Global Vulnerability Estimation Methods for the Global Earthquake Model

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SUMMARY:
There is a rich literature of seismic vulnerability and fragility functions, only exceeded by the vast need for more. "Seismic vulnerability function" refers here to a probabilistic relationship between seismic excitation (e.g., shaking intensity) and loss (e.g., repair cost) for a particular asset (e.g., a building) or asset class (e.g., a category of buildings). By "seismic fragility function" is meant here a relationship between seismic excitation and the probability of reaching or exceeding some limit state such as collapse. An international, multi-institutional project is developing guidelines to derive vulnerability and fragility functions empirically, analytically, and by expert judgment, and to update existing functions as new information becomes available. We are also creating new vulnerability and fragility functions to illustrate the guidelines, developing new relationships between collapse and fatality rate, and proposing guidelines to rate functions in several quality dimensions. The work is sponsored by the Global Earthquake Model.

Keywords: Global Earthquake Model, vulnerability, fragility

1. OBJECTIVES OF THE GEM VULNERABILITY CONSORTIUM

Part of the effort of the Global Earthquake Model (www.globalquakemodel.org) is to compile a library of seismic vulnerability relationships and standard guidelines for creating new ones. By "seismic vulnerability relationships" is meant here repair costs, casualty rates, and probabilities of exceeding important damage states, as functions of ground-motion intensity, often conditioned on building category. These will be used in the broader context of estimating and manage seismic risk anywhere in the world. The GEM Vulnerability Consortium (GVC), led by the authors with assistance from representatives of EERI, the Catholic University of Chile at Santiago, Geoscience Australia, Willis Ltd, and many others, has undertaken this task on behalf of GEM. This manuscript summarizes the objectives, schedule, and expected products of the GVC's project. It briefly summarizes the state of the art as we understand it, and how we are advancing that art.

The GVC effort has 5 general thrust areas: empirical vulnerability functions (led by University College London), analytical vulnerability functions (University of Bath), expert-opinion vulnerability functions, empirical-national vulnerability functions (both led by the US Geological Survey in Golden), and casualty modelling (by So, previously with the USGS). University of Colorado is coordinating GVC and leading efforts to deal with nonstructural vulnerability. In addition to its 5 thrust areas, GVC is supported by a team (Stanford) focusing on the proper treatment of uncertainty and on methods for performing Bayesian updating of existing vulnerability functions with new empirical information.

The work began in 2011 and will conclude in 2013. Each team spent 2011 and much of 2012 accumulating existing vulnerability information or other literature appropriate to its scope, and preparing guidelines for future development of new vulnerability functions. The remainder of 2012 and part of 2013 will be spent implementing, testing, and revising the guidelines. Part of 2012 and balance of 2013 are intended for outreach: delivering guidelines and vulnerability functions to regional efforts worldwide and assisting them to implement the guidelines for themselves.

2. THREE APPROACHES TO ESTIMATING SEISMIC VULNERABILITY

Current methods to estimate seismic vulnerability (relating uncertain financial or life-safety loss to shaking) and fragility (relating probability of exceeding specified damage states to shaking) can be generally categorized in 3 groups: empirical, analytical, and expert opinion, although in practice many efforts combine 2 or more of these approaches. Some have their origins at least as early as the 1930s, and all have an increasingly robust literature beginning in the 1970s.

3. EMPIRICAL METHODS

Empirical approaches involve regression analysis of observed seismic performance and (typically estimated) seismic excitation; relatively few observations of building performance in economic or life-safety terms were made where ground-motion recordings were made on site or nearby. In most cases these observations are grouped by building type and separate analyses performed for each. We limit our discussion to public efforts, ignoring the substantial proprietary works performed by commercial catastrophe risk modelling companies (especially RMS, AIR, and EQECAT) with the benefit of confidential insurance loss information.

A very large body of work exists on empirical damage data and seismic vulnerability functions. Five notable US examples are cited here. Martel (1936) provides configuration and damage statistics on unreinforced fired brick masonry buildings shaken during the 1933 Long Beach, California earthquake. Whitman et al. (1973) report on an empirical investigation into damaged buildings with 5 or more stories affected by the 1971 San Fernando earthquake, and later offered damage probability matrices based on their observations. Scholl et al. (1982) fit seismic vulnerability functions to high-rise building damage statistics. The data were compiled from a literature review of 249 reports, papers, and other manuscripts, documenting building damage in several dozen worldwide earthquakes between 1906 and 1978, with magnitudes of at least 5 and with maximum MMI ≥ V. ATC-38 (ATC, 2000) is particularly notable because observations of damage in the 1994 Northridge Earthquake were collected near locations where strong-motion recordings are available (ATC, 2000). The study is rare in that it presents the data-collection protocol, all the source data themselves, and most notably the observed ground motion near each observation. The work by Wesson et al. (2004) is also unusual in that it employs a large database of insurance claims from the 1994 Northridge earthquake, a rare occurrence in the public domain.

One novelty GVC is contributing to empirical methods is an attempt to harmonize a variety of damage scales and create one that can be applied globally. Also, we are drawing on the Global Earthquake Consequences Database (http://www.globalquakemodel.org/risk-global-components/consequence-database) to create what may be the first public library of global empirical vulnerability functions. Another contribution is that the guidelines explicitly treat uncertainty in the estimated excitation at each observation, using a kernel-smoothing approach that treats observations not as points in the x-y space of excitation and loss, but as probability distributions. See Noh (2011) for details on the use of kernel smoothing for estimating seismic fragility functions, but in brief the probability density of an uncertain fragility quantity (e.g., the capacity of a building to resist collapse in terms of a ground-motion intensity) can be estimated as:

$$P\left[X = x\right] \approx \frac{1}{n}\sum_{i=1}^{n} I\left(x_i = x\right) \approx \frac{1}{n}\sum_{i=1}^{n}\frac{1}{h}K\left(\frac{x - x_i}{h}\right) \tag{3.1}$$

where

X = the uncertain capacity of interest

x = a particular value of X

i = an index to samples or observations 1, 2, … n

x_i = estimated value of the capacity of sample i, e.g., the expected value of the shaking intensity at which specimen i collapsed

h = a smoothing parameter or the bandwidth of the kernel K

$K(\ )$ = a kernel, essentially a weighting function that provides higher weight the closer the value in parentheses is to zero. For example, the kernel can be a Gaussian probability density function—the familiar bell-shaped curve centered at zero.

Another, novel approach to empirical vulnerability is offered by the US Geological Survey's Prompt Assessment of Global Earthquakes for Response (PAGER) project. Instead of performing regression analyses of observations of damage or loss versus shaking for various structure types, PAGER's novel approach (referred to here as empirical-national) is to hindcast whole-earthquake fatality and economic losses, applying parametric vulnerability functions to estimates of number of people shaken at various levels of MMI, in earthquakes around the world since the early 1970s. Population by macroseismic intensity level is estimated using a global population database (especially Landscan) and ground-motion prediction equations applied to estimated magnitude and location in an historic earthquake catalogue. The parameter values that result in the best hindcast of losses within a country or region are used to estimate losses in new earthquakes as they occur. Hindcasting is performed to minimize both the natural logarithm of error at low excitation and the absolute value of error at high excitation, as shown in Equations (3.2) and (3.3). In them, j is an index of individual earthquakes in a country or region, E_j denotes the estimate of fatalities in earthquake j; s_i denotes shaking intensity at a level indexed by i, θ and β are the parameters of the vulnerability function, $P(s_i)$ is the estimated population shaken at intensity i, e_k is the error term to be minimized, N is the number of earthquakes in the catalogue for the country or region, and O_j is the recorded number of fatalities in earthquake j. See Jaiswal et al. (2009) for details. A related work (Jaiswal and Wald, 2011) addresses economic losses with a similar approach.

$$E_j = \sum_i \Phi\left(\frac{\ln\left(s_i/\theta\right)}{\beta}\right)\cdot P\left(s_i\right) \tag{3.2}$$

$$e_k = \ln\left(\sqrt{\frac{1}{N}\sum_j\left(E_j - O_j\right)^2}\right) + \sqrt{\frac{1}{N}\sum_j\left[\ln\left(E_j/O_j\right)\right]^2} \tag{3.3}$$

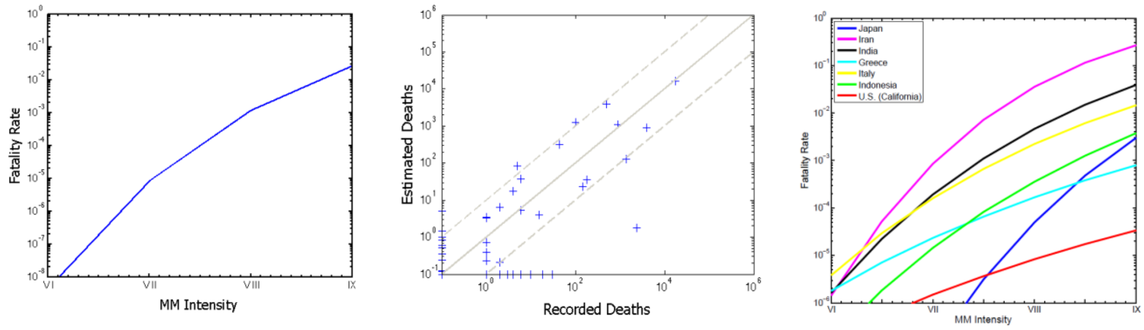

Figure 1. PAGER's empirical-national approach: find the parameters of a parametric curve (left) that best hindcast historic fatality or economic-loss data (center). Curves are fit by country or region (right).

4. ANALYTICAL METHODS

As used here, analytical approaches are those that use engineering principles to estimate damage or loss. Most tend to begin by defining the asset or category of assets to be analysed, and performing the analysis in three or four stages. Early examples of analytical approaches include Czarnecki (1973) and Kustu et al. (1982), the most recent (and in most respects the state of the art) is ATC-58 (ATC 2012).

The asset definition can be as modest as identifying construction material, lateral force resisting system, height category, occupancy category, and design parameters (such as design era), or as sophisticated as defining the structural, architectural, mechanical, electrical, and plumbing design to the same degree of detail used in structural design. Examples of a modest detail include HAZUS-MH (NIBS and FEMA 2009), EQRM (Robinson et al. 2006), and SELENA (Molina et al. 2010). Examples of the more extreme level of detail include Beck et al. (1999) and the related works by Porter (2000), Krawinkler et al. (2005) and ATC-58 (ATC, 2012).

In most cases, a single set of (often uncertain) parameter values is selected to represent structural response, component damageability, and the economic, functional, and life-safety consequences of damage. In the case of vulnerability methods intended to reflect behaviour of a building category this approach treats the category by representing it with a single prototypical building, albeit one with uncertain parameter values. The building is then subjected to a hazard analysis, in which seismic hazard is represented either by an idealized response spectrum with a small number of controlling parameters (e.g., 5% damped elastic spectral acceleration response at 0.3 sec and 1.0 sec periods) or by a suite of ground-motion time histories whose amplitudes are scaled to various levels of intensity, often using 5% damped elastic spectral acceleration response at the building's estimated small-amplitude fundamental period of vibration. The building's structural response is estimated at various levels of excitation. This response is input to a damage analysis, in which the probabilistic damage state of each of many building components is estimated using fragility functions. Given probabilistic damage, the analyst applies consequence functions that provide uncertain loss conditioned on damage state. Uncertainties are propagated by various means that we do not describe here.

Our challenge is to balance the desire for a transparent, reproducible method that minimizes recourse to expert opinion and allows one to examine the effects of detailed design changes (such as seismic retrofit), with the effort required. For the analyst who wishes to employ the state of the art in analytical vulnerability, we adopt by reference the methods of ATC-58 (2012). We note that to use ATC-58, the analyst must select and design one or more index buildings to represent the category of interest.

However, we offer new guidelines for an approach that reduces the required effort compared with ATC-58. In it, the structural system is characterized by a nonlinear single-degree-of-freedom harmonic oscillator with a two-parameter elastic-perfectly-plastic pushover curve, the parameters being elastic period of vibration and ultimate base-shear capacity normalized by building mass. Structural response to each of many levels of seismic excitation is estimated using the N2 nonlinear pseudostatic procedure specified by Fajfar (1999), which idealizes the building as noted above and the ground-motion is idealized using an idealized nonlinear response spectrum as shown in Figure 2. Unreinforced masonry and adobe systems are analysed using the FaMIVE method specified by D'Ayala and Speranza (2003) and D'Ayala (2005).

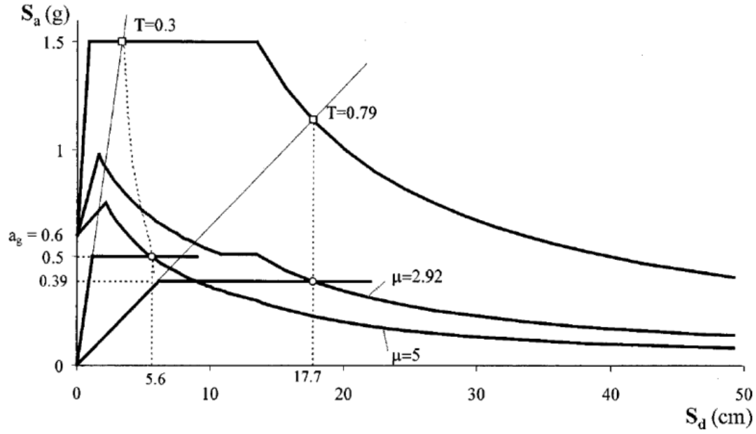

Figure 2. The N2 method of structural analysis (Fajfar 1999)
is used for all buildings except unreinforced masonry and adobe.

We then apply empirical fragility functions for the structural components and for the 5 or so nonstructural components that contribute most to the construction cost of the building. The fragility functions can be taken from the large and growing library exemplified by ATC-58 (ATC 2012) and Johnson et al. (1999), although other sources can also be used of the analyst can derive new fragility functions using the procedures of Porter et al. (2007). Damage-repair costs are estimated using consequence functions of ATC-58, or they can be extracted from locally applicable repair-cost data such as Xactimate (Xactware, 2012) or BCIS (2012), or from available local construction-contracting expertise. Since we only consider the fragility and costs of a subset of building components (albeit the most-costly ones), losses are normalized by the value of building components considered to arrive at an estimate of the mean damage factor.

One novelty of this approach is that it explicitly considers only the most-costly building components and applies the resulting damage factor to the entire building, thus avoiding the need to count every china saucer and glass doorknob in the asset definition and damage and loss analyses. Another is that it allows for an explicit treatment of key uncertainties in the asset definition, such as whether the wall partitions are of this versus that subtype, and have this versus that set of fragility and consequence functions. See Farokhnia and Porter (2012) for details of the nonstructural aspects of analytical vulnerability model.

5. EXPERT OPINION APPROACHES

ATC-13 (ATC 1985) represents a seminal expert-opinion approach to estimating seismic fragility and vulnerability. It is still used in some places throughout the world because of its accessibility, transparency and extensive library of fragility and vulnerability functions. Its authors created a library of damage probability matrices for 78 categories of California construction, of which 40 are buildings. They also offer relationships between damage state and restoration of function for 57 occupancy classes called social function classifications. The authors applied a modification of the Delphi Process (e.g., Dalkey, 1969), the modification being that evaluations of vulnerability and restoration were constructed using a weighted average of the experts judgments, the weights being a self-weighting of expertise in the facility type of interest and in the experts' confidence of individual judgments.

Delphi methods have been enhanced since the 1960s, for example in a somewhat different use of self-ratings to improve group estimates, where the self-ratings are used to exclude experts who do not rate their confidence highly (Dalkey et al. 1970). Cooke (1991) offers an alternative approach for characterizing the quality of an expert's judgment, using a quiz in which each expert is asked to estimate probability bounds, as narrow as possible, for quantities that the test-giver knows but the expert does not. The expert's judgment is then weighted using two measures of how well he or she performed on the quiz. The weight rewards both the ability of the expert to offer probability bounds for the quantity that properly bracket its true value (referred to by Cooke as calibration) and the expert's ability to make his or her probability bounds narrow (referred to by Cooke as informativeness).

In our work, we use Cooke's method to rate experts' ability to estimate the past seismic performance of buildings. The experts are then asked to judge fragility quantities of interest, particularly collapse probability of various building types subjected to various levels of intensity. See Jaiswal et al. (2012) for details.

6. CASUALTY RATES

Earthquakes-induced fatalities and nonfatal injuries are commonly estimated by multiplying the number of building occupants by a set of casualty rates that depend on building damage state. For example, the HAZUS-MH model (NIBS and FEMA 2009) estimates that 10% of indoor occupants in collapsed unreinforced masonry buildings will be killed by structural damage, 5% will experience life-threatening injuries, 20% experience non-life-threatening injuries that nonetheless require emergency-room treatment, 40% experience minor injuries that can be treated by paraprofessionals, and the remaining 25% are uninjured or their injuries do not require professional medical attention. These casualty rates vary by building type and damage state. The rates are based in part on the ATC-13 (ATC 1985) model and revised based on the judgment of the developers, after considering a limited amount of historical data. The ATC-13 casualty model was itself based on the judgment of the authors, prior models, and modest amounts of historical data. Petal (2004) offers a rare statistical study of earthquake casualties; she performed a random-digit-dialing study of survivors of the 1999 Kocaeli earthquake to estimate a mean fatality rate in collapsed buildings.

As part of our work, we undertook to provide a set of casualty rates for use in earthquake loss models and develop a method to update and improve fatality rates with new data. Like prior authors, our main challenge was data resolution and scarcity. We carried out detailed assessments of empirical fatality data from 25 earthquakes in the past 40 years. These earthquakes account for 27% of global earthquake life loss in that period. In new guidelines for GEM, we are proposing a set of (somewhat subjective) fatality rates for 31 global building types; publication is forthcoming.

7. RATING VULNERABILITY FUNCTIONS

It is generally recognized that not all seismic vulnerability functions are of equal value. Commercial catastrophe risk modelers and insurers value empirical methods over others. Empirical vulnerability functions offer the credibility of actual experience, and tractability with methods most familiar to actuaries. Analytical methods offer explanatory power and the ability to resolve the effects of detailed features such as vertical and plan irregularities, material properties, and connection details that do not appear in empirical loss data. But without validation against empirical observations (often lacking in analytical approaches, otherwise why would they be needed?), analytical models can lack credibility. Expert-opinion methods offer the ability to model building types for which empirical data are lacking and analytical methods are too costly, but they lack both the built-in credibility of empirical models and the explanatory power of analytical methods. Furthermore, not all vulnerability functions are equal, even if they use the same general approach. An empirical model can be based on a small or large number of observations, observations of a representative or unrepresentative group of buildings, or may be well or poorly documented.

We have therefore developed a vulnerability rating system to apply to the vulnerability functions that we or later developers create. GEM users confronted with two or more competing vulnerability or fragility functions for the same asset can choose between them based on a quality rating assigned to each function. The rating will be made available by the GEM software along with the vulnerability functions. The rating has 5 parts: data quality, relevance, rationality, documentation and overall quality. Users can consider whichever rating seems most relevant to their particular situation. Ratings are assigned by a panel of 3 or more experts who have developed and used vulnerability functions and fragility functions. Each rating can take one of four values: superior, average, marginal, or not applicable. The rating dimensions are the ones that seem to matter most to a sampling of notable authors of vulnerability functions and fragility functions, namely ATC-13 (1985), Calvi et al. (2006), Eguchi and Seligson (2008), Lang (2002), Kircher et al. (1997), Porter et al. (2001, 2006), Wesson et al. (2004), Reis et al. (2001), and Graf and Lee (2009). The rating system we have proposed is adapted and slightly modified from the ATC-58 project, which developed a similar system to rate component fragility functions. See Porter (2011) for details of the GEM Vulnerability Rating System, including an example of how a user might make a decision based on the rating scheme.

8. CONCLUSIONS

The GEM Vulnerability Consortium is in the process of developing standard guidelines for the creation of new seismic fragility functions and seismic vulnerability functions for use by the Global Earthquake Model. The guidelines address the use of observed seismic performance data to create empirical models, as well as the use of analytical models and expert opinion, each with its own guideline document, plus an additional guideline document that addresses the new approach of developing empirical-national vulnerability functions. We also have proposed guidelines for measuring the quality of each vulnerability function or fragility function in various dimensions, so that the user can judge between competing models. We are creating a library of existing and new vulnerability functions and fragility functions for use by GEM, but do not expect the library to be definitive—many times the effort spent on this project has been spent to date on developing such models, and probably many time more will be spent in the future. Hence the value of the guidelines for interpreting future observations of seismic performance. In 2013 we will focus on distributing these guidelines to interested parties around the world.

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