# FRAGILITY CURVES FOR NON-ENGINEERED RESIDENTIAL MASONRY BUILDINGS IN DEVELOPING COUNTRIES: A CASE STUDY ON NON-ENGINEERED UNREINFORCED MASONRY HOMES IN BANTUL, INDONESIA

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## ABSTRACT

Non-engineered masonry buildings are ubiquitous in developing countries and have shown to be susceptible to high levels of damage during earthquakes. The socioeconomic makeup of developing countries create a vicious cycle where non-engineered houses, which are vulnerable to damage during natural disasters, are the only affordable means of shelter. Subsequently, the loss of shelter, which also means the loss of the residents' capital, places them into deeper poverty. This study examines the vulnerability of homes in developing countries by deriving fragility curves for single-storey non-engineered unreinforced masonry (URM) residential buildings. Literature review indicates that fragility curves derived using real damage data are almost non-existent for developing countries due to the scarcity of post-earthquake damage data and the lack of accurate ground motion recordings in these countries. As a focused case study, this paper presents empirical (i.e. based on real damage data) fragility curves utilizing ground motion data from the USGS *ShakeMaps* and damage data collected in the aftermath of the May 2006 Yogyakarta earthquake in Indonesia. Fragility curves, in terms of PGA, are fitted using cumulative lognormal distribution, cumulative beta distribution, and exponential functions. The vulnerability of non-engineered URM homes is evident even at very low ground motion intensities. There is a probability of 80% that a PGA of only 0.1g will induce at least a moderate damage level. The derivation illustrates the mapping of *ShakeMaps* into fragility curves, which supplement the limited collection of fragility curves for houses in developing countries.

**KEYWORDS**: fragility curves, developing countries, non-engineered masonry, ShakeMaps

## INTRODUCTION

Developing countries suffer far greater than developed countries as a result of earthquakes. Poor socioeconomic conditions often lead to poorly constructed homes that are vulnerable to damage during earthquakes. The seismic vulnerability of buildings in developing countries can be observed from the recent earthquake in Haiti on January 12th, 2010 where a M7.0 earthquake caused severe damage or complete destruction to almost 300,000 homes and claimed over 300,000 lives [1]. The common saying that *earthquakes don't kill people, buildings do*, holds particularly true for developing countries where lives lost are generally a direct result of poorly

constructed structures. The social, economical, and political makeup of these countries make them more susceptible to loss of human lives and property damage.
International disaster risk reduction agreements such as the Yokohama Strategy [2] and Hyogo Framework [3] have advocated a paradigm shift from post-disaster relief efforts towards pre-disaster planning. These international disaster risk reduction principles also recognize the need to focus risk reduction strategies towards developing nations and this has led to significant efforts in the last decade towards developing seismic risk assessment and management programs with a more global focus. Given the uncertain nature of seismic events, damage risk assessment within a pre-disaster framework is established by examining the vulnerability and fragility of structures through relevant curves [4].

## EMPIRICAL FRAGILITY CURVES FOR DEVELOPING COUNTRIES

Fragility and vulnerability curves that take on the form of analytical functions are commonly used in seismic risk assessment and loss estimation applications [5]. The fragility of a structure can be defined as its *damageability* while the structure's vulnerability is a *consequence of this damageability*. Fragility curves describe the probability of reaching or exceeding specific damage levels as a function of a specific seismic intensity measure. Although fragility curves are specific to structural typologies, they are versatile in their use in seismic risk assessment applications as they can be adapted to any region of similar building typologies and ground conditions. In addition to their use in seismic risk assessments, fragility curves are also used to understand structural response to seismic forces particularly given the current shift in seismic design philosophy towards performance-based seismic design (PBSD) methodologies [6]. The use of *fragility functions* within PBSD is implemented through evaluating the fragility of the different building components, structural and non-structural, while *fragility curves* for seismic risk assessments generally evaluate overall structural performance.

Fragility curves are broadly developed using four techniques, namely: empirical, analytical, expert-opinion, and hybrid. The type of method employed is reflective of the source of damage data used in the derivation. For example, data for analytical fragility curves is compiled through seismic (typically inelastic dynamic analysis) simulation of structural analysis models using idealized and simplified structural representations. Alternatively, expert-opinion or judgment-based methods rely on estimates provided by earthquake engineering experts and experienced designers and stakeholders on potential building damage distributions when subjected to seismic events of different intensities, while the hybrid method uses a combination of data sources. Fragility curves presented in this paper are developed using the empirical method that utilizes real damage data collected during post-earthquake surveys.

The three key components required to develop fragility curves are: the damage data, the damage levels (with clear descriptions), and the level of ground shaking (represented as one of the key ground motion parameters). Post-earthquake reconnaissance data facilitate a broader and deeper understanding of the performance of different structures when significant damage levels are observed. Reconnaissance reports also provide means to evaluate societal impacts, and study the effects of other secondary phenomena such as liquefaction, landslides and tsunamis [7, 8]. Furthermore, seismic damage data is collected to evaluate the need for relief efforts, loss estimation, post-earthquake insurance claim payments and government statistics purposes.

However, post-earthquake damage data is usually very limited in developing countries, and therefore, empirical fragility curves are rarely developed for buildings in such countries.
The second component in the derivation of empirical fragility curves involves building damage classification using a clear description of the structure's damage level as indicated by the empirical data. Physical damage descriptions are most commonly used in post-earthquake surveys as they are visual and they can be recorded. The damage is described through broad *qualitative* terms such as "light", "moderate", "collapse" and other similar labels. Building damage classifications generally exist for engineered and well-defined structure types while most vulnerable structures in developing countries are typically non-engineered and incorporate locally available materials and inherited construction techniques. This reality combined with the variety of and variability in non-engineered constructions makes it extremely difficult to adopt standard definitions of damage states for non-engineered masonry houses in developing countries. Therefore, damage classification using damage scales that are calibrated for developed countries should be used with caution in seismic fragility assessment for their developing counterparts.

The final component required in the derivation of fragility curves is the selection of key ground motion parameter(s) that represent the severity of ground shaking during an earthquake. A variety of ground motion parameters have been adopted in the derivation of fragility curves. However, the most commonly applied are the peak ground motion values and response spectral ordinates. Typically, ground motion hazard levels at different sources are evaluated using local ground motion record(s). Appropriate attenuation relationships (also known as ground motion prediction equations, GMPEs) are then used to determine the ground shaking intensity of the areas around the source and they are selected based on the site location and seismic fault mechanism. Several parts of the developing world, that are prone to seismic events, lack sufficient functioning seismic recording stations making it difficult to find detailed and reliable strong ground motion data. Furthermore, the use of attenuation equations to determine the ground shaking intensity at each building site is not practical. As such, intensities are usually calculated for a whole municipality, town, or city using a central location. USGS provides an alternative to this conventional method through its catalogue of ground shaking maps referred to as *ShakeMaps* [9, 10] (freely available at: http://earthquake.usgs.gov/earthquakes/shakemap).

A *ShakeMap* is a near real-time map of ground motion and shaking intensity produced by an earthquake. *ShakeMaps* were originally developed for southern California, U.S., however, the program was extended in 2004 to produce *Global ShakeMaps* [11, 12] for earthquakes occurring anywhere in the world. The program also provided a set of *ShakeMaps* for historical earthquakes since 1973 where significant human populations were exposed. The *ShakeMaps* are produced in terms of: PGA; PGV; 5% critically damped pseudo-spectral acceleration (PSA) at periods of 0.3s, 1s, and 3s; and macro-seismic intensity. The methodology used to produce the maps involves a systematic process to combine data acquired from seismic monitoring stations, where available, with site geology and ground motion attenuation for the distance to the epicenter of the causative fault. *ShakeMaps* that are produced in real time apply an automatic earthquake discrimination scheme leading to an appropriate selection of the GMPEs while manual revisions are applied to the maps in the case of complex earthquake scenarios or as more accurate and recent site information becomes available.

As many parts of the world lack sufficient seismic monitoring stations, observed or felt macro-seismic intensities such as MMI are used to measure the severity of ground shaking. The *ShakeMap* methodology has adopted the use of MMI in two ways. Firstly, where there are adequate seismic recording stations, the peak ground motion values are converted to MMI and then contoured. Secondly, in areas that lack ground motion recordings, macro-seismic observations are obtained through various sources including USGS's *Did you Feel It?* (DYFI?) program; the observations are incorporated into the *ShakeMap* intensity maps. In addition, the intensity values are converted to peak ground motions using the inverted equations of Wald et al. [9] and used in the peak ground motion maps. A subsequent revision to this ground-motion and intensity interpolation scheme allows the combined use (through a weighted approach) of: direct observations of measured ground motion records or reported intensities; converted observations (from intensity to ground motion or vice versa); and estimated ground motion record intensities from GMPEs or intensity prediction equations (IPE) [11].

The availability of global *ShakeMaps* provides an opportunity to utilize them in the derivation of fragility curves. The use of *ShakeMaps* allows the application of spatial ground motion values to each building providing a more detailed assessment of ground shaking experienced by the building. As large amounts of damage data have to be processed and ground motion parameters have to be computed, derivation of fragility curves using empirical data can be very time-consuming and cumbersome. As such, the use of *ShakeMaps* provides a more efficient and consistent way of obtaining ground motion values.

**CASE STUDY**

After the Yogyakarta earthquake of May 27$^{th}$ 2006, the University of Gadjah Mada (UGM) collected damage data through an extensive surveying effort in the Bantul Regency of the Yogyakarta Province in Indonesia. Students and staff of UGM collected the data immediately in the aftermath of the earthquake to ensure the validity of the damage conditions and survey results. Most of the damage or destroyed buildings were non-engineered and were found to lack adequate seismic resistance [13]. It is not clear as to how many actual buildings were surveyed; however, the GIS files obtained had 53,116 buildings recorded. Out of the 53,116 buildings, a total of 1,736 buildings had no data at all or their data were clearly incorrect, and therefore were ignored from the onset. The GIS layers included data such as the structure type, the type of roof construction, the building function, the number and type of floors, and the damage level sustained. The survey was conducted in *rapid* and *detailed* categories, where the rapid category collected vital information such as building function, number of floors, structure type, type of roof construction, and level of damage while the detailed category also included the administrative boundary details (i.e. districts and villages) and additional notes. The dataset presented a substantial wealth of information that could be utilized to assess the consequences of earthquakes regarding the seismic performance of structures.

The dominant construction material in the surveyed areas was clay bricks used as unreinforced masonry (URM) while the rest were wood, concrete, bamboo, and mixed/unknown materials. The majority of the buildings were residential dwellings with approximately 95% single-storey houses. A small number of commercial buildings were also recorded in the survey. The use of clay tiles in residential roof construction is extensive in the region and was highlighted in the surveyed data where 97% of buildings featured clay tiles as the roofing material. Other roofing materials that were noted in the survey included corrugated metal sheeting, asbestos tiles, cement tiles and bamboo. Many of the URM houses were identified as mixed dwellings where either the front or the back of the home is used as a storefront, which is quite typical in rural areas of developing countries where the economy is reliant on home-based industries. A general overview of the data indicated that the majority of the surveyed buildings were single-storey clay brick URM houses with clay tile roofing.

The building construction type recorded in the survey does not specify the brick buildings to be reinforced. However, several reports suggest that most, if not all, single-storey brick homes in the Bantul area were unreinforced [14][15]. Most of the damaged or collapsed buildings in Yogyakarta were also non-engineered and primarily consisted of two types: one or one and half brick thick masonry building without reinforcement (see Figure 1) and half brick thick masonry building with and without reinforcement (see Figure 2)[13].

**Figure 1: One (or One and half) brick thick masonry buildings [13]**

**Figure 2: Half brick thick masonry buildings without reinforcements [13]**

## DAMAGE CLASSIFICATION

The available damage data were categorized as having suffered *Light, Moderate*, or *Heavy/Collapse damage*. However, it is not clear what damage classifications were used when surveying the houses. Several other assessments by local agencies also used similar damage states but also lacked descriptions. In order to produce meaningful fragility curves, it is necessary to clearly describe and subsequently adopt different damage states in the survey. For the purpose of the current study, the damage level definitions provided by Boen [16] for non-engineered single-storey URM houses in Indonesia have been adopted and mapped to the labels in the dataset according to Table 1. The use of the damage categories provided by Boen [16] is justified as they have been developed for buildings in Indonesia within the context of non-engineered construction. Six damage states with their descriptions have been related to three damage labels in the survey data. The damage descriptions are vital for the use of fragility curves in pre-disaster risk assessments and retrofitting of buildings but also within a post-disaster context to understand the behaviour of non-engineered buildings.

**Table 1: Damage states and definitions [16]**

<table>
<tr><th>Damage States (in dataset)</th><th>Damage Category</th><th>Definitions [16]</th></tr>
<tr><td rowspan="3">Light</td><td>Category 0: No Damage</td><td rowspan="3">No Damage<br>Thin cracks (less than 0.075 cm) in plaster, falling of plaster bits in limited parts<br>Small cracks in walls, falling of plaster in large bits over large areas<br>Damage to non-structural parts, projecting cornices, etc.<br>The load carrying capacity is not reduced appreciably</td></tr>
<tr><td>Category I: Slight – Non-structural Damage</td></tr>
<tr><td>Category II: Slight Structural Damage</td></tr>
<tr><td>Moderate</td><td>Category III: Moderate Structural Damage</td><td>Large and deep cracks in walls<br>Widespread cracking of walls<br>The load carrying capacity of structure is partially reduced</td></tr>
<tr><td rowspan="2">Heavy/Collapse</td><td>Category IV: Severe Structural Damage</td><td rowspan="2">Gaps in walls<br>Inner or outer walls collapse<br>Approximately 40% main structural components have failed<br>Large portion or whole building collapses</td></tr>
<tr><td>Category V: Collapse</td></tr>
</table>

## USGS SHAKEMAPS FOR MAY 2006 YOGYAKARTA EARTHQUAKE

Strong ground motion recordings from the Yogyakarta earthquake were limited. The main shock was recorded by one instrument at Mt. Merapi, 55 km from the epicentre, and the only other instrument located in region of the earthquake was not turned on during the earthquake [15]. Therefore, USGS *ShakeMaps* were used within a GIS framework to extend the damage dataset to include ground motion values for each building. GIS files for the most *recent run* of *ShakeMaps* for the Yogyakarta earthquake were provided by USGS. The historic *ShakeMaps* are regularly revisited and the *ShakeMap* generating program is run to include the most recent data for the earthquake. PGA *ShakeMap* layer was overlaid onto the damage layer in *ArcGIS* as illustrated in

**Figure 3: Illustration of USGS Shakemap and damage data overlay (black markers) in ArcGIS**

and metadata were joined to relate the ground motion measures to each building. Statistical analysis was carried out on the combined damage-ground motion dataset to develop damage probability matrices and subsequently the fragility curves.

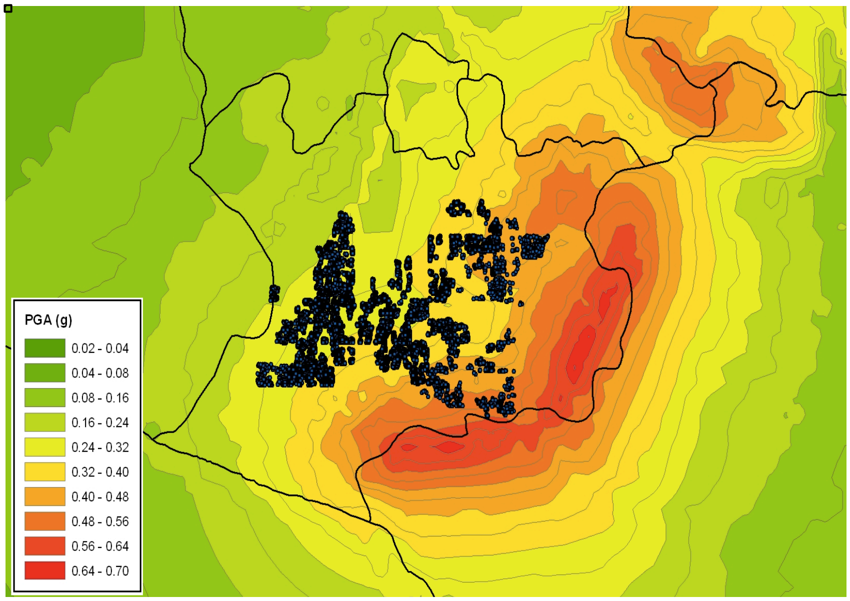


**Figure 3: Illustration of USGS Shakemap and damage data overlay (black markers) in ArcGIS**

## FRAGILITY CURVES FOR SINGLE-STOREY URM HOUSES IN INDONESIA

The probability of occurrence of each damage state in the form of damage probability matrices (DPMs) were calculated by dividing the number of buildings having experienced the damage state by the total number of buildings, within each ground motion range. Cumulative DPMs expressing the probability of reaching or exceeding a damage level at a given ground motion value were subsequently evaluated by adding the probabilities of occurrence from the highest damage levels to the damage levels of interest. The procedure is illustrated in the flowchart in Figure 4. The three functional forms that were considered in fitting curves to the cumulative DPM points are the cumulative lognormal distribution (Eq. 1), the cumulative beta distribution (Eq. 2), and the functional form used by Rossetto and Elnashai [7] herein referred to as the exponential function (Eq. 3).

$$F(\mu,\sigma) = \frac{1}{t\sigma\sqrt{2\pi}}\int_0^x e^{\frac{-(\ln(t)-\mu)^2}{2\sigma^2}} dt \tag{1}$$

$$F(x|v,\omega) = \int_0^x \frac{(t-a)^{v-1}(b-t)^{\omega-1}}{B(v,\omega)(b-a)^{v+\omega-1}} dt \tag{2}$$

$$where: B(v,\omega) = \int_0^1 u^{v-1}(1-u)^{\omega-1} du\,; and\ a \leq x \leq b$$

$$P(d \geq DS|GM) = 1 - e^{(-\alpha.GM^{\beta})} \tag{3}$$

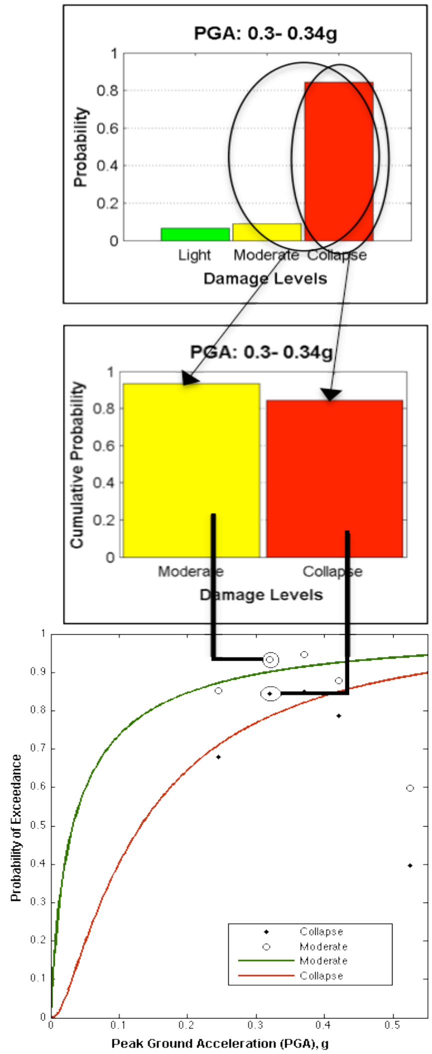


**Figure 4: Fragility curve derivation flow chart for PGA range 0.3-0.34g**

Parameters for the cumulative lognormal and beta distributions, and the exponential function were evaluated and the curve fitting results have been provided in Table 2. The shapes of the curves obtained from the fitted functions are quite similar, particularly at higher values of PGA as shown in Figure 7. The cumulative lognormal curves give the lowest estimates of probability of reaching or exceeding both the damage states followed by the exponential function and cumulative beta distribution, respectively. The curves demonstrate the high vulnerability associated with such non-engineered URM in developing countries. There is a probability of 80% that a PGA of only 0.1g will induce significant cracking of the walls and reduction in the load carrying capacity of a URM house components, resulting in moderate damage or collapse. In addition to the high probability of exceedance of the moderate damage state, it is important to assess the shapes of the fragility curves. All the fragility curves in this study exhibit a steep rise, almost vertical at the origin at low intensities. A comparison of the three analytical expressions used in the present study shows that the steep rise of the fragility curves is present in all (See Figure 5 and Figure 6). However, it is found to be more prominent in the cumulative beta distribution approach.

**Table 2: Fragility curve fitting results**

| DS[1] | Analytical Function | SSE[2] | R-Square[3] | Adjusted R-Square[4] | RMSE[5] | Parameters |
|---|---|---|---|---|---|---|
| M | Cumulative Lognormal | 0.0476 | 0.4080 | 0.2106 | 0.1259 | $\mu$ = -3.425, $\sigma$ = 1.777 |
| C | Cumulative Lognormal | 0.0817 | 0.4283 | 0.2377 | 0.1651 | $\mu$ = -2.028, $\sigma$ = 1.124 |
| M | Cumulative Beta | 0.0423 | 0.4729 | 0.2972 | 0.1188 | $\alpha$ = 0.0991, $\beta$ = 1.06 |
| C | Cumulative Beta | 0.0762 | 0.4672 | 0.2896 | 0.1593 | $\alpha$ = 0.4012, $\beta$ = 1.801 |
| M | Exponential | 0.0420 | 0.4774 | 0.3033 | 0.1183 | $\alpha$ = 3.681, $\beta$ = 0.41 |
| C | Exponential | 0.0829 | 0.4200 | 0.2267 | 0.1662 | $\alpha$ = 3.635, $\beta$ = 0.7586 |

[1] DS = Damage State; M = Moderate, C = Heavy/Collapse
[2] Sum of Square due to Errors (SSE) measures the discrepancy between the values from the fitted curve and the data
[1] R-square ($r^2$) the coefficient of determination measures the success of the fit in explaining the variation of the data
[3] Adjusted R-square is the R-square adjusted for the residual degrees of freedom calculated as number of data points (n) minus the number of fitted parameters (m) giving residual degrees of freedom (v); v=n-m
[4] Root Mean Square Error (RMSE) is the standard deviation of the residuals

R-square is often evaluated between 0 and 1, with values closer to unity indicating a good fit, and closer to 0 indicating a poor fit. However, it has been argued that the R-square is an inadequate measure of goodness of fit and can often be misleading [17, 18]. It is more appropriate to use the R-square value to evaluate the variation present in the data as fitted by the curve. The R-square values (given in Table 2) for the fragility curves are fairly low. However, Rossetto and Elnashai [7] also report low R-square values for empirically-derived fragility curves using the exponential function. The R-square values obtained in this fragility curve are considered reasonable. It is important to note that the unpredictable nature of earthquakes and the inconsistencies in data collection methods, contribute to the low R-square values for empirical fragility curves.

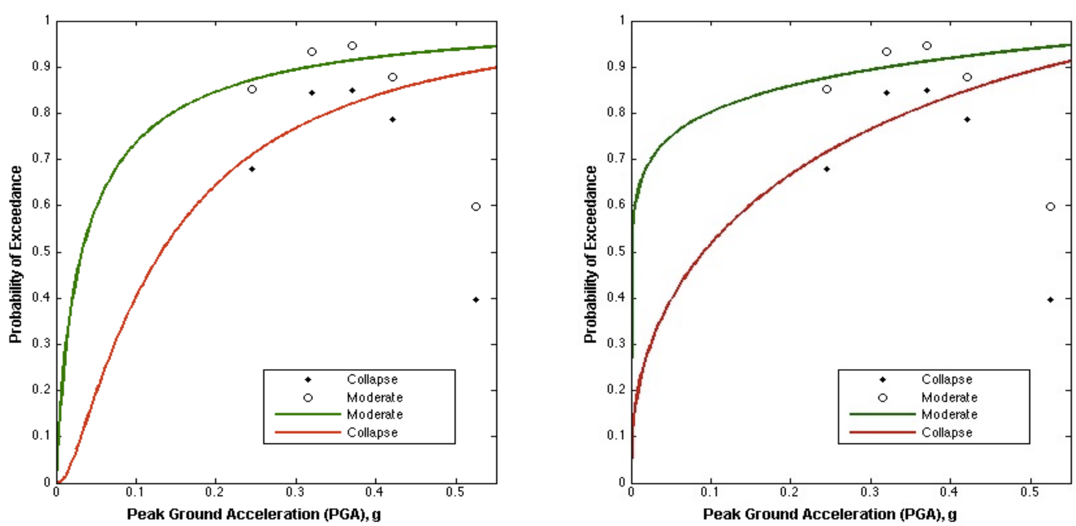


**Figure 5: Fragility curves – cumulative lognormal (left) and cumulative beta (right) distributions**

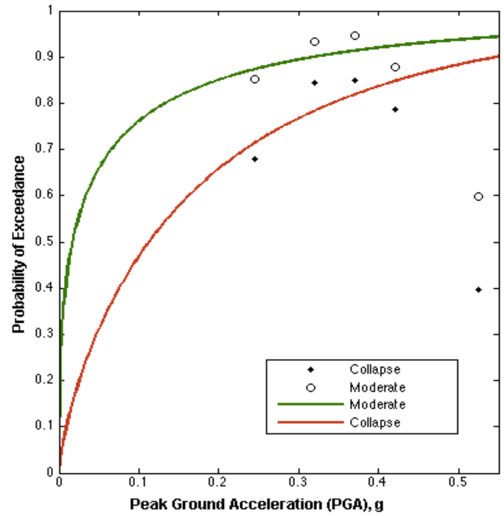


**Figure 6: Fragility curves - exponential function**

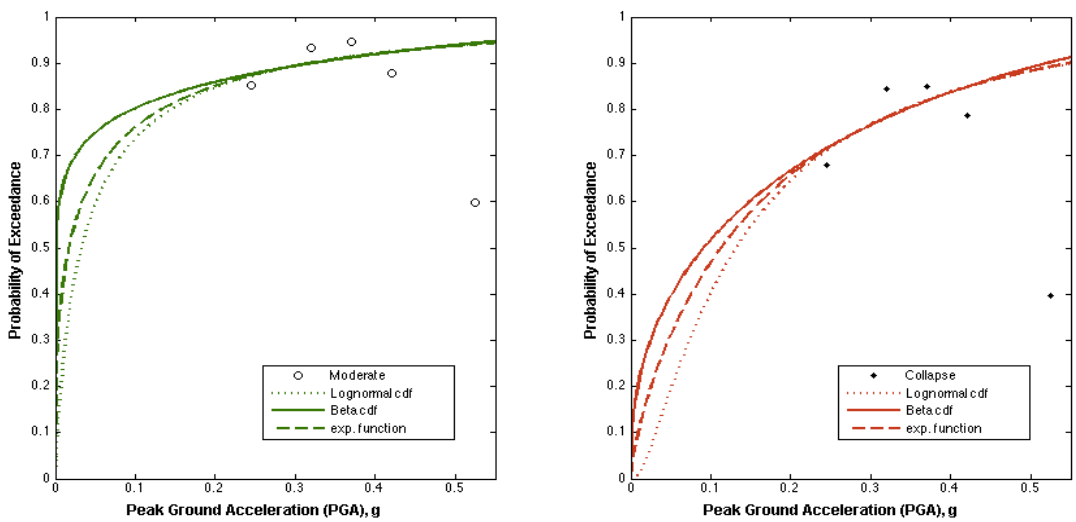


**Figure 7: Comparison of the fitted functions in PGA**

## CONCLUSIONS

There are several methods of deriving fragility curves and the primary difference between the methods is the data source. The analytical method is preferred for deriving fragility curves for developing countries, as it does not require damage data that is often unavailable. However, the diversity of construction techniques and details in non-engineered buildings commonly found in developing countries make it difficult for an analytical model to idealize all possible variations. The simplifications can lead to an over- or under-estimation of vulnerability. Empirical data inherently include the variations in a structural typology and give a better representation of the damage. Therefore, it is imperative to utilize any post-earthquake data when available to empirically derive fragility curves for developing countries.

The empirical method of deriving fragility curves is generally preferred over the other methods. However, a common concern with this approach is the lack of post-earthquake damage data. A concerted effort should be made by multinational organizations to encourage and provide incentives for local agencies to collect damage data after earthquakes that include sufficient information about the damaged buildings. The data should also be collected using GPS technology and presented in a GIS format. Furthermore, the data should be made available to the public for a variety of possible uses including research studies.

Fragility curves derived using empirical damage data indicate the high seismic vulnerability of non-engineered URM single-storey houses, particularly in developing countries. The exceedance of all damage states has a very high probability at all ground shaking intensities. It is obvious that the damage data collected after the 2006 Yogyakarta earthquake was not intended for the derivation of fragility curves. However, substantial effort has been undertaken to utilize and integrate the available data in the form of fragility curves.

Three analytical expressions were explored in fitting the empirical data to fragility curves, and the shapes were found to be very similar. The cumulative lognormal function is most commonly used for fragility curves. However, other analytical expressions should be reviewed as several of them have shown to give adequate results. In this study, the exponential function used by Rossetto and Elnashai [7] was applied and was observed to produce reasonable results. Minimal variation in quality of fit was observed between the choices of analytical functions used in this paper, however, the beta cumulative function showed an overall better fit to the case study data in comparison to the cumulative lognormal and exponential functions considering the R-square values in Table 2. The derived fragility curves can be considered to be reasonable given the size and quality of data. However, the direct use of these curves to assess the seismic risk is not recommended without further investigation.

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