Tenth U.S. National Conference on Earthquake Engineering
Frontiers of Earthquake Engineering
July 21-25, 2014
Anchorage, Alaska

A THREE-DIMENSION MODEL FOR SLOW HYBRID TESTING OF RETROFITS FOR SOFT-STORY WOOD-FRAME BUILDINGS

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ABSTRACT

This paper presents a new 3D seismic analysis package developed for analyzing the collapse mechanism of soft-story wood-frame buildings. This new seismic analysis package is developed as part of the NSF funded NEES-Soft project. The project objective is being accomplished through a combination of numerical modeling and experimental testing. The new dynamic analysis package for wood buildings allows improved predictions of the seismic performances over a wide range of seismic loading conditions, namely from small deformation all the way to collapse. In addition, this new dynamic analysis package can also be used to perform both slow and real-time hybrid tests. The focus of this paper is on the application of the 3D model for slow hybrid test. The slow hybrid test is used to study the effectiveness of different retrofits used for strengthening the soft first story. The retrofit options considered in NEES-Soft included cantilever column, steel moment frame, cross-laminated timber, viscous fluid damper, shape memory alloy and distributed knee-braces. In the slow hybrid test, the second and third stories are physical structure while the first-story (i.e. the soft-story) is being numerically analyzed with different retrofits. The formulation of the hybrid model and summary of selected test results are presented.

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A Three-dimension Model for Slow Hybrid Testing of Retrofits for Soft-story Wood-frame Buildings

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Introduction

About 75% of the San Francisco's housing was built before the introduction of modern building codes and seismic design requirements [1]. Many two to four stories light-frame wood buildings in the San Francisco Bay Area built between 1920 and 1970 have a structural deficiency known as "soft-story". The first story of these buildings is typically serves either as parking space or as open front retail space with very few interior walls while the upper stories are usually residential units with large number of interior walls. As a result, the lateral load carrying capacity in the ground floor can be significantly lower than that of the upper stories and, in some cases, the first floor strength can be as low as 30% to 40% of that in the upper stories [1]. As a result, the first story is susceptible to pancake collapse during earthquakes. The San Francisco Department of Building Inspection and the Applied Technology Council initiated the Community Action Plan

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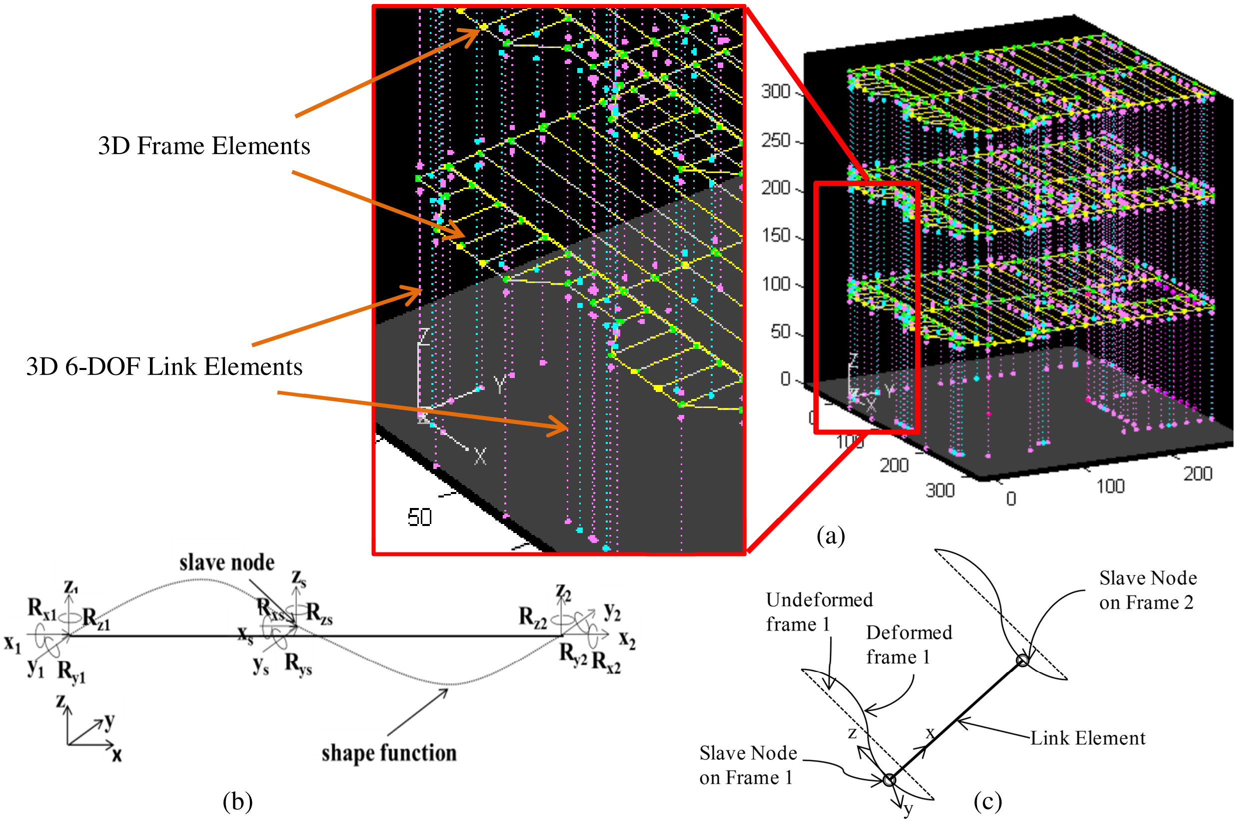
for Seismic Safety (CAPSS) project in 2008. The main goal of CAPSS project was to identify possible remedies for reducing seismic risks for the building stock in San Francisco. Based on the CAPSS study, it was estimated that 40% to 80% of multi-story wood buildings in San Francisco with soft-story deficiency will be deemed unsafe after a magnitude 7.2 earthquake, and about 25% of them could be completely destroyed [2].

This paper presents a numerical model developed for pseudo-dynamic (slow) hybrid testing of retrofits for a three-story wood-frame building with soft-story deficiency. A new 3D dynamic analysis package for light-frame wood buildings, called *Timber3D* [3-4], was used to perform the slow hybrid tests. This new seismic analysis package was developed as part of the NSF funded NEES-Soft project [5]. A series of slow hybrid tests were conducted at NEES@Buffalo to study the effectiveness of different retrofits used for strengthening the soft first story. Six retrofit options were tested: cross-laminated timber (CLT), distributed knee-braces (DKB), inverted steel moment frame (IMF), fluid viscous damper (FVD), shape memory alloy (SMA) and steel moment frame (SMF). The seismic retrofit objective is to reduce the risk of structural collapse in the ground floor and limit damages in the upper stories. Over strengthening the first story will result in both structural and non-structural damages propagate to the upper stories. To evaluate the impact of each retrofit on the upper stories, the three-story hybrid building was divided into two complimentary parts. The first story was numerically analyzed with different retrofits using Timber3D while the remaining part (i.e. upper stories) was constructed on the strong floor at NEES@Buffalo and physically tested using hydraulic loading equipment. This hybrid test setup allows the evaluation of different retrofits without having to physically re-construct the first story multiple times. The effectiveness of different retrofits can be determined or quantified by examining the damages occur in the physical second and third stories. The formulation of the 3D model and the application of Timber3D analysis package for slow hybrid testing of the three-story wood building are presented and discussed. Preliminary results of the slow hybrid testing are also presented.

Numerical Model

The Timber3D program is developed using Matlab/Simulink using a co-rotational formulation and large displacement theory. The floor and roof diaphragms of the three-story building are modeled using a two-node 12-DOF frame element with geometric nonlinearity (Fig. 1a). As shown in Fig. 1b, the 3D frame element has two nodes with six degrees of freedom (DOFs) at each node (three translations in the element local x, y and z directions and three rotations about the element x, y and z axes). The lateral stiffness of shear walls and axial stiffness of wall studs are modeled using a zero-length 6-DOF link element (three relative translations and three relative rotations between two frame elements).

In order to reduce the computational time, a nodal condensation technique, utilizing shape functions (Fig. 1c), is used to reduce the size of the global matrix [3]. Using this condensation technique, the size of the global stiffness matrix depends only on the number of frame elements. At each time step, the global stiffness matrix is assembled based on the rotated coordinate system of the individual frame and link elements (i.e. using a co-rotation formulation). The co-rotational formulation allows more accurate predictions for the building behavior under large deformation.



(a)

(b)

(c)

Figure 1. (a) 3D building model, (b) frame element, and (c) link element.

Physical Test Structure

The NEES-Soft hybrid test structure was a three-story light-frame wood building with a tuck-under parking garage in the first story. The test building was designed with features to represent typical San Francisco Bay Area wood buildings constructed between 1920 and 1970. As stated before, the hybrid test building consisted of two parts, namely physical and numerical parts. The first story was modeled numerically; hence only the upper two stories were constructed on the strong floor in NEES@Buffalo lab. Fig. 2 shows the plan views of the three stories. The physical test structure was constructed on a steel channel (MC6x15.3) which was bolted to the strong floor with 5/8 in. diameter threaded rods spaced at 24" on-center (o.c.). A 4x4 lumber was bolted onto the steel channel and served as a nailer for the physical substructure. The

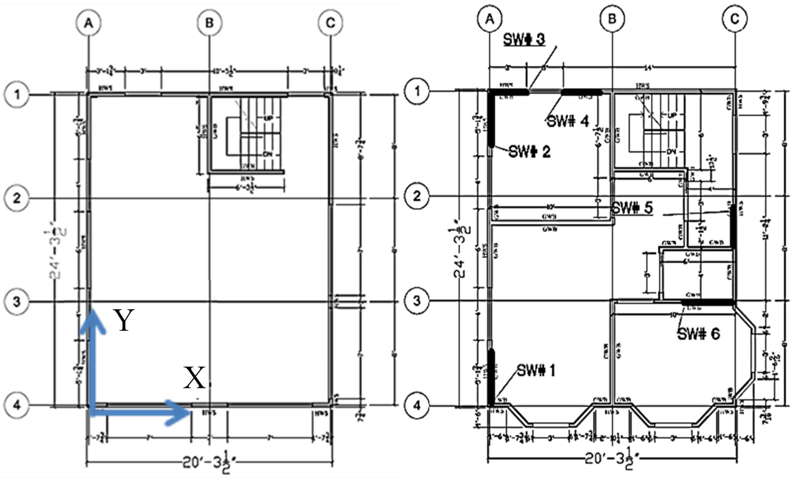


Figure 2. Test building floor plans; (a) story 1; (b) stories 2 and 3.

height of the physical building from the ground level to the roof, including the height of the steel channel and the 4x4 wood nailer, was 18.65 ft, and the height of numerical story was 9.75 ft. The plan dimension of the building was 20x24 ft.

The physical substructure was constructed of Douglas Fir-Larch lumber. The bottom plates of the 2nd story walls (i.e. the first story of physical substructure) were fastened to the nailer using 16d common nails spaced at 16 in. o.c. The wall framing consisted of 2x4 studs spaced at 16 in. o.c. with a 2x4 bottom plate and 2x4 double top plates. The floor joists were 2x10 spaced at 16 in. o.c. The building exterior was covered with 1x10 horizontal wood siding fastened with two 8d common nails per stud. The interior walls and the inner side of exterior walls were covered with 0.5 in. thick gypsum wall boards (GWB). Note that GWB was not a typical construction material for pre-1970's buildings. For this experimental study, GWB was selected to pre-produce stiffness characteristic similar to that of stucco on wood lathe.

Hybrid Simulation Framework

The hybrid simulation test setup is outlined in Fig. 3 and the complete list of tests performed is provided in Table 1. To impose translation and in-plane rotation commands from the numerical model to the physical structure, four 22-kip hydraulic actuators were attached to the building, with two on each diaphragm (Fig. 3). The actuators can rotate 13° at the point of connections in both horizontal directions.

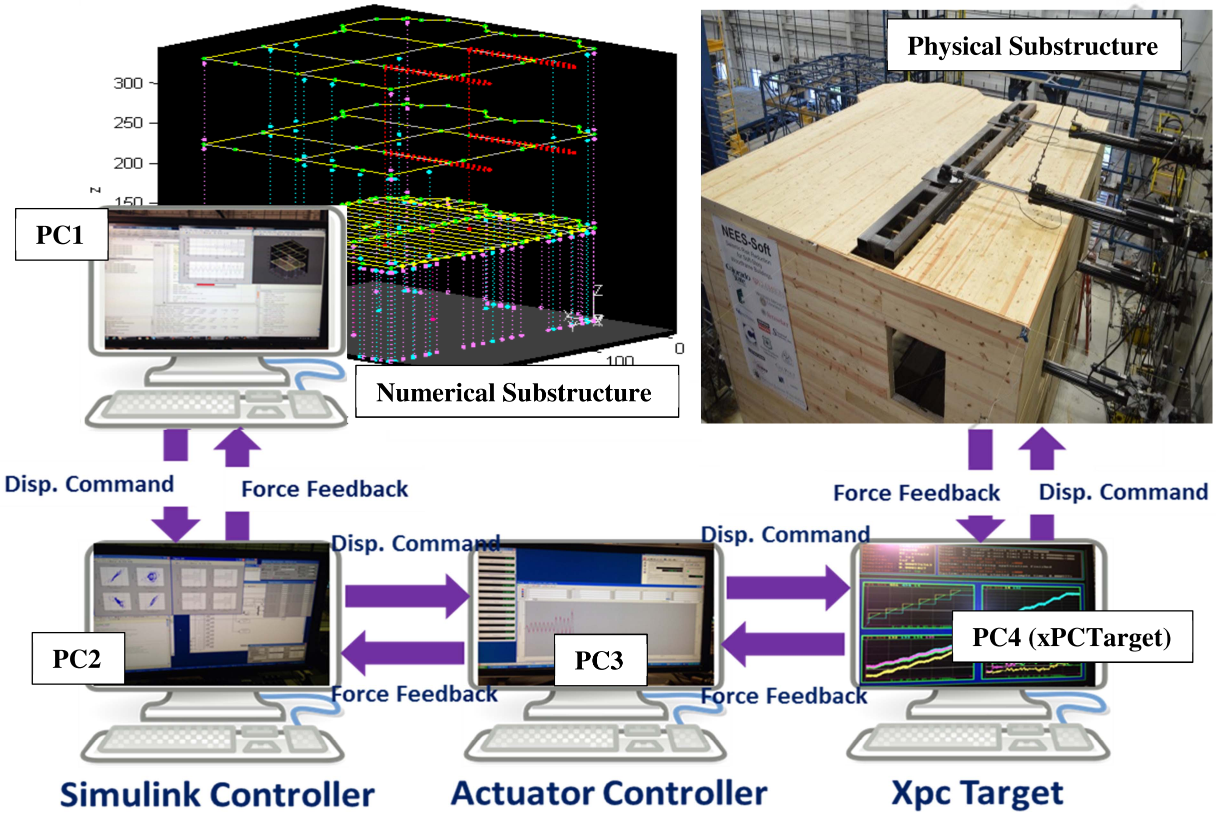


Figure 3. Hybrid simulation framework.

The hybrid test setup consisted of five main components (Fig. 3): (1) the numerical model for the three-story structure which was hosted on PC1, (2) the hybrid controller consisting of the Matlab-Simulink model which was hosted on PC2, (3) the actuator controller interface which was hosted on PC3, (4) the xPCTarget which processed the data from the actuators (hosted on PC4), and (5) the actuators connected to the two-story physical substructure.

System ID Test

Prior to each hybrid test, a System ID test was performed to determine the initial stiffness matrix of the physical substructure. Fig. 4 shows an example 4x4 stiffness matrix determined via the System ID test. The stiffness values for each column were determined by moving each actuator individually to displacements of +/-0.1” while holding the others in place and measuring the force feedbacks. This empirically determined stiffness matrix was used to quantify the pre-test condition of the physical substructure. The pre-test stiffness matrix was used for two purposes: (1) to perform a pre-test simulation, and (2) to determine the fundamental period of the full three-story building.

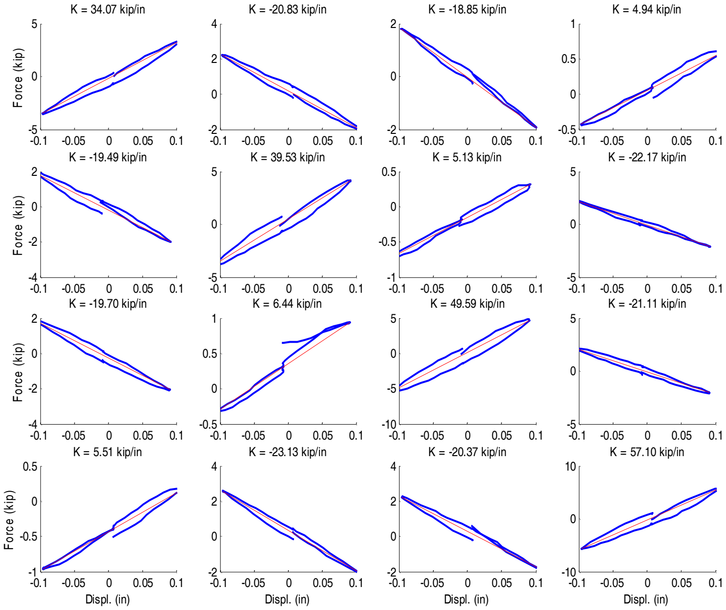


Figure 4. An example stiffness matrix determined via the System ID test.

Hybrid Test Process

The hybrid simulation began by creating the numerical substructure model on PC1 using Timber3D. The numerical model hosted on PC1 contained the input ground motions, numerical mass, damping as well as the hysteretic models for the retrofits options being considered. Next, the Matlab-Simulink controller program was compiled and uploaded to the xPCTarget (hosted on PC4). Once the controller program was loaded into the xPCTarget, a Matlab program, called *PSD*, was initialized on PC2. The PSD program served as a coordinator which simultaneously connected to the xPCTarget controller program and the numerical model on PC1. Note that the PSD program utilized the TCP/IP protocol to communicate to the numerical substructures. The PSD program can accommodate multiple TCP/IP connections

Using the 4x4 stiffness matrix obtained from the System ID test, the complete stiffness matrix was known. The following equation of motion was solved to determine the relative displacements of the four actuator connection points:

$$M\ddot{u} + C\dot{u} + Ku = -M\ddot{u}_g \tag{1}$$

The relative displacements were measured from the actuator connection points to the first-floor diaphragm in the Timber3D model (i.e. the strong floor). For each time step of the ground motions, the computed relative displacements at the four controlling degrees-of-freedom (DOFs) were sent from PC1 the PSD program. The PSD program then issued displacement commands to the xPCTarget controller program for the respective four actuators. For each time step, a 1-sec. ramp time was used to move the four actuators to the target displacements. Once the four actuators reached the target displacements, the restoring forces were measured and feedback to the PSD program. The restoring forces were used to update the numerical model in PC1 to determine the next displacements for the four actuators. A modified implicit Newmark-β integrator that does not impose iterative displacements on the physical substructure was used to solve the equation of motion. The process was repeated for the subsequent time steps until the end of the ground motions.

Table 1. Test matrix.

Retrofit	Level	Ground motion	Direction	Scale Factor
CLT	SRE	Loma Prieta, Capitola	2	0.450
CLT	Low percentile DBE	Loma Prieta, Capitola	2	1.022
CLT	High percentile DBE	Loma Prieta, Gilroy	1	1.162
CLT	Low percentile MCE	Loma Prieta, Capitola	2	1.534
Knee Brace	Low percentile DBE	Loma Prieta, Gilroy	2	1.162
Knee Brace	High percentile DBE	Loma Prieta, Gilroy	1	1.162
Knee Brace	Low percentile MCE	Loma Prieta, Gilroy	2	1.743
IMF	Low percentile DBE	Loma Prieta, Gilroy	2	1.162
IMF	High percentile DBE	San Fernando, LA	2	2.723
IMF	Low percentile MCE	Cape, Mendocino Rio	2	1.628
IMF	High percentile MCE	Loma Prieta, Gilroy	1	1.743
FVD	Low percentile DBE	Loma Prieta, Gilroy	2	1.162
FVD	High percentile DBE	Loma Prieta, Gilroy	1	1.162
FVD	Low percentile MCE	Loma Prieta, Gilroy	2	1.743
FVD	High percentile MCE	Loma Prieta, Gilroy	1	1.743
SMA	Low percentile DBE	Loma Prieta, Gilroy	2	1.162
SMA	High percentile DBE	Loma Prieta, Gilroy	1	1.162
SMA	Low percentile MCE	Loma Prieta, Gilroy	2	1.743
SMA	High percentile MCE	Loma Prieta, Gilroy	1	1.743
SMA	High percentile MCE	San Fernando, LA	2	4.085
SMF–10% eccentricity	PGA=0.25*g	Sinusoidal Load	-	-
SMF–20% eccentricity	PGA=0.50*g	Sinusoidal Load	-	-
SMF–30% eccentricity	PGA=0.50*g	Sinusoidal Load	-	-
SMF–30&20% eccentricity	PGA=0.25*g	Sinusoidal Load	-	-

Retrofit Strategies and Selected Preliminary Test Results

Table 1 shows the complete list of hybrid tests performed at the NEES@Buffalo site from June to October of 2013. Six retrofits were tested; they were (1) cross-laminated timber (CLT), (2) distributed knee-braces (DKB), (3) cantilever column (CC), also known as the inverted moment frame (IMF), (4) viscous fluid damper (VFD), (5) shape memory alloy (SMA), and (6) steel moment frame (SMF).

CLT Retrofit

The cross-laminated timber panel (CLT) retrofit design followed FEMA P807 guidelines and was implemented only in the ground floor (i.e. the numerical soft-story). The retrofit consisted of three 2-ft long CLT panels in the x-direction (see Fig. 2) set adjacent to each other width wise, and three 2 ft. CLT panels in the y-direction aligned lengthwise. More details on the CLT retrofit may be found in [5]. The inter-story drift time histories for the four CLT retrofit tests are shown in Fig. 5. For the highest intensity ground motion that the CLT retrofit was subjected to (i.e. MCE level), the maximum drift occurred in the second story (i.e. first physical story) reaching about 2.9% inter-story drift, with a residual drift of slightly below 2% in the second story at the end of the ground motion (Fig. 5).

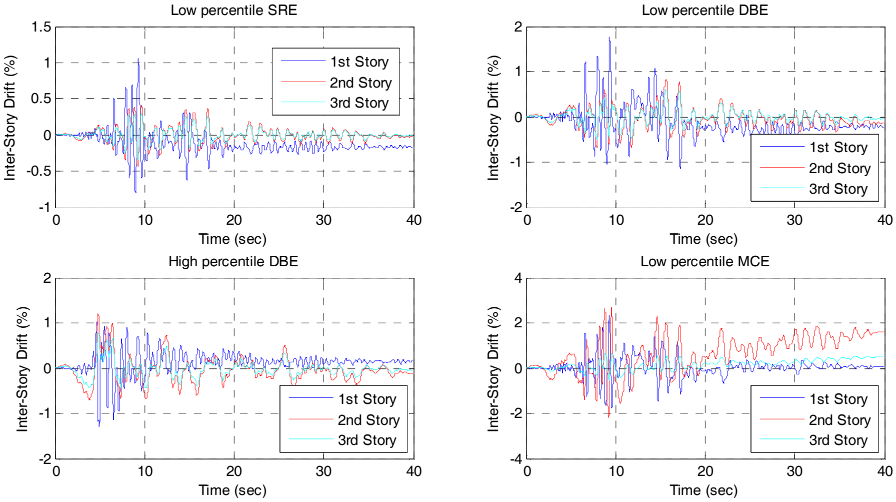


Figure 5. Inter-story drift time histories at the South-West corner for the CLT retrofit.

Cantilever Column Retrofit

The cantilevered column (CC) or inverted moment frame (IMF) retrofit was based on the FEMA P807 guidelines. Two IMFs were used for the retrofit design, and each IMF consisted of two columns. The inverted moment frame rotated lengthwise in the x-direction consisted of two W10x19 columns (Fig 2) and the frame rotated in the y-direction consisted of two W12x14 columns. Four hybrid tests were conducted on the IMF retrofit of varying intensity ground motions. The maximum inter-story drift at MCE level occurred in the first story (2.8%, Fig. 6).

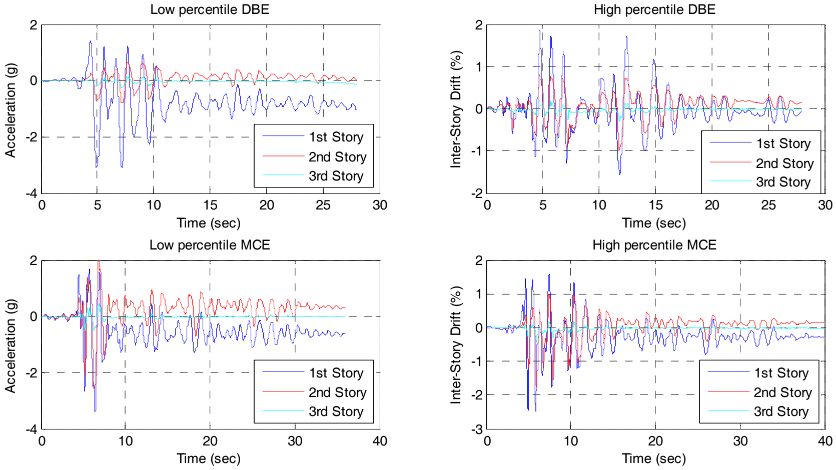


Figure 6. Inter-story drift time histories at the South-West corner for the IMF (CC) retrofit.

Shape Memory Alloy Retrofit

The shape memory alloy-steel (SMA) device retrofit was designed using the performance-based seismic retrofit (PBSR) methodology. The retrofit design consisted of four SMA devices on the bottom soft-story, six plywood-sheathed shear walls with 2 in. nail spacing (for the panel exterior; all field nailing was 12 in.) on the second story, and four plywood-sheathing shear walls with 6 in. nail spacing on the third story. The SMA devices were numerically modeled and the upper story shear walls were physically installed along with the Simpson Strong Tie's Anchor Tie Down (ATS) in each wall to provide uplift restraints. The retrofit layout can be found in [6]. Five hybrid tests were conducted on the retrofit, two at the DBE level and three at the MCE level. The inter-story drift time histories for all three numerical stories are provided in Fig. 7. The maximum drift occurred in the second story reaching 2.6% for the Loma Prieta, Gilroy ground motion scaled to MCE.

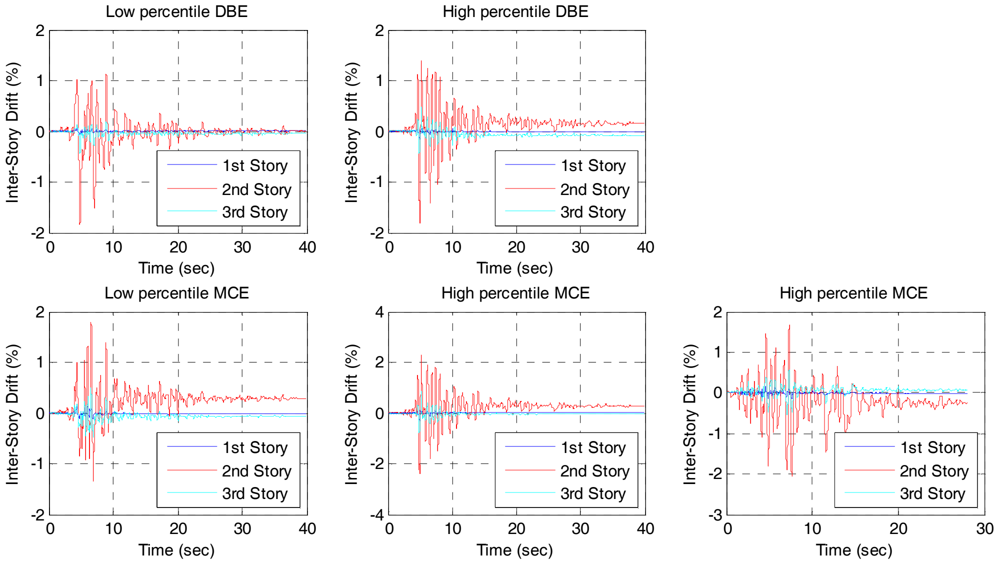


Figure 7. Inter-story drift time histories at the South-West corner for the SMA retrofit.

Fluid Viscous Damper Retrofit

The fluid viscous damper (FVD) retrofit was designed using the performance-based seismic retrofit (PBSR) concept. The FVDs installed in toggle-braced framing systems were modeled numerically and applied only in the first story of the building. Each linear fluid viscous damper had a damping coefficient based on the geometry of the toggle-braced framing, C_0, which was amplified according to an average displacement amplification factor, f_{avg}. Given the average displacement amplification factor and damping coefficient, the lateral force exerted on the damper assembly is given by:

$$F = C_0 f_{avg}^2 \dot{u} \qquad (2)$$

Four fluid viscous dampers, two in each direction were used in the design. The $C_0 f_{avg}$ term is called the effective damping coefficient which was taken as 0.5 *kip-sec/in*. For each location where the FVD retrofit was applied, the corresponding degree-of-freedom in the global damping matrix was determined, and the effective damping ratio was added to the relevant DOF in the damping matrix (C shown in Eqn. 1). More details on the FVD retrofit may be found in [7].

Substructure Repair Time History

A System ID test was conducted after each test and was used to track the damage stage of the substructure. The empirical stiffness matrix and the periods of the first three modes of the physical substructure were calculated from the System ID test data. Fig. 8 shows the time histories of the first three periods of the physical substructure. A total of nine major repairs were performed during the series of hybrid tests. These repairs are marked by drops in the periods in Fig. 8.

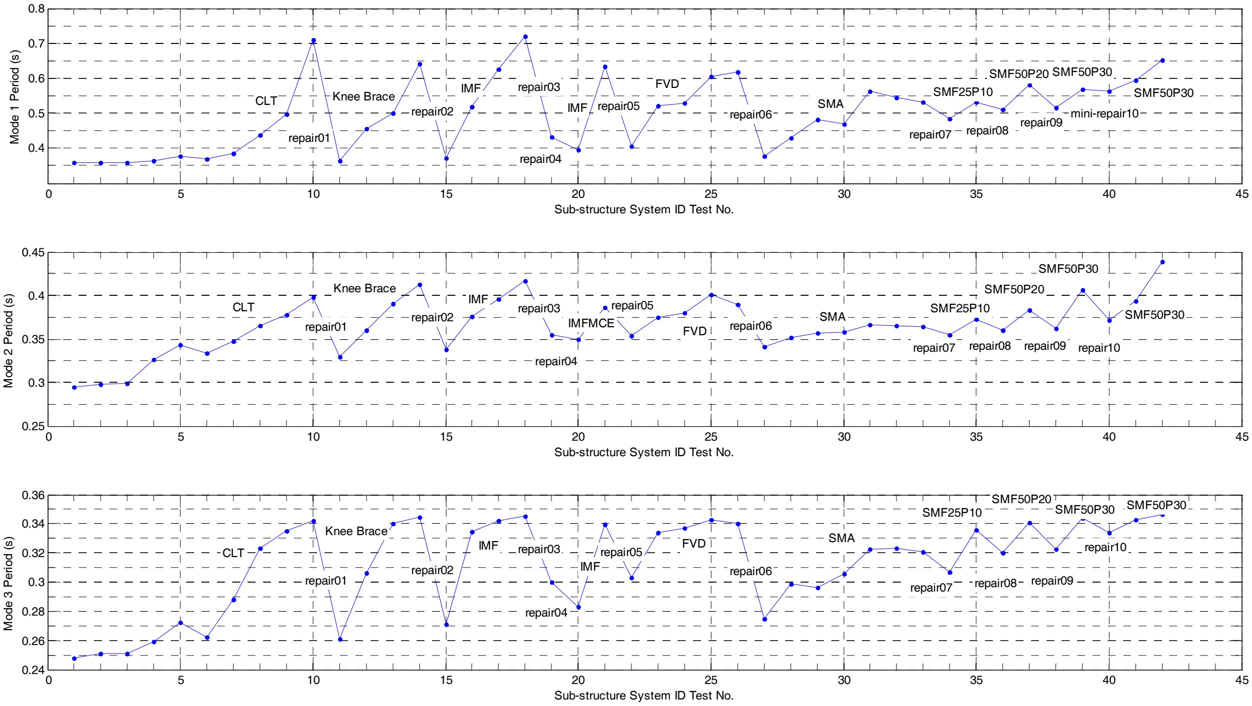


Figure 8. Evolution of the periods of the substructure for the first three modes.

Closure

As part of the NEES-soft project, 24 slow pseudo-dynamic hybrid tests were conducted at the NEES@UB site. A dynamic analysis package for light-frame wood buildings, called Timber3D, and Matlab-Simulink controller algorithm were developed and used to perform the slow hybrid tests. In this hybrid simulation, the first story was numerically analyzed with different retrofits while the upper two stories were constructed and physically tested. This hybrid test setup allows the evaluation of different retrofits without having to physically re-construct the first story multiple times.

Acknowledgments

This material is based upon work supported by the National Science Foundation under Grant No. CMMI-1041631 (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.

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