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Quantifying and communicating uncertainty in seismic risk assessment

Bruce R. Ellingwood
School of Civil and Environmental Engineering
Georgia Institute of Technology/790 Atlantic Drive/Atlanta, GA 30332-0355 USA

Abstract

Modern seismic risk assessment strives to support risk mitigation by providing insight into the performance of civil infrastructure, including buildings, bridges and transportation and utility systems, subjected to severe earthquake ground motions. A fully-coupled seismic risk or safety assessment of a structural system, and its accompanying analysis of uncertainty, provides estimates of the annual probability of exceeding pre-defined performance levels, defined either in terms of structural responses or more qualitatively defined damage states. This paper reviews uncertainty modeling concepts and illustrates how uncertainties are propagated through a seismic risk assessment of steel frame building structures that are typical of regions of low-to-moderate seismicity in the Central and Eastern United States. All sources of uncertainty, both inherent and knowledge-based, should be included in risk assessment; however, the manner in which they are displayed depends on the preferences of the stakeholders and decision-makers.

1. Introduction

The earthquake hazard is paramount among the natural hazards impacting civil infrastructure in the United States. The impacts of major earthquakes in recent times have provided the impetus for significant advances in engineering practices for earthquake-resistant design of buildings, bridges, lifelines and other civil infrastructure. In the presence of uncertainties, risk to civil infrastructure from earthquakes cannot be eliminated, but must be managed in the public interest by engineers, code-writers and other regulatory authorities. Structural reliability concepts and probabilistic risk analysis tools provide an essential framework to model uncertainties associated with earthquake prediction and infrastructure response and to trade off potential investments in infrastructure risk reduction against limited resources available for this purpose.

Much of the research to date on the performance of civil infrastructure during and after earthquakes has concentrated on areas exposed to high seismic hazard. However, the earthquake hazard in certain regions of the Central and Eastern United States (CEUS) is non-negligible when viewed on a competing risk basis with other extreme natural phenomena hazards. Building design, regulatory practices, and social attitudes toward earthquake risk differ in these areas, where civil infrastructure generally is not designed to withstand ground motions of the magnitude that modern seismology indicates are possible or probable. As a result, risks to affected communities (measured in terms of economic or social consequences) may be far more severe than commonly has been believed. Communicating these risks effectively to decision-makers with the authority or financial resources to address them effectively is difficult because of their lack of familiarity with earthquake hazards.

The state of the art in uncertainty modeling and risk analysis now has advanced to the point where integrated approaches to earthquake hazard analysis, performance evaluation for civil infrastructure, and seismic risk management are feasible. Consequence-based risk management (CBRM) – a framework to enable the effects of uncertainties and benefits of alternate seismic risk mitigation strategies to be assessed in terms of their impact on the performance of the built environment and on the affected population - is the unifying principle for research being conducted by the National Science Foundation-supported Mid-America Earthquake Center at the University of Illinois at Urbana-Champaign. This paper reviews some recent uncertainty modeling and risk-based decision tools that have been developed as part of CBRM for a spectrum of stakeholders with different backgrounds and talents – architects, engineers, urban planners, insurance underwriters, and local regulatory agencies – and identifies some of the research issues that must be addressed to make further advances toward risk-informed decision-making for civil infrastructure. The concepts are illustrated with an application to steel frames typical of building practices in an area of the CEUS that is at risk from large but infrequent earthquakes in the New Madrid Seismic Zone (NMSZ).

2. Framework for risk-informed decision-making

The term "risk" is often used interchangeably with "probability" when confronting a potentially hazardous situation; certainly, the notion of relative likelihood (expressed as probability or annual frequency) is essential to understanding risk in the everyday sense. However, the annual frequencies of earthquakes that pose a substantial threat to civil infrastructure are very small, making it difficult to communicate risks to stakeholders and decision-makers because there is little information against which the risks can be benchmarked. On the other hand, most risk analyses of civil infrastructure require an estimate of the limit state probability at some stage. Accordingly, in this paper, we focus on the limit state probability as the risk metric, with the understanding that the consequences (deaths or injuries, direct economic loss, or opportunity losses) often are most important in risk management.

The limit state probability in seismic risk assessment is defined as:

$$P_{LS} = \Sigma_x P[LS \,|Q = x] \;\; P[Q = x] \qquad (1)$$

in which Q defines the intensity of the seismic demand on the system (in recent years, the intensity often is expressed as a spectral acceleration or displacement) and LS = limit state, defined in terms of random variables that describe the capacity of the system. Equation (1) often is written in a form involving mean occurrence rates, under the assumption that the occurrence of significant earthquakes can be described by a Poisson process. Either way, Eq. (1) delineates the two essential ingredients of seismic risk assessment along disciplinary lines: the seismic hazard, P[Q = x] (seismology) and the fragility P[LS|Q = x] (structural engineering). The extension of Eq. (1) from summation to integration in the case of a continuously defined rather than discrete hazard is obvious. Damage state probabilities (with damage states being defined by terms such as "minor, moderate, severe," are the basis for estimating economic losses (Porter, et al, 2001; Wen, et al, 2003; Ellingwood and Wen, 2005), and can be developed from the limit state probabilities, once they are known. In much of the literature on seismic risk, a direct mapping between limit states and damage states is presumed (e.g., "severe" damage in steel frames may be implied by maximum inter-story drifts between, say, 0.02 and 0.05).

2.1 Modeling, analysis and display of uncertainties

Understanding and quantification of various sources of uncertainty are essential to develop the probabilistic models of behaviour needed for seismic risk assessment. All sources of uncertainty – both aleatoric and epistemic - must be considered in the risk assessment process. The modeling and evaluation of low-probability, high-consequence natural events involve significant uncertainties arising from imperfect scientific and engineering modeling, simplifications, and limited databases. Accordingly, epistemic uncertainties play a significant role in any seismic risk assessment, especially when applied to civil infrastructure in regions of low-to-moderate seismicity, such as the CEUS. In contrast to aleatoric uncertainties, which are essentially irreducible at the customary scales of engineering analysis, epistemic uncertainties generally can be reduced, at the expense of more comprehensive (and costly) analysis. Deciding whether to invest in additional data or more complex modeling in the hope of improving the estimate of risk is an important ingredient of risk-informed decision-making.

Useful results for risk-informed decision-making can be obtained by prescribing, *a priori*, probabilistic models of aleatoric uncertainty from reasonable physical arguments, supported to the extent possible by the available databases. Modern seismic risk analysis, beginning with the paper by Cornell (1968) and supported by later studies, has indicated that earthquake ground motion intensity (measured by peak ground motion or spectral ordinates) can be represented by the Cauchy-Pareto family of distributions. Similarly, a number of seismic fragility studies of buildings and bridges conducted during the past decade (Ellingwood, 1990; Singhal and Kiremidjian, 1996; Song and Ellingwood, 1999; Shinozuka et al., 2000; Wen and Ellingwood, 2005) have confirmed that the fragility term in Eqs (1) and (2) can be modeled by a lognormal distribution. Using these normative models, the risk analyst then can concentrate on the necessary information-gathering to define the descriptive parameters of these models and on methods for communicating the risk so determined.

With the normative selection of the distributions to model the uncertainties in demand and capacity, the fragility, $F_R(x)$ and the hazard, or probability that ground motion intensity exceeds x, H(x), become:

$$F_R(x) = P[LS\,|Q = x] = \Phi[(\ln x - \ln m_R)/\beta_R] \tag{2}$$

$$H(x) = 1 - \exp[-(x/k_o)^{-k}] \approx k_o x^{-k} \tag{3}$$

in which $\Phi[\ ]$ = standard normal probability integral and the fragility parameters, m_R and β_R, define the median capacity and logarithmic standard deviation in capacity; k_o = characteristic extreme, and k = shape parameter. The seismic hazard curves are provided by the US Geological Survey[1]. Substitution into Eq. (1) and numerically integrating leads to a point estimate or P_{LS}. The approximation in Eq. (2) is achieved by recognizing that only a small range of x in the integrand of Eq. (1) contributes significantly to P_{LS} [2]. Using this approximation,

$$P_{LS} \approx (k_o m_R^{-k}) \exp[(k\,\beta_R)^2/2] \tag{4}$$

With re-arrangement to express the demand and capacity in terms of inter-story drift, Eq. (4) is the basis of the capacity-demand factor design and assessment method developed in the SAC/FEMA project on steel buildings (Cornell, et al, 2002). Equation (4) also is the basis for a proposed new approach to seismic design in *ASCE Standard 43-05* (ASCE, 2005) for nuclear facilities based on uniform risk rather than uniform hazard.

2.2 Point vs interval estimates of risk (probability)

Equations (2) – (4) describe the hazard, fragility and limit state (or damage state) probability of the system when the state of knowledge is essentially perfect, at least within the bounds of normal seismology and structural engineering, and provide a point estimate of P_{LS}. In many decision contexts, this point estimate may be sufficient. Additional sources of uncertainty in capacity and demand arise from assumptions and approximations made in specifying the hazard, modeling the strength and stiffness of structural

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[1] http://earthquake.usgs.gov/hazmaps/products_data/2002/ceus2002.html
[2] Plots of mean seismic hazard provided by the USGS show that the seismic hazard curve is slightly concave downward when plotted on a log-log plot. The linearization of H(x) over the range contributing to the summation (integral) in Eq. (1) often is an acceptable approximation.

materials and components, and modeling the structural system by finite element methods, as well as from imitations in the supporting databases (Ellingwood, 2001). For example, it is generally understood that the seismic hazard curves provided by the USGS represent the *mean* seismic hazard, inasmuch as the values represent an average of values obtained from several alternate plausible ground motion models. Similarly, sources of epistemic uncertainty in the estimation of response of steel structures include two-dimensional models of three-dimensional structures, structural models based on beam and column centerline dimensions that neglect beam-column panel zones, support conditions and connections that are neither fully rigid nor simple, and granularity of finite element modeling.

The presence of epistemic uncertainty in seismic risk assessment implies that the hazard and fragility curves in Eqs. (2) and (3) are themselves random, reflecting incomplete knowledge regarding the distributions and parameters used to model the aleatoric uncertainty. Thus, one might view the hazard and fragility as being modeled by *families* of distributions, leading to an epistemic uncertainty in the limit state probability determined from Eqs. (1) or (4) that is described by a frequency distribution. If the epistemic uncertainty in the risk assessment is small, the distribution is centered on the point estimate P_{LS} and its frequency distribution is narrow; conversely, if the epistemic uncertainties are large, the frequency distribution of P_{LS} is broad. One can, of course, compute a mean value of this frequency distribution using customary analysis; that this mean value is the "best" point estimate of P_{LS}, if one is required, is supported by other decision-theoretic considerations and now is accepted in the nuclear industry[3]. While the mean (or other point estimate) of P_{LS} is an unambiguous metric of risk, and is a natural choice in performing minimum expected cost (or loss) analyses, it does not convey a sense of the confidence that the analyst has in the risk assessment. Two alternative analyses, one made with limited data and a second made with comprehensive effort, would lead to the same P_{LS} if the estimates of the aleatoric uncertainties were the same. Many decision-makers find this unacceptable; one way to address it is through an interval estimate of P_{LS}. Point and interval estimates of limit state probabilities of steel frames typical of building practices in the CEUS will be illustrated subsequently.

3. Risk assessment of steel moment frames

3.1 Description of Frames

Two professionally designed steel frames that are typical of construction in urban areas of the Eastern United States that are exposed to moderate seismic hazards are considered. These frames are illustrated in Figures 1 and 2. The frame in Figure 1 is the "Pre-Northridge" frame for Boston, MA that was designed as part of the recently completed SAC Project a consulting structural engineering firm using the *National Building Code, 1993 Edition*. The finite element model of this frame accounted for the beam-column panel zone, and both material and geometric nonlinearities (P-Δ effects) were included in the assessment. The fundamental period of the frame is T_1 = 2.0 s; the first mode is approximately linear and its participation factor is 84%[4]. The frame in Figure 2 is a braced frame designed for Memphis, TN using the *Standard Building Code, 1991 Edition*. The fundamental period of this frame is T_1 = 1.04 s, and the first-mode participation factor is 73%. The lateral stiffness of this frame is provided by the diagonal braces; the finite element model included an element that accounted for buckling in the diagonal braces under reversals of inelastic deformation.

3.2 Fragility Modeling of Steel Frames

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[3] In early seismic PRA and margin studies of nuclear plants conducted in the 1980's, the aleatoric and epistemic uncertainties were tracked and propagated through the risk analysis separately. In recent years, however, the NRC has adopted the mean value as basis for risk-informed decision-making.
[4] It is possible to model cracking or deterioration in the connections (Song and Ellingwood, 1999), but this was not done in the analysis presented herein.

The seismic fragilities are developed through a simulation process involving nonlinear time history analysis (NTHA) of frame response to ground motion. The ground motion ensembles are characterized in terms of seismic intensity by the 5% damped spectral acceleration, S_a, at the fundamental period of the frame. The seismic demand on the frames is measured in terms of maximum inter-story drift[5] since the performance limit states (structural system capacity) also are measured in terms of inter-story drift. Unlike the Western United States, there are few ground motion records available for the CEUS. Accordingly, the ground motions used in this study were generated as part of MAE Center research (Wen and Wu, 2001) for three sites in Mid-America: Memphis, TN, Carbondale, IL, and St. Louis, MO (believed to represent a cross-section of earthquake-prone sites in the central United States) and by Rix and Fernandez for Memphis, TN (private communication). Ensembles of 10 ground motions corresponding to probabilities of 2% and 10% of being exceeded in 50 years (abbreviated 2%/50yr and 10%/50yr)) were generated for soft soil conditions at these sites. The responses of the frames to earthquake ground motions were determined using OpenSees, an open-source computational platform being developed and maintained at the University of California at Berkeley (Mazzoni, et al, 2005). In the present study, the yield strength, ultimate strength, and modulus of elasticity of the steel were set equal to their respective mean values, since it has been found that the overall response variability is dictated mainly by the seismic demand.

For frames such as those in Figures 1 and 2, the uncertainty in seismic demand on a structural system can be characterized through a relation between the maximum inter-story drift, θ_{max}, and the spectral acceleration at the fundamental period of the building, S_a (Shome, et al, 1998):

$$\theta_{max} = a\, S_a^{\,b}\, \varepsilon \qquad (5)$$

in which *a* and *b* are model constants and ε is a random variable (with median unity) that describes the uncertainty (standard error) in the relationship. Estimates of these constants and the standard error can be determined by performing nonlinear dynamic analyses of the building frame using an appropriate ensemble of ground motions and performing a linear regression analysis of $\ln\theta_{max}$ on $\ln S_a$ to determine constants *a*, *b* and the standard error, $\sigma_{\ln\varepsilon}$. The results of this analysis are presented in Figure 3 for the three-story rigid moment frame. The seismic demand parameters are $a = 0.092$, $b = 0.78$ and $\sigma_{\ln\varepsilon} = 0.25$. Similar results are presented in Figure 4 for the six-story braced frame. Here, the median seismic demand is defined by parameters $a = 0.034$, $b = 0.98$, with standard error $\sigma_{\ln\varepsilon} = 0.26$. The Shome, et al (1998) study cited above, which utilized only natural records, as well as the current study, indicated that the median relation between deformation and S_a was relatively insensitive to the ensemble selected, provided that accelerograms were selected from events of similar magnitude and distance and no directivity (near-field) effects were reflected in the records. Thus, one might conclude that the parameters *a* and *b* in Eq. (5) are characteristic of a particular building but are not strongly dependent on the ensemble selected for its determination.

The seismic fragilities reflective of the aleatoric uncertainties can be obtained on the basis of the seismic demand relationships. Substituting Eq. (5) into Eq. (2),

$$P[LS|S_a = x] \;=\; 1 - \Phi[\,\ln (m_C/ax^b) \,/\, (\beta^2_{\,C} + \beta^2_{\,D|Sa})^{1/2}] \qquad (6)$$

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[5] Several metrics have been proposed as a means to measure the response of a structural system in the nonlinear range through one parameter. Inter-story drift is the most common of such metrics, and has been correlated (albeit subjectively) to performance levels and damage states in FEMA 356, HAZUS, and other documents dealing with seismic risk mitigation.

in which demand variability $\beta_{D|Sa} = \sigma_{\ln\varepsilon}$ and the "capacity" terms m_C and β_C depend on the performance level of interest. Analogous to FEMA 356, three levels are considered - Immediate Occupancy (IO), Life Safety[6] and Collapse Prevention (CP) – each of which is related to inter-story drift.[7] IO is associated with the limit of elastic behaviour (inter-story drifts typically 0.005 – 0.01) and CP with the point of instability determined from an incremental dynamic analysis (Vamvatsikos and Cornell, 2002), approximately 8% for the three-story frame and 5% for the braced frame. The drift defining the intermediate Structural Damage (SD) state is in the range 0.015 – 0.2, the lower value being for the braced frame (Kinali and Ellingwood, 2007), a drift at which moderate to severe structural damage may be expected to occur. The logarithmic standard deviation, β_C, reflects the uncertainty associated with the above-defined drift limits as measures of capacity, and is set equal to 0.25. The seismic fragilities for the IO, SD and CP performance levels are illustrated in Figure 5 for the braced frame. With a 2%/50yr spectral acceleration at 1 s of 0.35g on soft soil at Memphis, TN, this gravity-designed frame has a relatively high probability of sustaining damage but a substantial reserve capacity against collapse. These fragilities are useful in delineating damage states conditionally; for example, the difference between IO and SD might be categorized as "moderate," while the difference between SD and CP "severe." A local code official likely would find probabilities of moderate and severe damage of 56% and 44%, respectively, under a 2%/50yr event easier to grasp than an annual damage probability on the order of 10^{-4}.

4. Point and interval estimates of annual damage state probabilities

Point estimates of risk (measured in terms of annual probability of IO, SD or IC) is obtained by convolving the fragility in Eq. (6) with the (mean) seismic hazard for Memphis, TN, obtained from the USGS website, defined by $H(x) = 1.48 \times 10^{-4}\,(x)^{-1.0}$. For inter-story drift limits in the six-story braced frame of 0.004, 0.013 and 0.05 for IO, SD and CP, the point estimates of P_{IO}, P_{SD} and P_{CP} are, respectively, 1.5×10^{-3}/yr, 4.4×10^{-4}/yr and 1.1×10^{-4}/yr.

When epistemic uncertainties are considered in seismic risk analyses, it is customary to vest them in the estimates of the first-order statistics (here, median capacity, m_R, and characteristic extreme, k_o)[8]. Under this assumption, m_R and k_o are replaced by (Bayesian) random variables, M_R and K_o, which are assumed to be modeled by lognormal distributions with medians m_R and m_{ko} and logarithmic standard deviations, β_{RU} and β_{HU}. The limit state probability in Eq. (4) then becomes a random function of M_R and K_o, e.g.,

$$P_{SD} \approx (K_o M_R^{-k})\, \exp\,[(k\,\beta_R)^2/2] \qquad (7)$$

in which $\beta_R = (\beta^2{}_C + \beta^2{}_{D|Sa})^{1/2}$, with an associated frequency distribution which can be determined numerically.

The descriptions of M_R and K_o must be encoded by judgment in the absence of supporting databases. For example, one might assume that with current nonlinear finite element software and limitations in supporting databases, M_R can be estimated to with ±30% accuracy with 90% confidence. This implies that M_R is unbiased and its COV, β_{RU}, is approximately 0.20. Similarly, the ratio of 85th to 15th percentiles of

[6] Life safety is difficult to define in terms of structural response, because it depends on the performance of nonstructural as well as structural components. Accordingly, the intermediate performance level is stipulated as Structural Damage (SD) in this paper.
[7] The mapping between inter-story drift (or other structural demand parameter) and the performance level (or damage state) is an area where more research is required (Ellingwood, 2001). At the present state of the art, the mapping is subjective, and there is considerable uncertainty associated with it.
[8] Unpublished studies have shown that the contribution of uncertainty in the second-order terms is of lesser importance.

seismic hazard curves postulated by seismic experts at sites in the CEUS is typically on the order of 3[9], implying that β_{HU} is approximately 0.50. The frequency distribution of P_{SD} is illustrated in Figure 6. In this illustration, the median and mean damage state probabilities are 3.8 x 10^{-4}/year and 4.4 x 10^{-4}/year, respectively, and are close to the point estimate. Of equal interest to the decision-maker is the uncertainty or confidence in these risk estimates, which might be stated as: "The structural damage probability is between 1.3 and 11.0 x 10^{-4}/yr with 95% confidence. Recent experience[10] has revealed that many decision-makers would like to see such a statement of confidence accompany a risk estimate, particularly when the probabilities are very small.

5. Closure

Seismic risk analysis tools can be used to test the viability of proposed code provisions, to assess the need for upgrading an existing facility when new information suggests that the original design conditions may not have been sufficient, and to plan for structural maintenance or rehabilitation and repair following the occurrence of an earthquake. Setting target probabilities is problematic; the experience base used for benchmarking probability-based limit states design is much more limited. Many decision-makers who control investment resources for risk management are not expert in seismic risk assessment, and their needs (and the context of the decision process) must be taken into account. An integrated approach provides project stakeholders with a structured framework for thinking about uncertainty and how public safety and economic well-being may be threatened by the failure of civil infrastructure to perform under a spectrum of seismic events. The benefits of such an approach are an improved ability to assess the effectiveness of various risk mitigation strategies in terms of risk reduction per dollar invested, and better allocations of public and private resources for managing risk.

Acknowledgement

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[9] The author's experience with seismic PRAs of nuclear power plants in the US indicates that this ratio is typical. at return periods of relevance in civil infrastructure risk assessment (200 – 5,000 years).
[10] Stakeholder workshops held in connection with the ATC Project 58, "Guidelines for seismic performance assessment of buildings" have conveyed this message clearly.

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Figure 1. *Floor plan and elevation view of 3-story rigid moment frame.*

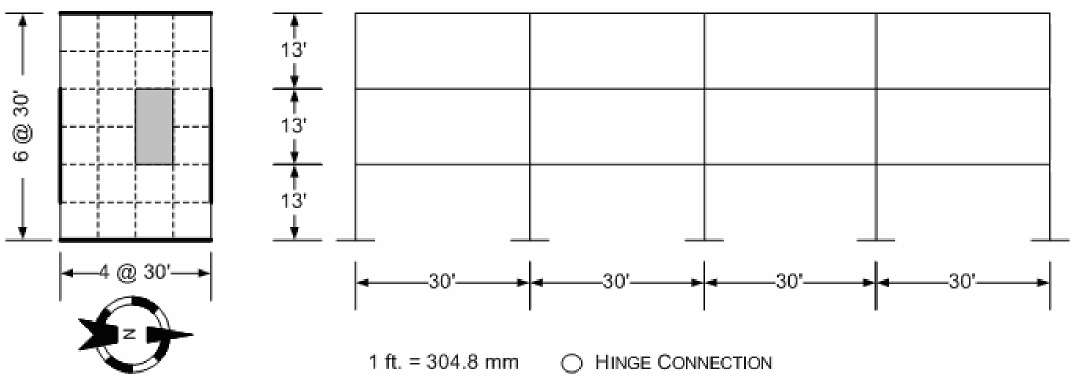

Figure 2. *Elevation view of 6-story braced frame.*

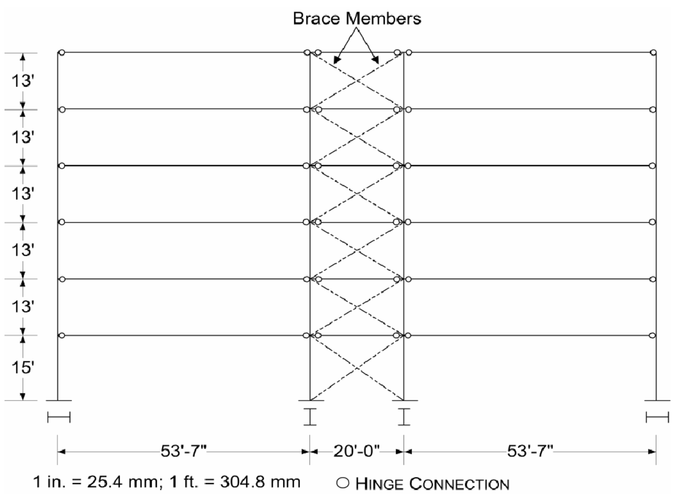

Figure 3 *Seismic demand on 3-story rigid moment frame from NTHA (Wen-Wu 2%/50 yr GMs).*

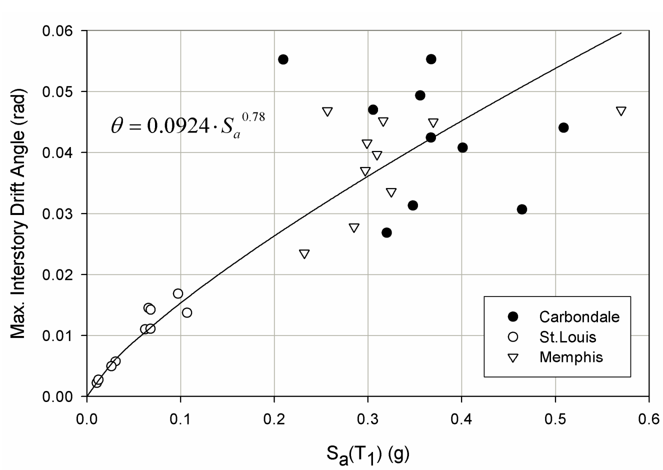

Figure 4. *Seismic demand on 6-story braced frame from NTHA.*

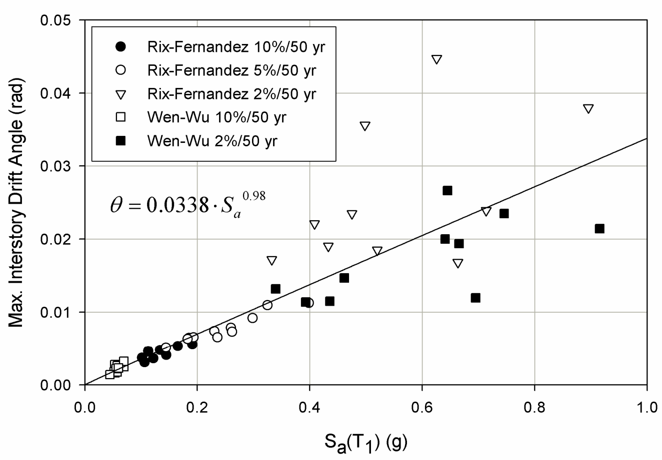

***Figure 5.** Seismic fragilities for the braced frame.*

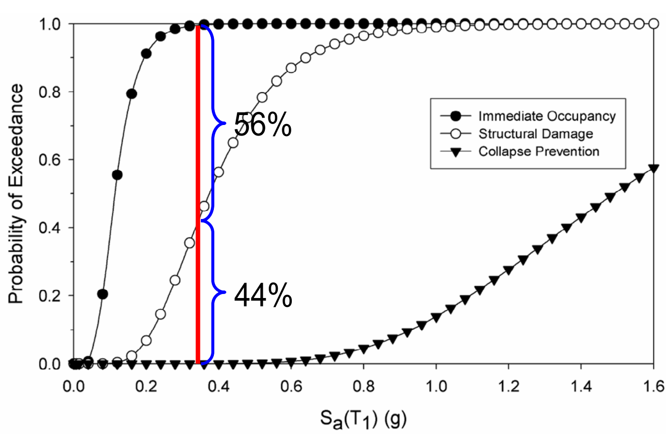

***Figure 6.** Frequency distribution of probability of structural damage showing the effect of epistemic uncertainty in fragility and hazard modeling.*