SEISMIC RISK REDUCTION FOR SOFT-STORY WOOD-FRAME BUILDINGS: TEST RESULTS AND RETROFIT RECOMMENDATIONS FROM THE NEES-SOFT PROJECT

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ABSTRACT: There are thousands of soft-story wood-frame buildings in California which have been recognized as a disaster preparedness problem with concerted mitigation efforts underway in many cities throughout the state. The vast majority of those efforts are based on numerical modelling, often with half-century old data in which assumptions have to be made based on engineering judgment and project committee consensus. The NEES-Soft project, whose full title is "Seismic Risk Reduction for Soft-Story Wood-frame Buildings," is a five-university multi-industry three-year project with many facets including improved nonlinear numerical modelling, outreach, design method development, and full-scale system-level experimental validation of soft-story retrofit techniques. In 2013, two full-scale buildings were tested within NEES-Soft. The first was a three-story building tested 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 reproduced by computer, while the damage to the two upper stories, representing the physical substructure, was observed in the lab and provided feedback to the actuators. This test had the main objective of determining the effect of the retrofits on damage to the upper stories and collapse risk of the complete structure. The second major test was on a full-scale four-story 400 square meter soft-story building. It was tested by the NEES-Soft project team at the UCSD NEES outdoor shake table facility using a variety of retrofits. These retrofits ranged from FEMA P-807 retrofits to performance-based seismic retrofits developed as part of the project. Both tests demonstrated the effectiveness of the FEMA P-807 retrofit guidelines and the NEES-UCSD test validated the PBSR methodology developed within the NEES-Soft project.

KEYWORDS: Wood-frame, soft-story, earthquake, collapse, seismic retrofit, FEMA P807, risk reduction

1 INTRODUCTION

Wood-frame construction constitutes the majority of the building stock in North America. Many low-rise commercial buildings, and the vast majority of residential buildings in the United States, especially in California, are wood-frame structures. These structures include single family dwellings as well as multi-unit multi-story apartment or office buildings, where many of these multi-story buildings have parking garages or simply large openings on the first level, resulting in soft- and weak-stories at the first level. These buildings, which number in the thousands throughout California (and other parts of the U.S.), are recognized as a disaster preparedness problem. The NEES-Soft project is a five-university multi-industry project funded primarily by the U.S. National Science Foundation (George E. Brown Jr. Network for Earthquake Engineering Simulation Program) with substantial industry involvement through a practitioner advisory committee. The primary objectives of the project are to (1) enable performance-based seismic retrofit (PBSR) for at-risk soft-story wood-frame buildings; (2) experimentally validate the U.S. Federal Emergency Management Agency

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(FEMA) P-807 retrofit methodology which was developed in direct response to the recognition of a disaster preparedness problem; and (3) experimentally validate an analytical collapse model via full-scale building collapse testing. Two major test programs, along with several other smaller test programs at non-NEES labs, were conducted during the summer of 2013.

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. Testing included five programs. Test Program 1: Real time hybrid testing (RTHT) of a 20-ft long wood shear wall with and without a toggle-braced damper assembly; University of Alabama Structural Engineering Laboratory. Test Program 2: Reversed cyclic testing of a light wood-frame 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 wood-frame DKB assembly to collapse; Colorado State University Structural Engineering Laboratory. Test Program 4: Slow hybrid testing of a full-scale soft-story wood-frame 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 wood-frame building with and without seismic retrofit; Network for Earthquake Engineering Simulation (NEES) laboratory at University of California – San Diego.

2 OVERVIEW OF TEST PROGRAMS

2.1 HYBRID DAMPER WALL TESTING AT UNIVERSITY OF ALABAMA

In preparation for the full-scale three-story slow hybrid test at the University at Buffalo laboratory, the control algorithm was developed and validated on a full-scale damper wall specimen tested at the University of Alabama structures laboratory [1]. The wall, shown in Figure 1, consisted of 2x6 dimension studs and typical plywood sheathing. A toggle-braced damper assembly was installed in the middle section of the wall as a retrofit method while a second identical wall without this assembly was also tested for comparison. The wall represented the bottom level of a three-story wood shear wall stack which is typical in multi-family wood-frame buildings in North America. The real-time hybrid testing control algorithm was successfully implemented and the damper wall was shown to reduce the response peaks and corresponding damage to the wood portion of the shear wall. The reductions were significant at a seismic intensity of 100% DBE. Specifically, a 32% reduction in the inter-story drift (ISD) was observed and much less damage occurred (although some buckling of the sheathing panel was observed where the damper was located).

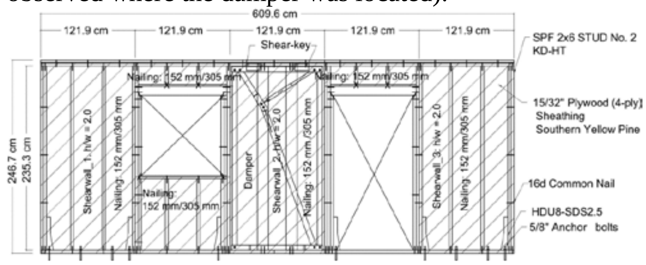


Figure 1: *Schematic showing the configuration of the damper wall assembly*

2.2 REVERSED-CYCLIC DISTRIBUTED KNEE-BRACE (DKB) TESTING AT CAL POLY

Soft-story wood-frame buildings observed in the field will typically have 2x4's at 16 in. o.c. in stud walls supporting 2x10 floor joists at 16 in. o.c. aligned with each other, i.e., joists are located directly over the studs. The building might have multiple open bays at the ground story thus allowing for reinforcement of single bay, double bays or selected bays. Regardless of the DKB system configuration, the knee-brace frame capacity is intended to be controlled by the capacity of the knee-brace connections.

The reversed-cyclic testing was performed at Cal Poly San Luis Obispo. The DKB system test structure was built to accommodate four knee-braced frames (4-frame DKB). The testing was performed for two different configurations: 20 ft and 10 ft knee-braced frames. The brace slope was approximately 2.5:1 for the test specimen. The 3D Revit model of the test setup for a 20 ft frame is shown in Figure 2. Weights of approximately 1600 lbs (360 kN) that replicate the additional two stories above were located over the two exterior walls but, for clarity, are not shown in Fig. 2.

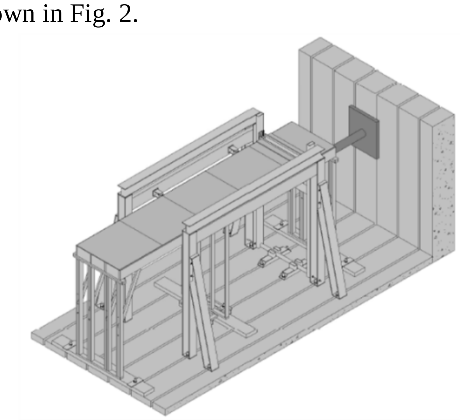


Figure 2: *Test setup at Cal Poly for DKB system*

2.3 SHAKE TABLE TESTING OF A DKB FRAME AT COLORADO STATE UNIVERSITY

The shake table test was performed at Colorado State University. The four-frame DKB specimen for the shake table test was identical to the reversed-cyclic test shown in Figure 2 except it was 3.05 m (10 ft) long. A large steel plate was bolted to the diaphragm to facilitate installation of seismic mass and a number of steel beams were welded to the plate to provide a total weight of 3200 lbs. Readers interested in the details of the reversed-cyclic test and shake table test on the DKB system are referred to the WCTE paper by Gershfeld et al [2].

2.4 SLOW HYBRID TESTING OF A THREE-STORY BUILDING AT NEES-UB

During the NEES-Soft hybrid testing, a full-scale three-story building was partitioned into a one-story numerical substructure and a two-story physical substructure to allow various retrofits to be numerically inserted into the first numerical soft-story; specifically, cross laminated timber rocking walls, steel cantilevered columns, fluid viscous dampers (FVDs) and a distributed knee-brace (DKB) system. Then, the physical substructure was retrofitted with wood shear walls and anchor tiedown rods and a performance-based seismic retrofit (PBSR) techniques was tested using shape memory alloy devices. Figure 3 shows the third story (second physical story) being constructed, and Figure 4 shows the actuator connections to the roof diaphragm (which is the same as the third floor diaphragm). Four actuators (two at each level) were used to impose both rotational and translational motion to the physical specimen representing the interactions between the numerical and physical substructures.

Figure 3: *Physical substructure under construction at NEES-UB Laboratory.*

The floor plan is shown in Figure 5 for the numerical substructure (first story) and the physical substructure (second and third stories). Note the open first floor plan for vehicle parking which, as discussed earlier, is a characteristic of these types of soft-story buildings that makes them difficult to retrofit.

Figure 4: *Roof level showing connection of actuators to diaphragm*

A number of retrofits were examined, but in the interest of brevity the results for the steel Cantilevered Column (CC) retrofit that followed the FEMA P-807 guidelines [3] is presented in detail herein. Four hybrid tests with increasing seismic intensity, starting with a design basis earthquake (DBE) and ending with a maximum considered earthquake (MCE), were conducted on the CC retrofit. The excitation for the second test was 1971 San Fernando ground motion and scaled to DBE. The maximum building displacement was 99 mm (3.9 in) and the peak ISD occurred at the second story (2.2%). The third test was an MCE using the 1992 Cape Mendocino ground motion recorded at the Rio station. The resulting maximum total building displacement was 147 mm (5.8 in) and the resulting peak ISD was 3.7% at the second story. The ISD time history for CC03 is provided in Fig. 6 for all three stories. Based on Fig. 6, it can be seen that torsion was completely eliminated from the building response. The drift response was distributed throughout all the stories with no story ever approaching a collapse condition or having any residual displacement.

In all retrofit cases, the retrofitted soft-story wood-frame building performed well, meeting the 4% drift limit at an even higher intensity than designed. The inter-story drift time histories provided for the specific tests demonstrated the effectiveness of the first-story-only retrofit in strengthening/damping the soft-story while not transferring too much force into the upper stories, and in eliminating any torsional response.

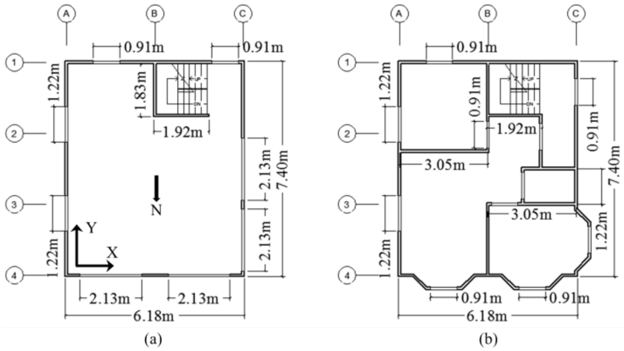


Figure 5: *Floor plan for three-story hybrid test building; (a) numerical story at level 1; (b) physical stories at level 2 and 3.*

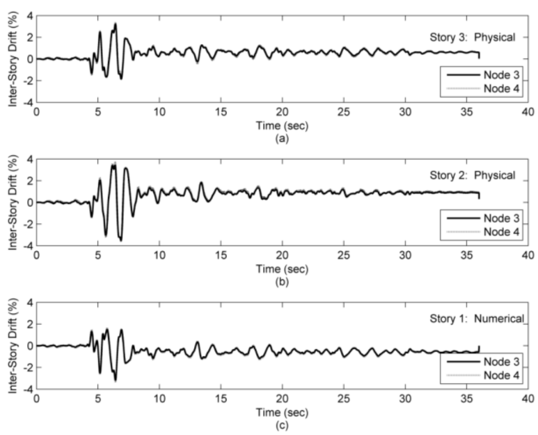


Figure 6: *CC Retrofit Inter-Story Drift Time History for Low Percentile MCE Hybrid Test: (a) Third Story; (b) Second Story; (c) First Story (Note: Node 3 and 4 are on opposite corners of the building and a difference would indicate torsion)*

2.5 SHAKE TABLE TESTING OF A FOUR-STORY BUILDING AT NEES-UCSD

Shake table testing was used to investigate four retrofits and the collapse of a full-scale four-story wood-frame building representative of 1920's to 1940's San Francisco Bay Area style construction. Similar to the hybrid test program, retrofits were developed by applying the methodology of FEMA P-807 and PBSR, developed as part of the NEES-Soft project. Figure 7 shows a photo of the full-scale four-story test building just prior to testing and Figure 8 presents the floor plans. All tested retrofits were designed for spectral accelerations ranging from 0.9g to 1.8g and experimental responses ranged from peak inter-story drifts of 20 mm to 60 mm.

(a) (b)

Figure 7*: Comparison of the architecture for a soft-story wood building: (a) in the San Francisco Bay Area, and (b) designed as part of the NEES-Soft project.*

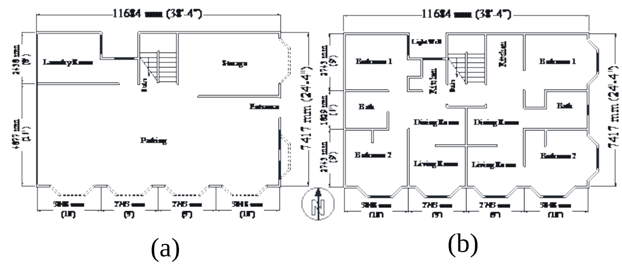
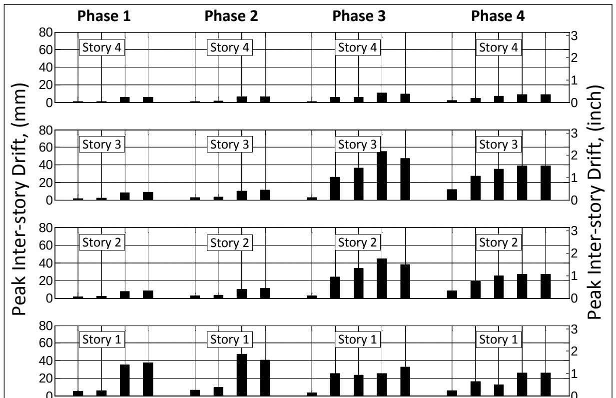


Figure 8*: Floor Plans for the four-story test building: (a) Ground story, and (b) Upper stories.*

The first retrofit (Test Phase 1) utilized cross laminated timber (CLT) and was designed to satisfy the FEMA P807 guidelines at 0.9g spectral acceleration with only a 20% probability of being exceeded (i.e., probability of non-exceedance (PNE) of 80%). In Phase 2 the retrofit design utilized a steel special moment frame (SSMF) to satisfy the FEMA-P807 guideline but at a spectral acceleration of 1.1g. Then, in Phase 3 and Phase 4, the building was retrofitted using PBSR to meet the performance criteria with a probability of non-exceedance of 50% at MCE level, i.e. 1.8g spectral acceleration, using a steel special moment frame and supplemental damper assemblies, respectively, both combined with wood shear wall retrofits in the upper stories. All retrofits included an added plywood diaphragm and collector elements at the first floor ceiling to channel the forces into the vertical elements of the lateral force resisting system. In order to verify the retrofit designs, extensive nonlinear time history analysis (NLTHA) was conducted using state-of-the-art software [4-7].

The ground motion acceleration records used during testing ranged in intensity depending on the retrofit type and methodology considered. Peak inter-story drifts are shown in Figure 9 and below that at the bottom of the Figure are the PGA and spectral accelerations (Sa) for the records. All records were scaled versions of the Loma Prieta or Cape Mendocino earthquake.



Test ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
PGA (g)	0.11	0.10	0.49	0.45	0.13	0.12	0.60	0.55	0.11	0.65	0.60	0.90	0.98	0.27	0.65	0.60	0.98	0.90
Sa (g)	0.20	0.20	0.90	0.90	0.24	0.24	1.10	1.10	0.20	1.20	1.20	1.80	1.80	0.50	1.20	1.20	1.80	1.80

***Figure 9**: Peak inter-story drifts for the 18 tests conducted as part of the NEES-Soft four-story shake table test program. Note that the ground motion intensities are not consistent between the different test phases.*

As shown in Figure 8, for the first two phases, which were retrofits applied at the first story only following the FEMA P-807 guideline, the seismic (and ductility) demand occurs only in the first story with minimal demand being transferred to the upper three stories. However, in the latter two phases where a PBSR approach was applied, the seismic response engaged all four stories, and seismic (and ductility) demand is more evenly distributed throughout the structure. This is consistent with the PBSR approach applied and allows the building to perform well in much more intense earthquakes than a single-story retrofit philosophy. Of course, to achieve higher levels of performance via a PBSR approach, there may be additional costs and occupant disruption. Figure 10 presents the global hysteresis for the Loma Prieta test for each of the retrofits. These represent the test that produced the largest base shear for each specific retrofit type/methodology combination, as specified at the bottom of Figure 9. The peak building drift was observed during Phase 3 at MCE and was only 114 mm (4.45 in) (or 4.6% ISD) with a corresponding base shear of 283 kN (63.6 kips). The building had a weight of approximately 450 kN (101 kips).

Full-scale collapse testing of wood-frame buildings subjected to seismic load has been conducted only a few times worldwide. Sakamoto et. al [8] discussed the planning of a series of tests on a full-scale two-story town house at the E-Defense laboratory in Miki, Japan as part of DAI-DAI-Toku project. The testing then occurred several years later at the Grand Opening of the laboratory. In 2004, a two-story Japanese conventional wood-frame house was tested to investigate the collapse mechanism and predict the collapse margin for these types of buildings [9,10]. These studies were conducted to improve numerical simulation models. The need for investigating the collapse of western style wood-frame buildings in the United States is critical for the following reasons: (1) there is no data for full-scale mid-rise residential buildings subjected to large drifts primarily because of laboratory safety concerns; and (2) the tests in Japan were on buildings representative of conventional post-and-beam, not light wood-frame construction and, while they provide an excellent body of knowledge, they may not be able to define good estimates of collapse drifts. Thus, collapse testing of a full-scale building subjected to seismic loads was considered to provide a valuable contribution to the understanding of the collapse behavior of these types of at-risk buildings. The objectives of this final test phase at NEES@UCSD were to: a) better understand the behavior of light wood-frame buildings near and at collapse; b) quantify the collapse displacement; and c) investigate the collapse mechanism of soft-story buildings. Figure 11 presents the spectral displacements at the top and the ground displacement time histories at the bottom for the records used in the collapse phase. All retrofits were removed and the rod tie down system disengaged and allowed to float within the wood shear walls at the upper stories during testing.

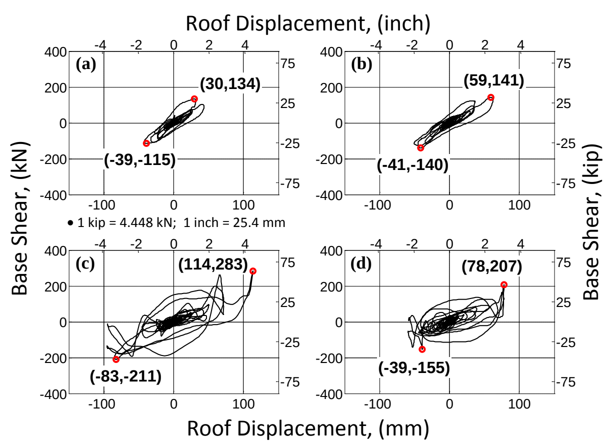


***Figure 10**: Global hysteresis curves in shake direction for the Loma Prieta ground motion: (a) Phase1-Test No. 3, (b) Phase 2-Test No. 7, (c) Phase 3-Test No. 13, (d) Phase 4-Test No. 17. Note that the ground motion intensities are not consistent between the different test phases.*

The testing sequence is presented in Table 1 and ultimately collapse occurred in test C8. Test C6 resulted in a 13% inter-story drift at story 1 with the building appearing to be very unstable prior to the final tests. There was some strength remaining, whether due to bearing or shear is as yet undetermined, but it was clear the building could not be entered safely and would need to be demolished if it had been an in-situ structure. Figure 12 presents the response of the building for test C6 and C8, the two MCE level scalings of the Superstition Hills earthquake. The string potentiometers measuring displacment at the second diaphragm level were damaged at 636 mm as shown in Figure 12.

Closer inspection of Figure 11 shows the large spectral displacements for the Superstition Hills record compared to Loma Prieta and Cape Mendocino. During the aforementioned tests in Japan, it was been shown that, while ground acceleration induces large inertial forces in wood-frame buildings, it is generally large reversing ground deformations that initiate collapse. This is perhaps because as the building softens and the period elongates the collapse mechanism moves from one based on material/strength to one based on geometry/deformation (i.e., p-delta effects primarily induce collapse of the weakened structure). This was observed during the shake table tests in the NEES-Soft program when the Superstition Hills earthquake was used as input.

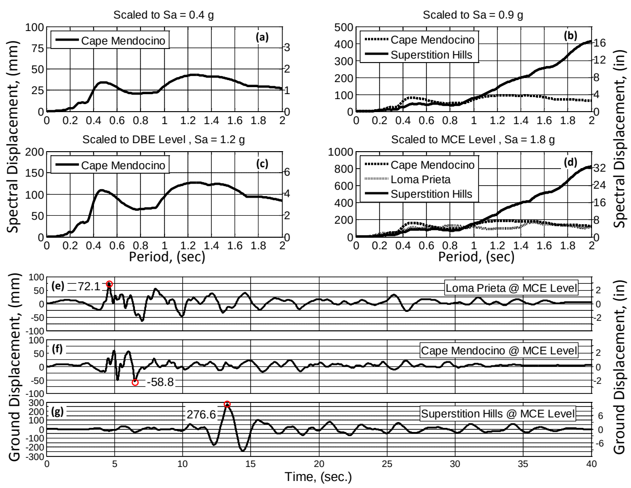


***Figure 11**: Spectral displacements and corresponding ground displacement time histories for motions used in collapse phase of the NEES-Soft test program*

2.6 NUMERICAL MODELING OF SOFT-STORY WOOD-FRAME BUILDINGS

As part of the NEES-Soft program, a 3D modeling package, called Timber3D, was developed. In the numerical model, the framing members of floor and roof diaphragms are modeled using two-node 12 degrees-of-freedom (DOFs) frame elements which account for geometric nonlinearity. The lateral stiffness of walls are modeled using two-node 6 DOFs link elements. The Modified Stewart Hysteretic (MSTEW) model, also known as the CUREE hysteresis model, was utilized to model the load-displacement hysteresis of two types of walls, namely walls sheathed with gypsum wall boards and horizontal wood sheathings. The values of the hysteretic parameters were obtained by fitting hysteresis loops obtained from full-scale wall tests, conducted as part of this NEES-Soft project [11].

In order to reduce the computational demand, shape functions of the frame elements are utilized to eliminate the DOFs of the link elements [12]. This modeling technique allows for the reduction of the global stiffness matrix size (depends only on the number of frame elements and is independent of the number of link elements).

***Table 1**: NEES-Soft collapse phase test motions*

Seismic Test ID*	Earthquake record	Sa (g)	PGA (g)	PGD** (mm)
1	Cape Medocino - Rio	0.40	0.21	13.1
2	Cape Medocino - Rio	0.90	0.44	29.4
3	Cape Medocino - Rio	1.20	0.56	39.2
4	Cape Medocino - Rio	1.80	0.90	58.8
5	Loma Prieta - Gilroy	1.80	0.98	72.1
6	Superstition Hills	1.80	0.86	277
7	Superstition Hills	0.90	0.42	138
8	Superstition Hills	1.80	0.86	277

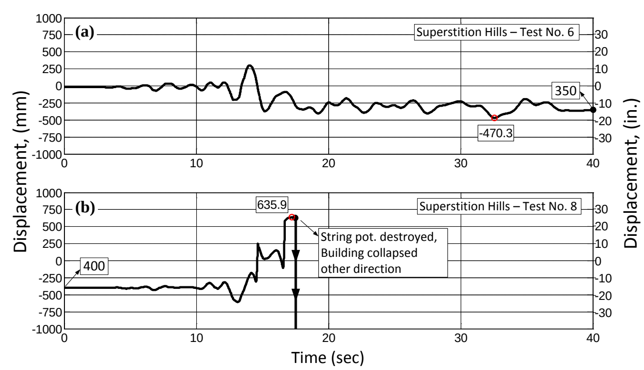


***Figure 12**: First-story response of the building subjected to the Superstitions Hills record scaled to MCE. Note a 50% MCE level shake was conducted between these tests but did not bring the building past its original equilibrium point and is therefore not shown.*

To evaluate the collapse risk of soft-story wood-frame buildings, incremental dynamic analyses (IDA) were performed using the FEMA P-695 22 bi-axial far field ground motions on a three-story building representative of typical older wood-frame buildings in the San Francisco bay area. Figure 13 shows the deformed shape of the three-story wood building at incipient collapse.

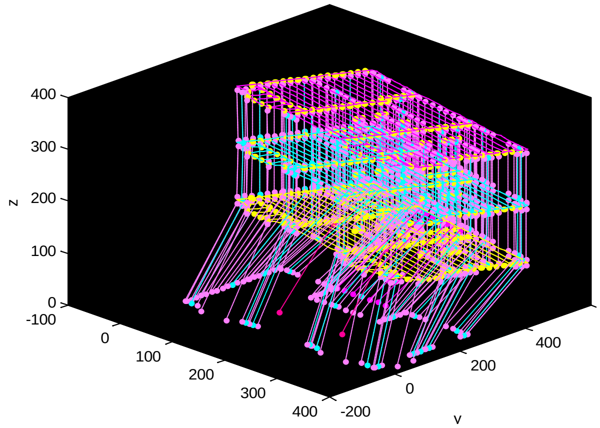


***Figure 13**: A three-story wood-frame building at incipient collapse.*

Figure 14 shows the collapse fragility curve presented in terms of the peak resultant inter-story drift obtained from IDA. The building is deemed to have collapsed when the tangent-to-initial slope ratio of the IDA curve is less than 0.2. As can be seen from Figure 14, the median collapse drift is about 13%, based on the analytical data points. From the fitted lognormal cumulative distribution function (CDF), the median collapse drift is approximately 12%, which is of the same order of magnitude recorded for the peak drift observed in the NEES-Soft full-scale shake-table collapse test.

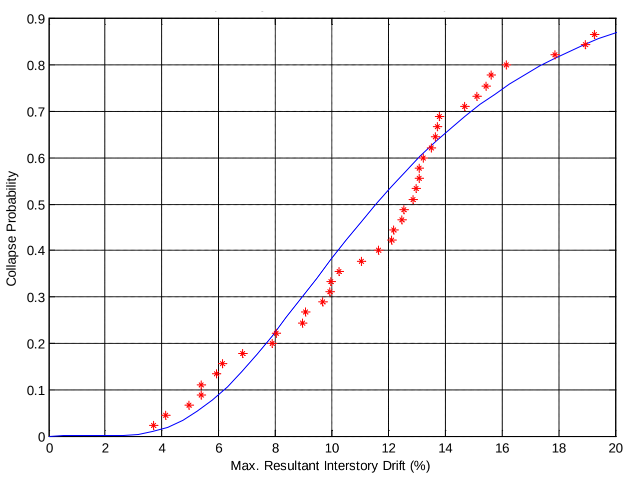


***Figure 14**: Cumulative distribution of collapse inter-story drifts.*

Figure 15 shows two photos of the building following the collapse test. The building fell forward and twisted indicating a failure resulting from a combination of translation and torsion at the first story. The upper stories behaved rigidly indicating a clear soft-story failure mechanism, as expected.

***Figure 15**: The test building following collapse: (a) front of building with garage openings not visible due to collapse; (b) back of the building*

3 RECOMMENDATIONS

Recall that the objectives of the NEES-Soft project were to: (1) enable performance-based seismic retrofit (PBSR) for at-risk soft-story wood-frame buildings; (2) experimentally validate the U.S. Federal Emergency Management Agency (FEMA) P-807 retrofit guidelines; and (3) experimentally validate an analytical/numerical collapse model via full-scale building collapse testing. Based on the retrofit designs, installation, and test results a number of initial recommendations can be made. Specifically, the FEMA P-807 retrofit guidelines provide a good alternative to fully code compliant retrofits when constraints, either financial or logistical, prevent a more comprehensive (e.g. code compliant or performance-based) approach. For the P-807 portion of the test program, the test building was retrofitted to 50% and 60% MCE level with a 20% exceedance probability and performed very well at these levels of seismic intensity. The un-retrofitted building was subjected to these same earthquakes which resulted in just slightly more than 4% inter-story drift. Thus, for these earthquake motions (Cape Mendocino and Loma Prieta) the P-807 retrofitted building would likely have about 2.5% to 3% drift when subjected to these MCE motions and be very unlikely to collapse.

The PBSR retrofits enabled distributed seismic demand over the height of the structure and resulted in very good performance at MCE level for the Cape Mendocino and Loma Prieta ground motions. These retrofits would likely allow the structure to survive a much more intense earthquake than the MCE scaling of Cape Mendocino and Loma Prieta, thus it is anticipated that it would also survive the MCE level scaling of the Superstition Hills earthquake, which is the more intense MCE that collapsed the un-retrofitted building. Recall from Figure 11 that the ground displacements for the Cape Mendocino and Loma Prieta records were small compared to the Superstition Hills record. Thus, one major conclusion is that the probability of collapse of these types of buildings is strongly dependent on whether or not they are retrofitted and on the characteristics of the particular ground motion record.

All tested retrofits were able to provide the desired performance and were deemed viable candidates for retrofit of soft-story buildings. They did, however, offer a substantial range of cost and performance. Regardless of the retrofit components used for vertical elements of the lateral load resisting system, it is clear that the foundation requirements (grade beams or deep foundations) for each retrofit would play an important role in the retrofit selection process.

4 CLOSURE

This paper presented an overview of the NEES-Soft testing conducted from 2011-2013. The objectives were outlined herein and initial recommendations made as a direct result of test planning and observations during testing. However, it is duly noted that these should be viewed by the wood-frame seismic community as initial recommendations that have not yet been peer-reviewed by the project Practitioner Advisory Committee.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. CMMI-1041631 and 1314957 (NEES Research) and NEES Operations. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the investigators and do not necessarily reflect the views of the National Science Foundation. A sincere thank you to Simpson Strong-Tie for their financial, personnel, and product support throughout the project, including the engineering support for the SMF in San Diego. Cash, personnel or in-kind contributions were provided by the USDA Forest Products Laboratory, Structural Engineers Association of Southern California, Taylor Devices, and Innovative Timber Solutions/Smartwood. The authors kindly acknowledge the senior personnel of the NEES-Soft project: David V. Rosowsky at University of Vermont, Andre Filiatrault at University at Buffalo, Shiling Pei at South Dakota State University, David Mar at Tipping Mar, and Charles Chadwell at Cal-Poly; MSc students Jason Au (CPP), and Robert McDougal (CPP); and the practitioner advisory committee: Laurence Kornfield, Tom Van Dorpe, Doug Thompson, Kelly Cobeen, Janiele Maffei, Douglas Taylor, and Rose Grant. A special thank you to all of the REU students Sandra Gutierrez, Faith Silva, Gabriel Banuelos, Rocky Chen, Connie Tsui, Karly Rager, and Philip Thompson. Others that have helped include Asif Iqbal, Vaishak Gopi, Steve Yang, Ed Santos, Tim Ellis, Omar Amini, Emma Jiang, and Russell Ek. Finally, our sincere thank you to NEES and all site staff and site PI's at NEES-UCSD and NEES-UB for their assistance in preparing for and conducting the tests.

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