# Developing Empirical Collapse Fragility Functions for Global Building Types

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Building collapse is the dominant cause of casualties during earthquakes. In order to better predict human fatalities, the U.S. Geological Survey's Prompt Assessment of Global Earthquakes for Response (PAGER) program requires collapse fragility functions for global building types. The collapse fragility is expressed as the probability of collapse at discrete levels of the input hazard defined in terms of macroseismic intensity. This article provides a simple procedure for quantifying collapse fragility using vulnerability criteria based on the European Macroseismic Scale (1998) for selected European building types. In addition, the collapse fragility functions are developed for global building types by fitting the beta distribution to the multiple experts' estimates for the same building type (obtained from EERI's World Housing Encyclopedia (WHE)-PAGER survey). Finally, using the collapse probability distributions at each shaking intensity level as a prior and field-based collapse-rate observations as likelihood, it is possible to update the collapse fragility functions for global building types using the Bayesian procedure. [DOI: 10.1193/1.3606398]

## INTRODUCTION

More than 200,000 people have lost their lives around the world during the last decade (2000–2009) due to causes directly related to earthquake shaking. The total death toll including non-shaking related causes such as tsunami, landslide, fire following earthquake reached close to half a million (among these events, the 2004 Indian Ocean tsunami killed 230,000+ people in fourteen countries). Recent earthquakes in Haiti, Chile, and China that occurred in early 2010 have already caused disproportionate damages and losses (both fatalities and economic impact) for this year. Overwhelmingly, the shaking-related casualties are attributed to structural collapses. In order to better estimate human fatalities in the immediate aftermath of a large earthquake worldwide, the U.S. Geological Survey's (USGS) Prompt Assessment of Global Earthquakes for Response (PAGER) program requires collapse fragility functions for global building types (Wald et al. 2008).

The HAZUS regional loss estimation package (FEMA 2006) is one of the first computer aided seismic hazard, vulnerability and risk modeling tools developed in late 1990s under the auspices of the National Institute of Building Sciences and Federal Emergency

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Management Agency for assessing multi-hazard risk for the United States. Several tools similar to HAZUS have been developed in the last decade (for example, HAZTURK[1] in Turkey, EQRM[2] in Australia, SELENA[3] in Norway, and TELES[4] in Taiwan).

These risk/loss-estimation tools are sophisticated enough to perform structural and damage analyses using engineering principles. These tools use damage states such as "slight," "moderate," "extensive," and "complete" to define the level of structural damage to the building type. For the "complete" damage state (which represents the highest state of damage), it is assumed that a fraction of area of a structure (actually, the average collapse area over many similar structures) is likely to collapse. However, obtaining a collapse fraction for the "complete" damage state for a given structure type entails substantial engineering judgment. Also, much of the damage and collapse data collected in the aftermath of historical earthquakes around the world is only associated with macroseismic shaking intensity observations at different locations rather than with structure-specific spectral acceleration/ displacement quantities directly, as required by the HAZUS-like analytical damage functions. The usage of macroseismic intensity to estimate damage and losses in general makes the loss estimation process circular, but not without a merit. The damage and collapse data available, primarily from the developing countries, are often the most reliable sources for the risk engineering community to calibrate their loss models and only infrequently are such data assigned anything other than macroseismic intensity levels. This is a fundamental premise of empirical collapse fragility function development discussed in this investigation.

Accordingly, a procedure is needed to utilize the existing knowledge of collapse occurrences of global building types in order to develop collapse fragility (defined as probability of collapse for a given input hazard) curves at different shaking intensities. The particular motivation here is for direct incorporation of these functions within the U.S. Geological Survey's PAGER program.

This article first reviews the concept of building collapse as typically used in earthquake engineering, discussing its applicability to nonengineered buildings and its relevance when estimating human casualties. This section is concluded by proposing definitions of collapse that best describe the failure of broad classes of structure types. Using the vulnerability classes described in the European Macroseismic Scale (EMS) (Grünthal 1998; abbreviated here as EMS'98), a procedure is then proposed that allows defining probable ranges of collapse ratios for specific building-structure types at different macroseismic intensity levels. The probable collapse ranges obtained using EMS'98 vulnerability classes served as a guide for further data compilation efforts. Within this framework, we present the results of a systematic data-gathering exercise carried out through the EERI's World Housing Encyclopedia (WHE) under the auspices of the joint WHE-PAGER project for selected countries and building types.

It is recognized that such a process is inherently susceptible to systemic uncertainties and biases due to the variability in the quality of the data gathered and their range of

[1]HAZTURK- http://www.ibb.gov.tr/en-US/SubSites/IstanbulEarthquake/Pages/RiskAnalysis.aspx
[2]EQRM - http://sourceforge.net/projects/eqrm/ OR http://catalogue.nla.gov.au/Record/3794291
[3]SELENA - http://www.norsar.no/c-144-SELENA.aspx
[4]TELES - http://www.ncree.gov.tw/eng/index.htm 2562

applicability. A strategy is proposed for improving the reliability of the collapse fragility functions: the suite of estimates or expert opinion samples are used at each intensity level to probabilistically assess the median collapse fragility using a beta distribution. These fragility estimates are further improved by using existing available field surveys and a Bayesian updating procedure.

## EMPIRICAL COLLAPSE DATA COLLECTION

Earthquake damage and loss data exist in different formats and are often not readily available in their entirety for engineering applications. In addition, the process of compiling damage and collapse data is not straightforward and is often not carried out with rigor, especially in the aftermath of a large earthquake disaster. Recent advancements in remote-sensing data and tools have shown it is possible to quickly identify and assess building damage in the aftermath of earthquakes. Although remote-sensing approaches provide the potential for streamlining data collection, recognized losses are typically limited to severely damaged structures. In order to derive vulnerability functions, statistics on the percentage of damage at different degrees—and of specific structure types—must be provided and thus substantial additional field-based reconnaissance work is typically required.

Due to lack of publicly available data on global building inventories, it becomes increasingly difficult to assess the collapse fractions of a particular type from a representative sample. Also, it can be quite challenging in the field to identify the structure type, to assign the collapse damage state, and to differentiate such structures from the stock of structures in a severe or complete damage state. Nevertheless, empirical collapse data do exist in the literature or other accessible or proprietary forms, and there has been a consistent effort to compile such information from global earthquakes. For example, Cambridge University's Earthquake Impact Database (CEQID) compiles the earthquake damage data assembled by the Martin Centre at Cambridge University (available at www.ceqid.org) since 1980, complemented by other more-recently published and some unpublished data (Spence et al. 2009). Similarly, a disaster inventory system called DesInventar (http://www.desinventar.org/) is a conceptual and methodological tool developed for the compilation of disaster damage and loss databases of nine Latin American countries.

## COLLAPSE PHENOMENA, DEFINITION AND ILLUSTRATION

The definition of collapse in earthquake engineering is dependent on the nature and material of the structural system, the scope of the study, and the method of analysis used in the study. The qualitative and quantitative parameters considered in defining the collapse might be floor area/volume reduction, local (partial) vs. global (complete) collapse, failure of one or more walls (internal or peripheral) leading to collapse of roofing structure, or collapse of one or more stories. In developing an intensity-based semi-empirical casualty-loss estimation approach, the issue therefore is not defining a limiting condition of lateral capacity or story drift, but rather providing a definition of partial and total collapse that is representative of a given structure type that is commonly observed and reported in earthquake reconnaissance work at many different sites. Critically, this definition must be directly relevant to earthquake fatalities.

Traditionally, intensity based scales, such as the Geofian scale, Modified Mercalli Intensity (MMI) scale, Mercalli-Cancani-Sieberg scale (MCS), Medvedev-Sponheuer-Karnik (MSK) intensity scale, Rossi-Forel (RF) scale, and European Macroseismic Scale (EMS), refer to the term "partial or complete collapse/destruction" of buildings and other structures as a basis for definition of the shaking intensity measure; however they do not clarify what defines the state of collapse/destruction. Loss modelers have used the concept of mean damage factor or damage grade to correlate the ground shaking measure with the level of damage for a given structure type (e.g., Algermissen et al. 1973, Shah and Sauter 1983, ATC-13 (ATC 1985), Shakhramanian et al. 2000, Lagomarsino and Giovinazzi 2006).

Push-over and dynamic structural analysis techniques often associate collapse of a building structure with a threshold story drift or plastic hinge rotation of one or more structural components. The collapse criteria can be dependent upon the type of structural model used or the numerical approach employed for structural analysis. For example, Zareian and Krawinkler (2007), while performing incremental dynamic analysis (IDA) on eight-story moment resisting frame, defined collapse as the ultimate limit state in which dynamic sidesway instability in one or several stories of the structural system is attained. Other limit states, such as progressive collapse or loss of vertical load-carrying capacity of individual components, are not considered in their study due to inadequacy of structural models.

In general, for a given structure type, more than one failure mechanism can be identified leading to collapse, involving different extents/parts of the total building envelope (D'Ayala & Speranza 2003). In order to ascertain the global validity of fragility functions, we need to address two issues pertaining to a definition of collapse: the definition needs to be flexible enough to be descriptive of different failure behaviors for apparently similar types of structures; and it needs to be directly related to the types of behaviors of structures that lead to the primary causes of fatalities. Within the WHE-PAGER project, in order to clarify what is intended by collapse in this context, specifically concerning causation of casualties, definitions were proposed for each structural type, focusing on the elements whose failure leads to partial or total collapse of the building (and thus casualties). Earthquake-induced collapse of single story building usually occurs because of collapse of the roof due to loss of support during earthquake shaking. For a multi-story building, it refers to more than 50% volume reduction of one or more floors, a critical factor for casualty estimation (Coburn et al. 1992). Table 1 shows the definitions adopted for each construction material and an image representative of typical collapse conditions.

In the process of defining expert-based fragility curves at a global level, once the definition of collapse for each structural type has been agreed to, then the collapse ratios specific to a given country can be solicited through expert-opinion surveys. In general, for similar structure types, the collapse ratios will depend on the construction methods, material strength, and workmanship, which might be substantially different from country to country. Also, the validity of the collapse data obtained for a certain building type must be ascertained carefully over a large number of similar structure types and at much wider geographic scale, while providing such inputs. To begin with, a framework is also needed to approximately assess the validity of the data gathered during the WHE-PAGER survey. This has been developed using the correlation between hazard and vulnerability proposed by the EMS'98 as explained in the next section.

**Table 1.** Illustration of collapse definition for the different building type

| Main Construction Material | Collapse Definition | Photo |
|---|---|---|
| Adobe | Partial structural failure of roof or floor due to loss of support from walls. |   (Source: http://www.eeri.org/site/images/lfe/china-yunnan2009/image008.jpg) |
| Masonry | Failure of one or more exterior walls resulting in partial or complete failure of roof/floor. |  (Source: http://www.world-housing.net/uploads/101358_080_20.jpg) |
| Timber | Failure of a particular floor or complete failure of part of the timber-framed structure |  (Source: http://www.world-housing.net/uploads/101246_086_14.jpg) |
| In situ Concrete | Failure of a single floor or complete failure of part of the framed structure. |  (Source: http://www.smate.wwu.edu/teched/geology/GeoHaz/eq-Kobe/eq-Kobe-09.JPG) |

**Table 1.** *Continued*

| Main Construction Material | Collapse Definition | Photo |
|---|---|---|
| Steel frame | Collapse of roof or floor due to instability of frame |  (Source: http://nisee.berkeley.edu/taiwan/mahin/day01/images/full/24Sta7Stee.jpg) |

## DEFAULT COLLAPSE FRAGILITY USING EMS (1998)

In EMS'98, the collapse state is generally associated with damage grade 5 and for each shaking intensity level, the probability of a particular vulnerability class experiencing such a damage state is provided. The EMS'98 collapse definition is limited to European observations and is applicable specifically to the European building stock; however, the consistency among EMS'98, MSK, and MMI, make such definitions sufficiently general to be applicable for the scope of the intensity-based model of the WHE-PAGER project at a global scale. EMS'98 provides damage-grade probability ranges for a given vulnerability class for each level of intensity. Although EMS'98 groups structures of different types into the same vulnerability classes, it is possible to disaggregate such definitions and assign collapse rates to each structure type for a given intensity. The process is briefly outlined in the flow chart shown in Figure 1a. For each of the types of structures listed by EMS'98, Figure 1b provides a fuzzy distribution of its occurrence in a given vulnerability class in terms of a most likely, probable and exceptional range. For the purpose of computing collapse fragility ratios, these definitions have been translated into probabilistic ranges as shown in the first two columns of Table 2.

The actual quantity chosen in the computation depends on the spread of the membership across different vulnerability classes. To illustrate the concept, if PAGER-STR type C3 (refer to PAGER structures catalogue, Jaiswal and Wald 2008) is assumed to be mapped to EMS type *frame-without-earthquake resistant design* (*ERD*), its membership spans four EMS'98 vulnerability classes, A to D (Figure 1b). The algorithm assigns 5% membership in class A, 20% membership in class B, 70% membership in class C and 5% membership in class D. Once the structure type has been disaggregated into vulnerability classes, then, for each portion in a given vulnerability class, the proportion in a state of near or total collapse is provided in fuzzy terms by EMS'98 for every level of macroseismic intensity.

Specifically, buildings in EMS'98 damage grade 5 will correspond to total collapse, while buildings in damage grade 4 are defined as severely damaged or partially collapsed.

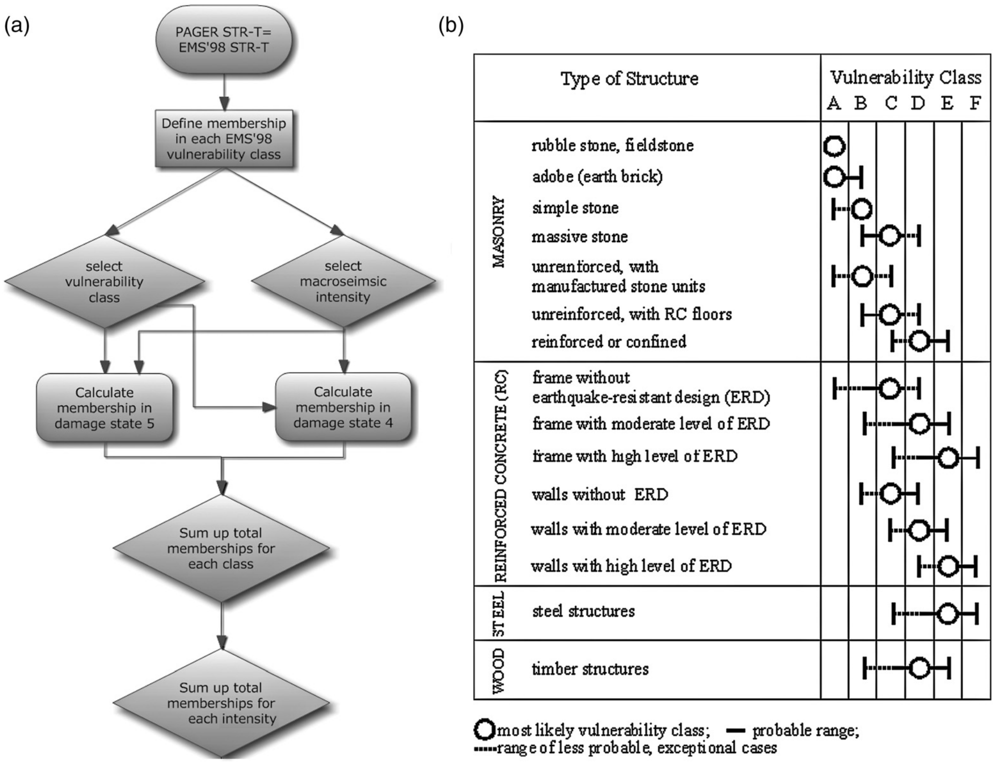


**Figure 1.** (a) Flow chart of procedure for estimating reference collapse ratio for PAGER-STR types and (b) correlation between vulnerability classes and structures type taken from EMS'98.

In case of masonry buildings damage grade 4 corresponds to partial structural failure of roofs and floors, and for reinforced concrete buildings it corresponds to collapse of a few columns or collapse of a single floor. Such damage patterns may lead to casualties in a minority of cases as seen in recent earthquakes in Pakistan, Indonesia and China. To include the partially collapsed buildings of damage grade 4, only 25% of the buildings of each

**Table 2.** Conversion of EMS'98 Fuzzy classes into probabilistic ranges

| Membership of Vulnerability Class by Description in Figure 1b. | | Quantities of Building types of each Vulnerability Class and Damage Grades According to their Description | | |
|---|---|---|---|---|
| Description | Quantity | Description | Quantity (Grade 5) | Quantity (Grade 4)* |
| Most likely | 50–90% | Few | 0 to 15–20 % | 0 to 5 % |
| Probable | 10–25% | Many | 10–15 to 50–60 % | 2.5 to 15 % |
| Exceptional | 0–5% | Most | 50–60 to 100% | 12.5 to 25 % |

*representing only 25% of the total of Grade 4 damage that are assumed to be collapsed.

vulnerability class in damage grade 4 are considered to be collapsed and likely to cause fatalities. This approach is especially suitable for determining a casualty-centric definition of collapse probability estimates and is relatively simple when compared with the damage-specific vulnerability curve estimation approach adopted by Lagomarsino and Giovinazzi (2006).

The correlation between the fuzzy definition and the assumed probability in WHE-PAGER is shown in the second block of three columns of Table 2. Once these values have been calculated, the probable collapse-ratio range for a structure type can be computed by aggregating the collapse ratios first for each vulnerability class and then for each intensity. The ranges obtained are presented in Table 3. Small fractions of collapse damage levels are predicted to occur at intensities below VIII, which is due to inclusion of 25% of damage grade 4 quantities for estimating the total collapse probability. It should be noted that for certain building types, the EMS'98 assigns their less probable vulnerability ranges (through fuzzy membership) reaching to the highest vulnerability levels. This represents range of uncertainty involved in their behavior during earthquakes. The estimated collapse quantities due to inclusion of 25% of these building types with grade 4 damage results in a small fraction of collapse damage levels at lower intensities. With this approach, when lacking expert opinion for a particular structure type, default EMS'98-based fragility estimates can be assigned. This is particularly relevant in countries where there is limited evidence of damage due to past earthquakes, yet the building stock has substantial vulnerability.

In Table 3, along with the EMS'98 structure description, the corresponding PAGER-STR structure type is included. During the first phase of this project it was realized that current literature did not provide a structures catalogue that would collate common typologies worldwide while at the same time univocally indicate the specific characteristics which qualify the seismic vulnerability or resilience of a given type. A comparative study was hence conducted of various catalogues of building types. Specific sources included ATC-13 (ATC 1985), HAZUS-MH (FEMA 2006), EMS'98 (Grünthal 1998), and Coburn and Spence (2002). As a result a new catalogue was compiled starting from very generic broad building type (when no detailed information is available) and then introducing specific subcategories to identify the variability in seismic behavior univocally.

Currently the PAGER-STR structures catalogue has in excess of 100 structure types (available at http://pager.world-housing.net/data-available/construction-types), and is organized in two tiers, where each subcategory is identified by a succinct description of the vertical structure providing earthquake resistance, the type of horizontal structure, and the height of the building. The procedure outlined above is applied to each PAGER–STR tier 1 generic class, predefining the expected proportion of collapses estimated using structure-dependent descriptions of damage within each macroseismic intensity level.

## WHE-PAGER: EXPERT OPINION-BASED COLLAPSE FRAGILITY

We have outlined a method of using EMS'98 definition of intensity to provide structure type-specific collapse fragility particularly applicable to European countries. What is needed is a procedure to estimate collapse fragility of structure types for the rest of the world. Here we demonstrate a procedure for obtaining collapse fragilities using expert opinion.

**Table 3.** Expected range of collapse probability (combination of EMS'98 Grade 4 and 5 damage states) as a function of EMS'98 shaking intensities for various structure types.

| Structure Type | PAGER-STR type | EMS'98 Most Likely Vul. Class | Probability of Collapse at Intensity | | | |
|---|---|---|---|---|---|---|
| | | | VI | VII | VIII | IX |
| Rubble stone, field stone | RS | A | 0 % | 0 to 5 % | 2.5 to 32 % | 21.25 to 70 % |
| Adobe (earth brick) | A | A | 0 % | 0 to 3.8 % | 1.9 to 25 % | 17 to 61 % |
| Simple stone (dressed) | DS | B | 0 % | 0 to 0.3 % | 0.13 to 6.5 % | 3.5 to 34 % |
| Massive stone | MS | C | 0 % | 0 % | 0 to 1.3 % | 0.6 to 12 % |
| Unreinforced brick | UFB | B | 0 % | 0 to 0.3 % | 0.13 to 6.1 % | 3.3 to 33 % |
| Unreinforced brick with RC floor | UFB4 | C | 0 % | 0 % | 0 to 1.3 % | 0.6 to 12 % |
| Reinforced or confined masonry (assuming 5 % in B, 50 % in C and 45 % in D) | RM1 | D | 0 % | 0 % | 0 to 0.3 % | 0.1 to 4 % |
| Reinforced concrete frame without Earthquake Resistant Design (ERD) | C3 | C | 0 % | 0 to 0.3 % | 0.13 to 2.6 % | 1.6 to 13.4 % |
| Reinforced concrete frame with moderate ERD | C3 | D | 0 % | 0 % | 0 to 0.25 % | 0.15 to 2.6 % |
| Reinforced concrete frame with high ERD | C1 | E | 0 % | 0 % | 0 % | 0 to 0.25 % |
| Reinforced concrete shear walls without ERD | C2* | C | 0 % | 0 % | 0 to 0.25 % | 0.13 to 5.1 % |
| Reinforced concrete shear walls with moderate ERD | C2* | D | 0 % | 0 % | 0 % | 0 to 0.25 % |
| Reinforced concrete shear walls with high ERD | C2* | E | 0 % | 0 % | 0 % | 0 % |
| Steel frame (all type) | S | E | 0 % | 0 % | 0 to 0.5 % | 0.25 to 4.5 % |
| Timber structures (all type as per EMS 98) | W | D | 0 % | 0 % | 0 to 0.25 % | 0.13 to 2.6 % |
| Timber structures (high ERD) | W1 | – | 0 % | 0 % | 0 % | 0 % |

**Table 3.** *Continued*

| Structure Type | PAGER-STR type | EMS'98 Most Likely Vul. Class | Probability of Collapse at Intensity | | | |
|---|---|---|---|---|---|---|
| | | | VI | VII | VIII | IX |
| Timber structures (medium ERD) | W2 | – | 0 % | 0 % | 0 to 0.25 % | 0.13 to 2.6 % |
| Timber structures (low ERD) | W3 | – | 0 % | 0 to 0.3 % | 0.13 to 5 % | 3 to 27 % |

RC = reinforced concrete, ERD = earthquake resistant design, C2* = generic class of reinforced concrete shear wall buildings.

The WHE-PAGER project is an ongoing collaborative effort, initiated by a group of experts from the World Housing Encyclopedia (WHE) and the USGS PAGER projects, for an initial estimate of building inventory and vulnerability worldwide. The WHE's housing prototype database (available online at http://www.world-housing.net), covers only residential building types and lacks information pertaining to (1) nonresidential building types, (2) the fraction of building types in rural or urban areas, (3) building collapse fragility (through both empirical and analytical approaches), and (4) occupancy characteristics (day and night occupancy patterns). The WHE-PAGER project provides a framework for compilation of this information in a simple and consistent format solicited mainly from earthquake engineering professionals from different countries. The data compiled in this exercise will also help in enhancing the distribution of housing inventory and vulnerability classes for the existing WHE housing reports for different countries.

For each country, a country-specific expert was requested to provide his/her best estimate on a) relative distribution of building types within the country and the fraction of the urban and rural population who live and work in each building type, and b) the probability of collapse as a function of intensity for these building types. These estimates are only preliminary, and they are not meant to substitute for the more sophisticated modeling and analysis work that are taking place in some countries. Rather, the estimates provided here are meant to complement such efforts, and to be a first step in promoting the need for development of a more rigorous database throughout the world. Furthermore the procedure also offers a paradigm for future development.

Within a year's time span, the WHE-PAGER survey resulted in the development of comprehensive inventory-specific information for 30+ countries (available at http://pager.world-housing.net/data-available/phase-i-data) in a standardized format covering specified aspects of human occupancy pattern, building/construction types and vulnerability for individual countries. Figure 2 shows the seismic collapse probability estimate for Taiwanese building types as a function of Modified Mercalli shaking intensity provided by an expert from Taiwan. These estimates are based on expert judgment to provide a broad overview of vulnerability in a particular country. As an example, Figure 3 shows the comparison

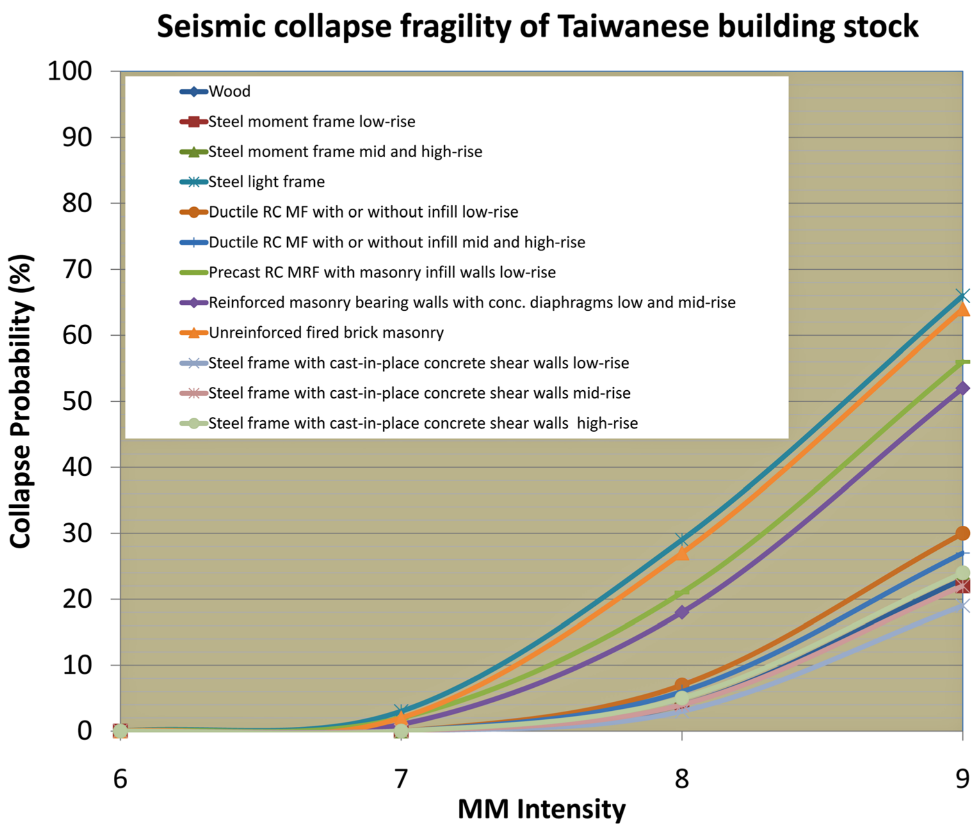


**Figure 2.** WHE-PAGER survey contribution for Taiwan (http://pager.world-housing.net/data-available/phase-i-data). Most of the light steel frame construction in Taiwan are one-story high and generally not detailed for seismic resistance characteristics (Lin 2009).

between the ranges set through the EMS'98 definitions and estimates from a number of regional experts for a particular structure type. While the majority of curves fit within the EMS-based range there are some notable exceptions from countries outside Europe.

Variation of collapse probability estimates could be expected, even for the same class of structure, due to potentially large variations in building design and construction practices from country to country and even within a country (rural vs. urban; pre- or post-code or level of building-code enforcement). Different estimates were offered by experts from different countries for the same structure types during the WHE-PAGER survey. Hence, a statistical procedure to model the collapse fragility based on prior data or expert opinion was needed together with a strategy to assess their reliability and update the estimates as new data based on field observations or other experts' opinion are obtained. The following sections discuss in detail the adopted solutions and present the results obtained.

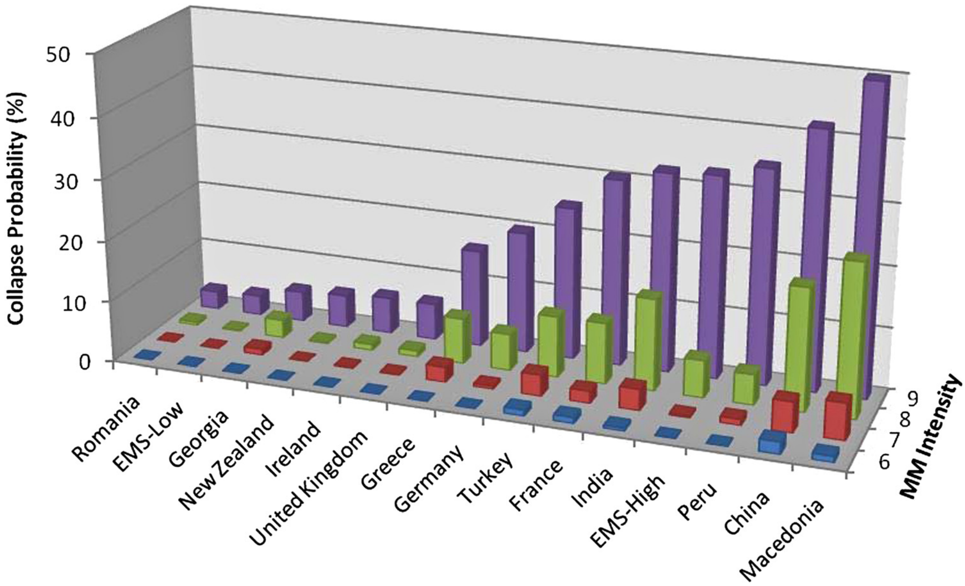


**Figure 3.** Comparison of expert judgment-based collapse fragility of unreinforced fired-brick masonry in cement mortar for selected countries. Also shown is their comparison with expected range in terms of EMS-low and EMS-high bounds from Table 3 based on the EMS'98 definition of vulnerability class and their membership for unreinforced brick masonry construction.

## COLLAPSE FRAGILITY FUNCTION DEVELOPMENT

The collapse fragility is expressed using a functional form with three independent parameters namely scale, shape and location of the fragility function. We demonstrate the behavior of the fragility function using individual expert's estimates of the collapse fragility at different intensity levels using this functional form. Next, we fit the beta distribution to model the uncertainty among the collapse fragility estimates of several experts at each intensity level. Finally, we tabulate the 50 (i.e., median) and 90 percentile bounds on collapse probability at each shaking intensity level for selected building types.

## FUNCTIONAL FORM FOR COLLAPSE FRAGILITY

If the collapse fragility is expressed as $[Y]=[y_1, y_2, y_3, \ldots\ldots y_n]$ at shaking intensity $[X]=[x_1, x_2, x_3, \ldots\ldots x_n]$, then we can fit the collapse fragility data using a power function as below

$$F(x_i) = A_j \times 10^{(B_j/(x_i - C_j))} \tag{1}$$

where $A_j$, $B_j$, and $C_j$ are scale, shape and location parameters of the distribution function to be estimated by fitting the prior expert-judgment of experts for building type '$j$'. Cousins (2004) has used the above functional form for modeling both the mean damage ratio and the

**Table 4.** Collapse fragility parameters for selected building types.

| Building Type | Expert's Country | $A$ | $B$ | $C$ | $R^2$ |
|---|---|---|---|---|---|
| Adobe buildings (A) | Chile | 10.76 | −5.34 | 4.05 | 0.99 |
| Mud wall buildings (M) | Macedonia | 2.56 | −1.69 | 5.18 | 0.99 |
| Nonductile concrete moment frame (C3) | United Kingdom | 3.42 | −5.03 | 5.62 | 0.99 |
| Precast framed buildings (PC1) | Switzerland | 0.85 | −2.35 | 5.90 | 0.99 |
| Block or dressed stone masonry (DS) | Germany | 9.52 | −4.89 | 5.32 | 0.99 |
| Rubble or field stone masonry (RS) | France | 6.17 | −4.58 | 5.03 | 0.99 |
| Brick masonry with lime/cement mortar (UFB2) | Slovenia | 8.03 | −7.59 | 4.60 | 0.99 |
| Steel moment frame with concrete infill wall (S4) | Japan | 0.44 | −6.10 | 4.40 | 0.99 |

mean collapse rate as functions of MMI shaking intensity for New Zealand buildings. In order to estimate the collapse fragility parameters ($A_j$, $B_j$, and $C_j$) for building type $j$, we use the standard minimization technique (Matlab v7.7.0) to minimize the following residual error

$$\varepsilon^2 = \sum_i [Y_i - F(x_i)]^2 \tag{2}$$

In order to measure how well the data fit the chosen fragility function, we estimate the squared multiple correlation coefficient as

$$R^2 = \frac{1}{n-1} \frac{\sum_{i=1}^{n} Y_i F(x_i) - n\bar{F}(x)\bar{Y}}{\sigma_Y \sigma_{F(x)}} \tag{3}$$

where $\bar{Y}$ and $\bar{F}(x)$ are sample mean and $\sigma_Y$ and $\sigma_F(x)$ are sample standard deviations of $Y$ and $F(x)$ respectively. Here, the $R^2$ ranges between 0 and 1 where higher correlation coefficient value (close to 1.0) indicates a tighter data-fit. Table 4 provides the parameters obtained for selected building types using the WHE-PAGER survey data. The shape and scale parameters provide desirable effects on the fragility function. For example, the higher collapse susceptibility of mud wall construction in Macedonia at lower intensities compared to adobe block construction in Chile, whereas their behavior at higher shaking intensities gets altered as demonstrated in Figure 4.

## FITTING THE UNCERTAINTY IN COLLAPSE FRAGILITY

In order to model for the epistemic uncertainty associated with collapse fragility $y$ at a given shaking intensity, we use a beta distribution. The choice of beta distribution is natural due to the fact that the variation in collapse probability can be bounded between the two values (i.e., 0% and 100%), and it can be skewed towards either end depending upon the parameters of the distribution; it has also already been identified as a suitable distribution to model the uncertainty associated with the damage factor at a given intensity (ATC 1985). The probability density function with median ($\eta_c$) and the dispersion ($\beta_c$) associated with collapse fragility $y$ is

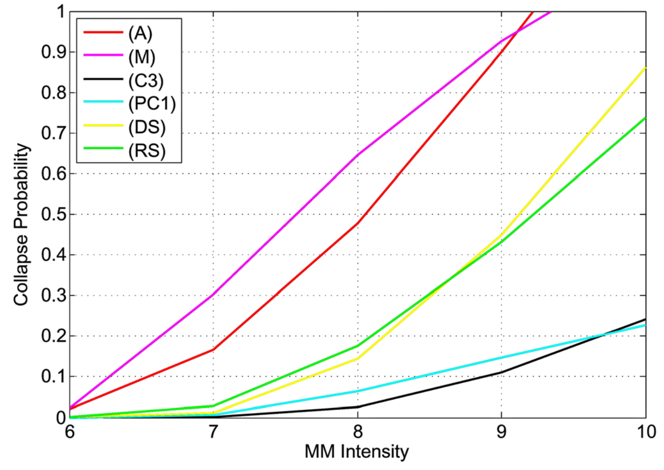


**Figure 4.** Fitting to the functional form of collapse fragility (in which collapse probability of 0% to 100% is represented as 0 to1.0) for selected building types in Table 4 obtained from WHE-PAGER Survey contribution (http://pager.world-housing.net/data-available/phase-i-data).

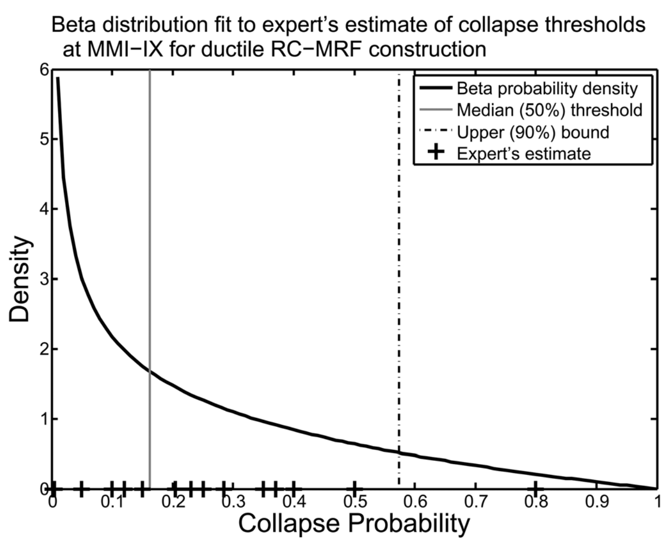


**Figure 5.** Beta distribution fit to experts' estimates of collapse thresholds (between 0 and 1, corresponding to 0 and 100% collapse probability, respectively) at a given shaking intensity. The experts' estimates are –0.14%, 0.4%, 0.5%, 5.0%, 10.0%, 12.0%, 15.0%, 20.5%, 23.0%, 25.0%, 28.5%, 35.0%, 37.0%, 40.0%, 50.0%, and 80% of collapse probability at shaking intensity IX.

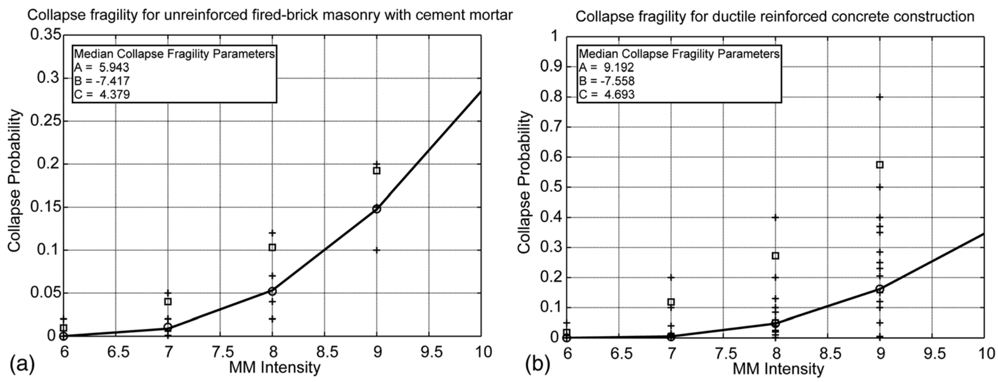


**Figure 6.** Collapse fragility function showing median collapse probability function shown with solid line for (a) unreinforced fired-brick masonry construction with cement mortar (UFB3), and (b) ductile reinforced concrete moment resisting frame (C1) construction based on WHE expert survey data. The squares are ninety percent probability bound on collapse probability at each shaking intensity level.

$$f(y;\eta_c,\beta_c) = \frac{1}{B(\eta_c,\beta_c)}(1-y)^{(\beta_c-1)}y^{(\eta_c-1)} \quad \textit{with } 0 \le y \le 1, \quad \eta_c > 0, \quad \beta_c > 0 \tag{4}$$

where $B(\eta_c,\beta_c)$ is beta function that can be easily computed using the gamma ($\Gamma$) function as

$$B(\eta_c,\beta_c) = \frac{\Gamma(\eta_c,\beta_c)}{\Gamma(\eta_c)\Gamma(\beta_c)} \tag{5}$$

The effect of the epistemic uncertainty is such that the median of the collapse probability estimate is shifted at the lower or upper ends according to the dispersion ($\beta_c$). Figure 5 illustrates the beta distribution fit obtained for the collapse probability estimate provided by experts from different countries for ductile reinforced-concrete moment resisting frame at shaking intensity IX. The median collapse probability (i.e., 50% likelihood of occurrence) estimates obtained using the beta distribution and its ninety percentile bound are also provided.

Figure 6a and 6b illustrate the median collapse fragility curve for unreinforced fired-brick masonry with cement mortar and for ductile reinforced-concrete construction, respectively. This curve (shown with solid line) is derived by fitting the median collapse fragility estimates by using Equation 1 and is shown with the collapse fragility curve parameters. Such a curve helps to estimate collapse fragility at intermediate intensities and also to extrapolate the collapse probability estimate beyond the shaking intensity range if necessary. The median and upper bound (90% occurrence probability) collapse fragility estimates along with associated beta distribution parameters for selected generic building types are shown in Table 5.

**Table 5.** Uncertainty in collapse fragility parameters for selected building types

| Structure Type | MM Intensity | No. of Responses | Sample Mean | Sample Standard Deviation | $\eta_c$ | $\beta_c$ | Median Prob. (50%) | 90% Prob. Bound |
|---|---|---|---|---|---|---|---|---|
| Non-ductile reinforced concrete MRF (C3) | VI | 21 | 0.0038 | 0.0077 | 0.0873 | 22.998 | 0.0000 | 0.0096 |
| | VII | 21 | 0.0417 | 0.0551 | 0.2025 | 4.9577 | 0.0047 | 0.1254 |
| | VIII | 21 | 0.1283 | 0.1251 | 0.7791 | 5.3548 | 0.0877 | 0.3045 |
| | IX | 21 | 0.2945 | 0.2189 | 1.0004 | 2.3222 | 0.2582 | 0.6291 |
| Concrete block masonry (UCB) | VI | 11 | 0.0145 | 0.0222 | 0.1309 | 9.2188 | 0.0004 | 0.0422 |
| | VII | 11 | 0.0727 | 0.0724 | 0.4325 | 5.7905 | 0.0305 | 0.1961 |
| | VIII | 11 | 0.1700 | 0.1366 | 0.6972 | 3.6295 | 0.1097 | 0.3946 |
| | IX | 11 | 0.3312 | 0.1909 | 1.0751 | 2.4016 | 0.2699 | 0.6318 |
| Precast framed construction (PC2) | VI | 4 | 0.0100 | 0.0082 | 0.1919 | 19.449 | 0.0009 | 0.0300 |
| | VII | 4 | 0.0750 | 0.0705 | 1.0109 | 12.607 | 0.0543 | 0.1681 |
| | VIII | 4 | 0.2463 | 0.1378 | 2.2705 | 7.1134 | 0.2231 | 0.4271 |
| | IX | 4 | 0.3938 | 0.1919 | 3.0016 | 4.6918 | 0.3802 | 0.6166 |
| Unreinforced fired brick masonry with RC floors (UFB4) | VI | 8 | 0.0038 | 0.0074 | 0.0780 | 21.080 | 0.0000 | 0.0088 |
| | VII | 8 | 0.0165 | 0.0243 | 0.2976 | 17.946 | 0.0041 | 0.0487 |
| | VIII | 8 | 0.0698 | 0.0980 | 0.5522 | 7.3330 | 0.0376 | 0.1858 |
| | IX | 8 | 0.1905 | 0.1972 | 0.8754 | 3.6862 | 0.1462 | 0.4366 |
| Rubble stone masonry (RS) | VI | 7 | 0.0344 | 0.0270 | 0.2806 | 8.2831 | 0.0077 | 0.0998 |
| | VII | 7 | 0.1687 | 0.1153 | 1.9841 | 9.7851 | 0.1496 | 0.3142 |
| | VIII | 7 | 0.4020 | 0.2142 | 2.0389 | 3.1365 | 0.3794 | 0.6687 |
| | IX | 7 | 0.7450 | 0.2037 | 4.8273 | 2.0414 | 0.7234 | 0.9012 |
| Adobe constructions (A) | VI | 8 | 0.0519 | 0.0357 | 0.1761 | 3.6556 | 0.0039 | 0.1501 |
| | VII | 8 | 0.2313 | 0.1453 | 2.4575 | 8.0609 | 0.2164 | 0.4065 |
| | VIII | 8 | 0.5444 | 0.1511 | 6.2014 | 5.1588 | 0.5487 | 0.7302 |
| | IX | 8 | 0.8244 | 0.0891 | 17.960 | 3.8365 | 0.8340 | 0.9189 |
| Wood frame construction (W) | VI | 5 | 0.0070 | 0.0130 | 0.0891 | 13.010 | 0.0000 | 0.0177 |
| | VII | 5 | 0.0230 | 0.0390 | 0.0837 | 3.9339 | 0.0000 | 0.0568 |
| | VIII | 5 | 0.0680 | 0.0507 | 2.2509 | 30.804 | 0.0595 | 0.1268 |
| | IX | 5 | 0.2270 | 0.1607 | 1.6643 | 5.7237 | 0.1998 | 0.4294 |

## FRAGILITY REFINEMENT PROCEDURE USING BAYESIAN UPDATING

The principle of Bayes' theorem allows updating a prior distribution as additional data/observations become available. Both natural variability (due to lack of predictability of physical processes, e.g., natural phenomena) and statistical uncertainties (due to lack of data) can be addressed while estimating the posterior distribution. New field observations/data on specific building types' collapses during past earthquakes can be used to update the statistical uncertainty; the process is described below.

Bayes' theorem in principle is used to update the prior knowledge or distribution using the likelihood function obtained from a set of observation. Everything we want to learn about $a$ (i.e., the posterior distribution of $a$ given that $b$ has already been observed) is provided through the likelihood function L[$a|b$] and the prior knowledge on $a$, which is available through P($a$). Using Bayes' theorem, the posterior probability $P[a|b]$ (which is a conditional probability of $a$ given that $b$ has already occurred) can be written as

$$P[a|b] = \frac{P[b|a]P(a)}{\int_a P[b|a]P(a)da} = \frac{L[a|b]P(a)}{\int_a L[a|b]P(a)da} \tag{6}$$

in which $P(a)$ represent the prior distribution on $a$ (represents our current knowledge on $a$, e.g., engineering judgment or prior hypothesis about $a$) before observing $b$. The term $L[a|b]$ represents the likelihood function constructed using a set of new observations $b$. The denominator of Equation 6 is a normalizing factor obtained using an integration of the product of the prior and likelihood functions.

In the present case, the collapse fragility $y$ represents the probability of collapse of a certain building type at a given shaking intensity level. The collapse fragility is defined using the beta distribution with parameters $\eta_c$ and $\beta_c$ shown in Equation 4. Assuming that $y_o$ represents a new observation on collapse probability for the same building type at the same level of intensity, we can update the prior distribution on collapse fragility $y$ by rewriting Equation 6 as

$$P\left[y; \eta'_c, \beta'_c | y_o\right] = \frac{l\left[y; \eta_i, \beta_i | y_o\right] f(y; \eta_c, \beta_c)}{\int_y l\left[y; \eta_i, \beta_i | y_o\right] f(y; \eta_c, \beta_c) dy} \tag{7}$$

where P[$y$; $\eta'_c$, $\beta'_c$| $y_o$] is the posterior density function of $y$ (with new parameters $\eta'_c$ and $\beta'_c$) conditioned on the new field observations $y_o$. The function $f(y; \eta_c, \beta_c)$ with parameters $\eta_c$ and $\beta_c$ represents the prior distribution on collapse fragility $y$ previously obtained using Equation 4, and the term $l[y; \eta_i, \beta_i \mid y_o]$ represents the likelihood function whose parameters $\eta_i$ and $\beta_i$ are derived using the field observations $y_o$. Both prior and likelihood functions in this case are the beta distribution, so the posterior distribution is also a beta distribution whose parameters are obtained as

$$P\left[y; \eta'_c, \beta'_c | y_o\right] = P[y; \eta_i + \eta_c, \beta_i + \beta_c] \tag{8}$$

The conjugate property (the posterior being in the same family of the prior probability distributions) allows sequential updating of the posterior in which the posterior at some stage was the prior distribution. Both prior and posterior densities represent the statistical uncertainty on collapse fragility $y$.

For PAGER applications, we use either EMS'98 based collapse fragility estimates (for certain building types) or expert-judgment-based collapse fragility derived in the previous section as a prior distribution on collapse fragility at a given intensity. This serves as a starting model at a global scale for a particular building type. In cases for regions or countries, wherein the recent post-earthquake collapse fragility data are available or become available, we use such data for updating the prior estimates and also updating the uncertainty measure on collapse fragility as discussed below.

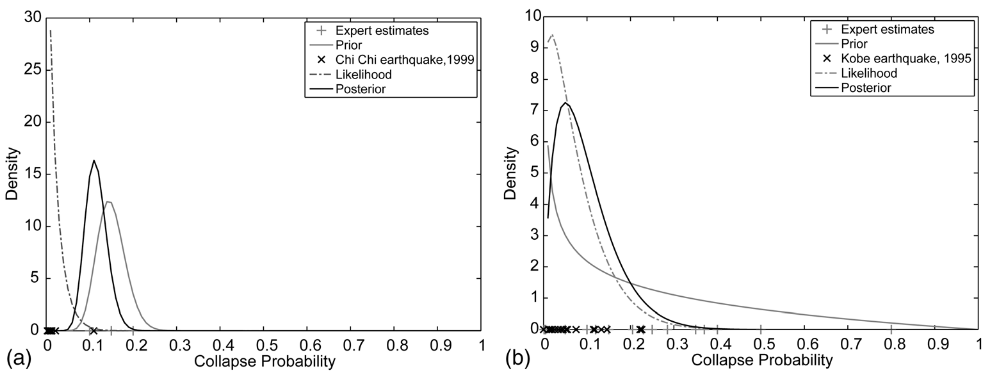


**Figure 7.** Bayesian updating illustration for empirical collapse fragility at intensity IX for (a) unreinforced masonry construction using field survey data $y' = [0.0049, 0.01, 0.1096, 0.0214, 0.0132, 0.0122, 0.005, 0.0084, 0.0047, 0.00266]$ in the Nantau County after the 1999 Chi-Chi, Taiwan, earthquake (b) collapsed reinforced concrete building (both pre-and post 1981) data $y' = [0.045, 0.034, 0.04, 0.075, 0.118, 0.115, 0.226, 0.133, 0.222, 0.146, 0.0, 0.012, 0.015, 0.026, 0.012, 0.02, 0.019, 0.052, 0.0, 0.055]$ in Nada and Higashi-Nada wards of Kobe city at MM intensity IX, or JMA intensity VII after the 1995 Kobe, Japan, earthquake.

To illustrate the process, using the WHE-PAGER expert survey data (shown in gray color + symbol in Figure 7a), we obtain a beta distribution $f(y; 18.36, 104.06)$ on collapse probability (shown in gray line) at MM intensity IX for unreinforced fired-brick masonry. This forms a starting model or prior for global applications for unreinforced fired-brick masonry. For Taiwan unreinforced masonry construction, we use the collapse fraction data provided by Tien et al. (2002) after the Chi Chi 2005 earthquake. The field observations at shaking intensity IX (i.e., estimated instrumental intensity of 8.8 to 9.4) are used to determine the likelihood function (shown in a dot-dashed line), which here is a beta distribution. Because the prior and likelihood are beta distributions, we obtain the beta posterior distribution parameters using Equation 8 (shown in a solid line in Figure 7a). This posterior distribution allows us to determine not only the mean or median value of collapse, but also the upper bound estimates on building collapse potential for a given type of building at a given shaking intensity level.

Similarly, in the case of Japanese reinforced concrete buildings, the collapse estimates provided by Otani (1999) for Nada and Higashi-Nada wards of Kobe city after the 1995 Kobe Japan earthquake can be used to update the collapse fragility. These collapse fractions represented 3,911 buildings (both pre-1981 and post-1981) in the region of JMA intensity VII (equivalent to MMI IX). The median collapse probability of 16.2% at IX obtained using the prior beta distribution $f[y; 0.61, 2.02]$ on WHE-PAGER survey data (shown using a gray-colored line) is updated to 8.37% for Japanese reinforced concrete buildings with posterior beta distribution function $f[y; 1.86, 17.17]$ shown in solid line. This is in agreement with the combined total reported collapses of pre-1981 (5.7%) and post-1981 (2.6%) built reinforced concrete buildings after this earthquake.

## DISCUSSIONS AND CONCLUSIONS

Using the EMS'98 definition of intensity and description of damageability of different vulnerability classes at each intensity level, this article provides a simple procedure to derive the expected range of collapse probability of different structure types. It includes disaggregation of qualitative descriptions of EMS'98 for choosing the collapse-specific damage grade quantities, and combining them based on fuzzy membership of vulnerability classes of specific structure types at each intensity level. Although the EMS'98 based collapse fragility ranges are most pertinent to European structure types, they could potentially be used as a default or as a point of reference when the collapse data/information are lacking for other countries.

In order to assess the collapse fragility of other non-European structure types, the WHE-PAGER survey (Phase I & II) was carried out involving experts from 30+ countries worldwide. Several aspects related to Phase I of the are discussed, including addressing some of the concerns associated with definition of structural types, input shaking hazard in terms of shaking intensity, defining collapse and providing an improved guidelines document to the experts for conducting future surveys.

A three-parameter functional form is used to fit the experts' estimates on collapse probability for each selected structure type. The uncertainty on collapse fragility at each shaking intensity level is modeled using the beta distribution on the experts' responses on specific structure type. The median collapse probability estimates at each shaking intensity level are fitted using a functional form in order to either interpolate collapse fragility estimates at non-discrete intensity levels or to extrapolate to other intensity levels.

The collapse fragility functions developed for global building types using the procedure described in this article form a starting building damage estimation model within the PAGER semi-empirical vulnerability model. These prior distributions on collapse fragility of specific building types are then updated using the country or region-specific field survey data such as those being assembled by Cambridge University (CUEDD available at www.ceqid.org), among others, on building collapses recorded during historical earthquakes. The Bayesian procedure directly helps to calibrate the prior seismic collapse fragility functions (defined using beta distribution) to the statistical field data at any or all levels of shaking intensity while preserving the capability to account for statistical uncertainty associated with collapse potential through posterior distributions.

It is envisioned that the collapse fragility function development procedure could also be adopted at a regional scale by developing region-specific functions and by updating them using regional collapse data. The collapse fragility-function procedure can be more generally adopted for development of similar default noncollapse damage-state functions using additional loss data sets.

Several long-term improvements requiring significant efforts could be made to the present approach, including (i) incorporating the uncertainty in the shaking intensity at which collapse probability estimates are assigned, (ii) improving the process of elicitation, e.g., selection and weighing the expert judgments, incorporating the Delphi process (Dalkey et al. 1970, ATC 1985) while conducting surveys, and using Cooke's method (Cooke 1991) to quantify uncertainties associated with expert advice, and (iii) careful consideration of the rise levels (number of stories), variability in construction practices and levels of building code adoption within different countries, and effects of secondary characteristics (e.g., irregularities, size and location of openings, presence or absence of soft story etc.) while comparing the experts' judgments for the same building types.

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