Overview of the NEES-Soft Experimental Program for Seismic Risk Reduction of Soft-Story Woodframe Buildings

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ABSTRACT

The existence of thousands of soft-story woodframe buildings in California has been recognized as a disaster preparedness problem resulting in mitigation efforts throughout the state. The considerable presence of these large multi-family buildings in San Francisco prompted the city to mandate their retrofitting over the next seven years. 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, retrofit methodology development, and full-scale system-level experimental validation of soft-story retrofit techniques. In 2013, two full-scale buildings were tested within NEES-Soft. A hybrid test of a three-story building consisting of a one-story numerical substructure and a two-story physical structure above at the University at Buffalo, and a shake table test of a four-story building at the University of California – San Diego. A series of retrofits, based on methodologies ranging from FEMA P-807 to performance-based seismic retrofits developed as part of the project, were tested at both sites. Collapse testing for both building specimens was also conducted at the end of each test program. This paper presents a summary of selected test results for these full-scale building tests within the NEES-Soft project.

INTRODUCTION

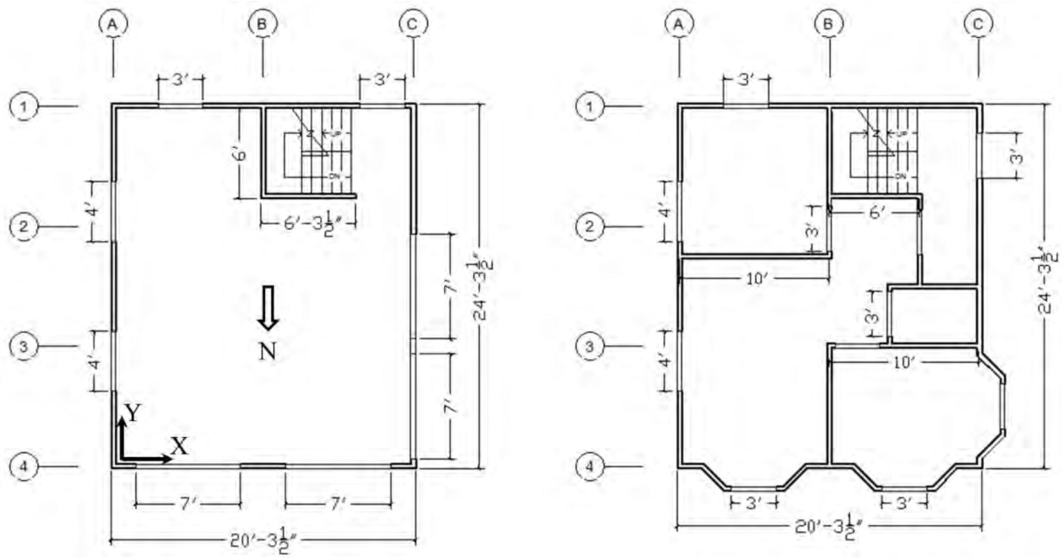
The NEES-Soft Project, whose full title is "Seismic Risk Reduction for Soft-Story Woodframe buildings," is a five-university, multi-industry, NSF-funded project that has the objectives of: (1) enabling performance-based seismic retrofit (PBSR) for at-risk soft-story woodframe buildings; and (2) experimentally 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. Figure 1 shows a photo of a soft-story woodframe building in San Francisco, CA. The vast majority of these buildings are soft because of parking garages for tenants at the bottom story. 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. These include the following test programs: 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. 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. Test Program 3: Shake table testing of a woodframe

DKB assembly to collapse; Colorado State University Structural Engineering Laboratory. Test Program 4: Slow pseudo-dynamic 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. 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. This paper presents a summary of the selected results from Test Programs 4 and 5.

Figure 1. Example of a soft-story woodframe building in California (Photo credit: M. Gershfeld)

TEST PROGRAM OVERVIEW

For all test buildings typical construction for this era was reproduced to the extent possible based on several site visits to buildings undergoing retrofit or renovation. Test program 4 at the University at Buffalo focused on several FEMA P-807 retrofits and two performance-based retrofits based on controlling the inter-story drift. Two select FEMA P-807 retrofits are presented in this paper but interested readers may find information on other retrofits that were tested in journal papers and technical reports to be published in 2014 and 2015. Figure 2a shows the numerical substructure being modeled using software developed as part of the NEES-Soft project (Pang et al, 2014) and the physical substructure. Figure 3 shows a photo of the building with four actuators attached to the joists of the floor and roof diaphragm through a load transfer system. The hybrid test was a slow test (hundreds of times slower than a real-time earthquake) meaning a single earthquake took several hours to run. Inertial and damping forces were reproduced (modeled) numerically.



(a) **(b)**

Figure 2. Floor plan for the 3-story hybrid test building; (a) first story (numerical substructure); (b) second and third stories (physical substructure)

Figure 3. The hybrid test building at the NEES@Buffalo laboratory

Test Program 5 at the University of California-San Diego laboratory also consisted of a series of retrofits and a final collapse test for comparative purposes. Again the reader is encouraged to look for upcoming documentation of test results for multiple retrofits; the results in this paper are limited to one of the P-807 retrofit tests which used a cross laminated timber panel and the collapse test. Figure 4 presents the floor plans of the four-story building and Figure 5 shows the building nearing completion of construction at the UCSD shake table facility.

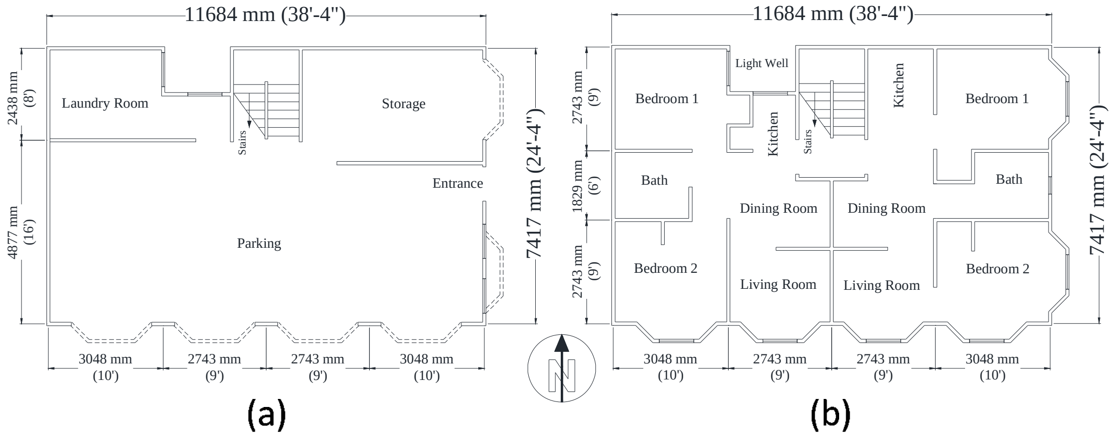


Figure 4. Floor plan for the 4-story shake table test building; (a) first story; (b) upper stories.

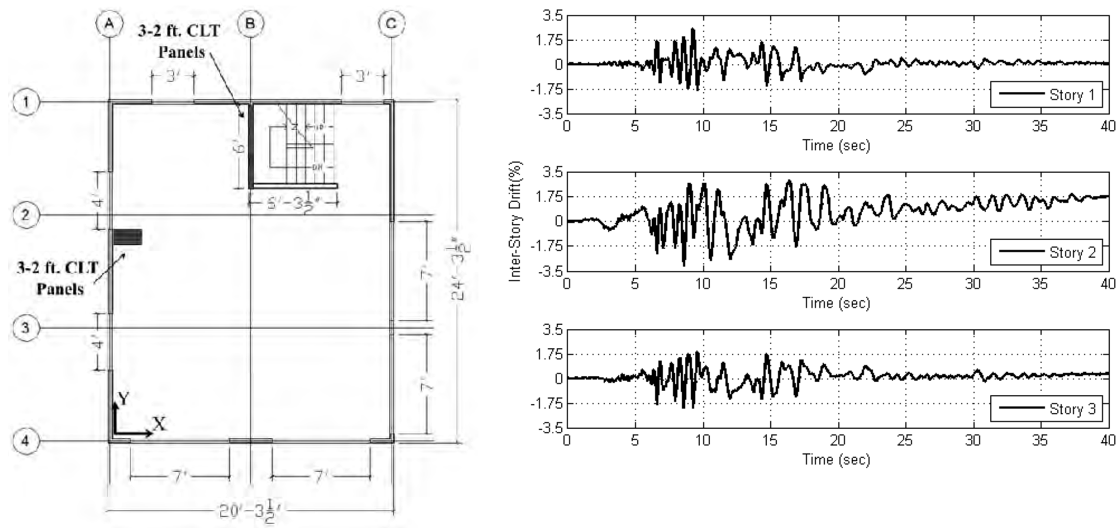
Figure 5. Four story shake table test building at NEES@UCSD

Both buildings had an array of instrumentation which remained fairly consistent for the hybrid test building, but changed for each retrofit test of the shake table test specimen. This is because the retrofits were physical retrofits for the building in San Diego but part of the numerical substructure for the retrofits in Buffalo. One exception was the installation of wood shear walls in the physical substructure in Buffalo as part of the performance-based retrofits.

THREE-STORY HYBRID TEST RESULTS

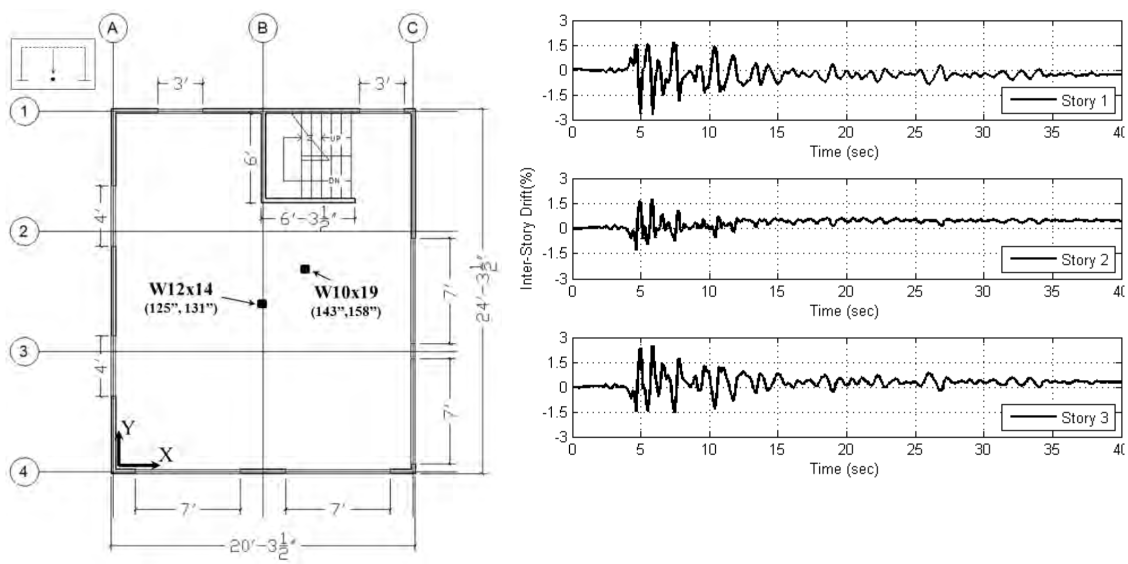
Hybrid testing was conducted on several soft-story retrofit designs following FEMA P-807 guidelines, but only two are presented here. The first of these is the cross-laminated timber panel (CLT) retrofit design which was fully contained within the numerical soft-story. The retrofit consisted of three 2 ft. CLT panels in the x-direction set adjacent to each other width-wise, and three 2 ft. CLT panels in the y-direction aligned length-wise. Figure 6a provides the layout of the CLT retrofit design in the soft-story, with the CLT panels labeled. Four hybrid tests, using ground motions of varying intensity, were conducted on the CLT retrofit. The inter-story drift time history for all three numerical stories is provided in Figure 6b for the highest intensity ground motion that the retrofit was subjected to (i.e., MCE level). This test used the Loma Prieta ground motion recorded at Capitola scaled to a MCE level seismic event for San Francisco, California providing a scaled PGA of 0.680g. Referring to Figure 6b, the first story data is from the hybrid test numerical model and the upper story data was recorded from string potentiometers attached to the physical building. The maximum inter-story drift occurred in the second story (i.e., first physical story) reaching 3.1%, with a 1.75% residual developing in the second story at the end of the ground motion.

The second retrofit applied in the NEES-Soft test program at Buffalo was the cantilevered column (CC) retrofit design which also followed the FEMA P-807 guidelines. Two CCs were used for the retrofit design, and each CC consisted of two columns. The layout is provided in Figure 7a with the center points of the two CCs labeled with an example of the two-column frame shown in the top left corner. The frame rotated lengthwise in the x-direction consisted of two W10x19 columns, and the frame rotated in the y-direction consisted of two W12x14 columns. Four hybrid tests were conducted on the CC retrofit using ground motions of varying intensity. The inter-story drift for all three stories resulting from the final test is provided in Figure 7b. This test used the Loma Prieta ground motion recorded at Gilroy scaled to a MCE level seismic event for San Francisco, California providing a scaled PGA of 0.976g. Referring to Figure 7b, the first story data is from the hybrid test numerical model and the upper story data was recorded from string potentiometers attached to the physical building. The maximum inter-drift (-2.7%) occurred in the numerical first story.



(a) **(b)**

Figure 6. CLT retrofit (a) design layout; (b) inter-story drift time history response to MCE level earthquake ground motion.



(a) **(b)**

Figure 7. CC retrofit (a) design layout; (b) inter-story drift time history response to MCE level earthquake ground motion.

FOUR-STORY SHAKE TABLE TEST RESULTS

The retrofits for the four-story test building consisted of physically installed retrofits. One retrofit, which is described herein, was designed using the FEMA P-807 methodology (FEMA, 2012) such that it aligned with the City of San Francisco ordinance passed in 2013 mandating retrofit of these types of at-risk buildings. The ordinance calls for a limitation of 20% exceedance probability of the FEMA P-807 guidelines at Maximum Credible Earthquake (MCE) intensity. For the generic site used within the NEES-Soft project, the MCE seismic intensity was assumed to be equal to a spectral acceleration of 1.8g. Thus, the first retrofit tested was designed to satisfy the FEMA P-807 guidelines at 0.9g spectral acceleration with only a 20% probability of being exceeded in 50 years. The FEMA P-807 retrofit guidelines specify that the shear stiffness of the retrofitted soft-story fall between a calculated lower and upper threshold which are computed based on the stiffness and strength of the upper stories. This retrofit used a relatively new engineered wood product known as cross laminated timber (CLT). CLT was developed in Europe almost two decades ago but is just finding its way into the U.S. market. Figure 8 shows the location of the CLT retrofit and Figure 9 shows details of the CLT panel installation itself within the ground floor-only of the test building.

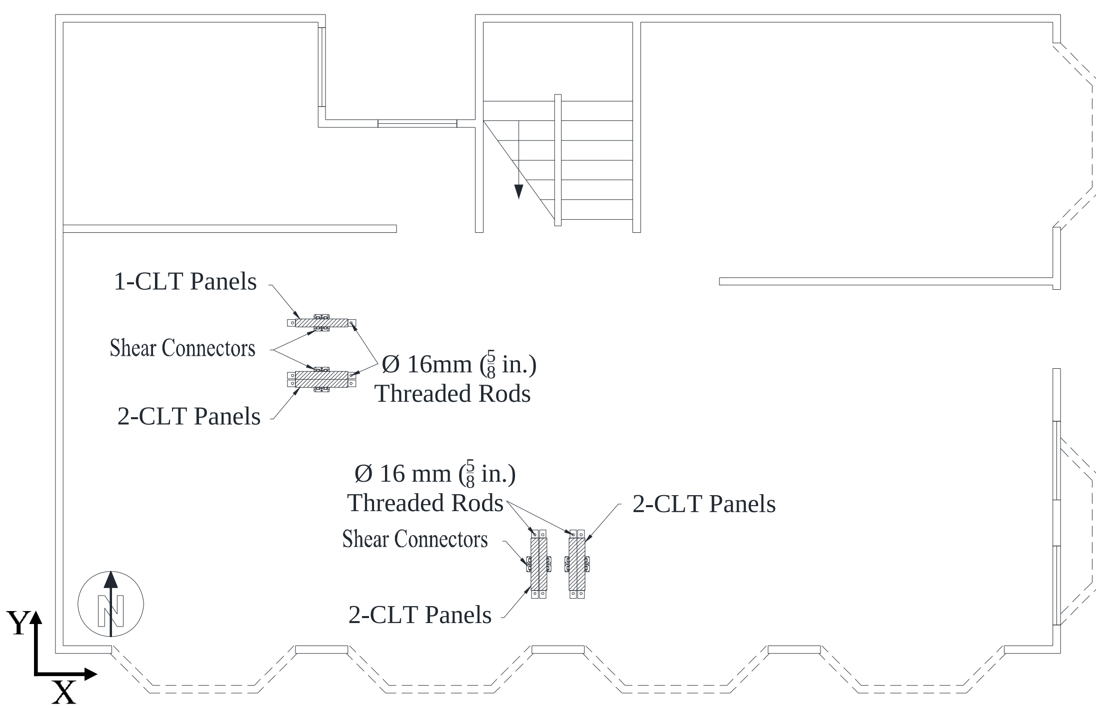


Figure 8. Location of Cross Laminated Timber (CLT) panels in the ground story installed parallel (X) and perpendicular (Y) to the motion of the shake table.

The peak lateral deformation profiles and time histories of each story are presented in Figure 10. The ground story had an average inter-story drift of approximately 1.4% with the upper story drifts being between 0.2% and 0.6%. This average was computed using the deformation of the four corners of the building. This deformation profile confirmed the behavior of this type of building as a soft-story with a relatively rigid body above the soft story (even with the P-807 retrofit methodology applied).

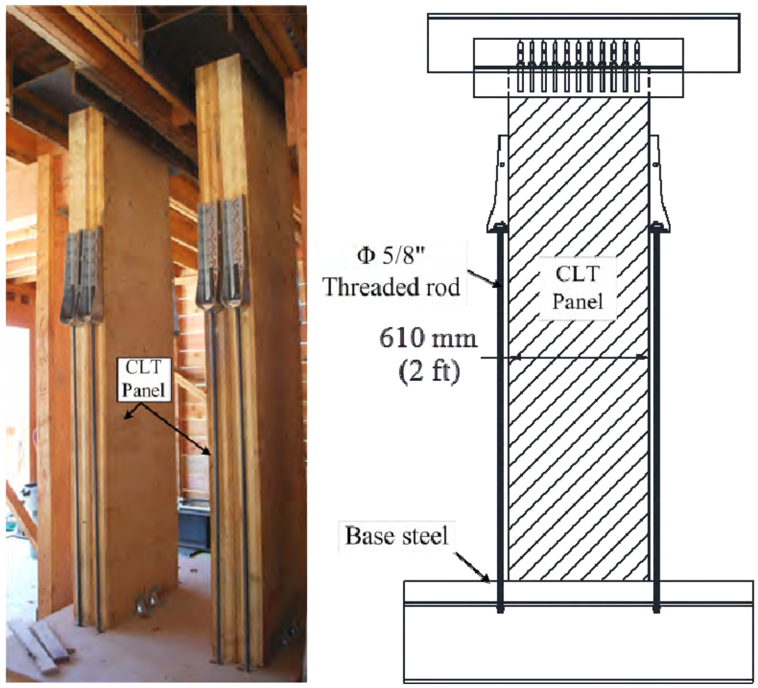


Figure 9. Cross laminated timber (CLT) panels.

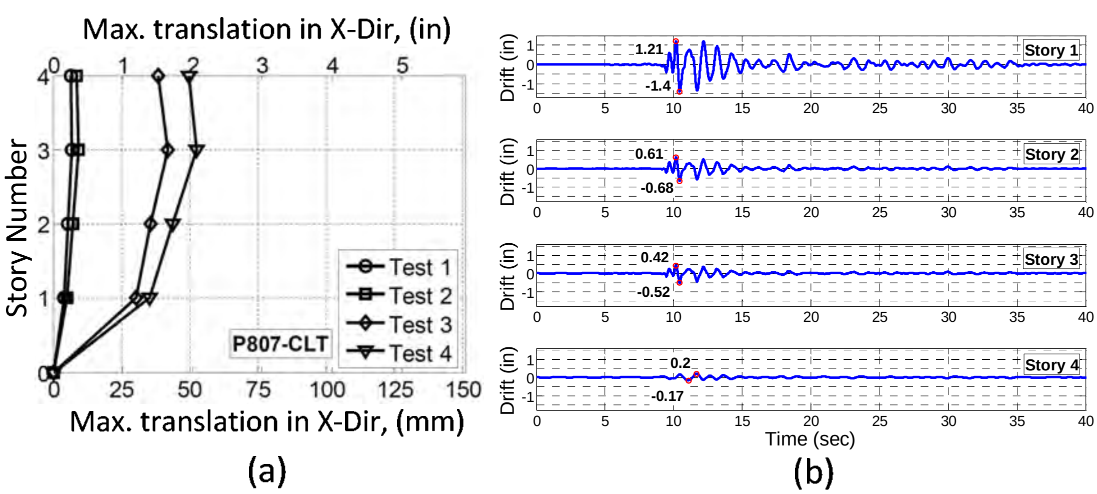


Figure 10. P-807-CLT Retrofit. (a) Building maximum deformation profile, and (b) Time-history response to Cape Mendocino Earthquake record with PGA of 0.45g.

COLLAPSE TESTING

Ultimately it was necessary to compare the behavior of the building with various retrofits installed to the behavior of the building with no retrofits since without retrofit the building would be prone to collapse. In addition, collapse testing was necessary in order to provide the engineering practitioner and research communities with a better understanding of: (1) the deformation capacity of soft-story woodframe buildings, (2) the behavior of soft-story woodframe buildings up to the point of collapse, and (3) the effect of torsion and, in the present case, the effect of having two soft sides on the soft-story collapse mechanism. The building collapsed after a series of smaller less intense shakes followed by the Superstition Hills record scaled to MCE. After the first Superstition Hills shake the building was badly damaged and on the verge of collapse (i.e., racking deformation of 15% at the first story). Figure 11 shows a photo of the collapsed building which, as oriented, collapsed toward one of the soft-side corners even though uni-axial shaking was applied.

Figure 11. The collapsed NEES-Soft test building on the shake table at NEES@UCSD.

SUMMARY AND CONCLUSIONS

The full results of the NEES-Soft project and test programs are under development at the time of the writing of this paper. However, two key conclusions already reached are that: (1) the FEMA P-807 retrofit methodology does what was intended when it was developed. It may be slightly conservative in its approach but this is still under investigation, and (2) the deformation capacity of buildings with horizontal wood siding is much higher than originally expected (i.e., it is in excess of 10% inter-story drift for the story and can potentially be even higher on one wall line).

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