# The NEES-Soft Project: Seismic Risk Reduction for Soft-Story Woodframe Buildings

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**SUMMARY:**
As early as 1970, the structural engineering and building safety community recognized that a large number of two-, three- and four-story woodframe buildings designed with the first floor used either for parking or commercial space were built with readily identifiable structural system deficiencies, referred to as a "soft story". Thus, many multi-story woodframe buildings are susceptible to collapse at the first story during earthquakes. This paper presents the progress of a U.S. National Science Foundation (NSF) funded Network for Earthquake Engineering Simulation (NEES), five-university multi-industry three-year project entitled "NEES-Soft: Seismic Risk Reduction for Soft-Story Woodframe Buildings" with three major objectives, (1) experimentally validate economical retrofit concepts for these types of buildings; (2) develop a performance-based seismic retrofit (PBSR) philosophy for soft-story woodframe buildings; and (3) experimentally validate performance-based seismic retrofit for these types of at-risk structures.

*Keywords: Soft-story; light-frame wood; woodframe; collapse; large-scale experimentation*

## 1. INTRODUCTION

Many older multi-story woodframe buildings built in the 1960's and before are susceptible to collapse at the first story during design code-level earthquakes. The majority of these older multi-story woodframe buildings have large openings and few partition walls at the ground level. This open space condition results in the lateral stiffness and strength of the first story being significantly lower than that of the upper stories. Figure 1 shows a photograph of an existing soft-story woodframe multi-family building in San Francisco, California. At the bottom story are a number of single panel garage doors which provide very little lateral resistance. In 2008, the San Francisco Department of Building Inspection and the Applied Technology Council initiated a Community Action Plan for Seismic Safety (CAPSS) project with the main goal of identifying possible action plans for reducing earthquake risks in existing buildings. According to the CAPSS study, 43 to 80 percent of multi-story woodframe buildings in San Francisco will be deemed unsafe after a magnitude 7.2 earthquake and a quarter of these buildings would be expected to collapse. These soft story structures are primarily rental apartments and rental houses with an estimated 58,000 people residing in these buildings. It is anticipated that thousands more could be displaced from their homes and many could lose their lives should a major earthquake occur before a retrofitting plan can be implemented. The NEES-Soft project whose full title is "Seismic Risk Reduction for Soft-Story Woodframe Buildings" is a five-university multi-industry partnership that has two major components. One component is to provide experimental verification of the existing ATC 71.1 guidance being provided for retrofitting many of these soft-story buildings. The other is to provide a methodology and experimental validation for performance-based seismic retrofit (PBSR) of soft-story buildings. The PBSR procedure must account for excessive torsion, which is often present in these types of buildings.

**Figure 1.** Example of a soft-story woodframe building in San Francisco, California (Photo courtesy of M. Gershfeld)

The project is a three year project with 10 major tasks as shown in the timeline in Figure 2. Tasks range from numerical model improvement for collapse modelling to two full-scale system level tests.

| Task | Year 1 | | | | Year 2 | | | | Year 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Hybrid Testing of Soft-Story Woodframe Building | | | | | | | | 1.1 | | 1.2 | | |
| 2. 3-D Collapse Model Development | 2.1 | | | | | | | | | | | |
| 3. PBR Method for Soft Story | 3.1 | | 3.2 | | | | 3.3 | | | | | |
| 4. Evaluation of ATC-71.1 Retrofit Guidelines | | | | | | | 4.1 | | 4.2 | | | |
| 5. Seismic Protection Systems for Higher Performance | 5.1 | | 5.2 | | | | | | 5.3 | | | |
| 6. Performance-Based Retrofit Guidelines | | | | | | | | | 6.1 | | | |
| 7. Project Advisory Committee | 7.1 | | | | | | | | | | | |
| 8. System Level Verification of Retrofit Procedures | | | | | | | | | | | 8.1,2,3 | |
| 9. Education, Outreach, and Technology Transfer | 9.1 | | | | | | | | | | | |
| 10. NEES Awardee Meetings (every 18 months) | | | 10.1 | | | | | | | | | |

**Figure 2.** NEES-Soft Project three year timeline and tasks

The retrofit of a weak story structure is a delicate balancing of several conflicting criteria: (1) the public policy driven need to limit the retrofit to the ground floor level only and the desire to meet acceptable performance criteria; (2) the practical need to reconcile current and archaic construction assemblies and practices and minimize the necessity for onsite testing, and (3) the engineering need for sophisticated tools and analysis techniques for the design of this type of structure and the desire to reduce the cost and complexity of engineering effort.

The majority of these soft and weak story buildings use ground level for parking or retail space. From the public policy perspective, allowing ground level only retrofit schemes prevents displacement of the occupants during retrofit, thus reducing financial burden on the occupants and significantly reducing the cost of construction and loss of revenue from rent during construction. A policy that is friendly to occupants and property owners enables public support and speeds up implementation. However, this constraint creates a physical limit on the level of performance that can be achieved. Since the dynamic behavior of the ground level and upper levels are fundamentally linked, leaving upper levels "as-is" establishes an upper bound on the overall building performance. As the strength of the ground level is increased by the retrofit, the seismic demand on the upper level increases as well and once the capacity of the upper level is reached further increase in ground level strength simply shifts the critical mode of failure from ground floor to the level above. Thus, the ability to determine the capacity of the existing upper floors becomes a critical component of any procedure for a weak story retrofit. The task of determining the floor capacity considering the contribution of all available components is complicated by the significant differences between present and archaic construction practices. For example, the archaic construction practices did not include any of the steel hardware in wood to wood and wood to concrete connections which is now standard practice in modern construction. There is no reliable data to determine the contribution of the hardware to the system capacity and precise evaluation using numerical methods is a complex process. The current best engineering judgment is that it might be responsible for anywhere between 25-35% of the overall system capacity. This is further complicated by lack of reliable data or total lack of data on the performance of the archaic assemblies.

The current design methods available to engineers are not very helpful in addressing these concerns without significantly increasing engineering cost, the need for complex analysis tools and sophisticated and highly trained engineers. The methodologies presently available to practicing engineers can be divided into force-based and performance based methods. The force based methods would include the requirements of the latest ASCE 7 - Minimum Design Loads for Buildings and Other Structures and International Building Code (IBC), and International Existing Building (IEBC). If the retrofit design is attempted using ASCE 7 and IBC it would likely be to bring the building into compliance with the latest code requirements, and would focus on life safety. The analysis with this method would be fairly simple and straight forward, but would in most cases result in full reconstruction of the structural system with intent to eliminate weak story and replacement of existing archaic finishes with modern. Most of the connections would have to be reinforced and most of the wall and floor assemblies would likely have to be removed and replaced, thus making this approach economically unfeasible in most cases. The IEBC (International Existing Building Code) requirements allow one to limit the retrofit to the ground floor only by significantly increasing the demand on the ground level, but there are no mechanisms in the procedure to ensure that ground level is not over-strengthened and the damage is simply shifted to the level above. The performance based methods include ASCE 41- Seismic Rehabilitation of Existing Buildings and Direct Displacement Design (DDD). The analyses requirements of ASCE 41 for this type of building require significant field investigation of the existing materials and sophisticated modeling and non-linear dynamic analysis. This significantly increases engineering cost and in most cases also becomes impractical. The DDD methodology could be used for this analysis, but in its past form it did not account for torsion, which is a critical consideration for this type of structure. Therefore, as part of the NEES-Soft project a DDD procedure that includes torsion as well as vertical irregularities in stiffness and strength has been developed. In the interest of brevity, the readers interested in DDD with torsion are referred to Bahmani and van de Lindt (2012).

Another methodology soon to become available is ATC 71.1. It specifically targets the retrofit design of weak story buildings and attempts to address some of the concerns outlined above. The ATC 71.1 is a simplified performance based approach. The ATC 71.1 methodology attempts to develop ground-floor-only retrofit option by basing the level of ground floor retrofit on several key factors, such as ratio of strength between ground and upper levels, relationship between torsion characteristics of ground and upper levels and capacities of archaic materials. This methodology seems to be able to address the shortcomings of other methodologies. However, a number of assumptions would benefit from test verifications.

## 2. RETROFITS FOR INVESTIGATION

As discussed above, many multi-story wood-framed buildings have a structural weakness due to large openings in their perimeter walls and to a lack of interior walls at the ground level, resulting in a ground story that is significantly weaker and more flexible (softer) than the upper stories and thus the structure is vulnerable to collapse. Furthermore, these buildings exhibit plan asymmetries in their first story and thus are subjected to significant torsional response. Within the framework of the NEES-Soft project, in general, two basic approaches are being considered for retrofits. The first is a minimum level retrofit (ATC 71.1 methodology) in which the focus is on increasing the stiffness and strength of the first story. Such an approach is effective in reducing displacement demands in the first story. However, it tends to increase the transfer of forces to the upper stories. The objective of this approach is to achieve a "shelter-in-place" performance level for the design earthquake. Such a performance level implies that the structure may sustain significant structural damage and could be prone to collapse during large aftershocks. As an alternative, a retrofit philosophy can be developed based on the concept of performance-based-seismic retrofit (PBSR) wherein a methodology that includes advanced technologies can be used to achieve higher performance levels. This can also include conventional approaches such as a tighter nailing schedule, steel frames or cantilever columns (sometimes referred to as an inverted moment frame). These approaches are discussed in section 3 of this paper.

If one considers that the deformation pattern of a soft-story structure is, in some sense, similar to that of a base-isolated structure, one logical approach to limit the spectral displacement in a soft story is to increase the damping while at the same time maintaining the soft story. This can be accomplished by adding a supplemental damping system to the first story capable of reducing displacements while at the same time limiting the transfer of forces to the upper stories and thereby achieving higher levels of performances (e.g., Fully Operational (FO) to Immediate Occupancy (IO)). The effectiveness of an energy dissipation system consisting of toggle-braced fluid viscous dampers (FVDs) has been demonstrated by Shinde and Symans (2010) for application to wood-framed shear walls. However, in the case of soft-story wood-framed buildings, the wall lengths in the first story may be quite small and thus require a more compact framing assembly that results in a near-vertical installation. At the same time, magnification of the damper displacement is needed to increase the effective damping applied to the structure. Such requirements can potentially be met with a scissor-jack framing assembly (see Figure 3).

**Figure 3.** Scissor-jack bracing assembly in "Olympic House and Park Building" in Nicosia, Cyprus

Within the NEES-Soft Project, numerical simulations have been performed to study the strategic placement of linear fluid viscous dampers (both in terms of their location and damping capacity) for reducing both the translational and torsional structural response of soft-story woodframed buildings while at the same time limiting the transfer of forces to the upper stories of such structures. In the case of the three-story NEES-Soft test specimen to be tested at the UB-NEES Laboratory, two damper layouts were considered (see Figure 4) in which the scissor-jack bracing system for both cases is assumed to provide an amplified damping coefficient for each damper of 1.0 kip-sec/in. For the incremental dynamic analyses that were performed (using the SAWS2.1 software program; Christovasilis and Filiatrault (2009)), the structural response of interest is the maximum inter-story drift ratio of the south wall line in the first story (weak wall line) with respect to the earthquake scaling factor ranging from 0 to 1.5. The ground motions used in the analysis are a moderate near-field motion recorded at the Newhall County Fire station (NCF90) and a moderate far-field motion recorded at the Canoga Park station (CP106) (both motions from the 1994 Northridge earthquake and applied along the east-west direction of the building).

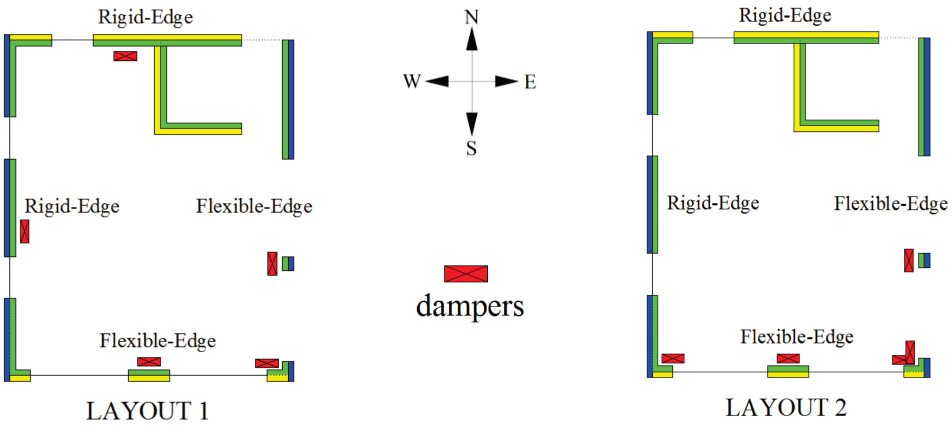



**Figure 4.** Plan views of ground story and possible damper layouts for NEES-Soft test specimen

The simulation results for the NCF90 motion are shown in Figure 5. For 100% of the ground motion, the conventional structure has a first story (soft story) drift ratio greater than 4%, indicating severe damage and potential collapse. On the other hand, the upper-story drift ratios are maintained under 0.5% at the same ground motion intensity due to the protection afforded by the soft story behavior. For the damper retrofit cases, the drift ratio of the soft first story is less than 1% for both damper layouts, indicating no significant structural damage. However, there is an increase in drift response for the second story, although it is still maintained below a level of about 1%, again suggesting minimal or no damage. Hence, the analysis indicates that the supplemental damping system works efficiently in dissipating a large amount of seismic input energy and thus reducing the energy dissipation demand on the lateral force resisting components of the wood framing system (and thus reducing damage to the structure). In addition, comparison of the structural deformations for the two different damper layouts shows that the different damper distributions result in different levels of second-story drift, particularly at higher drift levels. Thus, the response of the upper stories can potentially be controlled via strategic distribution of dampers at the ground story level. A more systematic evaluation of the optimized plan-wise distribution of dampers is in progress.

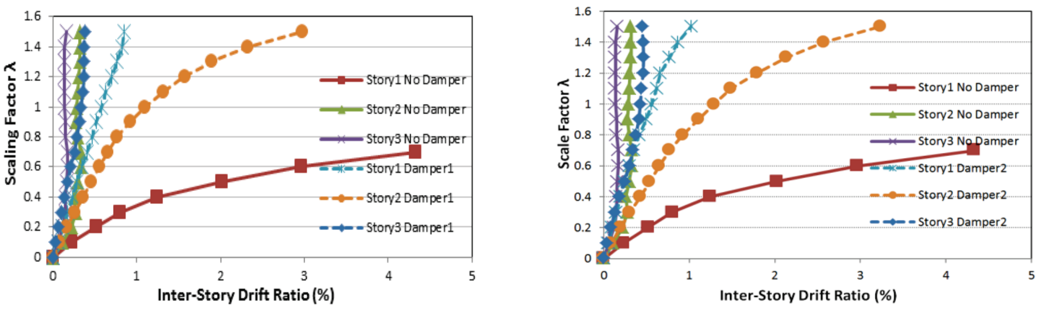



**Figure 5.** South wall line deformations for NCF90 record in East-West direction for damper layout 1(left) and layout 2 (right)

An additional retrofit method that will be investigated experimentally and does not necessarily fall into either PBSR or the ATC 71.1 methodology is the use of distributed knee braces. During site visits it was observed that it is very common for a floor joist to span from one exterior wall to another with the middle support provided by a beam. In addition, it was noted that the spacing of joists and studs was typically aligned. This provides an opportunity to install knee braces at 0.4 m (16 in.) intervals along the full length of the wall. Thus, close to 20 knee brace frames could be installed in a typical 6 m to

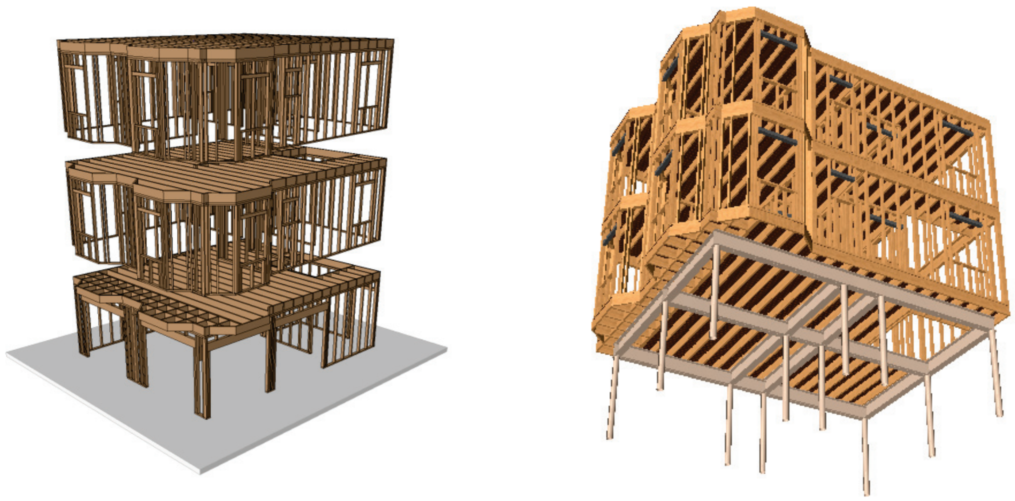
8m deep mid-block type building. In the case of a corner building with openings on one of the sides an additional wall may have to be installed along a column line. Testing of the knee brace framing system will be performed to develop the backbone curve data that is needed for the hybrid testing of a full-scale three-story structure that will be conducted at the UB-NEES site.

## 3. SUB-ASSEMBLY AND SYSTEM LEVEL TESTING

Two testing configurations are currently under development within the NEES-Soft project. Test 1 consists of individual wall segments that include older non-structural finish materials such as plaster on wood lathe. The walls will be subjected to cyclic loading with the objective of calibrating an improved hysteretic model to define the behavior of the wall. The ATC 71.1 methodology utilizes backbone curves as part of the process to compute strength and stiffness, but the data used to develop those backbone curves was not reversed cyclic data and was more than 60 years old. Thus, a series of tests will be performed to validate and, if necessary, modify those backbone curves.

Test 2 consists of a full-scale three-story slow pseudo dynamic test at the NEES facility at the University at Buffalo (UB). The test structure was designed to be representative of a variety of three to four-story wood-frame buildings built in the greater San Francisco, California, area during the early and mid 20th century, presently classified as soft/weak story structures. A number of site visits to examine existing buildings under retrofit construction and the review of the retrofit drawings were undertaken to assist in developing the test structure. The visual observations confirmed a number of known deficiencies associated with early 20th century construction practices. For example, the lack of steel hardware in the connections, lack of connections to foundations, and the use of diagonal block bracing for the lateral load resisting system were confirmed. It was also confirmed that architectural layouts featured relatively open ground floors used as either tenant parking or leasable commercial office space, while upper levels were used as residential space and had a large number of interior walls. The architectural finishes for exterior walls included stucco, plaster on wood lath, and wood siding. The interior wall finishes were mostly plaster on wood lath, plaster on gypsum board, or, where some remodeling may have occurred, gypsum wall board. The exterior property line walls were primarily wood siding to accommodate constructability requirements (the exterior architectural finish had to be installed prior to wall placement, since no exterior access would be available). The floor and roof were typically covered with straight wood sheathing and in some cases additional wood flooring, thus forming diaphragms of undefined properties. Based on the site visits, and considering the constraints imposed by available space in the laboratory, the test structure is specified as a three-story building with a 6 m x 7 m (20 ft x 24 ft) footprint and 2.44 m (8 ft) typical wall height and is shown without wall finish materials in Figure 6a and with the steel base frame for hybrid testing in Figure 6b.

The objective of the NEES@UB testing is to develop an increased understanding of the effects of first floor (soft-story) retrofits on the upper stories. During the first test phase, a slow pseudo-dynamic hybrid (substructure) test of the woodframe building (two-bedroom apartment at floors 2 and 3, and parking at floor 1) will be conducted. The first story will be constructed in the form of a steel-framed mechanism and will be treated as a substructure in the numerical portion of the hybrid test. The substructure will be defined using numerical models to represent the behavior of 8 different retrofit approaches that are being investigated. The upper stories will be physically constructed and located on top of the first story steel framing (see Figure 6b and 7). The hybrid testing approach is particularly suitable for evaluating a number of different retrofits without the need to physically construct each retrofit case. Interactions between the numerical substructure (first story) and physical substructure (upper stories) will be simulated and applied using hydraulic actuators. During the second test phase, the most promising retrofits of the first story, as identified from the first test phase, will be constructed and the steel support frame will be removed. Together with the upper two stories, the entire retrofitted woodframe structure will be tested using the pseudodynamic testing approach.



**(a)** **(b)**

**Figure 6. (a)** Model of three-story testing building without finish materials; **(b)** Building with steel framing in the first story which allows for evaluation of multiple first-story retrofit methods via hybrid testing.

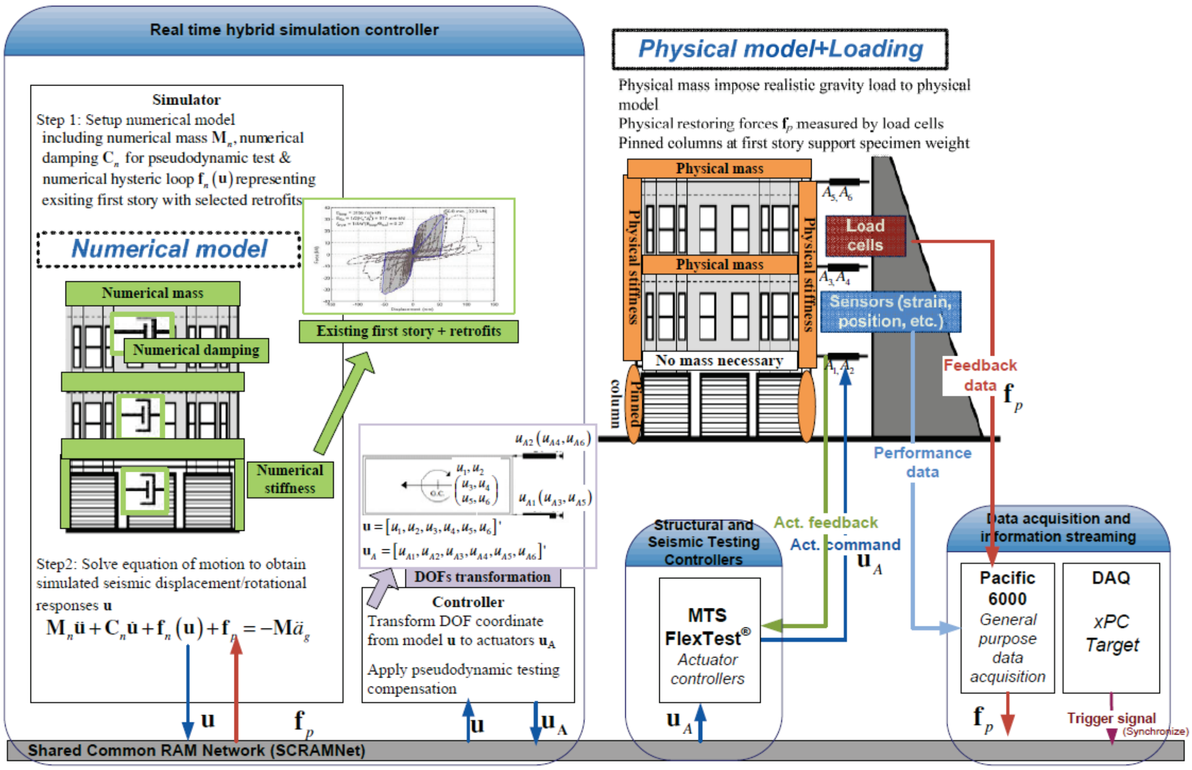



**Figure 7.** Schematic of the hybrid test algorithm to be used for testing the UB-NEES test specimen

In both test phases, six actuators (two at each floor level) will be used to apply the simulated translational displacement and rotational responses at the floor level with restoring forces measured and used as feedback to the numerical model to calculate the command signals for the next step. For seamless integration of the numerical and physical domains, both numerical simulation and physical testing compensation will be implemented via UB's real time hybrid simulation controller (Shao et al. 2011).

A number of retrofits will be examined during the Phase I and Phase II system-level testing at NEES@UB. Tables 1 and 2 list the retrofit type and the design approach targeted for verification. For example, for an inverted moment frame (cantilevered column) and wood shear walls, a particular performance level will be sought based on the retrofit design procedure. The full-scale hybrid test will enable the project team to examine the behaviour of the building at all story levels with each retrofit in place and compare it against the performance expectations.

**Table 3.1** Retrofits and design approach targeted for verification for Phase I of the system level testing

| Retrofit Type | Target Verification |
|---|---|
| Steel Special Moment Frame (SSMF) or Inverted Moment Frame (IMF) | ATC 71.1 |
| Wood Shear Walls | |
| SSMF/IMF and Wood Shear Walls | Performance-Based Seismic Retrofit |
| Cross-Laminated Timber (CLT) | |
| Energy Dissipation System (Dampers) | |

**Table 3.2** Retrofits and design approach targeted for verification for Phase II of the system level testing

| Retrofit Type | Target Verification |
|---|---|
| Steel Special Moment Frame (SSMF) or Inverted Moment Frame (IMF) | ATC 71.1 |
| SSMF/IMF and Wood Shear Walls | Performance-Based Seismic Retrofit |
| Knee-brace | Other (only a limited numerical prediction being performed) |

## 4. NUMERICAL MODELING OF COLLAPSE

One major task within NEES-Soft is the refinement of numerical modelling procedures such that the ability to predict collapse is improved. In past studies, numerical models for light-frame wood buildings were formulated based on small rotation theory and the diaphragms were assumed to be rigid. These simplified modeling assumptions lead to inaccurate boundary conditions, particularly under large deformations. Therefore, these models are not suitable for use in large displacement or collapse analyses of wood buildings. Improved nonlinear time history analysis models are being developed within the NEES-Soft project. A new three-dimensional (3D) light-frame wood building model which is capable of capturing the collapse mechanism of buildings with a soft first story has been developed (Figure 8).

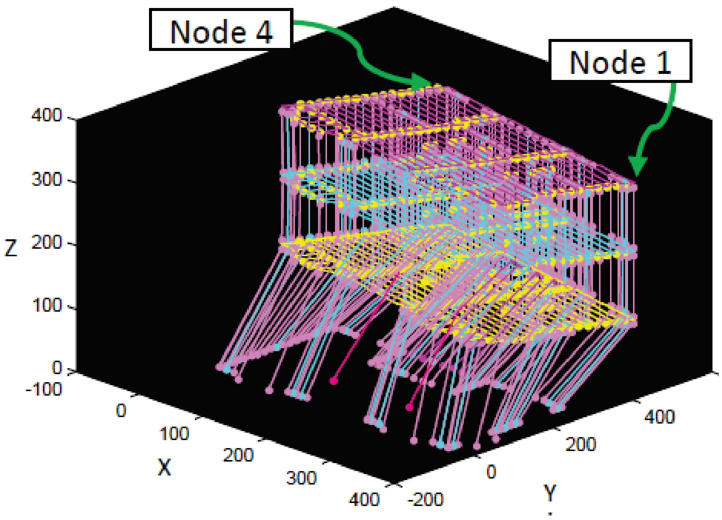



**Figure 8.** 3-D collapse model developed within the NEES-Soft project

The in-plane and out-of-plane flexibilities of floor and roof diaphragms are explicitly considered using 3D elements and a co-rotational formulation is used in the 3D model. In a co-rotational formulation, the orientation of the frame elements is updated in each modeling time step. The use of co-rotational formulation and 3D element allows the numerical model to accurately capture the in-plane and out-of-plane motions of the diaphragms under large rotations. To reduce the computational overhead of the model, a condensation technique using shape functions is employed to condense the DOFs of the link elements and eliminate those DOFs from the global DOFs. The nodal condensation technique has been successfully applied in a 2D shear wall model (Pang and Shirazi 2012). The same condensation technique employed in the 2D shear wall model is utilized to develop the NEES-soft 3D building model (UB-NEES test specimen).

Figure 9 shows the incremental dynamic analysis (IDA) curves of the three-story building performed using an ensemble of 22 bi-axial far field ground motions in the FEMA P-695 report (FEMA, 2009). The intensity measure of the IDA curves (i.e., the vertical axis) is defined in terms of the median spectral acceleration at the fundamental period of the building, $S_a(T_1)$. The IDA results confirmed that the building is susceptible to collapse in the first story under a design level earthquake (roughly corresponding to a 500-year return period earthquake). The design $S_a$ value for a typical location in Southern California is about 1g for periods between 0.2s to 0.6s. The IDA results show that there is slightly more than a 50% chance that the three-story building considered in this study would collapse at the design level earthquake and the median collapse drift capacity is approximately equal to 13% (inter-story drift).

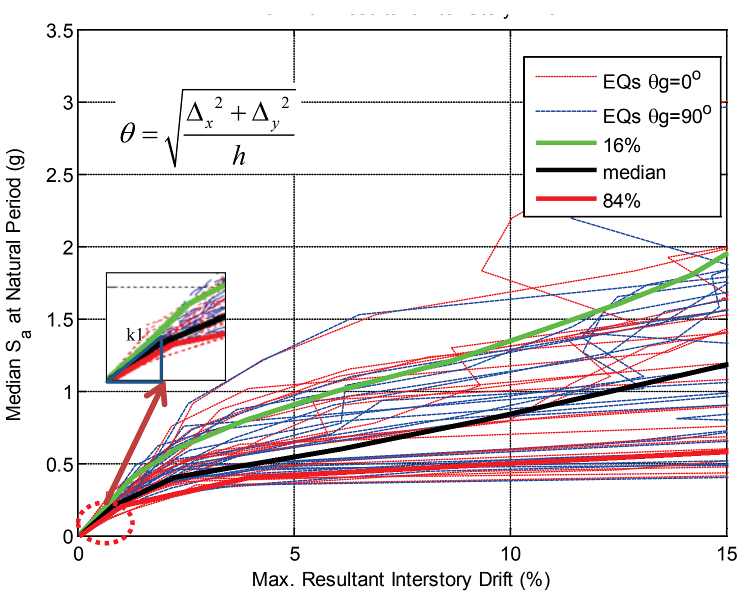



**Figure 9.** IDA curves of NEES-Soft test specimen (3-story building with soft first-story).

## 5. TECHNOLOGY TRANSFER

This research related to retrofit of wood frame soft/weak story structures offers a number of opportunities to provide engineering educators with educational content to illustrate valuable engineering concepts. The educational outreach for the NEES-Soft project consists of development of rich media modules that could be easily incorporated into online or blended courseware of various engineering courses. The modules presently planned include "NS 10 - Classification, typical construction and behavior of soft story wood frame buildings" which will serve as an introductory module outlining basic engineering concepts related to soft/weak story buildings, public policy concerns and analysis and design considerations and "NS20-Understanding design options for retrofit of soft/weak story buildings" which will describe available retrofit options and their strengths and weaknesses. The imagery and data from testing of the full-scale test specimen at UB-NEES will provide effective illustrations of various retrofit options. The final two modules, NS-30 and NS-40, will include design examples of the UB-NEES test specimen using two design methodologies; that presented in ATC 71.1, part of an on-going ATC effort, and the Direct Displacement Design approach which is being developed as part of the NEES-Soft project.

## 6. SUMMARY AND NEXT STEPS

In this paper, an overview of the NEES-Soft project was presented and several key tasks described including the collapse model, hybrid testing, and several retrofit techniques, including a high-performance retrofit approach that utilizes an energy dissipation system. In addition, a performance-based retrofit philosophy proposed for application within the project is described in another paper that is referenced herein and contained within these conference proceedings. Also, to complement the pseudo-dynamic hybrid testing of the full-scale, three-story building at the UB-NEES test facility, a full-scale four-story wood-framed structure with soft first story will be tested at the UCSD-NEES outdoor shake table facility in late 2013. This testing will provide validation of the performance-based seismic retrofit methodology developed as part of the project as well as provide verification of the ATC 71.1 retrofit philosophy proposed for use in California. In addition, the dynamic nature of the shake table test will allow for testing of retrofit approaches that include rate-dependent devices such as viscous damping elements. Finally, controlled collapse testing of the full-scale building will be conducted in order to validate the numerical model presented in this paper.

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