Full-Scale Dynamic Testing of Soft-Story Retrofitted and Un-Retrofitted 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 with concerted mitigation efforts underway in many cities throughout the state. The vast majority of those efforts are based on numerical modeling, often with half-century old data in which assumptions have to be made based on best engineering judgment and project committee consensus. 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. In 2013, two full-scale buildings will be tested within NEES-Soft. The first is a three-story building which will be tested at the University at Buffalo NEES facility using slow pseudo-dynamic testing. The bottom story, representing a soft story with garage openings, will be the numerical substructure and reproduced by computer, while the damage to the two upper stories, representing the physical substructure, will be observed in the lab and provide feedback to the actuators. This test has 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, to be conducted in the summer of 2013, is on a full-scale four-story 4,000 sq-ft soft-story building. It will be tested by the NEES-Soft project team at the UCSD NEES outdoor shake table using a variety of retrofits. These retrofits will range from FEMA P-807 retrofits to performance-based seismic retrofits developed as part of the project. Full-scale test results for both full-scale system specimens will be presented and comparisons made to the FEMA P-807 performance expectation and the performance-based seismic retrofit.

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. 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. Figure 1 shows a typical soft-story building in San Francisco, California. It is estimated that there are thousands of these buildings in San Francisco alone and many more throughout California and the United States. 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. For example, many of these buildings do not have wood structural panels but rather rely on plaster on wood lathe, horizontal wood siding made up of dimension lumber planks, and diagonal bridging for shear resistance. These archaic assemblies require significant wall lengths in order to supply the necessary lateral capacity. The wall lengths available for soft-story buildings are, in general, too short at the bottom story, thereby resulting in a soft-story. The soft-story condition is exacerbated by the poor performance of these archaic assemblies, making it difficult to retrofit in many

cases. In addition, as the buildings have undergone remodeling over the years, either additional layers of what are considered non-structural finishes by today's engineering standards have been added, or some portions of the assemblies have been replaced, further complicating the analysis and retrofit of these buildings.

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

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 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.

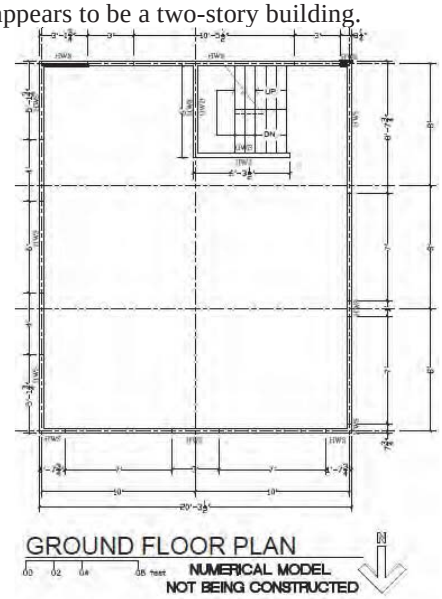
Test Program 5: Shake table testing of a full-scale four-story soft-story woodframe building with and without seismic retrofit; Network for Earthquake Engineering Simulation (NEES) laboratory at University of California – San Diego.

The focus of this paper and presentation are Test programs 4 and 5, the full-scale building tests. However, it should be noted that at the time of the writing of this paper the testing is in progress for both of the test programs and therefore the focus of the paper is on the design and construction. The results will be presented at the 2013 Convention.

Both buildings were designed to be as representative of typical 1920's to 1930's San Francisco soft-story woodframe construction as was reasonably possible given time, budget, and testing constraints.

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

The design of the three-story building began with the project team visiting several buildings undergoing seismic retrofit in the California Bay Area. Figure 2 shows a floor plan of the ground floor and the second/third floors. The ground story has primarily horizontal wood siding on the outside of the building and drywall on the inside for both the laundry room and storage closet. The horizontal wood siding has two 8d common nails per board spaced vertically at each stud location (i.e. 16" oc), which forms a couple moment when racking. One aspect that was different than typical 1920's construction was that drywall was used in place of plaster. The weight of the drywall was used in all analysis. The drywall screws were 1.25" long, coarse-threaded, and were spaced at 16" oc. The second and third floors consist of a two bedroom apartment on each floor with a corner stairwell. Lab space was a limiting factor on the 20 ft x 24 ft plan dimensions. Recall that the first story was a numerical sub-structure and thus, in the photographs that follow, the building appears to be a two-story building.



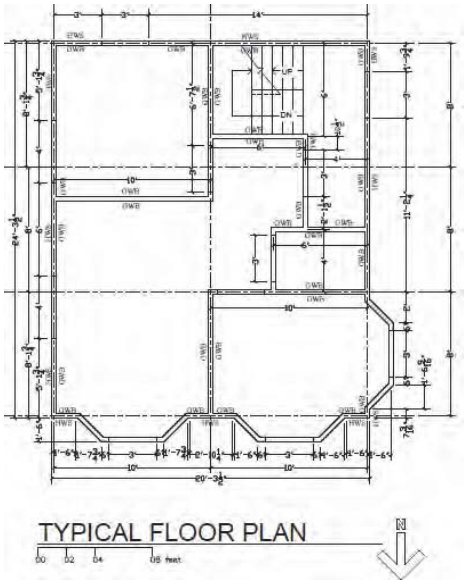


Figure 2. Floor plans for the NEES-Soft three-story hybrid test building

Figure 3 shows the NEES@Buffalo laboratory just prior to installation of the woodframe building. The steel interface frame can be seen in Figure 3 and the 30 ft tall strong wall, where the actuators for the slow hybrid test will be mounted, is also visible. Figure 4 shows placement of the first wall and Figure 5 shows the third story framing being completed. Horizontal wood siding at the second story, which provided stability as the building was constructed, is also visible. 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 6. Two actuators at each level allowed for control of both translation and in-plane torsion. However, one major challenge was ensuring that the actuator forces, and associated moments, were transferred to the diaphragm, and subsequently to the walls, in a manner as consistent as possible with inertial forces experienced by a building during an earthquake

Figure 3. Steel interface plate and strong wall at NEES@Buffalo

Figure 4. First wall being installed for the second story of the NEES-Soft test building

It was decided that for the testing at NEES@Buffalo the focus would be on the damage to the upper stories when the bottom story or bottom two stories are retrofitted (via stiffening/strengthening or damping) The hybrid test allowed evaluation of the impact of various retrofit options on the performance of the upper stories without requiring physical construction of the retrofits.

Figure 5. Third story framing nearing completion

Figure 6. Roof level showing the force transfer mechanism from the actuators to the diaphragm

In order to connect the actuators, a portion of the 1x6 flooring boards were left off the floor (or roof) diaphragm and a steel frame force transfer mechanism was installed. It consisted of steel "fins" that were adjacent to the 2x10 wood joists and connected to the joists with bolts (see Fig. 7). This force transfer mechanism allowed for the transfer of both shear and moment from the actuators to the floor (or roof) diaphragm

Figure 7. Ceiling view of the force transfer mechanism showing the bolted connections between the steel fins made of ½" steel plate and the 2x10 joists.

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 8 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 positioned as described previously. 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 8.

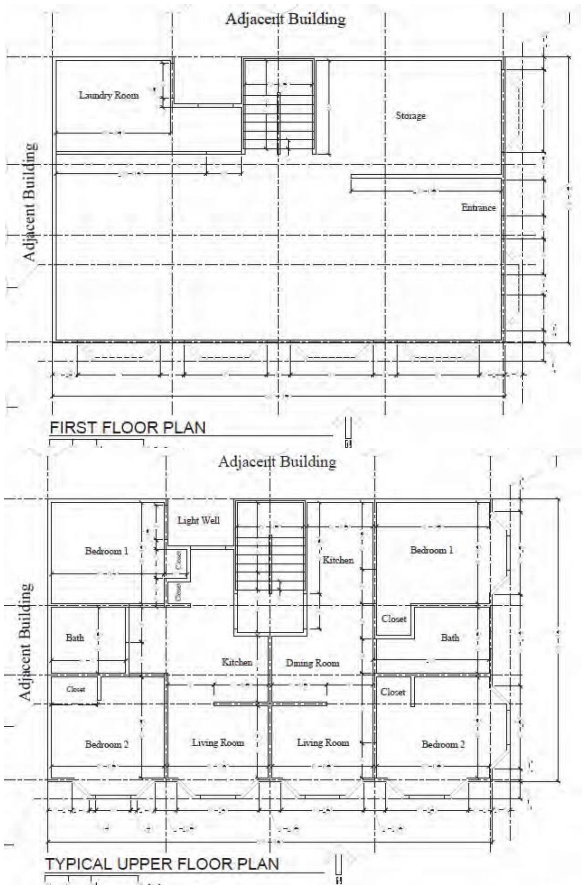


Figure 8. Floor Plans for NEES-Soft four-story building dynamic test

Figure 9 shows the steel interface plates which will be installed between the bottom sill plate and the shake table surface. Because there are four different retrofits planned for testing of the four-story building, the interface plates, which consist of W14x61 steel beams with stiffeners where needed, are divided into a number of small lengths so their placement can be customized for each retrofit.

Figure 9. Steel interface plates

Figure 10 shows the steel plates attached to the shake table prior to building construction and for the first retrofit. The first retrofit uses cross-laminated timber (CLT) panels which will be installed on top of four short parallel steel plates, with two of them oriented along each direction of the building (see Fig. 10).

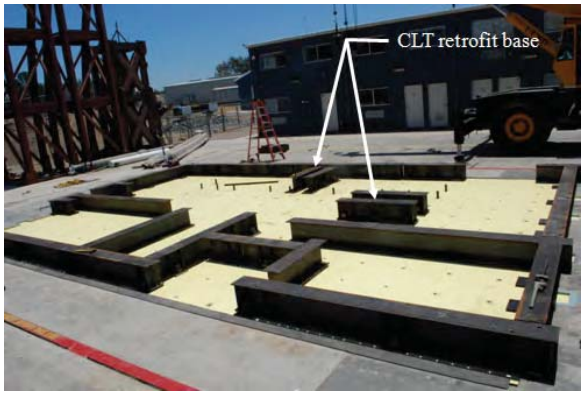


Figure 10. Steel interface framing prior to wood framing construction.

The location of CLT panels was selected to avoid interference with normal use of the space. The seismic demand was determined using FEMA P-807 requirements. Load deformation characteristics of the CLT panels were obtained via cyclic testing that was conducted as part of the NEES-Soft project. Collectors were provided by reinforcing existing floor framing with additional framing members, blocking and strapping as needed to match the capacity of the CLT panels. The location of the CLT lines of resistance and collectors is shown in Figure 11.

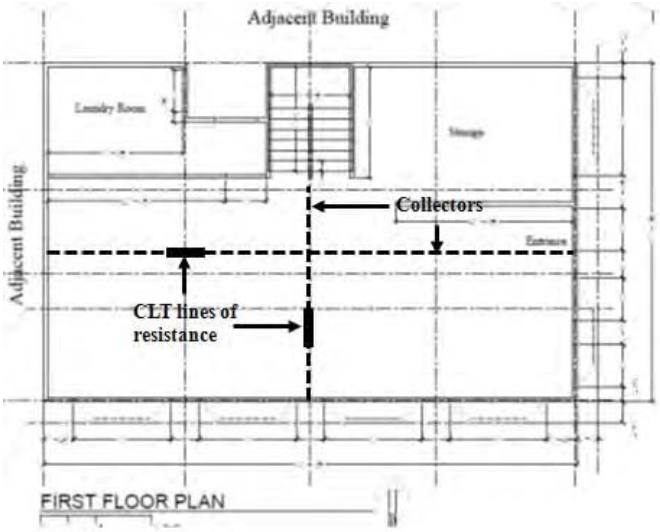


Figure 11. Layout of CLT panel retrofit based on FEMA P-807

Each CLT line of resistance consisted of two doubled CLT panels. The panels were installed over CLT bases which were bolted to the steel framing. The transfer of shear forces was accomplished using four HGA-10 KT (Simpson Hurricane Gusset Angle) for each double panel. The transfer of uplift force was accomplished using HDU-8 hold-downs with 5-ft long mild steel threaded rods designed to stretch and provide the required ductility during rocking. The top of each panel was connected to the floor framing above using a wide flange beam. The web of the beam was connected to the CLT panel using screws and the flanges were bolted to the collectors through vertical slotted holes. The CLT assembly is shown in Figure 12.

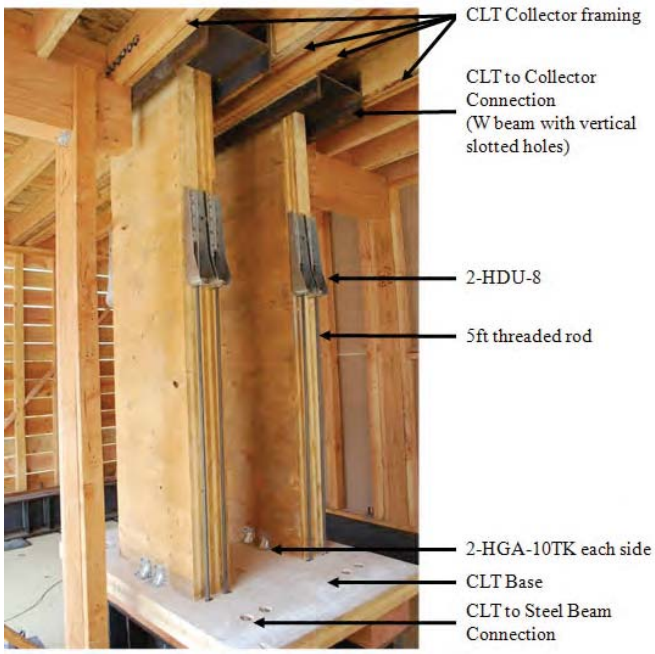


Figure 12. CLT Panel Retrofit Assembly

A similar assembly was used for the transverse direction and a combination of strapping and blocking was used to develop the collector.

The threaded rod length was selected to allow for the required deformation at the top of the CLT panel through rod elongation, since CLT observed behavior is that of a rigid body. The vertical slotted holes in the wide flange beams connecting the CLT panels to the collectors was provided to allow for rotation at the top of the CLT panel while still transferring shear.

The floor diaphragm above the CLT panels was reinforced with structural wood panels attached to the bottom of the framing. The area over which diaphragm was reinforced is shown in Figure 13.

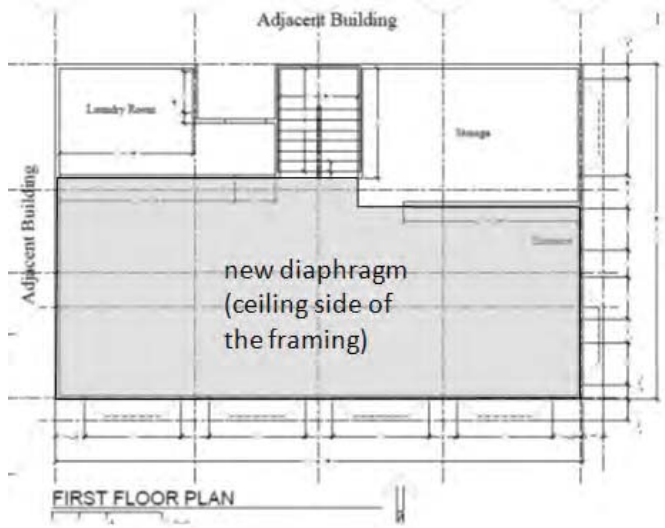


Figure 13. Diaphragm Reinforcement for CLT Retrofit

The second retrofit is a steel moment frame retrofit. Two retrofits are being tested. The first retrofit to be tested is based on FEMA P-807 design recommendations and the second follow-up test is based on the direct displacement design (DDD) procedure.

For the DDD retrofit, proprietary Simpson Strong-Tie special seismic moment resisting frames were used. The custom SMF frames were placed along gridlines D and 5 (see Fig. 14). Wood structural shear walls were also added along lines 1 and A. The existing floor framing was reinforced to accommodate collector forces along all lines of resistance. The diaphragm reinforcement used for the CLT retrofit remained in place for this retrofit test.

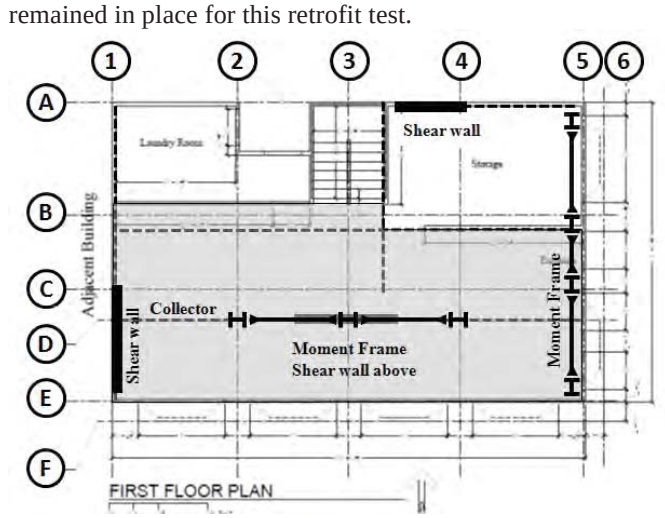


Figure 14. Layout of Main Lateral Load Resisting System for DDD retrofit

The DDD steel SMF retrofit was designed to provide a 50% probability of exceedance of a 2% story drift at MCE intensity. This means that for a full suite of earthquakes, drifts of up to 5% are possible for the most intense MCE earthquakes.

The FEMA P-807 retrofit is limited to ground floor reinforcements only and also uses the proprietary Simpson Strong-Tie steel special moment frame product. The location of lines of resistance remained the same for shear walls and moment frames as used in the DDD retrofit. The diaphragm reinforcement was also unchanged. The layout of the main lateral load resisting system for the FEMA P-807 retrofit is shown in Figure 15.

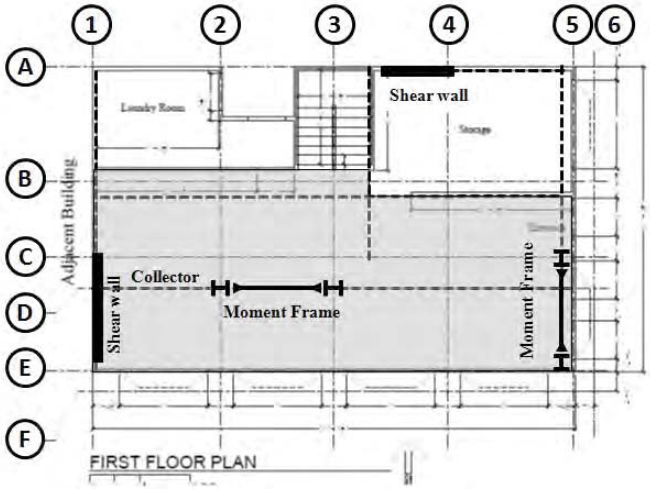


Figure 15. Layout of Main Lateral Load Resisting System for FEMA P-807 retrofit

The third retrofit focuses on the use of energy dissipation instead of stiffening/strengthing. In this retrofit, damping devices are installed around the perimeter of the building to provide both translational and torsional resistance. The damping devices are installed in light steel frames that are pin-connected and are designed to amplify the effects of the damping device through the geometry of the frame. The layout of the damper framing assemblies in the first story of the structure is shown in Figure 16.

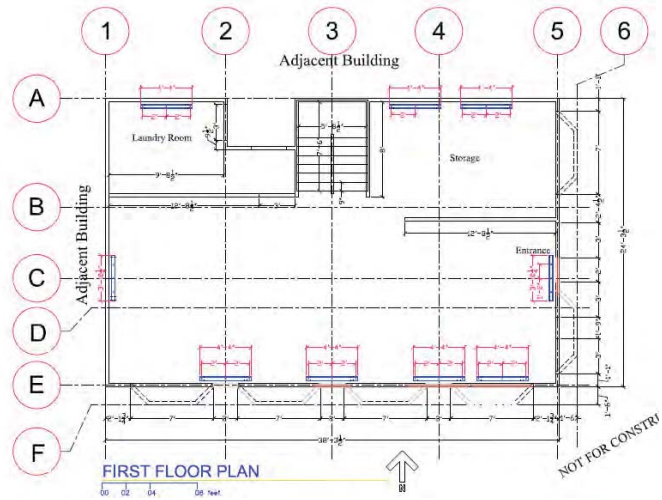


Figure 16. Layout of Damper Framing Assemblies

The details of the damper frames are shown in Fig. 17. The damper is located in the upper right and is connected to the top of the frame at one end and to toggle-bracing at the other end. Such toggle-braced dampers provide displacement amplification (i.e., the axial displacement of the damper is larger than the shear deformation of the frame). Due to the short time frame for manufacturing, the toggle-braced frames used in the tests made use of an existing design and thus are about twice as wide as the approximately 2-ft wide wall piers along line E of the building. Alternate designs that make use of narrow frames are under development. The toggle frames were interconnected with collectors and the same diaphragm reinforcement as used in the CLT and moment frame retrofits was used. The energy dissipation retrofit was designed to provide a 50% probability of exceedance for a 1.5% story drift at MCE seismic intensity.

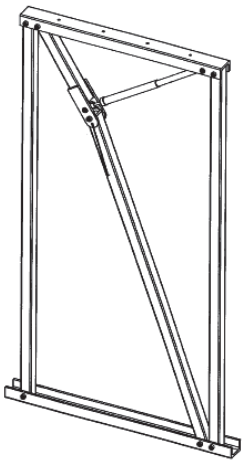


Figure 17. Toggle-Braced Damper Framing Assembly

The final test for the four-story building will be for the un-retrofitted condition and will be used to establish the performance of the un-retrofitted building up through collapse. This test will assist in validating 3D numerical models with collapse prediction capabilities, establish a capacity baseline against which performance of various retrofits can be normalized, and will provide insight to design engineers on the ability of an un-retrofitted soft-story wood-frame multistory building to resist seismic loading. The test structure employs diagonal bridging along the exterior walls of the ground story (see Fig. 18); such bridging has very low lateral load capacity. Furthermore, the walls with openings rely on horizontal wood siding for lateral load resistance.

Figure 18. Exterior wall bridge bracing

Conclusions

These types of retrofits primarily upgrades the detailing of the existing structure to ensure positive connections of various components and load-path continuity. This would typically involve anchoring ground floor wall plates, installing strapping and blocking to develop collectors at all lines of resistance, and reinforcing diaphragm and diaphragm chords. This level of retrofit is intended to ensure that a meaningful and predictable load path exists for lateral load flow at the ground story. In the test structure, this level of retrofit included anchorage of all walls to the steel base, nominal bracing, blocking, strapping and nailing at various points of shear transfer.

The ground floor only retrofit design using FEMA P-807 produces intuitively weak designs and may therefore be outside of the comfort zone for practicing engineers. It is important to recognize that the intent of this retrofit is to obtain the most capacity out of the system within financial and public policy constraints. Thus the performance could be significantly lower than what most engineers are accustomed to providing.

The DDD retrofit design is a simplified performance-based procedure and it is best suited to developing designs that meet any desired level of seismic performance. With the addition of torsion considerations and the availability of backbone curves for various assemblies of lateral load resisting elements, it is a powerful tool for dealing with these types of retrofits.

The seismic energy dissipation retrofit offers an alternative to a stiffening/strengthening retrofit approach. If properly designed (both magnitude of damping and location of damping in plan), numerical simulations indicate that the drift levels in the soft ground story can be reduced while any increase in forces in the upper stories is limited so as to avoid propagation of damage from the ground story to the upper stories.

The results of the testing were not available during the writing of the paper and will be included in the presentation at the convention and in future papers. The design of a soft-story wood frame building retrofit offers several lessons that could be beneficial to engineers involved in designing this type of retrofit. The level of retrofit from the design and detailing perspective could be divided into three distinct categories: the essential minimum load path reinforcement: ground level only retrofit; and full retrofit.

Figure 19. Completed structure

Figure 18. Interior view of completed structure (2nd floor)

Figure 21. Structure with steel towers in place to prevent the building from hitting the control room should it collapse during testing

Acknowledgments

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