Development of a Performance-Based Seismic Design Philosophy for Mid-Rise Woodframe Construction: Progress on the NEESWood Project

J.W. van de Lindt (Associate Professor)
Department of Civil Engineering, Colorado State University
Fort Collins, CO, USA

D.V. Rosowsky (A.P. Florence Wiley Chair Professor)
Texas A&M University, Department of Civil Engineering
College Station, TX, USA

A. Filiatrault (Professor)
Department of Civil, Structural, and Environmental Engineering, SUNY at Buffalo
Buffalo, NY, USA

M.D. Symans (Associate Professor)
Department of Civil and Environmental Engineering, Rensselaer Polytechnic Institute
Troy, NY, USA

R.A. Davidson (Assistant Professor)
School of Civil and Environmental Engineering, Cornell University
Ithaca, NY, USA

Summary

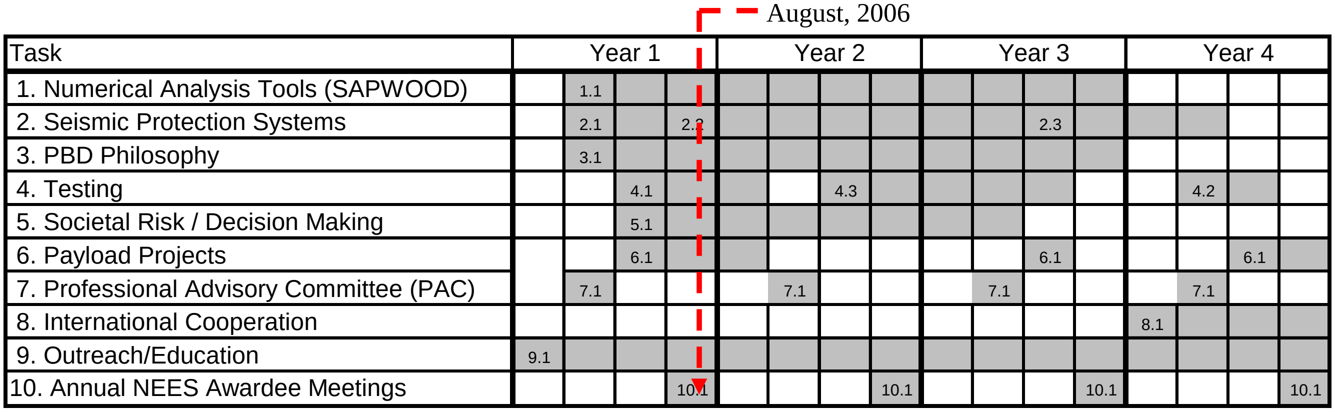
This paper presents an overview of the U.S. National Science Foundation-funded NEESWood project entitled "Development of a Performance-Based Seismic Design Philosophy for Mid-Rise Woodframe Construction." The Network for Earthquake Engineering Simulation (NEES) is a network of experimental and computational 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 the project. The primary objective of the NEESWood project (www.engr.colostate.edu/NEESWood/) is to develop a seismic design philosophy that will provide the necessary mechanisms to safely increase the height of woodframe structures in active seismic zones of the U.S. as well as mitigating damage to low-rise woodframe structures. Such a design philosophy falls under the umbrella of the performance-based design paradigm.

1 Introduction

To date, the height of woodframe construction has been limited to approximately four or five stories, mainly due to the lack of understanding of the dynamic response of taller (mid-rise) woodframe construction, non-structural limitations such as material fire requirements, and potential damage considerations for non-structural finishes. 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 may have on other structural components within the complete structural system.

The NEESWood project involves two full-scale woodframe structure shake table tests in Years 1 and 4. The first is a full-scale seismic benchmark test of a two-story woodframe townhouse that requires the simultaneous use of the two 50-ton three-dimensional shake tables at the SUNY-Buffalo NEES node

(Task 4.1). This test will include investigations on the effect of interior and exterior wall finish materials and the application of passive energy dissipation systems to woodframe buildings. For the second set of shake table tests (Task 4.2), the design philosophy that has been developed in Task 3 will be applied to the seismic design of a mid-rise (six or seven-story) multi-family residential woodframe apartment building. This full-scale mid-rise woodframe structure will be constructed and tested 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 and invite the world timber engineering community to participate through payload projects in the E-defense shake table test tentatively scheduled for 2009. The project schedule shown in figure 1 provides an overview of the NEESWood tasks. Note that the red dashed line represents the current time (i.e., August, 2006).



August, 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

Fig 1 Tasks within the NEESWood Project

2 Progress on Benchmark Tests at UB NEES site (Task 4.1)

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

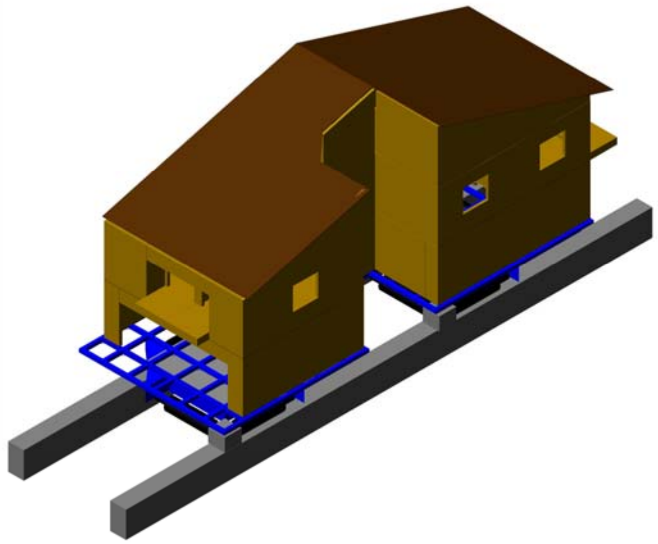


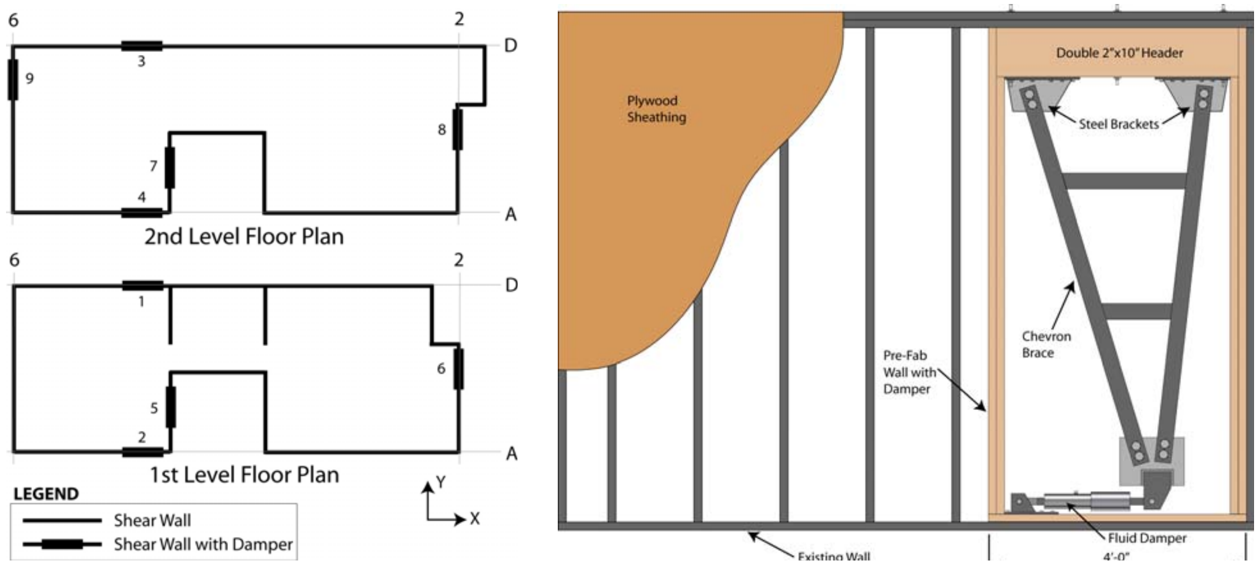
Fig 2 NEESWood Benchmark Test Structure on Twin UB-SEESL Shake Tables.

The twin 50-ton capacity UB-SEESL shake tables are being utilized for the NEESWood benchmark experiment. The two tables acting in unison are required to accommodate the weight of the full-scale building. The benchmark test structure is essentially one of the four index buildings designed within

Fig 3 Construction of Foundation for NEESWood Benchmark Test Structure.

the recent CUREE-Caltech Woodframe Project [1] 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 (see 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. The design is based on engineered construction. The height of the townhouse from the first floor slab to the roof eaves is 5.49 m. Its seismic weight is 320 kN (36 tons) and the calculated initial (elastic) fundamental period is 0.16 sec. The existing extension steel frames available on each of the UB-SEESL shake tables are connected together by a steel link structure to support the entire woodframe structure across the two shake tables with minimal vertical deflection. 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. Details regarding the two-story townhouse are available in [1]. The shake table testing will involve six different testing phases, with each phase representing a different configuration of the building. The building will be repaired at the start of each phase in order to recover its initial dynamic characteristics. Within each phase, the building will be subjected to a three-dimensional ground motion recorded during the 1994 Northridge earthquake in California and scaled to increasing intensities. The benchmark structure will be tested both with and without interior and exterior wall finish materials. Also, seismic protection systems, in the form of fluid dampers will be included in one of the test phases.

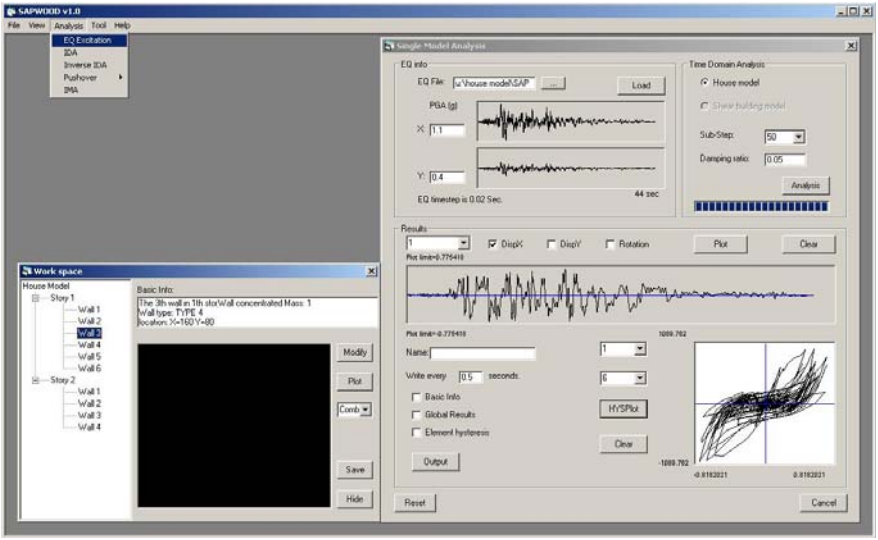
At the time of this writing, the steel link structure required to connect both shake tables has been designed and fabricated and the construction of the foundation is underway, as shown in Fig. 3. The measurement instrumentation has been identified and includes the deployment of more than 250 sensors to measure the detailed seismic response of the building. The testing protocol has been defined and preliminary seismic simulations have been conducted using the computer program SAWS [2]. In preparation for Phase II of the benchmark structure shake table tests, nonlinear dynamic analyses of the benchmark structure with fluid viscous dampers was performed using the computer software SAWS (Seismic Analysis of Wood Structures) [2]. In Phase II, the structure will not have exterior or interior finish materials applied and thus the analysis was performed for that configuration. Version 2.0 of SAWS was utilized, which includes code modifications by researchers at SUNY Buffalo to incorporate modeling of viscous damping elements. The Canoga Park record of the 1994 Northridge Earthquake was used as the input earthquake ground motion in the simulations. Four different intensities were investigated, wherein intensity levels 1 to 4 consisted of the Canoga Park record amplified with scaling factors of 0.12, 0.53, 0.86 and 1.20, respectively. Two components of the Canoga Park record, one along each of the two principal axes of the structure, were used to create biaxial excitation. Due to the important role inter-story drifts play in controlling damage in wood-frame structures, the main criteria used in designing the energy dissipation system was to limit the inter-story drift to a prescribed value. Due to safety concerns and limitations associated with the experimental testing space, it was determined early in the design phase that the peak drift ratio in all shear walls should be limited to 2%. Therefore, the overall objective in retrofitting the structure with fluid viscous dampers was to limit inter-story drifts in all walls to 2% for the level 4 intensity ground motion. Because of the plan asymmetric distribution of lateral stiffness (in both the X and Y directions), torsional response is expected to be significant, resulting in increased inter-story drifts, particularly along the edges of the building. Design of the energy dissipation system involved consideration of three major issues: 1) location of each damper, 2) design specifications for each damper and 3) transfer of damper forces into shear walls. In the process of evaluating possible damper locations, a number of locations were deemed unacceptable due to insufficient horizontal clearance due to the presence of windows and doors. Other locations, such as the second-level overhang along column line 2 (see Figure 4(a)), were avoided due to load path concerns. The SAWS program was used to select the damper locations based on an iterative trial-and-error procedure. The result is the nine locations shown in Figure 4(a). Note that dampers were incorporated in the second-level due to predictions of significant second-level inter-story drifts. Determination of design specifications for each damper was approached in two ways: 1) an iterative trail-and-error approach in which the damping coefficient of each damper was varied, and 2) an approach wherein all dampers are constrained to have the same specifications. One advantage to allowing different damping coefficients for each damper in plan-asymmetric structures, such as the NEESWood Benchmark Building, is that it allows the designer to shift the center of supplemental damping. Goel [3] has shown that the center of supplemental damping can be shifted by having an asymmetric distribution of dampers, and that this shift can be designed such that it significantly reduces the inter-story drifts as compared to a structure with a symmetric damper distribution. One disadvantage of specifying multiple damper configurations is that it tends to increase costs. For this project, the trial-and-error numerical process led to the selection of nine dampers, all having the same specifications (i.e., all nine dampers are identical and are linear viscous dampers). Although the selected dampers and associated locations result in peak inter-story drifts ratios of less than 2%, it should be recognized that the numerical modeling in SAWS relies upon a number of assumptions (e.g., 100% efficient transfer of damper forces to the shear walls and zero slack in damper connections). The degree to which these assumptions are valid depends on how the dampers are installed. Given the space constraints, metallic chevron braces were determined to be the simplest and most effective approach for damper installation. Such an installation configuration has been utilized previously in experimental shaking table tests of a single wood-framed shear wall [4]. A schematic of a typical retrofitted wall for the NEESWood Benchmark Building is shown in Figure 4(b). Note from this figure that the retrofitted wall consists of a 4-ft wide pre-fabricated wall that is installed within an existing wall by removal of existing studs. The pre-fabricated wall includes the chevron braces, fluid damper, and a header to transfer the gravity loads to the base of the wall. The 4-ft width allows for a standard 4-ft wide sheathing panel to be attached to the perimeter of the pre-fabricated wall.



(a) (b)

Fig 4 (a) Plan view of 1^{st} and 2^{nd} floor levels showing location of dampers and (b) Schematic of typical retrofitted shear wall

3 Development of SAPWood Software Package (Task 1)



EQ File: u:\house model\SAP

PGA (g)

X: 1.1

Y: 0.4

EQ timestep is 0.02 Sec.

44 sec

● House model

○ Shear building model

Sub-Step: 50

Damping ratio: 0.05

1

☑ DispX ☐ DispY ☐ Rotation

Name:

Write every 0.5 seconds.

☐ Basic Info

☐ Global Results

☐ Element hysteresis

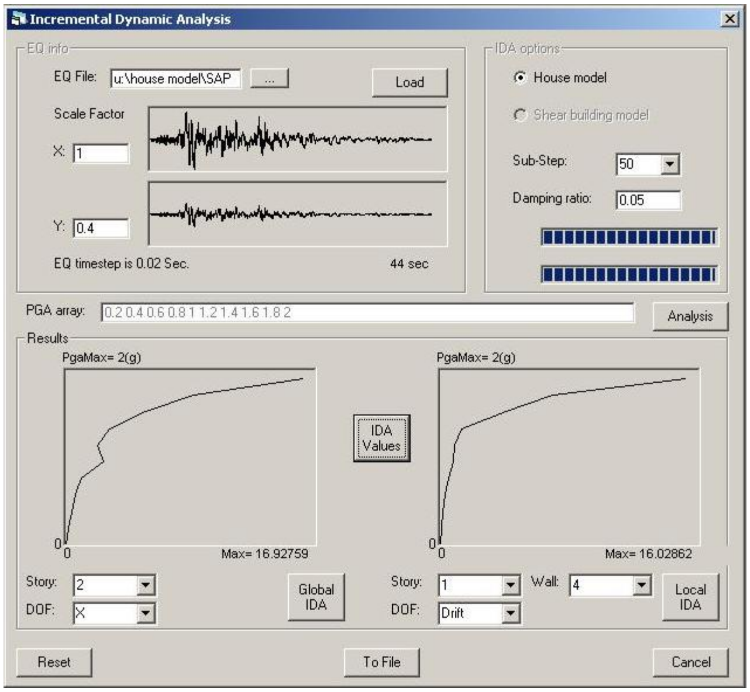
1

6

Basic Info:
The 3th wall in 1th storWall concentrated Mass: 1
Wall type: TYPE 4
location: X=160 Y=80

Fig. 5 Screen capture of a bi-directional nonlinear time history analysis in SAPWood

As part of Task 1 in the NEESWood project (see Figure 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 [2] that was developed as part of the CUREE-Caltech Woodframe project . The SAPWood program is capable of utilizing an array of hysteretic spring elements ranging from linear, ten-parameter CUREE element, to the 16-parameter evolutionary hysteretic parameter model springs [5,6]. A version 1.0 release is scheduled for September, 2006. The program will be available free of charge on the NEESWood website in the Fall of 2006, with only registration required. The new software package has the ability to perform nonlinear bi-directional time history 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. Figure 5 shows a screen capture of a time history analysis in SAPWood and Figure 6 shows the results of a single record IDA. SAPWood is expected to serve as both a research tool and a design tool for development and application of the new design philosophy, respectively.



EQ File: u:\house model\SAP

Scale Factor

X: 1

Y: 0.4

EQ timestep is 0.02 Sec.

44 sec

● House model

○ Shear building model

Sub-Step: 50

Damping ratio: 0.05

PGA array: 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

Story: 2

DOF: X

Story: 1

Wall: 4

DOF: Drift

Fig. 6 Screen capture showing a bi-directional IDA of a two-story house model in SAPWood

4 Early Development of PBSD (Task 3)

Performance-based seismic design (PBSD) is a developing design philosophy that provides flexibility for the designer with regard to the design approach and for the owner with regard to performance expectations. While the concept itself has been reasonably developed through vision documents, the performance requirements, corresponding structural response quantities, and repeatable techniques have not been developed for woodframe structures. PBSD for woodframe structures has been only preliminarily investigated by several researchers.

4.1 Direct Displacement Design

Direct Displacement Design (DDD) was first proposed and elaborated upon by Priestley [7] for concrete structures. More recently, the approach first described by Priestly was applied to woodframe structures by Filiatrault et al. [8]. [Also see paper by the same authors at this conference.] The proposed DDD procedure simplifies the prediction of displacement response of an actual nonlinear structural system through the use of a linear-elastic SDOF model with equivalent elastic secant stiffness and equivalent viscous damping, determined at a target displacement. Procedures for determining equivalent stiffness and damping may vary, and there are additional challenges with wood structural systems owing to the highly pinched and degrading hysteresis curves, as well as the aleatoric variability (inherent in the material properties, for example) and the epistemic uncertainty (arising from incomplete knowledge about how the system was assembled, issues of construction quality, and so forth). Nonetheless, as part of the NEESWood project, progress is being made in both direct displacement design (DDD) and direct displacement assessment (DDA) procedures as one alternative to performing full nonlinear time-history analyses using a suite of ground motions. Figure 7 illustrates the effect of openings on equivalent secant stiffness and equivalent period. It appears that it will be possible to generalize both equivalent secant stiffness (e.g., as a function of initial stiffness or some other measure) as well as equivalent viscous damping (not shown here) across a broad range of structural configurations. This will greatly improve the likelihood that DDD procedures can be made simple

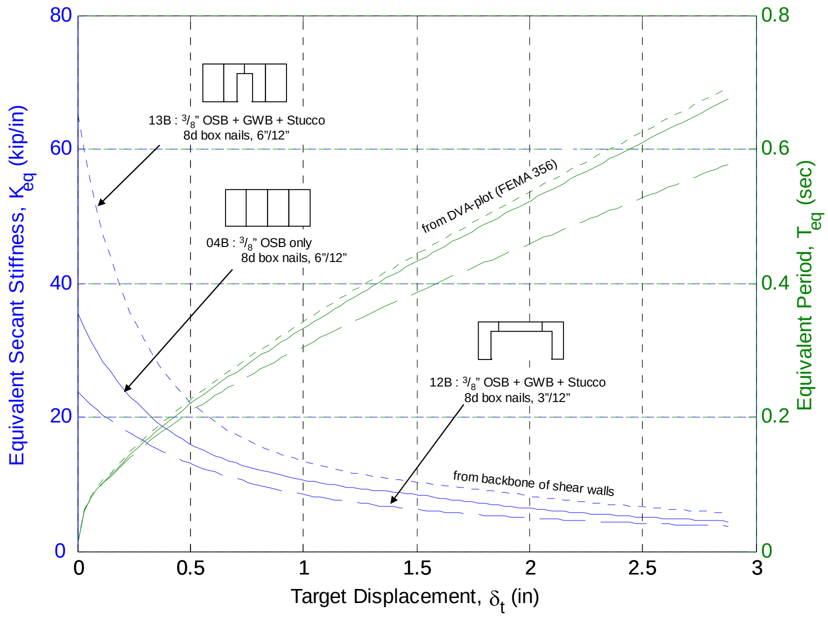


Fig. 7 Effect of opening size on equivalent secant stiffness and equivalent period (1 in = 25.4 mm)

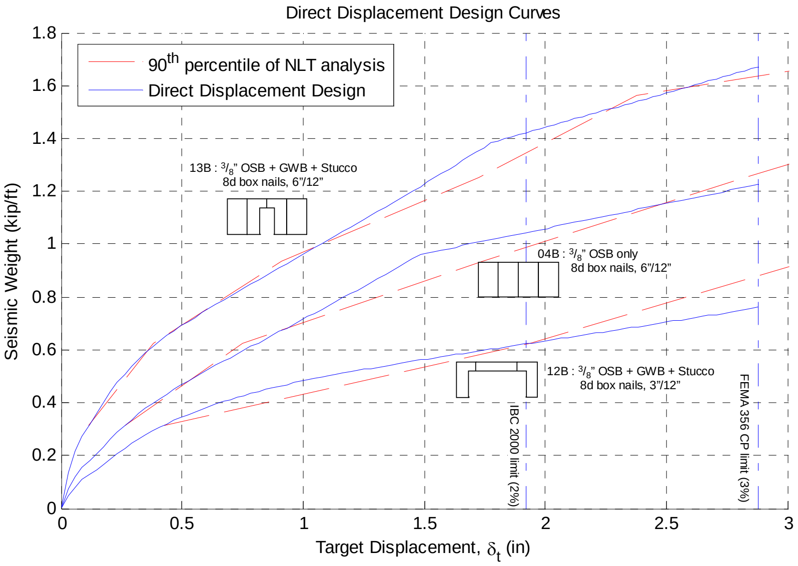


Fig. 8. Example of DDD curves for shearwalls with different openings

enough for widespread use among engineers involved in the design or assessment of woodframe structures. Figure 8 presents an example of a set of design curves obtained using DDD procedures. It is likely that DDD design tools will provide the engineer with allowable seismic weight as a function of target displacement for a given structural configuration (as illustrated in Figure 8). DDA tools, on the other hand, would allow engineers to predict displacement for a given value of seismic weight and structural configuration. Different levels of analysis ranging from the proposed DDD procedures, which may only consider a planar representation of a wall system and which rely only on some representation of the backbone curve obtained from a pushover analysis and some estimate of damping, all the way up to full nonlinear time-history analysis using a full 3D model of the complete structure and a suite of ground motion records selected to characterize the seismic hazard, are being considered. The former approach may see the most widespread use among design engineers.

4.2 Full Time-History Analysis

Another option for PBSD of woodframe structures, which is being investigated concurrently with DDD, is full nonlinear time-history analysis as was mentioned earlier. It is clear that, for application of a time-history approach, readily available and user-friendly tools will need to be in place. SAPWood may be able to serve as an initial example tool with commercial software building on this concept. Assuming (for simplicity) peak transient inter-story drift is the damage measure being used as the basis for assessing performance for a woodframe structure, a multi-record IDA provides a statistical distribution of the drift at each spectral acceleration of interest as illustrated in Figure 9. This spectral acceleration level has a return period, and thus an associated occurrence probability. Thus, the probability distribution for the drift is conditioned on seismic intensity, e.g., spectral acceleration. This conditional distribution can be used directly, or the marginal distribution can be calculated and used for communication and decision-making during the design process. One can easily surmise from the above description that this is actually an analysis and not a design approach. Several methods of reversing or inverting the procedure are being investigated.

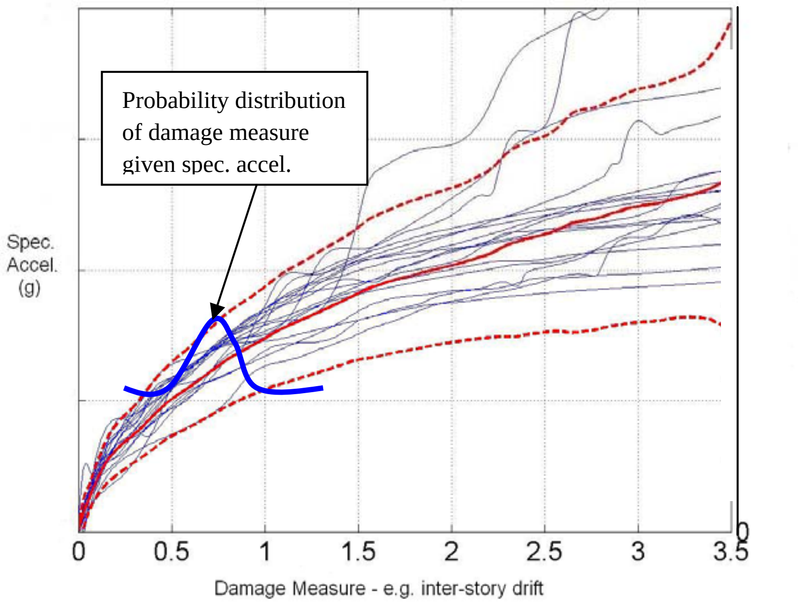


Fig 9 Example of a multi-record IDA for a woodframe structure and the resulting conditional distribution for drift

5 Societal Risk (Task 5)

The project includes an effort to assess the impact of implementing the new PBSD philosophy for low- and mid-rise woodframe structures on a region's seismic risk over time, and to identify the most effective ways to implement it (i.e., how to encourage its use in a targeted way so as to maximize its risk reduction benefits). Focusing on southern California as a case study region, this task involves estimating regional seismic losses for the case study region under many different scenarios and comparing the estimated losses. The different scenarios include various performance objectives for the new PBSD philosophy, ways of including of seismic protective systems, and implementation strategies. An implementation strategy defines, for example, which buildings should use the new PBSD philosophy (e.g., only buildings based on geographic location or occupancy type, or all buildings) and when (e.g., all buildings immediately or increasing over time), and which buildings they replace (e.g., low-rise wood buildings, mid-rise buildings of other materials).

6 Acknowledgements

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