last 0.5 sec. The difference between the residual displacements in the same direction at different walls is indicative of the residual twist in the test building. The runs after which the laser scans were performed are indicated on Figure 6.

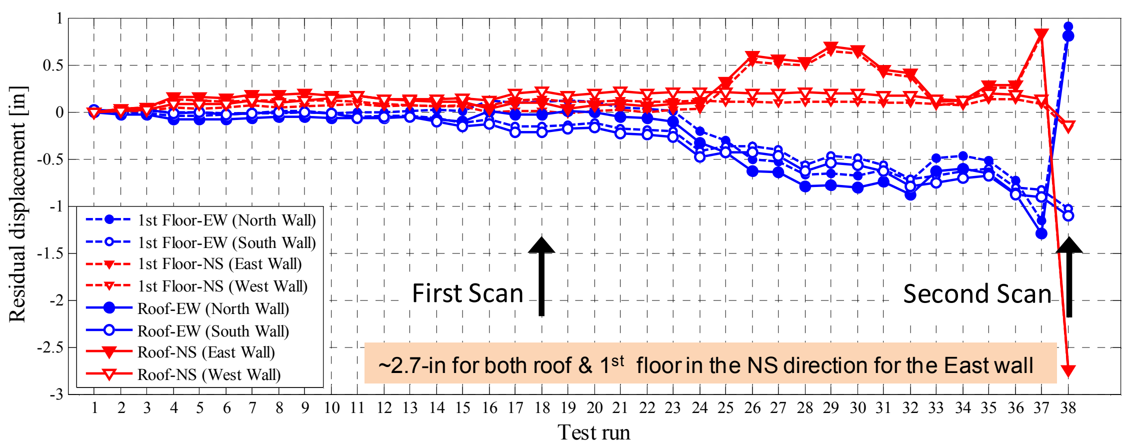
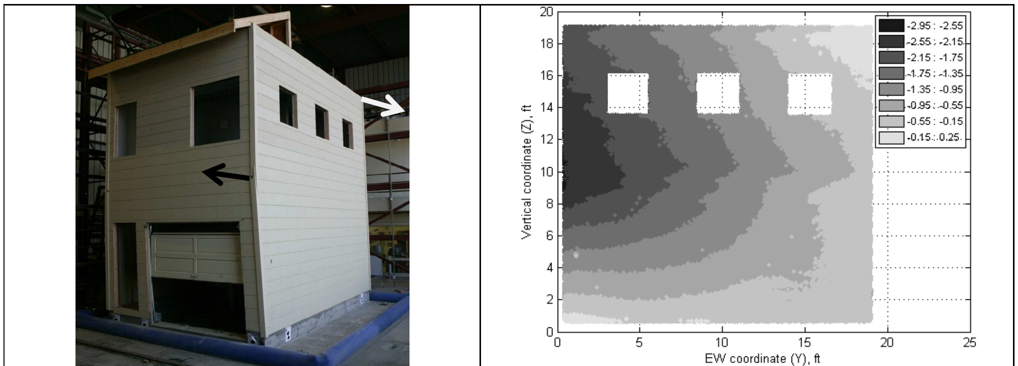


Figure 6 Variation of the residual displacements for different shake table runs using conventional measurements

5. LASER SCANNING RESULTS

Four scans were conducted with a variety of locations and details. Complete discussion of the global and local results obtained from these laser scans can be found in [5]. High definition laser scanning targets are necessary for referencing and stitching scans to combine them into one image. Correctly selected targets are valuable for creating a consistent coordinate system for studying 'before' and 'after' conditions of test structures. Figure 7b reflects the permanent (residual) deformation in the out-of-plane direction of the north longitudinal wall, Figure 7a. Several slices in the horizontal and vertical directions of the building's point cloud were investigated. The horizontal slices were taken at the ceiling elevations of the first and second story. One vertical slice was taken one foot to the west of the east wall. The horizontal slices showed the twist of first floor and roof dictated by the asymmetric plan of the test building. Figure 8 presents the point clouds before and after testing along the height of the test building for the vertical slice showing the soft story mechanism due to the garage opening in the east wall of the first story. The average residual deformation in the transverse direction were about 2.7" from the south and north sides. This result is consistent with the findings from Figure 6 using the conventional measurements.



a) Deformation after the last shaking run | b) Residual deflection from laser scanning

Figure 7 Out-of-plane deformation of the north longitudinal wall

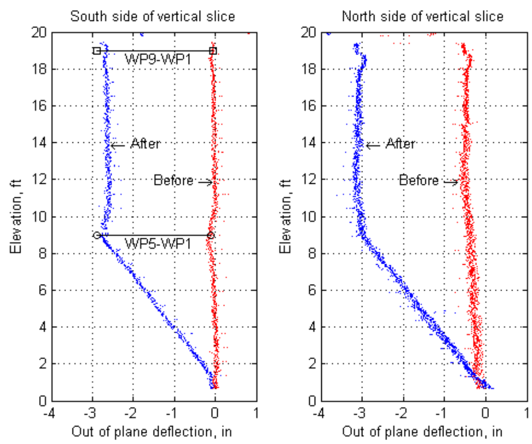


Figure 8 Residual north-south deflections of east wall sides (view from east)

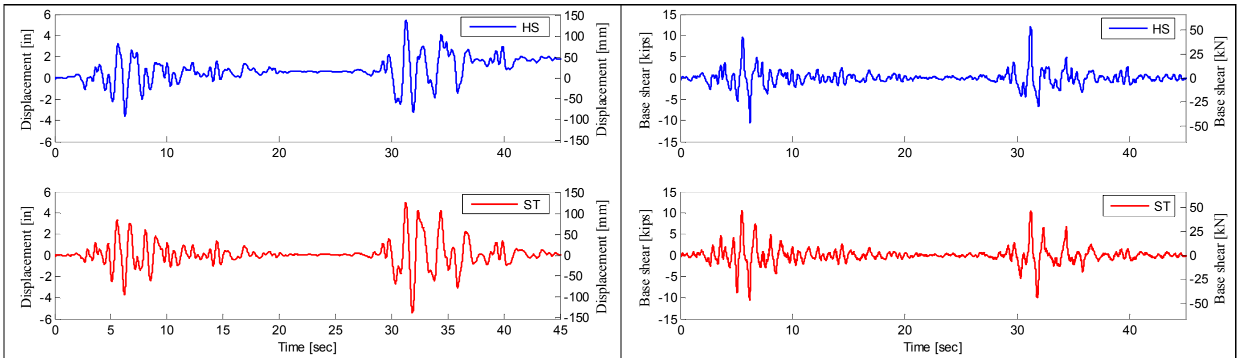
6. PSEUDO-DYNAMIC TESTS AND COMPARISON WITH SHAKE TABLE RESULTS

In the shake table experiment, the second story behaved very closely to a rigid mass atop the first story shear walls. Therefore, the two longitudinal shear walls were tested pseudo-dynamically as substructure, Figure 9, with test structure idealized as a single degree of freedom (SDOF) excited by motion parallel to the EW direction. Three high-strength steel rods, Figure 9b, were connected to the strong floor at one end and the loading steel frame at the other end and were post-tensioned to simulate the gravity load present in the case of the shake table test structure. The equivalent inertia mass of 0.065 kip-sec^2/in was taken as that of the test building. Mass proportional damping was selected with 5% damping ratio. The initial stiffness for the undamaged test structure was estimated from low level tests as 15 kip/in with natural period of T =0.4 sec. The integration time step was taken as $T/80$. Details about the numerical integration algorithm used in these simulations can be found in [2].

a) Physical substructure b) Post-tensioned high-strength steel rod

Figure 9 Pseudo-dynamic test setup

The obtained results show similarity between the HS and the shake table (ST) tests, Figure 10. However, in the HS, larger residual displacement of 1.84 in is recorded, while in the ST test, there was no residual displacement. In the HS test, the actuator was locked at the last displacement position, while in the ST, the test structure vibrated freely and returned to original position. Moreover, the HS considered a SDOF model neglecting higher modes which contributed in the ST to counteract the fundamental modal response, minimizing residual displacement.



a) First story displacement time histories | b) Total base shear time histories

Figure 10 Comparisons between hybrid simulations (HS - top) and shake table (ST - bottom) results for level 5

7. CONCLUDING REMARKS

From the study presented in this paper, the following remarks can be made:

1) The shake table test results confirmed the significant deficiencies in the “house-over-garage” system. These deficiencies are due to the lack of shear resistance and asymmetric plan of the first story transverse direction. They are exhibited as: a) low stiffness and strength, b) significant twisting, c) low damping ratio, d) large permanent lateral displacement, and e) severe damage in the transverse direction. House-over-garage systems remain a concern requiring innovative, effective, and inexpensive retrofit techniques [1].
2) The laser scans showed good correlation with test data from conventional transducers. The study confirmed the accuracy of the point acquisition of about ±1/6 in is achievable for monitoring small displacements.
3) Comparison between shake table and pseudo-dynamic tests is presented. Residual displacement was larger in the pseudo-dynamic test due to effects of boundary conditions of the test setups and higher modes.

8. ACKNOWLEDGEMENTS

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