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TOWARDS A PERFORMANCE-BASED SEISMIC DESIGN PROCEDURE FOR WOODFRAME CONSTRUCTION

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ABSTRACT

While woodframe structures have historically performed well with regard to life safety in regions of moderate to high seismicity, these types of low-rise structures have sustained significant structural and non-structural damage in recent earthquakes. Current building code requirements for engineered wood construction around the world are not based on a global seismic design philosophy. Rather, wood elements are designed independently of each other without consideration of the influence that their stiffness and strength have on the other structural components of the structural system. Furthermore, load paths in woodframe construction arising during earthquake shaking are not well understood. These factors, rather than economic considerations, have limited the use of wood to low-rise construction and, thereby, have reduced the economical competitiveness of the wood industry in the U.S. and abroad relative to the steel and concrete industry. A project recently underway in the U.S. entitled "NEESWood: Development of a Performance-Based Seismic Design Philosophy for Mid-Rise Woodframe Construction" seeks to develop a seismic design philosophy that will provide the necessary mechanisms to safely increase the height of woodframe structures in active seismic zones and to mitigate seismic damage to low-rise woodframe structures. This will be accomplished through the development of a new seismic design philosophy that will make mid-rise woodframe construction a truly viable option in regions of moderate to high seismicity. Such a design philosophy falls under the umbrella of the performance-based design paradigm. This paper presents a summary of year 1 activities of the NEESWood project, which consisted primarily of (1) full-scale three-dimensional shake table testing of a two-story, 350 kN two-story townhouse with 150 square meters of living space and a two-car garage at different stages of finish, i.e. no non-structural finishes, non-structural finishes, as well as supplemental damping in key walls, (2) initial development of seismic analysis software based on an existing platform, and (3) preliminary philosophical development of the design approach and the associated societal impacts. Summary results and conclusions of these tests and activities are presented.

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Introduction

NEESWood (www.engr.colostate.edu/NEESWood) is a four-year, five-university project that encompasses ten tasks, five of those tasks are major analysis and/or testing tasks. Testing consists of two full-scale woodframe shake table tests in Years 1 and 4, and assembly-level tests in year 2. The first test was a full-scale seismic benchmark test of a two-story woodframe townhouse that required the simultaneous use of the two 50-ton three-dimensional shake tables at the SUNY-Buffalo NEES node. These tests were completed in November, 2006. The Network for Earthquake Engineering Simulation (NEES) is a network of experimental and computational earthquake engineering resources located throughout the United States (full details are available at www.nees.org) and provides the equipment resources for a large portion of this project.

The benchmark tests included investigations of the application of supplemental energy dissipation systems to woodframe buildings. Based upon what is learned following the benchmark tests, modeling will be improved and the Performance Based Seismic Design (PBSD) philosophy developed. The design approach will be applied to the seismic design of a six or seven-story mixed-use woodframe apartment building. This mid-rise woodframe structure will be constructed and tested at full-scale in a series of shake table tests on the E-Defense (Miki) shake table in Japan. The use of the E-Defense shake table, the largest 3-D shake table in the world, is necessary to accommodate the height and payload of the mid-rise building. One objective of this paper is to inform the timber engineering community worldwide of the opportunity to participate through payload projects in the E-defense shake table test scheduled for 2009. The project schedule shown in Fig. 1 provides a list of tasks within the NEESWood project and the red dashed line represents the time corresponding to the writing of this paper (i.e. November, 2006).

November 2006

Task	Year 1				Year 2				Year 3				Year 4			
1. Numerical Analysis Tools (SAPWOOD)		1.1														
2. Seismic Protection Systems		2.1		2.2							2.3					
3. PBD Philosophy		3.1														
4. Testing			4.1				4.3							4.2		
5. Societal Risk / Decision Making			5.1													
6. Payload Projects			6.1								6.1				6.1	
7. Professional Advisory Committee (PAC)		7.1				7.1				7.1				7.1		
8. International Cooperation													8.1			
9. Outreach/Education	9.1															
10. Annual NEES Awardee Meetings				10.1				10.1				10.1				10.1

Figure 1. Task Schedule for the NEESWood Project.

Also within the NEESWood project, there are several other major tasks including societal risk and decision making and numerical model development. Some initial work has been performed on numerical model development. Since the design philosophy must be sufficiently developed for societal risk studies to proceed, that task had only just begun at the time this paper was written.

Shake Table Testing

Benchmark Tests at UB NEES site (Task 4.1)

General Testing with Various Building Finishes (Phases 1, 3, 4, and 5)

The main objective of the first Benchmark experiment of the NEESWood Project, recently completed in the Structural Engineering and Earthquake Simulation Laboratory (SEESL) at the University at Buffalo (UB), was to generate a landmark experimental data set that can be used by all NEESWood project participants for integrated project activities and that can be fully shared with the broader earthquake engineering community. A full-scale, two-story, townhouse woodframe building, designed according to modern code requirements, was tested in a series of shake table tests. Note that these types of modern woodframe buildings are not designed according to any unifying seismic design philosophy and therefore are susceptible to sequential damage propagation.

As mentioned, the twin 50-ton capacity UB-SEESL shake tables were utilized for the NEESWood benchmark experiment. The two tables acting in unison were required to accommodate the weight of the full-scale building. The benchmark test structure is one of the four index buildings designed within the CUREE-Caltech Woodframe Project (Reitherman et al., 2003) and represents one unit of a two-story townhouse containing three units, having approximately 150 m^2 of living space with an attached two-car garage. The floor plan of the building is shown in Fig. 2. This building is assumed to have been built as a production house in either the 1980's or 1990's, located in either Northern or Southern California, and is based on engineered construction. The height of the townhouse from the first floor slab to the roof eaves is 5.49 m. The exterior walls of the townhouse building are covered on the outside with 20 mm thick stucco over 11 mm thick OSB sheathed shear walls on the outside and 12 mm thick gypsum wallboard on the inside. The shake table tests involved five different testing phases, with each phase representing a different configuration of the building. The building was repaired at the start of each phase in an effort to recover its initial dynamic characteristics. Within each phase, the building was subjected to a three-dimensional ground motions recorded during the 1994 Northridge earthquake in California. The ground motions were scaled to produce varying intensities of ground shaking. The benchmark structure was tested both with and without interior and exterior wall finish materials. Fig. 3 shows the bare structure during the OSB-only testing and the completed structure with drywall and stucco. Also, a seismic protection system was included in test phase 2 and is discussed later in this paper..

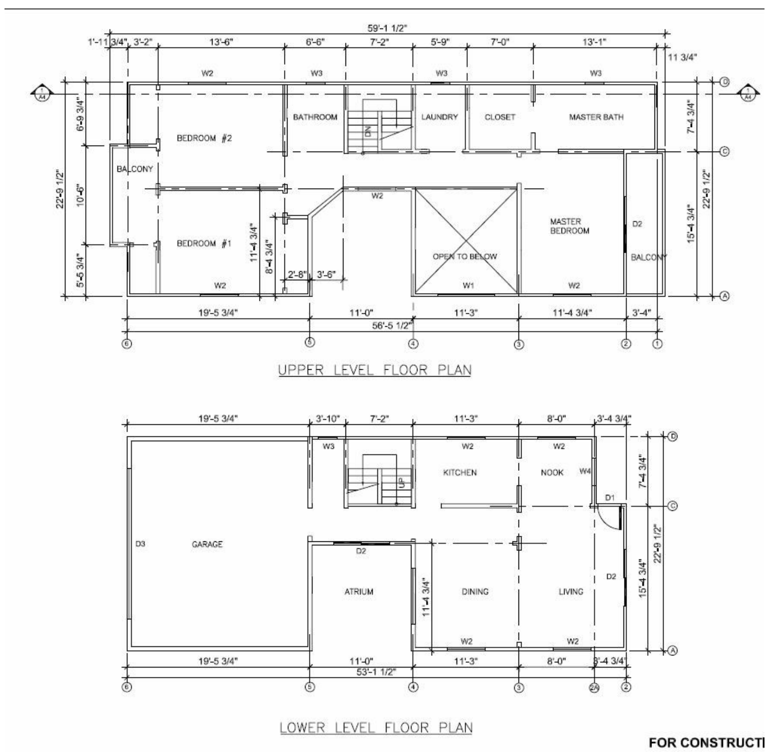

Figure 2. Floor Plan of Benchmark Test Structure.

The complete set of data obtained from the benchmark structure testing remains to be processed since testing was completed just prior to the writing of this paper. Detailed results from the benchmark testing will be available when this paper is presented at the 9CCEE. Some initial experimental observations include: (1) the addition of drywall on only the structural (shearwalls) walls (no drywall on the partition walls) increased the building stiffness by more than 30%; (2) drywall on the partition walls had no effect on the structure properties or its response to seismic loading; (3) the addition of stucco did not have a significant effect on the dynamic properties of the building (this was an unexpected result); and (4) current state-of-the-art modeling techniques are unable to account for the rocking motion seen at very high ground acceleration levels (i.e., 0.4g to 0.9g). Thus, it will be important to include uplift in numerical models in order to capture this behavior.

The most significant displacement occurred in the garage wall line as expected. During the study the level 2 seismic intensity (0.19g EW; 0.22g NS; 0.26g Vertical Canoga Park Record of the Northridge earthquake) was used to compare the structural response from one phase to another. Fig. 4 shows an example of this comparison in the form of measured time histories along the garage wall line. There were five levels total and level 5 consisted of a near-fault ground motion with a NS peak ground motion of 0.84g. The level 5 structural responses were still being processed at the time this paper was written. However, it should be noted that the response along the garage wall line was approximately 4% inter-story drift with significant damage resulting. Full damage photos and analysis will be presented at the conference.

Figure 3. Benchmark Test Structure During Phase 1 (OSB Only) and Phase 5 (All finishes).

Supplemental Damping (Phase 2)

To a limited extent, seismic protection systems have been explored for application to woodframe structural systems (Symans et al. 2002). Within the NEESWood Project, Phase 2 of the benchmark tests focused on the development and application of prefabricated modular damper walls within the two-story, townhouse structure. The damper walls incorporated fluid viscous dampers within an inverted chevron brace. The damping system was designed using a modified version of the SAWS computer software (Folz and Filiatrault, 2004) wherein discrete viscous damping elements were incorporated in parallel with the damper shear wall elements. The structure had already been constructed for Phase I of the benchmark study and thus the implementation of the modular damper walls may be regarded as a retrofit application.

The modular damper walls are constructed of wood framing around the perimeter and steel bracing within the central region (see Fig. 5). The width of each wall was 1.22m to accommodate the standard width of wood sheathing panels. As the top of the wall displaces laterally with respect to the bottom of the wall, the damper is stroked and dissipates a portion of the seismic input energy, thereby reducing the hysteretic energy dissipation demand on the wood framing within the structure. The fluid dampers used in the townhouse structure were nonlinear velocity-dependent devices (force output nonlinearly related to velocity). Within the U.S., such dampers have been implemented within numerous steel and concrete buildings. However, the testing of such dampers within the NEESWood benchmark structure represents the first application within a full-scale, three-dimensional woodframed building. In that sense, one of the objectives of the benchmark structure testing was simply to establish the feasibility of implementing a seismic damping system within a full-scale, woodframe structural system.

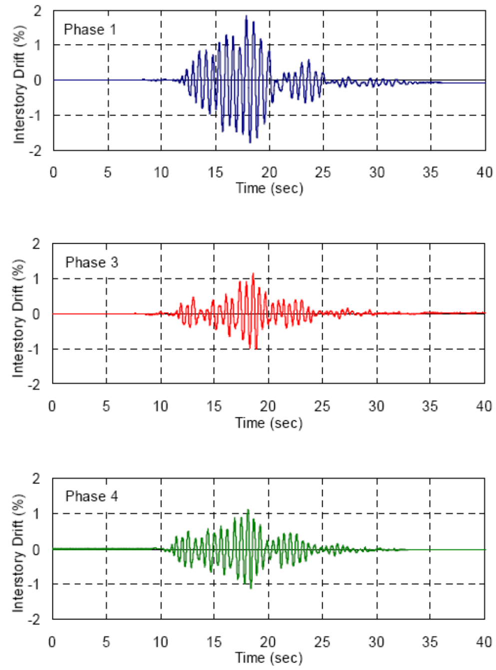

Figure 4. Comparison of Garage Wall Drift for OSB-only (top), Drywall on structural walls (middle), and Drywall on all walls (bottom).

Figure 5. Prefabricated Damper Walls - Phase 2.

The Phase 2 benchmark tests were recently completed and thus a complete assessment of the results is not yet available. However, a preliminary review of the data suggests that the inclusion of the dampers improved the performance of the building. For example, the peak interstory drift was consistently reduced as compared to the building without the dampers (see Fig. 6). However, due to the inherent flexibility in the wood framing system and difficulty in tightly coupling the modular wall and the main wood framing system, the engagement of the dampers was limited and thus the full effectiveness of the dampers was not realized. Based on what was learned from the Phase 2 testing, a new design for the prefabricated modular damper walls has been developed and will undergo testing in the near future

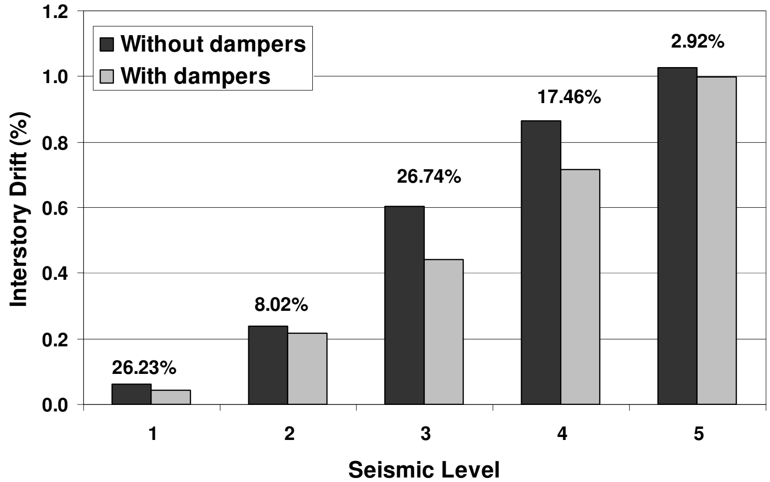

Figure 6. Peak Drift Response of Building With and Without Prefabricated Damper Walls.

Numerical Model Development

As part of Task 1 of the NEESWood project (see Fig. 1), a software package entitled SAPWood (Seismic Analysis Package for Woodframe Structures) is being developed. It is based on the Seismic Analysis of Woodframe Structures (SAWS) software (Folz and Filiatrault, 2004) that was developed as part of the CUREE-Caltech Woodframe project. The SAPWood program is capable of utilizing an array of hysteretic springs, has the ability to perform nonlinear bi-directional time history dynamic analysis, single and multi-record uni- or bi-directional incremental dynamic analysis (IDA), uni- or bi-directional incremental mass analysis (IMA), system identification, and has a graphic model builder feature. A free Beta version release is available on the NEESWood project website. Uplift capabilities are being added and will be available in the first official release of SAPWood in early summer, 2007, in order to capture the rocking motion observed during the benchmark tests.

PBSD: A Hierarchical Approach

A working definition for performance-based engineering is an engineering approach that is based on (1) specific performance objectives and safety goals of building occupants, owners, and the public, (2) probabilistic or deterministic evaluation of hazards, and (3) quantitative evaluation of design alternatives against performance objectives; but does not prescribe specific technical solutions (Ellingwood et al., 2006). In keeping with this working definition, the concept of PBSD is being pursued within the NEESWood project as a hierarchical, or more accurately, a tiered approach. For example, consider PBSD as a simple input-output (IO) problem. The designer knows the desired outputs which are the target performance objectives sought by the owner and/or building occupants, and the input consists of some type of representation of the seismic hazard. Thus, the designer seeks to provide the design which, for the given input, gives the specified output. Obviously, the PBSD is complicated by the probabilistic nature of earthquakes and structural behavior, but these uncertainties can be accounted for within a well-articulated philosophy. For example, a tiered approach consists of alternative levels of design method such that as the analysis is made more complex, less conservatism is present/required and the resulting structure is made more economical. Tiers under consideration are the following: (Level I) Force-based design with iteration or checking; (Level II) direct displacement-based design (Filiatrault and Folz, 2002); and (Level III) Full time-history dynamic analysis which, at this stage, can be considered inclusive of multi-record incremental dynamic analysis and probabilistic system identification techniques. The same level of risk is present in all cases, but the uncertainties arise from different sources depending on which design approach/method tier is selected.

Summary and Closure

The NEESWood project is currently beginning its second year of four years. This paper has outlined the year 1 activities including shake table testing of the largest woodframe structure ever tested. The beginning of a tiered PBSD philosophy is underway and will be developed based on the result of these tests.

Acknowledgments

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References

B.E. Ellingwood, J.W. van de Lindt, D. Gromala, D.V. Rosowsky, R. Gupta, and S. Pryor, 2006. "Performance-Based Engineering for Light-Frame Wood Construction in the United States: Status and Challenges." Proceedings of the *2006 World Conference on Timber Engineering*, Portland, OR

Folz, B., and Filiatrault, A., 2004."Seismic Analysis of Woodframe Structures Buildings I: Model Formulation", *ASCE Journal of Structural Engineering*, 130, No. 9, 1353-1360.

Filiatrault, A. and Folz, B., 2002. "Performance-based seismic design of wood framed buildings," *ASCE Journal of Structural Engineering*, 128(1):39-47.

Reitherman, R., Cobeen, K., and Serban, K., 2003."Design Documentation of Woodframe Project Index Buildings", Report No. W-29, CUREE, Richmond, CA.

Symans, M.D., Cofer, W.F., and Fridley, K.J., 2002. "Base Isolation and Supplemental Damping Systems for Seismic Protection of Wood Structures: Literature Review," *Earthquake Spectra*, EERI, 18(3): 549-572.