ASSESSMENT OF WOOD RESIDENTIAL CONSTRUCTION SUBJECTED TO EARTHQUAKES

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SUMMARY

Most housing in the United States is light-frame wood construction. The vulnerability of wood residential construction to earthquake effects was apparent in the 1994 Northridge earthquake. New concepts and methodologies are required to better predict and evaluate the performance of wood frame residential structures during earthquakes. In this study, a combination of finite element-based analysis and stochastic modeling is used to simulate the behavior of lateral force-resisting systems typical of light-frame wood residential construction subjected to earthquakes. The probabilities that specified drift limits of typical lateral force-resisting shear wall systems are exceeded when subjected to various levels of ground motion are presented and a relationship between response spectral ordinates and maximum drift that has been suggested for steel frames is investigated for a wood shear wall system.

INTRODUCTION

The vulnerability of wood residential construction to earthquake ground motion was made apparent by its performance during the 1994 Northridge earthquake, where the property losses ($20 billion) to residences far outweighed the loss to any other single type of building construction. Furthermore, more fatalities (24 of 25) and injuries occurred in light-frame buildings than in all other types of buildings combined. These failures highlight the vulnerability of wood residential construction and the weakness of current residential building practices. There is a clear need to develop new concepts and methodologies to evaluate and enhance the performance of wood frame construction during earthquakes. Such advances require an integration of analytical models of structural behavior and methods of structural reliability assessment for treating the large uncertainties that are inherent to this problem.

In this study, finite element analysis and stochastic models of ground motion are integrated to simulate the behavior of wood frame lateral force-resisting system subjected to earthquakes. Post-disaster surveys have

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shown that a large portion of the structural and nonstructural damage to light-frame wood residential construction can be related to excessive lateral drift of the building system. Performance levels (continued occupancy, life safety, etc) for wood frame buildings have been defined in terms of lateral drift limits in FEMA 273/356 [1][2]. Accordingly, the focus of the research reported herein is on the load-displacement response and energy dissipation characteristics of wood shear walls with different sheathing and nailing patterns subjected to earthquake ground motions.

Identification and quantification of various sources of uncertainty are essential for building risk assessment. Uncertainties in ground motion are reflected in the suites of accelerograms (e.g., from the recent SAC project [5]), appropriately scaled, and selected for the analysis. This methodology can be used to predict behavior of wood frame construction under various levels of seismic hazards (ground motion intensities), thus suggesting avenues for improving construction practices.

MODEL OF LATERAL FORCE-RESISTING SYSTEM

Shear walls are the primary lateral force-resisting components for seismic loading in wood residential construction. The response of wood frame shear walls during minor earthquakes is essentially linear-elastic. However, under severe earthquake ground motion, such systems exhibit highly nonlinear hysteretic behavior, with significant stiffness degradation, pinching of the hysteresis loops and energy dissipation. This hysteretic behavior is strongly dependent on the shear wall aspect ratio and the sheathing and nailing patterns used in construction.

CASHEW (Cyclic Analysis of SHEar Walls) is a numerical model developed as part of the CUREE-Caltech Woodframe Project that is capable of predicting the force-displacement response of wood shear walls under quasi-static cyclic loading. Construction details such as openings for doors and windows, connector patterns and properties, and thickness and arrangement of sheathing panels can be included in the model. In this study, CASHEW is used to model the hysteretic behavior of a shear wall system with door and window openings, which is typical of residential wall construction in the United States (Figure 1).
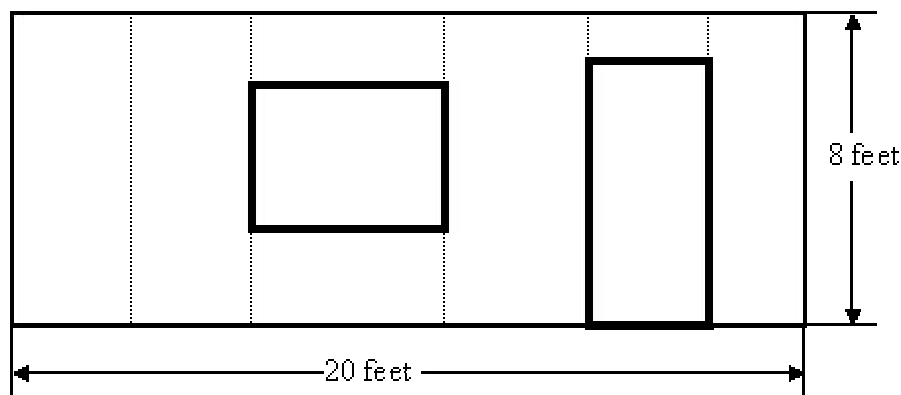

Figure 1. Shear Wall Model with Door and Window

The sheathing pattern indicated in Figure 1 is typical of shear wall construction in the Western United States. The sheathing is provided by 0.375 in (9.5 mm) OSB panels with 8d nails spaced 6 in (152 mm) along the panel perimeter and 12 in (305 mm) in the panel interior. These nails are 0.113 in (3.3mm) in diameter. Studs are spaced in 24 in (610mm) on centers. Krawinkler et. al [6] developed a testing protocol for wood frame structures, which can be applied to the CASHEW model to determine the

hysteretic behavior of this specific wall. The loading protocol and hysteretic force-displacement loop are illustrated in Figure 2 and Figure 3, respectively.
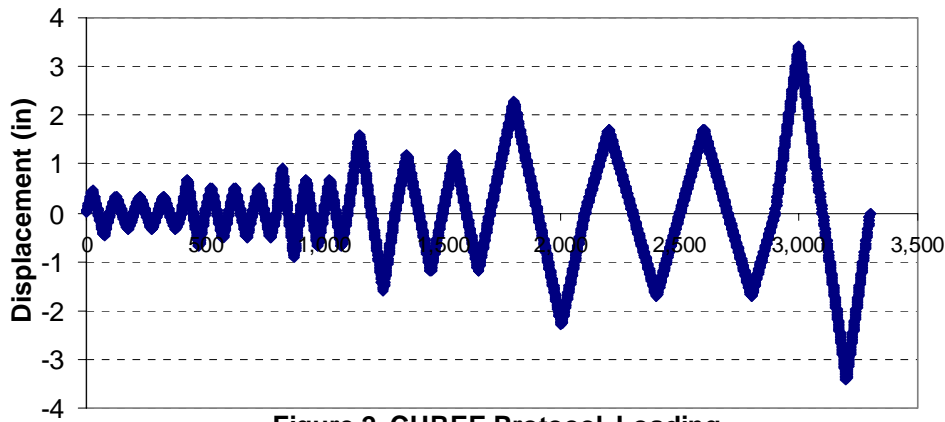

Figure 2. CUREE Protocol Loading (Krawinkler, et al, 2000)
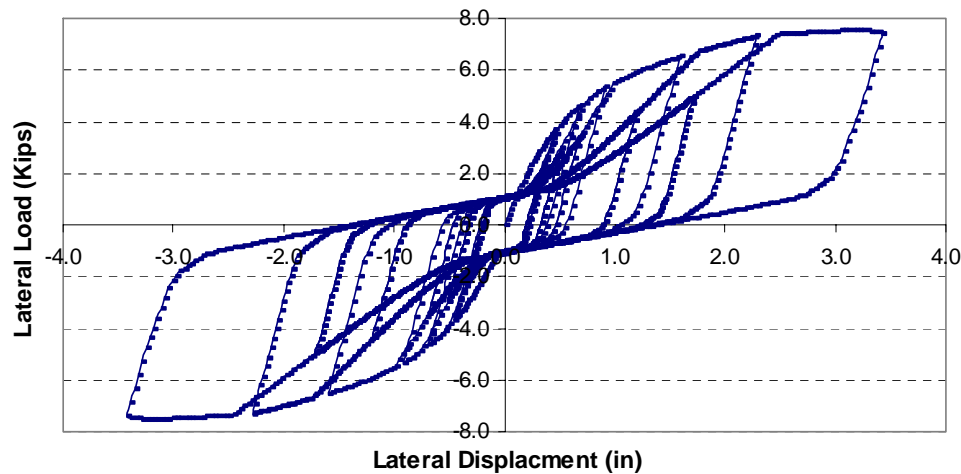

Lateral Displacment (in)

Figure 3. Load - Displacement of Shear Wall in CASHEW Model - CUREE Loading Protocol

The hysteretic behavior of the shear wall in Figure 1 predicted by CASHEW is incorporated in a planar structural model of a typical one-story residential building developed in OpenSees (Open System for Earthquake Engineering Simulation), a finite element platform developed at the Pacific Earthquake Engineering Research (PEER) to perform nonlinear dynamic time history analysis of structural systems subjected to earthquake ground motion. The rate of change in the pinching of the hysteresis and the energy dissipation in OpenSees are adjusted by trial and error to be consistent with the prediction provided by CASHEW model under the same loading protocol (Figure 2). The hysteretic behavior of the shear wall model in OpenSees, illustrated in Figure 4, is consistent with that predicted by CASHEW model.
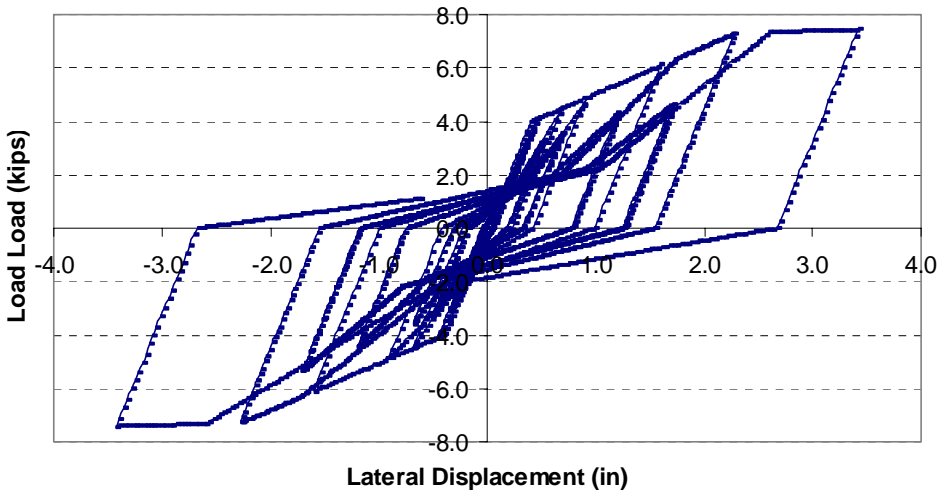
Figure 4. Load - Displacement of Shear Wall in OpenSees Model - CUREE Loading Protocol

The fundamental natural period of the building with the shear wall in Figure 1 is 0.22 sec, which falls in the range that is typical of low-rise wood residential construction [7]. The total energy dissipation in the shear wall system is due to both viscous and hysteretic damping. The hysteretic damping is taken into account by the nonlinear force-displacement model in Figure 4, while the viscous damping ratio is assumed to be 2% [8].

PERFORMANCE BASED DESIGN AND DISPLACEMENT LIMIT STATES

Performance-based engineering is aimed at ensuring that a building achieves the desired performance objectives when subjected to a spectrum of natural or man-made hazards. All proposals for PBE require that life safety (LS) must be preserved under "severe" events. Beyond this, they stipulate that collapse shall not occur under "extreme" events and that function shall be preserved under "moderate" events. As an example, one might require that the building be designed so that there is no disruption of function following an event with 50% probability of being exceeded in 50 years (abbreviated in the sequel as a 50%/50-yr event), that life safety is preserved under a 10%/50-yr event, and that collapse will not occur under a 2%/50-yr event.

Verification that the building performance requirement is met requires a mapping between a qualitatively stated objective (e.g., continuation of building occupancy following a 50%/50-yr event) and a response quantity and limit state (force or deformation) that can be checked using principles of structural analysis and mechanics. Such a mapping invariably requires that the behavior of the building structural system be considered as a whole. The deformation of the structural system often has been selected when system behavior must be measured through one structural response quantity. For example, in FEMA Report 356 (and its widely cited 1997 predecessor, FEMA Report 273) (FEMA, 2000), the immediate occupancy, life safety and collapse prevention performance levels for lateral force-resisting structural elements in light-frame wood construction subjected to seismic effects are related to transient lateral drifts of 0.01, 0.02 and 0.03, respectively. Consistent with the results of FEMA 273/356, then, the structural response quantity of interest in this study is the maximum drift (D) of the structural model.

SOURCES OF UNCERTAINTY

Structural performance during earthquake is impacted by uncertainties in both seismic loading and structural resistance.   The uncertainty in seismic demand is known to be very large in comparison to the inherent variability in structural system and its capacity [9].   Thus, this source of uncertainty is not included in the current evaluation process. However, the variability in the capacity of typical wood-frame structural systems is being explicitly quantified in research in progress, and its relative contribution to overall variability of structural response will be reported at a later time.

The uncertainty in seismic demand is reflected in the suite of ground motions chosen in this study. The SAC Project Phase II ground motions for Los Angeles [5] are used in the analysis. The ensembles of earthquake ground motions represent events with 50% probability of being exceeded in 50 years (LA41-LA60), 10% probability of being exceeded in 50 years (LA01-LA20) and 2% probability of being exceeded in 50 years (LA21-LA40). The corresponding mean return periods are 72 years, 475 years, and 2,475 years, respectively.

STRUCTURAL RESPONSE TO EARTHQUAKE GROUND MOTIONS

The maximum drifts for the three sets of ground motions corresponding to the three hazard levels above are determined by nonlinear dynamic analysis from OpenSees. The resulting drifts are rank-ordered in terms of the probability that the drift is exceeded and plotted in Figure 5.   The FEMA 273/356 deformation limit for life safety is 2% drift, or 1.92 in (49 mm) displacement in a wall 8 ft (2.4 m) in height; the probability of exceeding this limit is virtually 0 for the 50/50 ground motions, while it is about 15% and 40% for the 10/50 and 2/50 ground motions, respectively. For comparison, the probability that the 10/50 ground motions exceed the functional limit of 1% or 0.96 in (24 mm), is approximately 42%, indicating that such shear walls are likely to suffer nonstructural damage under such ground motions.
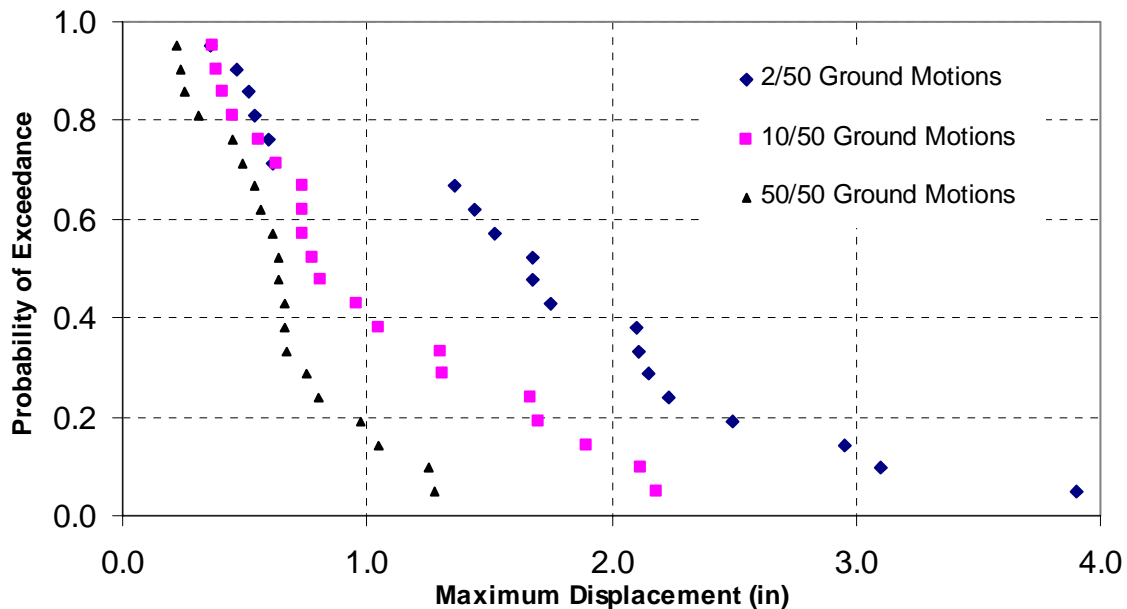

Figure 5. Probability of Exceedance VS Maximum

For purposes of damage estimation and code development, it is convenient to relate the seismic demand (drift) above to a measure of earthquake ground motion intensity. For example, the median seismic demand on a structure can be modeled, in first approximation, by,

$$D = a(S_a)^b \qquad\qquad\qquad (1)$$

in which S_a = spectral acceleration at the fundamental period of the structure, D = deformation, and a and b are constants. The constants in Equation (1) can be determined by a regression analysis of demands determined from OpenSees upon spectral acceleration of an elastic single-degree-of-freedom oscillator. The scatter around this median (logarithmic standard deviation) represents the aleatory uncertainty in structural demand due random amplitude and phasing of the accelerograms in the ground motion ensemble. Equation (1) was first proposed in the SAC Project for modeling seismic demand on steel moment frames and as a basis for determining simple and appropriate design criteria [10,11]. Its suitability for modeling seismic demand on a wood frame structure is considered in this study. With the assumption that the seismic demand can be described by a lognormal distribution, with median as defined in Equation (1) and logarithmic standard deviation as defined by the scatter around the median, one can determine the probability of exceeding drift limits associated with stipulated performance levels for the building structure (denoted the fragility), given a specific S_a. Furthermore, hazard curves determined by the U.S. Geological Survey [http://eqhazmaps.usgs.gov] define the probability that specific spectral accelerations are exceeded. If the relationship between median S_a and median D can be estimated, the unconditional probability of a wood frame structure exceeding certain deformation limits or failing to meet a performance objective can be obtained by convolving the structural fragility with the seismic hazard curve.
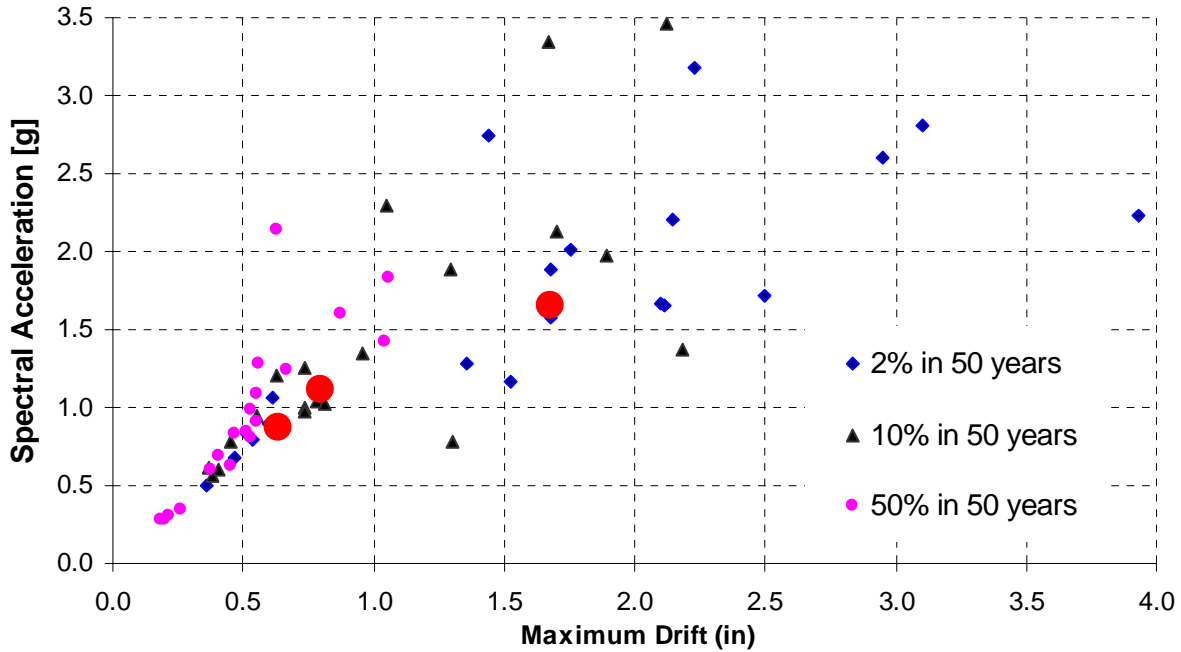

Fig. 6 Model Shear Wall, Ground Motion SAC LA01-60

Figure 6 presents the relationship between maximum drift and spectral acceleration expressed by Equation (1). Spectral accelerations (S_a) at the fundamental period of the structure are obtained from response spectra of the ground motions LA01-LA60., The median spectral accelerations and median maximum drifts for the 2%/50 yr, 5%/50 yr, and 10%/50 yr hazard levels are shown by the heavy solid dots in Figure

6.   Figure 6 shows that, as might be expected, the deformations increase as the return period of the ensemble increases, although there is some overlap in the patterns. With the exception of two points in the 2/50 set, it appears that the functional relationship between deformation and spectral acceleration is not strongly dependent on the ensembles of ground motion selected to develop the relationship. This finding is consistent with that of other investigators for steel structures [11].

A regression analysis of all 60 D-S_a pairs results in parameters a = 0.772 and b = 1.023 in equation (1), with logarithmic standard deviation $\beta_{D \mid Sa}$ = 0.321.   Thus, the median seismic demand for this particular shear wall model is $D = 0.772(S_a)^{1.023}$.   While the standard deviation in the deformation increases with spectral acceleration, the logarithmic standard deviation (approximately the coefficient of variation) can be assumed to be constant at 0.321. Again, this level of aleatory uncertainty in seismic demand is not inconsistent with what has been observed by other investigators of other structural systems.

The exponent b in Equation (1) found from the analysis of the response data in Figure 6 is very close to 1.0, suggesting a (nearly) linear relationship between shear wall deformation and spectral acceleration. This result also has been observed for steel moment frames [e.g., 11] and for some reinforced concrete moment frames, where the fundamental periods were larger than 1.0 sec.   The structural behavior of the wood shear wall represented in Figure 6 ranges from the elastic at small S_a to the highly nonlinear at large S_a (the deformation range is approximately h/500 to h/25, in which h is the height of the shear wall). The implication is that one cannot clearly distinguish linear and nonlinear system behavior in terms of the total deformations in Figure 6. In other words, displacements of linear and nonlinear systems are essentially the same, an observation first made by Newmark over 40 years ago for systems in which the fundamental period exceeded approximately 1.0 sec.   It is somewhat surprising to observe a similar result for low-rise wood structures, where the fundamental periods tend to be much less (for the shear wall in the current study, 0.22 sec). Research is continuing on this topic, in the hope of arriving at a relatively simply tool for estimating seismic demand on light-frame wood structures.

Assuming that the seismic demand can be described by a lognormal distribution, with median defined in Equation 1, the conditional probability that drift demand (D) exceeds a defined drift limit (d), given a specific spectral acceleration (S_a), is [10]

$$P(D>d \mid S_a = x) = 1 - \Phi(\ln[d/ ax^b]/ \beta_{D|Sa}) \tag{2}$$

in which $\Phi( )$ = standard normal distribution and a, b and $\beta_{D \mid Sa}$ are determined from the regression analysis described above. Equation (2) offers a convenient way to predict the conditional probability of exceeding stipulated drift limits and associated performance goals. Figure 7 presents these conditional probabilities (fragilities) for immediate occupancy, life safety and collapse prevention performance levels (drift limits of 1%, 2% and 3%, respectively [1]).
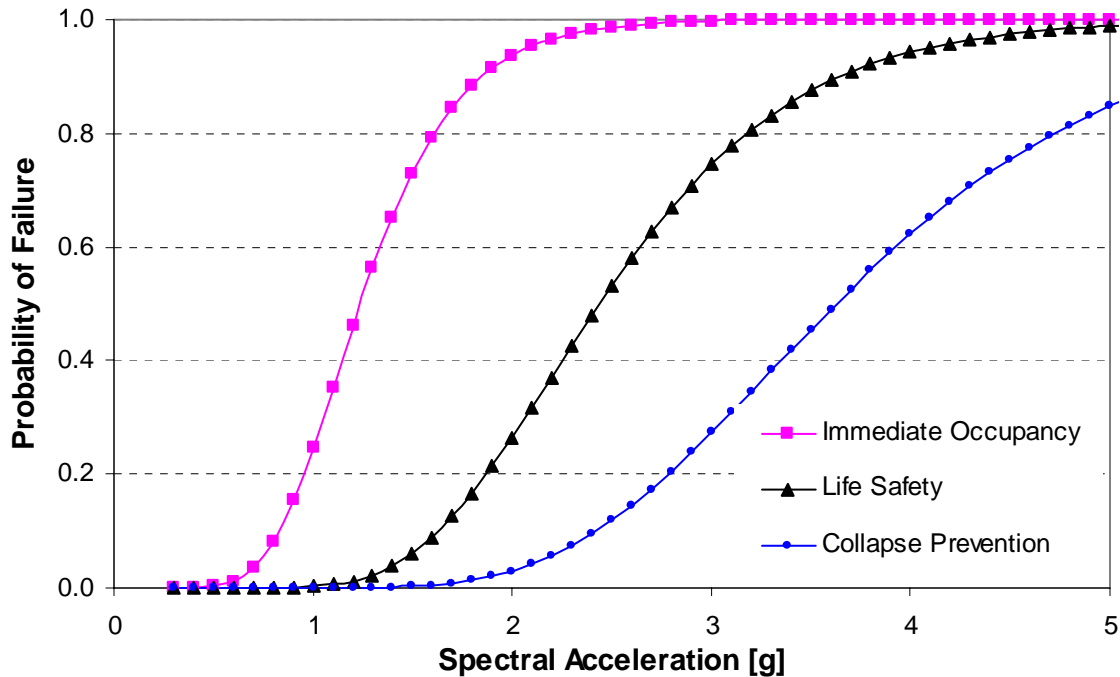
Figure 7. Conditional Probability of Failure (Fragility) of Shear Wall Model

For example, if the median spectral acceleration (at a period of 0.2 sec) associated with the design earthquake is 1.5 g, as might be typical in areas of southern California, the probabilities of impaired function, life-threatening damage and incipient collapse are, respectively, 72.9%, 6.1% and 0.2%. Such information can be used to evaluate the effectiveness of current building practices and to suggest cost-effective improvements to building codes.

CONCLUSIONS

This paper has presented a probabilistic methodology for assessing performance of wood frame residential construction subjected to seismic loading. It combines finite element-based analysis and stochastic modeling to predict the response of a typical lateral force-resisting shear wall subjected to earthquakes. The study predicts the probability that shear wall drift limits are exceeded for 2%, 10%, and 50% probability in 50 years level seismic hazards. The relationship between spectral acceleration and maximum drift as a simple tool for estimating seismic demand is discussed. This methodology can be used to predict the response of wood frame residential construction under various levels of seismic hazards, and to evaluate proposals for improving its performance when exposed to earthquake hazards.

ACKNOWLEDGEMENTS

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