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Full-Scale Testing of Soft-Story Woodframe Buildings with Stiffness-Based Retrofits

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ABSTRACT

The existence of thousands of soft-story woodframe buildings in California has been recognized as a disaster preparedness problem with concerted mitigation efforts underway in many cities throughout the state. The NEES-Soft project, whose full title is "Seismic Risk Reduction for Soft-Story Woodframe Buildings," is a five-university multi-industry three-year project which has many facets including improved nonlinear numerical modeling, outreach, design method development, and full-scale system-level experimental validation of soft-story retrofit techniques. This paper summarizes the retrofit and test results for two full-scale buildings that were tested in 2013. The first is a three-story building at the University at Buffalo NEES facility using slow pseudo-dynamic testing. The bottom story, representing a soft story with garage openings, was the numerical substructure and reproduced by computer, while the damage to the two upper stories, representing the physical substructure, was observed in the lab. Then, testing of a full-scale four-story 4,000 sq-ft soft-story building at the UCSD NEES outdoor shake table was conducted. Retrofits ranged from crosslaminated timber rocking walls with rod hold downs to steel special moment frames combined with wood structural panels.

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ABSTRACT

The existence of thousands of soft-story woodframe buildings in California has been recognized as a disaster preparedness problem with concerted mitigation efforts underway in many cities throughout the state. The NEES-Soft project, whose full title is "Seismic Risk Reduction for Soft-Story Woodframe Buildings," is a five-university multi-industry three-year project which has many facets including improved nonlinear numerical modeling, outreach, design method development, and full-scale system-level experimental validation of soft-story retrofit techniques. This paper summarizes the retrofit and test results for two full-scale buildings that were tested in 2013. The first is a three-story building at the University at Buffalo NEES facility using slow pseudo-dynamic testing. The bottom story, representing a soft story with garage openings, was the numerical substructure and reproduced by computer, while the damage to the two upper stories, representing the physical substructure, was observed in the lab. Then, testing of a full-scale four-story 4,000 sq-ft soft-story building at the UCSD NEES outdoor shake table was conducted. Retrofits ranged from cross laminated timber rocking walls with rod hold downs to steel special moment frames combined with wood structural panels.

Introduction

The NEES-Soft Project, whose full title is "Seismic Risk Reduction for Soft-Story Woodframe buildings," is a five-university, multi-industry, NSF-funded project that has the objectives of: (1)

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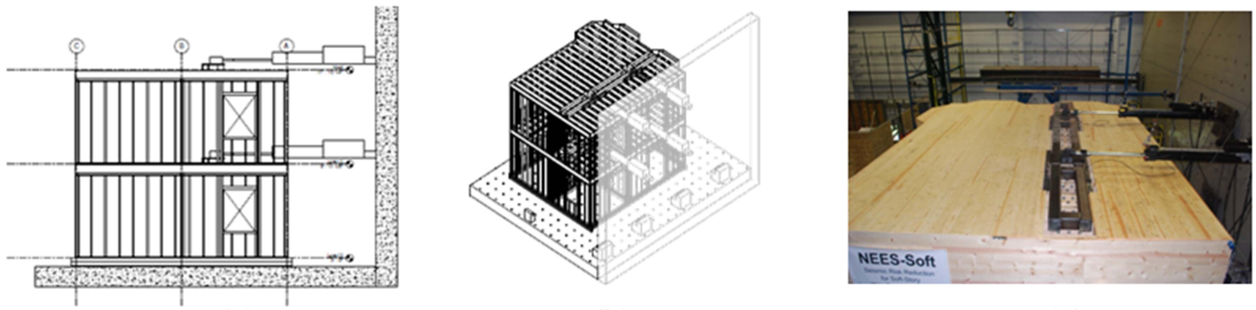
enabling performance-based seismic retrofit (PBSR) for at-risk soft-story woodframe buildings; and (2) experimentally validating the U.S. Federal Emergency Management Agency (FEMA) P-807 retrofit procedure. A soft-story building is a building that has one or more stories with significantly less stiffness (and strength) than the stories above or below. This condition usually occurs at the bottom story of a multi-story building and is often the result of large openings that are used for main building entrances or parking garages. These buildings were generally built before 1970 and many as early as the 1920's, which means that they used construction practices not considered acceptable by today's codified standards. The wall lengths available to resist lateral loads, in general, are too short at the bottom story, thereby resulting in a soft-story.

The NEES-Soft project consists of a number of tasks including extensive numerical analysis, development of a performance-based seismic retrofit methodology, and a major testing program with testing at five university-based laboratories to better understand the behavior of these at-risk structures and the retrofit techniques. These include the following test programs: (1) Test Program 1: Real time hybrid testing (RTHT) of a 20-ft long wood wall with and without a toggle-braced damper assembly; University of Alabama Structural Engineering Laboratory. (2) Test Program 2: Reversed cyclic testing of a light woodframe distributed knee-brace (DKB) assembly for seismic retrofit; California State Polytechnic University San Luis Obispo Structures Laboratory. (3) Test Program 3: Shake table testing of a woodframe DKB assembly to collapse; Colorado State University Structural Engineering Laboratory. (4)Test Program 4: Slow hybrid testing of a full-scale soft-story woodframe building with various retrofits; Network for Earthquake Engineering Simulation (NEES) laboratory at the University at Buffalo. (5)Test Program 5: Shake table testing of a full-scale four-story soft-story woodframe building with and without seismic retrofit; Network for Earthquake Engineering Simulation (NEES) laboratory at University of California – San Diego.

Hybrid Testing of a Three-Story Soft-Story Woodframe Building

At the NEES laboratory in Buffalo, a three-story soft-story woodframe building was designed and modeled based on 1920's to 1940's construction to be representative of structurally deficient buildings in California. Slow pseudo-dynamic hybrid simulation was conducted with the numerical bottom soft-story and the physical upper two stories. The full-scale physical substructure of the upper two stories had a plan dimension of 20' – 3 ½" x 24' – 3 ½". It was constructed with finishing materials and anchored to the strong floor through the sill plates sitting on top of a steel channel section. Two actuators with a stroke capacity of +/- 40 in. were mounted at the third floor diaphragm and at the roof level as shown in Figure 1. Two actuators at each level allowed for control of both translation and in-plane torsion. One major challenge in this hybrid simulation setup was to ensure that the actuator forces, and the associated moments, would be transferred to the diaphragm, and subsequently to the walls, in a manner as consistently as possible with inertial forces experienced by a building during an earthquake. Various retrofits following either the FEMA P807 guidelines or performance-based design criteria were numerically modeled on the soft-story. Additionally, two performance-based seismic retrofits were numerically modeled on the soft-story but also consisted of physical retrofits on the upper stories. The performances of all retrofits were evaluated against varying intensity earthquake ground motions via hybrid simulations.



(a) (b) (c)

Figure 1. Roof level of the hybrid soft-story test setup in Buffalo

Displacement-Based Pseudo-Dynamic Hybrid Test Description

Prior to the hybrid testing, a System ID was run on the physical substructure. The System ID test pushed each actuator individually to a set displacement of 0.1 in., holding the other three actuators static, measuring the force feedback in all four actuators. This information was used to determine the fundamental period of the physical substructure which was employed in the initial time step of the hybrid simulation that followed. A Matlab program, Timber3D, was used to simulate the seismic response of the three-story structure by combining the restoring forces from the numerical and the physical substructures. For each time step of the ground motions, the simulated displacement responses at the four controlling degrees-of-freedom (DOFs) were sent to the respective four actuators where restoring forces were measured and sent back to the numerical model. This information was used to update the numerical model, and the process was repeated for the next time step.

Soft-Story Numerical Seismic Retrofit Testing, Results and Discussion

Slow pseudo-dynamic hybrid testing was carried out on five different stiffness-based retrofits and one damping-based retrofit from June to October of 2013 at the NEES@Buffalo site. Several of the stiffness-based retrofit designs are briefly discussed below.

The cross-laminated timber panel (CLT) retrofit design followed FEMA P807 guidelines and was fully contained on the numerical soft-story. The retrofit consisted of three 2 ft. long CLT panels in the x-direction set adjacent to each other width wise, and three 2 ft. CLT panels in the y-direction aligned lengthwise. Fig. 2a provides the layout of the CLT retrofit design on the soft-story, where the CLT panels are shown in blue. Four hybrid simulations, of varying intensity ground motions, were conducted on the CLT retrofit. The story drift time history for all three numerical stories is provided in Fig. 2b for the highest intensity ground motion that the retrofit was subjected to (i.e. MCE level). The maximum drift occurred in the second story (i.e. first physical story) reaching 2.9% story drift, with a residual drift of just under 2% developing in the second story at the end of the ground motion.

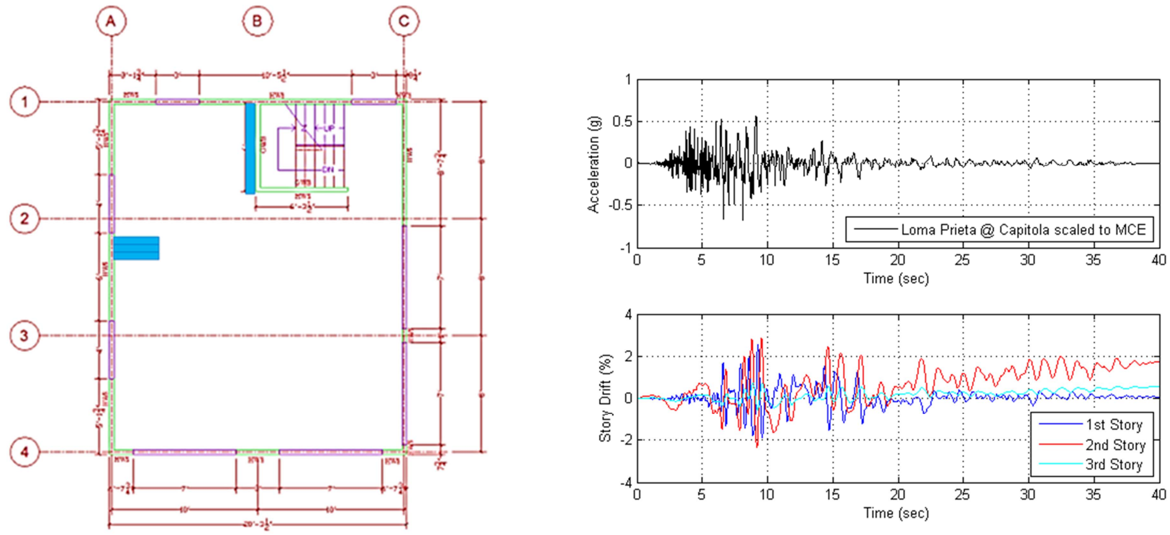


Figure 2. CLT retrofit (a) design layout; (b) DBE level earthquake ground motion with resulting story drift time history.

The cantilevered column (CC) retrofit design following the FEMA P807 guidelines. Two CCs were used for the retrofit design, and each CC consisted of two columns. The layout is provided in Fig. 3a where the blue dots are the center points of the two CCs, and an example of the two-column frame is shown in the top left corner. The frame rotated lengthwise in the x-direction (top blue dot in Fig. 3a) consisted of two W10x19 columns, and the frame rotated in the y-direction (bottom blue dot in Fig. 3a) consisted of two W12x14 columns. Four hybrid tests were conducted on the CC retrofit of varying intensity ground motions. The story drift for all three numerical stories resulting from the final test is provided in Fig. 3b. The maximum drift occurred in the first story reaching 2.8%.

The shape memory alloy-steel (SMA) device retrofit was designed using principles of performance-based seismic design. The retrofit design consisted of four SMA devices on the bottom soft-story, six plywood-sheathed shearwalls with 2 in. nail spacing (for the panel exterior; all field nailing was 12 in.) on the second story, and four plywood-sheathing shearwalls with 6 in. nail spacing on the third story. The SMA devices were numerically modeled and the upper story shearwalls were physically installed and included installation of Simpson Strong Tie's Anchor Tiedown System (ATS) in each wall. The retrofit layout on the soft-story is provided in Fig. 4a, where the blue lines represent the SMA devices. The devices were placed in sets of two and rotated 90 degrees from each other allowing all devices to engage during motion in either principal building direction. Five hybrid tests were conducted on the retrofit, two at the DBE level and three at the MCE level. The story drift time history response for all three numerical stories resulting from an MCE level test is provided in Fig. 4b. The maximum drift occurred in the second story reaching 2.6%.

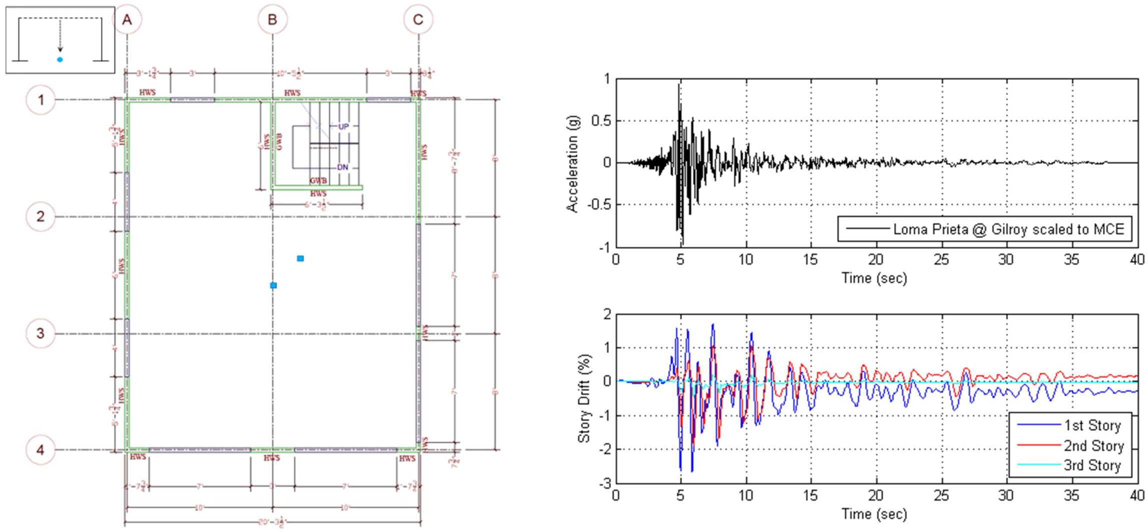


Figure 3. CC retrofit (a) design layout; (b) MCE level earthquake ground motion with resulting story drift time history.

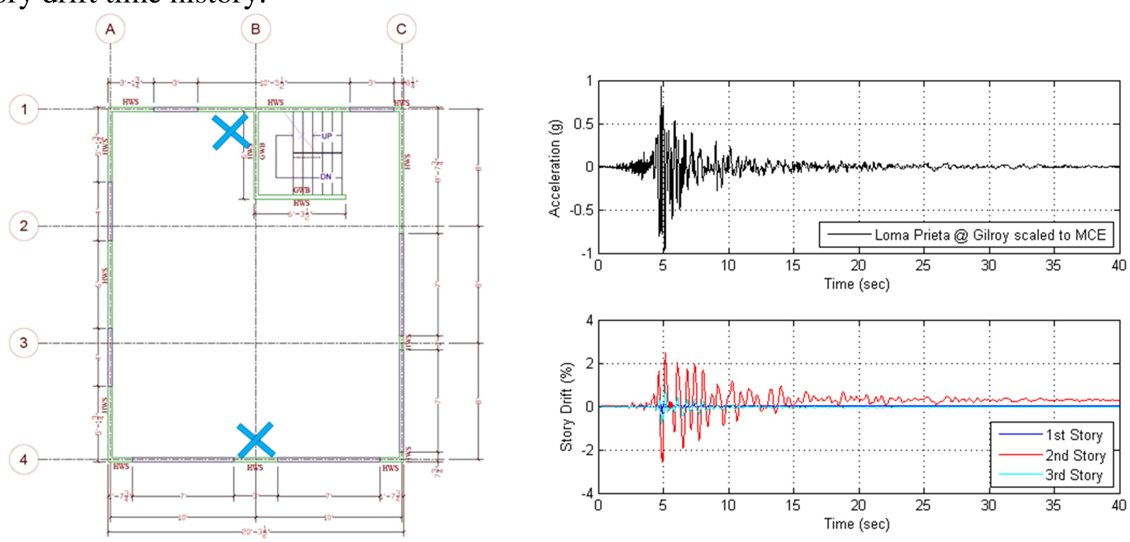
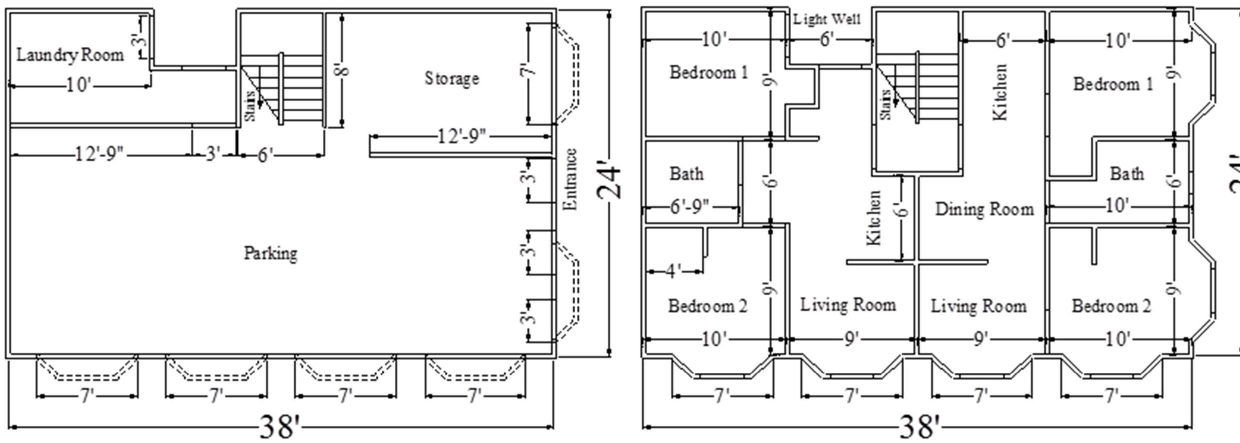


Figure 4. SMA retrofit (a) first-story design layout; (b) MCE level earthquake ground motion with resulting story drift time history.

Shake Table Testing of a Full-Scale Four-story Soft-Story Woodframe Building

The design of the four-story soft-story woodframe building for shake table testing at NEES@UCSD was very similar to the 3-story hybrid test building described previously. Figure 5 shows the ground and upper story floor plans for the building (plan dimensions are 24 ft x 38 ft). On the ground floor, there is a large laundry room, a storage room, and a light well. The light well was included since many of these buildings are surrounded by other buildings on two sides and therefore have two essentially solid sides and two more open sides. The test building was designed to replicate these conditions, thus making it, in many ways, a worst case scenario. The wall density in the upper stories was designed to be livable but dense since this is how many of the soft-story woodframe buildings of that era were designed. Similar to the three-story hybrid test building, the outside is covered with horizontal wood siding with two 8d common nails connected to each vertical wall stud. The inside walls are covered with drywall instead of plaster. Each of the upper three stories had two two-bedroom apartment units as can be seen in Figure 5. Figure 6 shows the finished building ready for shake table testing at the UCSD NEES laboratory.



(a) **(b)**

Figure 5. Floor Plans for the four-story building. (a) Ground story, (b) Upper stories

Soft-Story Shake Table Retrofit Testing, Results and Discussion

Four different retrofit designs were developed for the four-story woodframe building. The retrofits were designed based on FEMA P807 retrofit guideline and performance-based seismic retrofit (PBSR) concept. The building was retrofitted and tested in four different phases where the first two phases were conducted to verify the FEMA-P807 retrofit guideline and the last two phases were conducted to verify the effectiveness of the PBSR retrofit procedure. Cross laminated timber (CLT), steel special moment frames (SSMF), and viscous dampers combined with wood structural panels (WSP) were used as retrofit techniques in these tests. In the P807 retrofit procedure, the goal is to achieve an acceptable performance by limiting the retrofit to the bottom story (i.e., soft story) to reduce the cost and time of retrofit. Whereas, in the PBSR methodology, the retrofits are not limited to the bottom story and can be applied to upper stories to increase the strength of the building which leads to better overall performance. The building was subjected to the similar ground motions that were recorded after the Loma Prieta, 1989 and Cape Mendocino-Rio, 1992 earthquakes. The earthquakes were scaled to DBE and MCE levels with maximum spectral accelerations of 1.2g and 1.8g, respectively. Before and after each seismic tests, white noise tests with root mean square (RMS) of 0.05g were conducted to get the fundamental period of the building and its mode shapes.

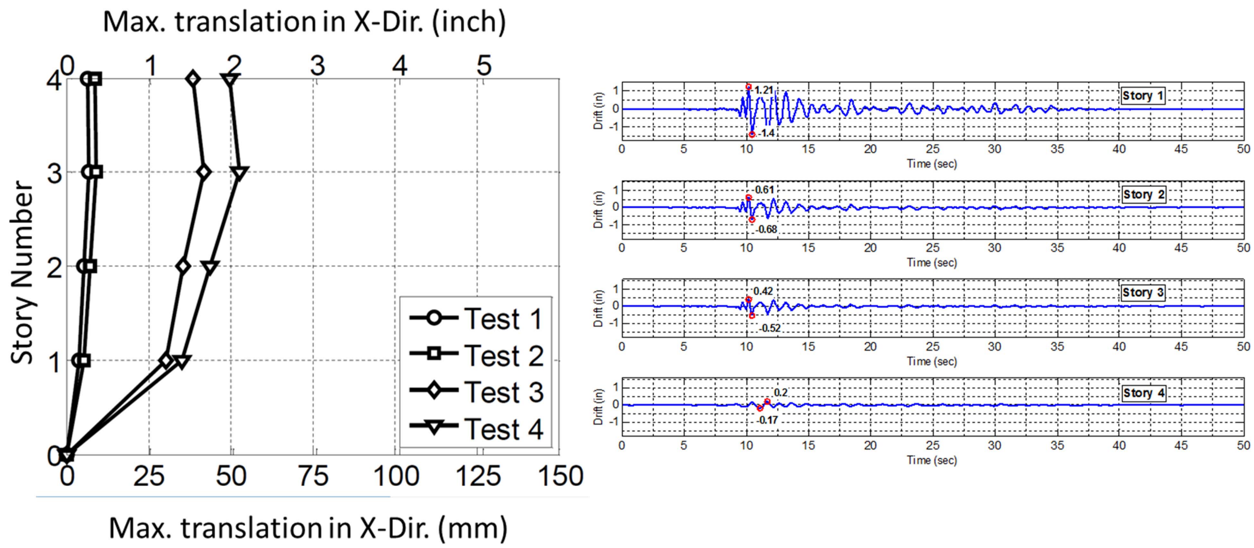
Figure 6. Completed 4-story 4000 sq ft soft-story building ready for shake table testing

Phase 1, FEMA P807 – Cross Laminated Timber (CLT)

CLT panels were installed at the ground level in order to provide stiffness and strength required by FEMA P807 retrofit guideline. Furthermore, the panels were located such that the center of gravity of the first story moves toward the center of gravity of the upper stories which led to reduction in the torsional response of the first story and satisfied the second limitation in P807 retrofit design. The CLT panels were positioned such as to be practically constructible and do not interfere with the usability of the ground floor. The locations of the CLT panels at the ground level can be found in the forthcoming report by the authors. Figure 7a presents the building profile in its maximum deformations for four seismic tests with a time-history response for the test with the highest peak ground acceleration (PGA) shown in Figure 7b.

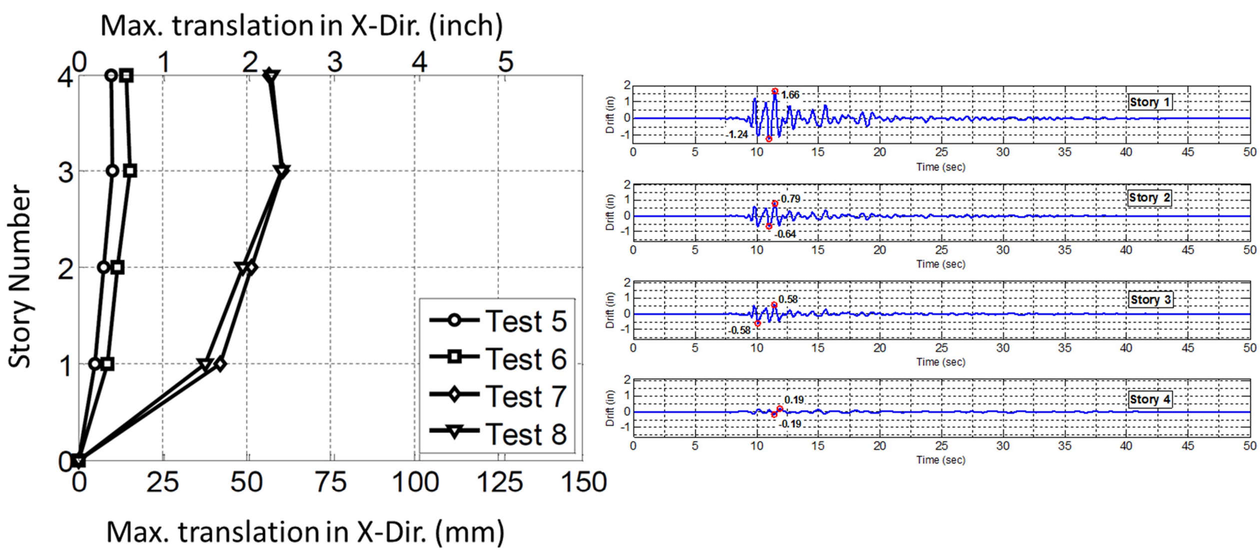
Phase 2, FEMA P807 – Steel Special Moment Frames (SSMF)

In the second phases of the tests, steel special moment frames were installed at the ground level to provide adequate stiffness and strength to the soft story to meet the P807 guideline requirements. The SSMF were designed such that this retrofit technique can be applied practically to the existing buildings in a short period of time which reduces the cost of the retrofit. Perfect pined connections were used in column-to-foundation connections. The beam-to-column connections were designed such that the beam yields and dissipates energy without losing stability due to lateral torsional buckling. Figure 8 presents the building profile in its maximum deformations for four seismic tests with a time-history response for the test with the highest peak ground acceleration (PGA).



(a) **(b)**

Figure 7. P807-CLT Retrofit. (a) Building maximum deformation profile (b) Time-history response for all four stories during Test 4.

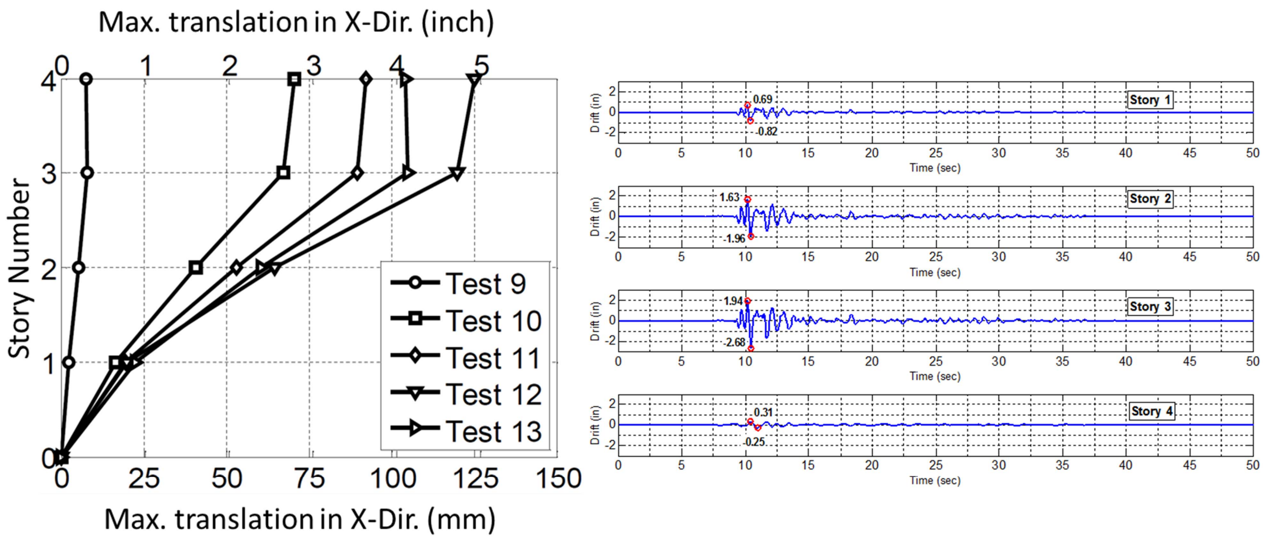


(a) **(b)**

Figure 8. P807-SSMF Retrofit. (a) Building maximum deformation profile (b) Time-history response for all four stories during Test 7.

Phase 3, PBSR – Steel Special Moment Frames (SSMF) and WSP

In the third phase of shake table testing, a performance-based seismic retrofit (PBSR) procedure was used to retrofit the entire building. In the PBSR procedure, the building should be designed such that almost all the stories experience the same level of inter-story drift. This utilizes the capacity of the upper stories to resist seismic loads and increases the probability of survival of the building under higher earthquake intensities. The four-story building was retrofitted using steel special moment frames at the ground level and wood structural panels with different nail schedule at the upper stories. Anchor Tiedown System (ATS) rods were placed at the end posts of the wood structural panels to transfer the uplift forces to the foundation and also limit the out of plane deformation of the diaphragms. Figure 9 presents the building profile in its maximum deformations for five seismic tests with a time-history response for the test with the highest peak ground acceleration (PGA).



(a) **(b)**

Figure 9. PBSR-SSMF Retrofit. (a) Building maximum deformation profile (b) Time-history response for all four stories during Test 12.

Closure

The NEES-Soft test program results are still being interpreted and synthesized. Overall results, as presented for the two full-scale building test programs in this paper show that (1) the FEMA P807 methodology is a logical engineering approach for seismic retrofit of these at-risk buildings when certain constraints such as first-story-only retrofits, are in place; and (2) the PBSR approaches work very well if good building performance at higher seismic intensity levels is the objective of the stakeholders and the constraints associated with (1) above is not imposed. Full project reports with all acknowledgements will be available in the two project reports in 2014 at www.nees.org .

Acknowledgments

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