IMPROVED FRAGILITY RELATIONSHIPS FOR POPULATIONS OF BUILDINGS BASED ON INELASTIC RESPONSE

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ABSTRACT :

In this paper, a new procedure for fragility analysis of populations of buildings is proposed. The procedure is divided into four components, namely (i) capacity of building; (ii) earthquake demand; (iii) structural assessment and (iv) fragility curve generation. Each of these elements is handled rigorously in order to arrive at reliable fragility relationships. The capacity of the building is represented using either analytically-derived or expert-opinion-based pushover curves. Earthquake demand is modeled by synthetically generated site specific ground motions for the Central and Eastern United States (CEUS). Structural assessment is carried out using an advanced Capacity Spectrum Method (CSM). Finally, fragility curves are presented in two different formats, conventional and HAZUS-compatible. The proposed procedure is applied to a wide range of buildings from construction classes of wood, steel, reinforced concrete, masonry and mobile homes. The uniformly derived fragility relationships are proposed as a reliable tool for earthquake impact assessment.

KEYWORDS: Fragility relationships, Earthquake loss estimation, Capacity Spectrum Method

1. INTRODUCTION

Inventory of a loss assessment study includes buildings from various construction materials, heights, aspect ratios, irregular features, and seismic design levels, amongst others. Although extensive literature is available on earthquake fragility curves of specific structures, the key requirement of uniformly-derived fragility relationships for populations of buildings, which is essential for reliable impact estimation, does not allow for the utilization of these curves in the literature. It is known that even a small modification in geometry or material properties can alter the overall response of a structure, therefore, when groups of buildings are considered, representation of the building capacity becomes a difficult task to achieve. It is impractical to design hundreds of structures for inelastic assessment and develop representative advanced models; moreover, the probabilistic nature of fragility analysis entails performing a large number of structural analyses, using a set of ground motions that is descriptive of the hazard, which further inhibits this option. In conclusion, a simple representation of building capacity which is at the same time reflective of the real behavior is needed. Variation in the ground motion constitutes the major portion of the total uncertainty in fragility analysis; hence, the selected representation method should be capable of capturing various features of earthquake process such as the site conditions, distance, depth and type of fault rupture in addition to the ground motion characteristics, particularly, frequency content, duration, time varying amplitude, and site conditions. Besides, each earthquake zone has peculiar attributes which justifies the use of site specific earthquake records that reflect the seismo-tectonic characteristics of the region. Accurate predictions of the displacement demand and the ability to accommodate large number analysis are the main requisites for the methodology for structural assessment. The developed fragility relationships are proposed to be used in earthquake loss assessment studies, thus, they should conform to the input requirements of the latter. In other words, the results of the fragility procedure should be provided such that they can be ingested by different loss assessment software.

Figure 1 is an illustration of the proposed procedure. Pushover curves and time histories form the capacity of building and earthquake demand, respectively. These first two components are inputs to the methodology for structural assessment. Statistical analysis of structural response data is performed under the component: methodology for fragility curve generation that provides the desired relationships. Limit states which are determined using the pushover curves are also utilized in this step.

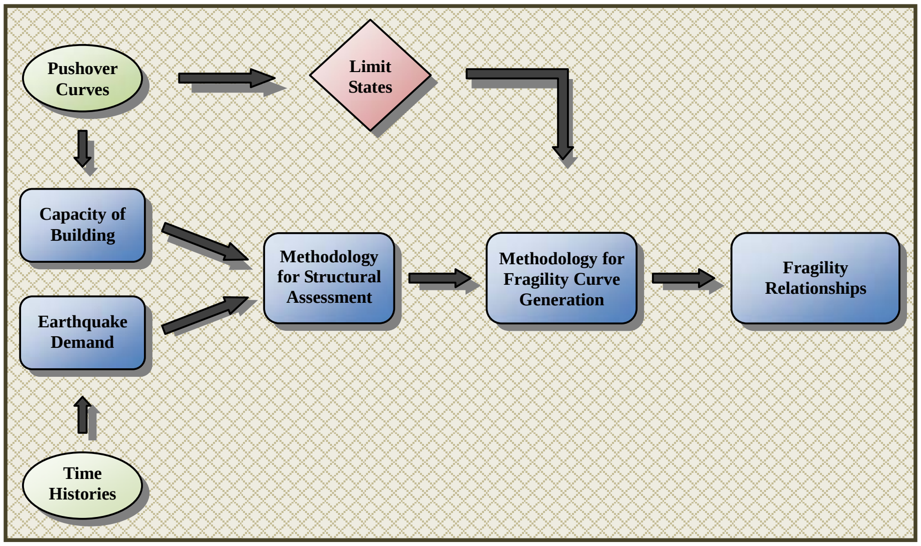

Figure 1 Flowchart for the proposed procedure of fragility analysis

The following sections elaborate on each of the four components of the proposed fragility procedure. Selective results as well as comparisons with other studies are also provided. For a full description of the procedure the reader is referred to Gencturk (2007).

2. CAPACITY OF BUILDING AND LIMIT STATES

Pushover curves show characteristic nonlinear force-deformation relationships for structures. They can accurately describe the lateral load resistance of buildings, which have limited amount of irregularity of mass and stiffness in plan and elevation, at the same time they are amenable to perform a large number of analyses. Pushover curves derived using analytical models are preferable whenever they are available; however, expert-opinion-based force-deformation relationships can also be employed due to lack of data. The presented procedure proposes the formation of a database of pushover curves for the building classes of interest, through which a reliable representation of the building capacity and the associated variability can be achieved. Gencturk et al. (2008) applied the fragility procedure presented in this paper to woodframe buildings by forming a database of pushover curves from the available literature. In this paper, definitions for building types in HAZUS (National Institute of Building Sciences, 2003) are adopted, and the default HAZUS pushover curves that comprise the construction classes of wood, steel, RC, masonry and mobile houses are employed for analyses.

The representation of the building capacity (pushover curves) in acceleration-displacement format is shown in Figure 2 (a). In order to represent the variability, as suggested by HAZUS manual, lognormal distribution is assumed for building capacity, and importance sampling technique is used to generate a set of pushover curves.

With regards to determination of limit-states associated with the objective performance levels, when simulation-based pushover curves are available, use of well known engineering criteria such as the yield and ultimate point definitions by Park (1988) is recommended. The associated limit states are employed for the HAZUS pushover curves used in this paper.

3. EARTHQUAKE DEMAND

When developing fragility relationships, a standardized code spectrum that is formed of distinct regions of constant spectral acceleration, velocity and displacement is often employed due to the simplicity that it provides. However, design spectra have inherent conservatism that may lead to biased results in fragility analysis and hence in the loss assessment study. In addition, this type of a representation falls short in characterizing the aforementioned features of earthquake processes. Due to these reasons, the proposed procedure uses acceleration time histories. By utilizing ground motions directly, better quantification of the variability in earthquake demand in terms of frequency content, duration, time varying amplitude, site conditions, amongst others can also be realized.

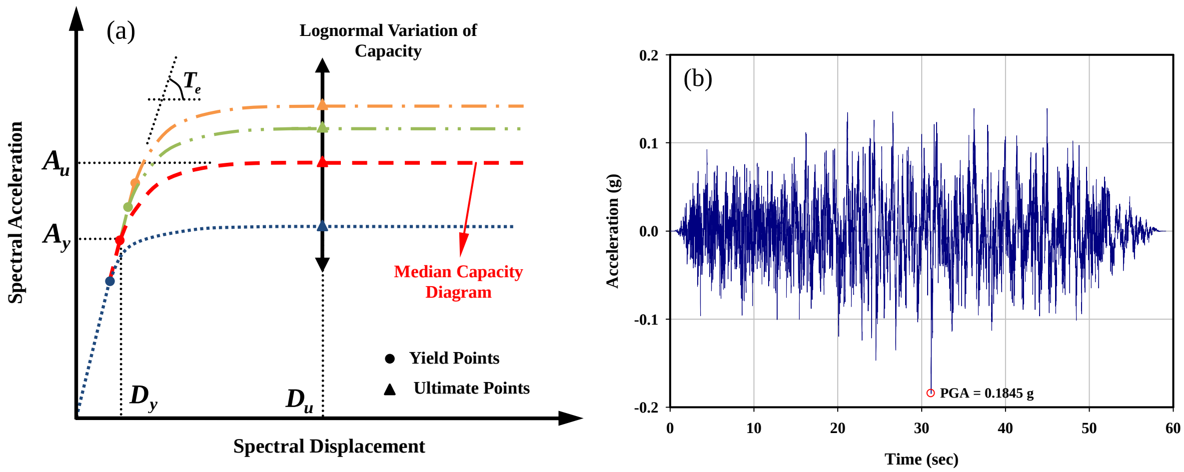

Figure 2 (a) Representation of the building capacity (b) Example accelerograms for lowlands soil profile

Each earthquake zone has its unique characteristics; thus, in order to represent the seismo-tectonic characteristics of the region of interest, site-specific ground motion records are used. Moreover, the aforementioned features of earthquakes can be accounted for with an appropriate selection of time histories.

Because CEUS is a low-probability earthquake region, the available natural records that correspond to a large magnitude event are sparse. Therefore, this study uses synthetically derived accelerograms (Fernandez, 2007) for two soil profiles: lowlands (soft soil) and uplands (rock sites), with a hazard level of 5% probability of exceedance in 50 years (975 years return period). An example accelerogram and the composite spectra for lowlands soil profile are shown in Figure 2 (b) and Figure 3 (a), respectively.

4. METHODOLOGY FOR STRUCTURAL ASSESSMENT

The methodology for structural assessment is of considerable importance inasmuch as it should yield an accurate prediction of displacement response of a structure under a given ground motion. On the grounds that pushover curves are employed in order to represent the building capacity, adoption of a procedure similar to CSM is required. CSM was first proposed by Freeman et al. (1975) which was followed by several improvements and revisions suggested by other researchers. In its simplest form, in CSM, displacement response is obtained as the intersection of structural capacity (pushover curves) and earthquake demand (spectra) in an acceleration-displacement (AD) representation.

Gencturk and Elnashai (2008) investigated the accuracy and applicability of existing variants of the CSM using experimental shake table test data of a woodframe structure. It is demonstrated that the existing CSM approaches exhibit several shortcomings including: failure to predict the displacement demand, incompatibility between the demand and capacity diagrams and non-convergence. An advanced CSM, incorporating inelastic response history analysis was proposed, and through application to the woodframe structure it was shown that the advanced method yields the least overall error amongst the considered approaches. The overcoming of deficiencies with the advanced method are due to the use of inelastic dynamic analysis that eliminates approximations and hence errors that are introduced into the solution by employing equivalent linear systems.

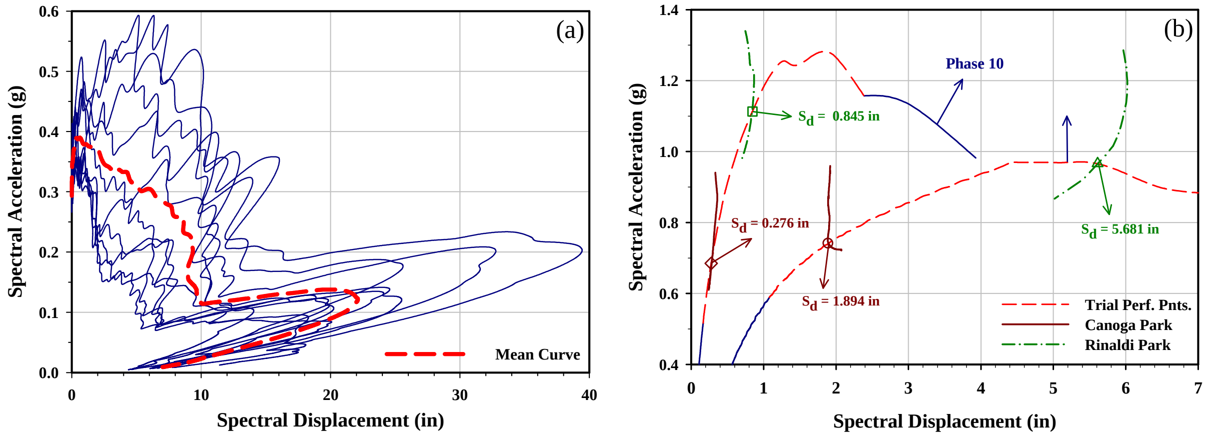

Figure 3 (a) Composite spectra for lowlands soil profile (b) Graphical results from the advanced CSM

The visualization of the iterative solution of the CSM in an AD representation is preserved in the advanced method. As a case in point, results obtained from the evaluation of the woodframe structure using the advanced method is provided in Figure 3 (b).

5. METHODOLOGY FOR FRAGILITY CURVE GENERATION

Fragility curve generation deals with the statistical analysis of the displacement response data obtained from the structural assessments.

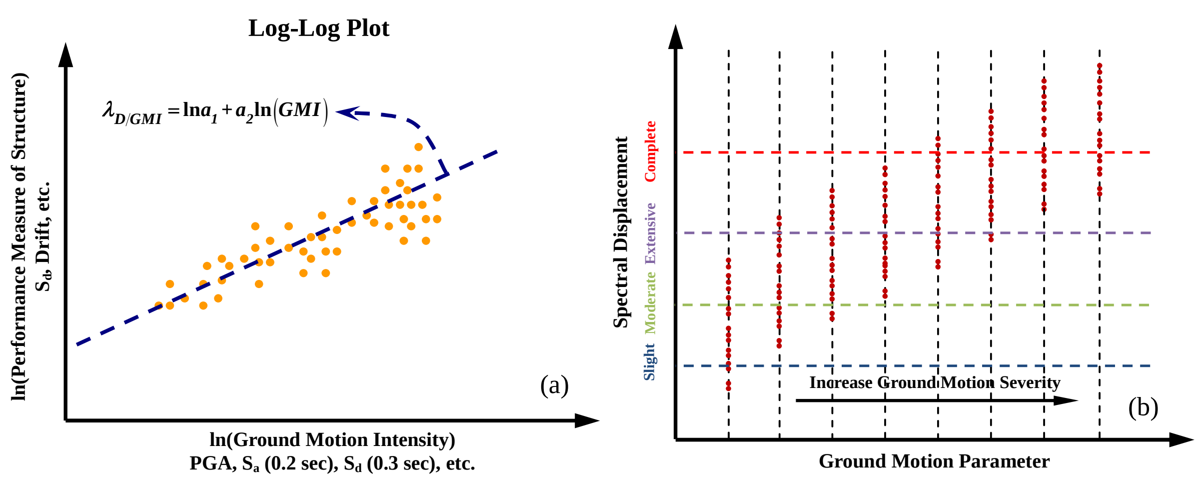

Figure 4 Illustrations for the derivation of (a) Conventional (b) HAZUS compatible fragility relationships

It is convenient to classify the structural earthquake fragility relationships into two categories. The commonly adopted approach is to directly associate the exceedance probabilities of certain performance levels with the ground motion parameters, e.g. peak ground acceleration (PGA), peak ground velocity (PGV). This first category herein is referred to as “conventional fragility relationships.” On the other hand, the widely used loss estimation software HAZUS prefers a description where the exceedance probabilities are related to structural response which is here called as “HAZUS compatible fragility relationships.” To clarify, in order to determine the probability of exceedance of certain damage metrics using HAZUS compatible fragility curves, one first needs to determine the structural response for a given ground motion. The proposed procedure allows for the derivation of fragility relationships in both formats that renders their use feasible in future impact assessment studies utilizing HAZUS or other software.

The methodology shown in Wen et al. (2004) is used for the derivation of conventional fragility relationships. The modeling and the combined uncertainty of capacity and demand as well as the uncertainty associated with the determination of limit state threshold values are accounted for in this formulation. As illustrated in Figure 4 (a), linear regression analysis is performed on the structural response data to determine the combined uncertainty of capacity and demand in addition to the constants that describe the equation which yields average structural response for a given Ground Motion Intensity (GMI).

In the formulation of HAZUS compatible fragility relationships, the only parameter that is needed to be determined is the combined uncertainty of capacity and demand. The so called "convolution process" (National Institute of Building Sciences, 2003) is used for this purpose. First, the structural response, spectral displacement in Figure 4 (b), is plotted against the ground motion parameter. Based on the histogram of data points at each level of GMI, the probability of reaching or exceeding each performance level is determined. The obtained probability values are plotted against the mean values of structural response at each increment of GMI with which the desired conversion from the "GMI – structural response" to "structural response – failure probability" is achieved. Similar to conventional fragility relationships, HAZUS compatible fragility relationships also account for the uncertainty associated with the determination of the limit state threshold values.

6. FRAGILITY RELATIONSHIPS

Figure 5 shows fragility relationships in conventional format for slight and complete damage limit states of pre-code and high code seismic design levels of W1 and W2 woodframe building classes, respectively. W1 corresponds to small, residential buildings, whereas W2 is delineated for large, commercial buildings. For the derivation of relationships designated as "Lowlands and Uplands" pushover curves from the assembled database are used while default expert-opinion-based HAZUS pushover curves are utilized within the developed procedure to obtain the "HAZUS Lowlands and HAZUS Uplands" curves. In general it is observed that the representation of building capacity has a significant effect on the fragility relationships and it is proposed that the use of simulation-based pushover curves along with the consistent limit states lead to more reliable fragility outcomes.

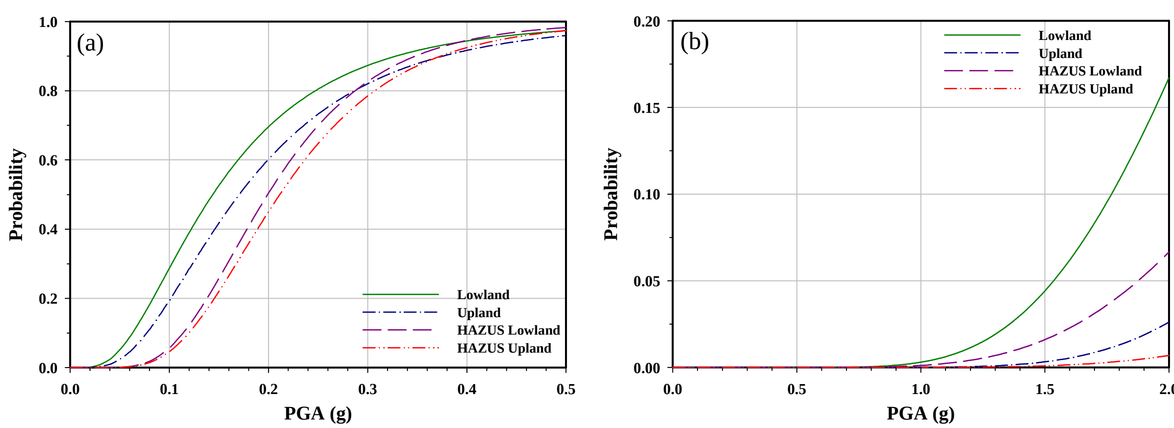

Figure 5 Fragility relationships for (a) W1 pre-code, slight damage (b) W2 high code, complete damage

Ellingwood et al. (2007) developed fragility relationships for a single storey woodframe house. Spectral acceleration is taken as the representative ground motion parameter and two limit states are considered:

Immediate Occupancy (IO) and Life Safety (LS). In Figure 6 (a) the fragility curves for W1 moderate code building category are compared with those by Ellingwood et al. (2007). IO performance level falls between the slight and moderate damage limit states considered in the procedure, and LS performance level approximately corresponds to extensive damage limit state, therefore a good agreement is observed between the results from the two studies.

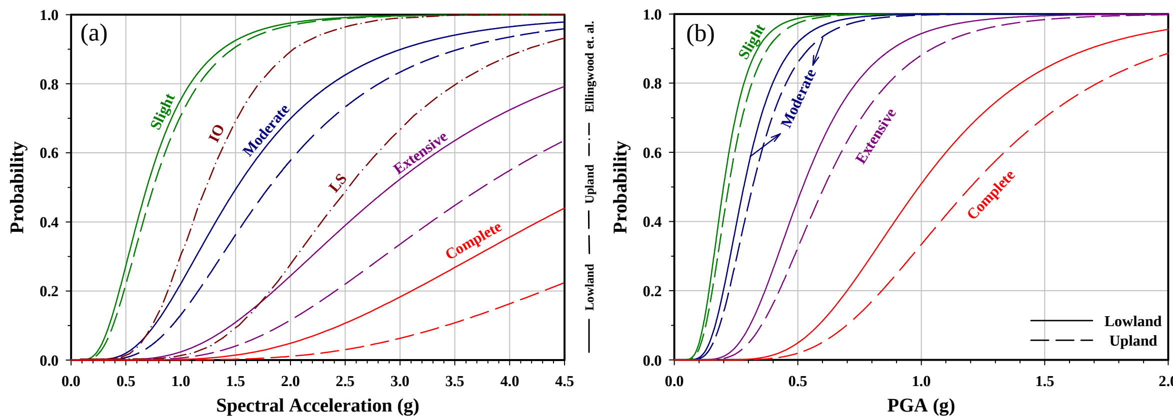

Figure 6 (a) Comparison with fragility relationships by Ellingwood et al. (b) Effect of soil profile

The effect of soil profile is demonstrated in Figure 6 (b) where conventional fragility relationships for moderate code seismic design level of S3 building group are shown. S3 comprises steel, single storey, light frame, pre-engineered and prefabricated structures. Ground motions recorded on soft soils are in general more demanding when compared to those from rock sites and this is manifested in the obtained fragility relationships as higher failure probabilities.

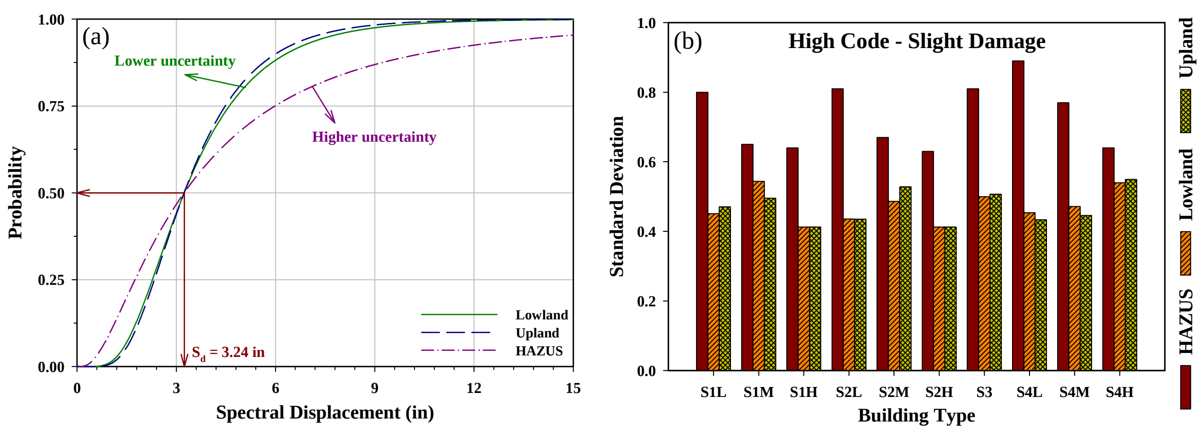

Figure 7 (a) HAZUS compatible fragility relationships (b) Effect on uncertainty parameter

In Figure 7 (a) the results from the proposed fragility procedure are compared with default HAZUS fragility curves for extensive damage limit state of S3 high code building category. Since the same pushover curves and limit states are used, the fragility curves are anchored to the same point that is 50% probability and the associated limit state threshold value. The only parameter that changes the shape of the curves is the standard deviation parameter that describes the total uncertainty. It is observed that a significantly higher uncertainty is incorporated in the default HAZUS curves. The standard deviation values are compared in a bar chart in Figure 7 (b) for high code seismic design level of a range of steel building groups and slight damage limit state. Although lowlands and uplands soil profile yield similar uncertainty estimates, as previously stated, HAZUS curves exhibit significantly higher uncertainty. For the sake of brevity other cases are omitted here, however, the latter observation applies to other building types as well as seismic design and performance levels. Selection of higher standard deviation values for expert-opinion-based HAZUS curves can be attributed to the goal of rendering these fragility relationships suitable for use in loss assessment studies throughout the United States. On the other hand, as demonstrated, the proposed procedure allows derivation of more reliable fragility relationships having lower level of uncertainty by using a set of selected site-specific ground motion records.

7. CONCLUSIONS

This paper outlines a new procedure that can derive fragility relationships for populations of buildings in a consistent manner. Rigorous formulations are proposed for each component of the procedure, i.e. (i) capacity of building, (ii) earthquake demand, (iii) structural assessment, and (iv) fragility curve generation, while preserving the simplicity of formulation to facilitate a large number of analyses. Selected examples from the application to a wide range of building classes are also provided. The procedure is generic and is therefore applicable to any type of structure (or groups of structures) the earthquake response of which can be characterized by a pushover curve. The new procedure also allows for the use of acceleration time histories through which the characteristics of region-specific earthquake records would be reflected in the fragility relationships. The realism of structural assessment is enhanced by utilizing an advanced capacity spectrum method developed by the authors. The fragility relationships are given in two different formats in order to avail of their use in different loss assessment software. By virtue of its improved accuracy and uniform reliability, the fragility relationships resulting from the proposal given in this paper are recommended for use in impact assessment studies on a regional basis.

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REFERENCES

Ellingwood, B. R., D. Rosowsky and W. Pang (2007). Performance of Light-Frame Wood Residential Construction Subjected to Earthquake in Regions of Moderate Seismicity. *ASCE Journal of Structural Engineering*, (in press).

Fernandez, A. (2007). Numerical Simulation of Earthquake Ground Motions in the Upper Mississippi Embayment. School of Civil and Environmental Engineering. Georgia Institute of Technology. Atlanta, GA. **PhD Thesis**.

Freeman, S. A., J. P. Nicoletti and J. V. Tyrell (1975). Evaluations of Existing Buildings for Seismic Risk - A Case Study of Puget Sound Naval Shipyard, Bremerton, Washington. *1st U. S. National Conference on Earthquake Engineering*, Berkeley, EERI, 113-122.

Gencturk, B. (2007). Improved Fragility Relationships for Populations of Buildings Based on Inelastic Response. Department of Civil and Environmental Engineering. University of Illinois at Urbana-Champaign.

Urbana, IL. **MS Thesis**.

Gencturk, B. and A. S. Elnashai (2008). Development and Application of an Advanced Capacity Spectrum Method. *Engineering Structures*, **doi:10.1016/j.engstruct.2008.05.008** (in press).

Gencturk, B., A. S. Elnashai and J. Song (2008). Fragility Relationships for Populations of Woodframe Structures Based on Inelastic Response. *Journal of Earthquake Engineering* **12**(1 supp 2), 119 - 128.

National Institute of Building Sciences, N. (2003). Multi-Hazard Loss Estimation Methodology, Earthquake Model. Washington, D.C., Federal Emergency Management Agency (FEMA). **Technical and User's Manual**.

Park, R. (1988). Ductility Evaluation from Laboratory and Analytical Testing. *9th World Conference on Earthquake Engineering*, Tokyo-Kyoto, Japan. **VIII**, 605-616.

Wen, Y. K., B. R. Ellingwood and J. M. Bracci (2004). Vulnerability Functions. **Project FD-2 Report**. Mid-America Earthquake (MAE) Center. Urbana, IL.