Simulation-Based Fragility Relationships for Unreinforced Masonry Buildings

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Abstract: Unreinforced masonry (URM) structures represent a significant portion of the residential building stock of the central and eastern United States. Fifteen percent of homes in the eight-state region impacted by the New Madrid Seismic Zone are URM buildings. The brittle nature of URM buildings further supports a thorough consideration of seismic response given the susceptibility to severe failure modes. Currently, there is a pressing need for analytically based fragility curves for URM buildings. To improve the estimation of damage-state probabilities through the development of simulation-based URM fragilities, an extensive literature survey is conducted on pushover analysis. Using these data, capacity curves are generated, from which damage performance limit states are defined. Demand is simulated using synthetically derived accelerograms representative of the central and eastern United States. Structural response is evaluated using an advanced capacity spectrum method. Capacity, demand, and response are thus derived analytically and utilized to generate a more reliable and uniform set of fragility curves for use in loss-assessment software. This paper presents a framework amenable to rapid, flexible updating that, with the appropriate database of studies, is capable of producing curves representative of any URM building typology subjected to a specified hazard. The curves are expressed in multiple forms to demonstrate capability of use in various loss-assessment applications. DOI: 10.1061/(ASCE)ST.1943-541X.0000648. © 2013 American Society of Civil Engineers.

CE Database subject headings: Masonry; Seismic effects; Residential buildings.

Author keywords: Masonry; Fragility relationships; Seismic vulnerability; Loss assessment; Capacity spectrum method; HAZUS.

Introduction

Earthquakes pose one of the greatest threats and challenges to humankind in terms of significant loss of life and livelihood. In the past decade, nearly 60% of all fatalities caused by natural disasters were due to earthquakes (The International Disaster Database 2009). Annual global averages exceeded 50,000 deaths (including tsunami effects) and economic losses of up to US$100 billion. The devastation caused to unreinforced-masonry (URM) building populations by recent seismic events such as those in eastern Sichuan, China, in 2008, Port au Prince, Haiti, in 2010, and Christchurch, New Zealand, in 2010–2011 highlight the importance of estimating impact and mitigating potential consequences of earthquakes to URM buildings.

URM buildings are specifically considered due to brittle and severe failure modes under seismic demands. A brief survey of lethal earthquakes since 1960 confirms that building collapses remain the major cause of mortality due to seismic events (Spence 2007). This survey also notes that URM buildings are one of the most vulnerable building types in the world. Numerous studies have indicated that the death tolls from several other notable earthquakes were largely dependent on the poor performance of nonengineered masonry buildings (Ghafory-Ashtiany and Mousavi 2005; Madabhushi and Haigh 2005; Taucer et al. 2009).

In the eight-state region impacted by the New Madrid Seismic Zone, 15% of homes are URM-type buildings. This is significant compared with reinforced concrete and steel buildings, which each account for only 1% of the population. In some regions of the world, such as in Pakistan, Iran, and Mexico, URM buildings make up more than 75% of building populations. The percentage of building stock composed of unreinforced adobe, block masonry, and brick masonry construction for select countries is provided in Table 1. High probability of severe seismic events in countries listed in Table 1, combined with significant URM building inventory, poses great risk.

A brief review of fragility relationships developed for URM buildings in literature was performed to provide insight into the relationships developed in this study. Bothara et al. (2010) performed an experimental investigation of the seismic performance of a two-story, half-scale brick-masonry home representative of New Zealand. Fragility curves were then developed for URM buildings based on the results of this test. A separate study by Park et al. (2009) performed seismic fragility analysis of a two-story URM building designed to represent a firehouse located in the central and southern United States (CSUS). A method is proposed for use in fragility analysis for buildings with several different types of wall configurations. Rota et al. (2010) introduced an analytical approach for the derivation of fragility curves for masonry buildings. This methodology is based on nonlinear stochastic analyses of three-story building prototypes representative of southern Italy. Prototype buildings were assumed to be representative of a wider set of building types. Fragility curves were also developed in the Hazard-Us (HAZUS) Multihazard program (FEMA 2003). HAZUS adopts opinion-based estimates of both building capacity and uncertainty associated with earthquake demand. Results produced using the methodology introduced in this paper are compared with those used.
in HAZUS, along with the fragilities derived by Park et al. (2009) and Rota et al. (2010) that were mentioned earlier.

**Objectives**

The objective of this study is to develop URM fragility relationships for use in seismic loss-assessment studies. Fragility curves are appropriate since they are a required input for many commercial loss-assessment software programs. Fragility curves are useful for identifying damage levels reached under a spectrum of earthquake intensities. This makes fragility curves a good approach for probabilistic assessment of a diverse building stock. The basis of the framework was originally introduced by Gencturk (2007) and applied to timber buildings. This paper provides a methodology and set of best practices for the procedure, while making new developments for application to URM structures.

Developments include a set of considerations for accurate selection and use of experimental and analytical data from the literature to model seismic capacity. Uncertainty introduced in modeling demand with input ground motions is discussed as well. Additional novelties for URM building typology include a procedure for defining a seismic-design level of URM fragility curve groups according to strength-based characteristics. These developments produce a set of curves useful for performing loss assessment on residential URM buildings in the central and eastern United States (CEUS). These curves provide relationships based entirely on structural behavior, in contrast to the generic opinion-based fragility relationships currently used for performing loss assessment. It is important to note here that due to lack of available information, the capacity representation of buildings does not take into account the out-of-plane failure of walls. Some of the URM buildings in the CEUS are expected to exhibit out-of-plane failures, and the use of results provided in this study for these buildings might yield unconservative estimates.

Analysis of structural capacity, allocation of buildings into seismic design categories, and probabilistic analysis are performed to develop fragility relationships. The current study is subdivided into four parts: building capacity; seismic demand; methodology for structural assessment; and methodology for fragility curve generation. These topics also form the structure of the paper. Fig. 1 provides a flowchart that can be used for reference as the details of this procedure are discussed. Future studies using the methodology proposed in this paper may be applied to regions of the world with even more significant URM inventory. The framework presented here is applicable to any URM building system for any earthquake hazard defined by either response spectra or acceleration time histories.

**Capacity of Buildings**

Building capacity and earthquake demand are the two inputs necessary to perform structural assessment. These results are used to derive the fragility relationships required by loss-assessment programs. Uncertainties and errors in fragility relationships result from variability and inaccuracies of two constituents—building capacity and seismic hazard. It is important that the assessed buildings are an accurate representation of the regional inventory for which the loss assessment is being performed. Variability in ground motion representation will introduce even larger levels of uncertainty to the resulting fragility relationships than capacity and modeling techniques. It is critical to the accuracy of the loss-assessment study, therefore, that the building capacity is modeled with great care and that ground motions represent the characteristics of the study region.

Many current software packages for performing loss-assessment studies utilize fragility relationships that are based on expert-opinion rather than experimental data or analytical simulation. Thus, there

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**Table 1. Percentage of URM Buildings in Global Building Inventory**

<table>
<thead>
<tr>
<th>Country</th>
<th>Vintage</th>
<th>Data source</th>
<th>URM as % of inventory³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>2000</td>
<td>Census of Population and Housing</td>
<td>52.9</td>
</tr>
<tr>
<td>El Salvador</td>
<td>1990</td>
<td>Census of Population and Housing</td>
<td>48.0</td>
</tr>
<tr>
<td>Indonesia</td>
<td>2001</td>
<td>Census of Population and Housing</td>
<td>60.0</td>
</tr>
<tr>
<td>Iran</td>
<td>2005</td>
<td>Ghafory-Ashtiany and Mousavi (2005)</td>
<td>56.7</td>
</tr>
<tr>
<td>Italy</td>
<td>2006</td>
<td>Dolce et al. (2006)</td>
<td>62.2</td>
</tr>
<tr>
<td>Mexico</td>
<td>2000</td>
<td>Housing Study Report</td>
<td>75.7</td>
</tr>
<tr>
<td>New Zealand</td>
<td>1998</td>
<td>Dowrick (1998)</td>
<td>7.0</td>
</tr>
<tr>
<td>Pakistan</td>
<td>1998</td>
<td>Pakistan Population Census Org.</td>
<td>93.0</td>
</tr>
<tr>
<td>Peru</td>
<td>2007</td>
<td>(UN-HABITAT, internal report, 2008)</td>
<td>73.2</td>
</tr>
<tr>
<td>Philippines</td>
<td>2000</td>
<td>Housing Census</td>
<td>30.8</td>
</tr>
<tr>
<td>Turkey</td>
<td>2002</td>
<td>Bommer et al. (2002)</td>
<td>47.1</td>
</tr>
<tr>
<td>United States</td>
<td>2002</td>
<td>HAZUS inventory data (CEUS) (FEMA 2006)</td>
<td>15.0</td>
</tr>
</tbody>
</table>

Note: Data are from Jaiswal and Wald (2008).

³Here, URM denotes adobe, unreinforced block masonry, and unreinforced brick masonry homes.

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**Fig. 1.** Framework for fragility curve development
is a concern over whether such relationships are capable of capturing the true performance of structures subjected to seismic events. It is shown in this study that opinion-based methods fail to account for the brittle nature of URM structures. The characteristics of these opinion-based relationships are later contrasted to the simulation-based curves developed in this study.

**Pushover Curves**

It is useful to obtain fragility relationships for a population of buildings with many varying parameters. Therefore, a relatively simple, yet accurate, method is necessary to perform the structural response assessment. Pushover curves from the literature are therefore used to represent structural capacity. Despite shortcomings in predicting the behavior of irregular buildings and capturing local responses, pushover analysis has been confirmed as a practical tool for the evaluation of the seismic response of structures (Krawinkler and Seneviratne 1998; Magenes 2000; Mwafy and Elناسhī 2001; Papanikolaou et al. 2006).

The URM database for this study is composed of structures that are regular in geometry, exhibit global box-type behavior where walls are sufficiently anchored to the diaphragm, and have responses governed by the First Mode. It is assumed that the walls in the out-of-plane direction provide negligible strength and stiffness to the system in the in-plane direction, even when they are adequately restrained from developing out-of-plane failures. It is acknowledged that they can provide additional vertical load capacity (Benedetti and Benzoni 1984) and minimal lateral shear resistance (Kim and White 2002). Regardless, these generally have little effect on the overall strength capacity of most URM buildings that undergo shear deformation and are governed by the response of the in-plane walls. If there is a particularly sound connection between the out-of-plane and in-plane walls, flange effects can be present under significant flexural deformation, though this can be assumed to be minimal for low-rise URM buildings. These considerations, along with several others explained in the following section, are taken into account in developing the database. The assumptions made previously in this paper result in the use of in-plane wall strength to model seismic capacity of URM buildings. This decision is rooted in the description of the features of URM-bearing wall structures in the U.S. provided by the HAZUS-MH Technical Manual (FEMA 2003). The procedures used in selecting the appropriate curves for deriving fragilities are explained later in the article, and subsequently followed by a brief overview of the final database.

**Selection of Sources**

Rigorous criteria are used in selecting pushover curves from existing literature to represent capacity for URM buildings. Care is taken to ensure representation of the appropriate building inventory and compatibility with the methodology being implemented. The sources are evaluated based on a set of criteria that accounts for the following:

- Ensure that adequate information exists to perform the conversion of the pushover curves to capacity diagrams.
- Confirm that the specimens analyzed or tested do not differ significantly from the target building stock (URM buildings that have high potential to show out-of-plane failure of walls could not be considered in the database due to lack of information on such buildings).
- Exclude data representing the performance of unique, irregular, or special performance buildings.
- Avoid the use of analytical data resulting from models that encountered computational stability issues.
- Confirm that the failure mode observed in reduced-scale testing is a valid representation of full-scale behavior.
- Data necessary to determine building capacity include mass, loading methods, and testing procedure. It is critical that buildings tested are accurate representations of the types of structures present in the target region of the loss-assessment study. Curves can be unrepresentative due to regional design and construction procedures. Differences are also often due to the tendency for studies to examine unique or abnormal buildings within the building population. It is necessary to ensure accuracy or completeness by avoiding data from analyses with any numerical problems. These typically occur during postpeak response in certain computer programs. It is also necessary to ensure compatibility with the procedure of the fragility development itself. This occurs most often in instances where small-scale experimental testing yields data for a failure mode that are not scalable.

With these considerations taken into account, the database avoids excessive epistemic uncertainty by providing force and displacement capacities that represent the behavior of URM buildings in the region of interest. In contrast to opinion-based methods, fragility relationships derived from analytical and experimental testing allow for increased reliability in loss-assessment studies.

**URM Database**

The database is composed of nearly 50 curves from six studies found in the literature. The curves are selected according to the parameters described earlier as representative of URM behavior for the CEUS. Many of the studies listed are cited in FEMA 307 (FEMA 1998), where these tests were used to evaluate the accuracy of the methods of FEMA 273 (FEMA 1997) and ATC-43 (ATC 1999) in predicting URM seismic behavior. The structural configurations were assessed both analytically and experimentally. Buildings in the database span 1–3 stories and include a variety of floor plans (ranging from residential to apartment buildings), strengths of materials, and sizes of masonry spandrels and piers. Buildings are modeled with rigid floor diaphragms that have adequate support of out-of-plane walls and /h/ ratios ranging from 5 to 12. The six studies from which pushover curves are selected for use in the database are provided in Table 2. A summary of the structural configurations and testing method implemented in each study is also provided. Complete

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### Table 2. Data Sources for Capacity Curves

<table>
<thead>
<tr>
<th>Data source</th>
<th>Related study</th>
<th>Structural configuration</th>
<th>Data source</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penelis et al. (2002)</td>
<td>RISK-UE Project</td>
<td>One-to-three story, large-plan, varying components</td>
<td>Analytical</td>
<td>SAP 2000—Nonlinear pushover</td>
</tr>
<tr>
<td>Magenes et al. (1995)</td>
<td>Seismic testing</td>
<td>Two-story full scale</td>
<td>Experimental</td>
<td>Cyclic-shake table</td>
</tr>
<tr>
<td>Abrams and Shah (1992)</td>
<td>Cyclic load testing</td>
<td>Three one-story walls</td>
<td>Experimental</td>
<td>Cyclic</td>
</tr>
<tr>
<td>Epperson and Abrams (1989)</td>
<td>NDT confirmation</td>
<td>Five one-story walls from 1917 building</td>
<td>Experimental</td>
<td>Full scale monotonic</td>
</tr>
</tbody>
</table>
discussion of the assumptions, geometrical details, and testing procedures used in each of these studies from the literature can be found in Frankie (2010).

Buildings from this database are first split into building height categories of one, two, and three stories. In addition to grouping buildings by number of stories, each building type is classified according to three seismic design levels. These are defined as low, medium, and high to provide a more comprehensive set of fragility relationships. Seismic design groups in this study are categorized within each height group, creating a set of nine building categories.

The nonlinear pushover curves plotting the base shear $V_b$ and top (roof) displacement $D_{\text{roof}}$ are converted to capacity diagrams. This is achieved by replacing the multidegree-of-freedom system with an equivalent single-degree-of-freedom system through the use of a modal participation factor based on a set of assumed mode shapes. The normalized acceleration-displacement format is spectral acceleration (equivalent force divided by equivalent mass) plotted against equivalent displacement. The details of this procedure are described in Fajfar (2000). This format is necessary to perform the capacity spectrum method (CSM).

**Performance Limit States**

Limit states are defined according to drift and strength values determined upon examining the behavior of the structure. Recall that there are nine building categories resulting from three building-height and seismic-design-level categories. For each pushover curve in every building category, the threshold values for four limit states (slight, moderate, extensive, and complete) are defined. These limit states are based on the relationships for yield and ultimate points defined by Park (1988). The values are obtained from first yield (slight), yield-point of equivalent elastoplastic system with equal energy absorption (moderate), median point of peak plateau (extensive), and reduced postpeak load capacity (complete). These definitions are shown in Fig. 2. An example of the capacity diagrams with limit states plotted is provided in Fig. 3 for the two-story buildings in the database. The capacity curves on which these limit states are displayed are the normalized pushover curves used for performing structural assessment. The variability in structural capacity is naturally incorporated into the fragility analysis by compiling a set of capacity curves for each building category, as illustrated in Fig. 3.

Once the limit threshold values are determined for each capacity curve, the mean threshold values for each building category are calculated. These are provided in Table 3. In accordance with the definition of the limit states, damage regions are defined as none, slight, moderate, extensive, or complete. Input parameters from the seismic event being simulated will drive the structure into one of these regions. The region is determined by examining the maximum displacement of the structure relative to the predefined limit-state threshold values. The use of behavior-based limit states results in a direct correspondence between the structural capacity and earthquake demand. This is because the evaluation of demand also involves the pushover curves. This leads to a more reliable estimation of the limit-state exceedance probabilities as opposed to using generic limit states that are code- or expert-opinion-based. These steps conclude the procedure outlined in the capacity block of the flowchart provided in Fig. 1.

**Seismic Design Levels**

Based on the limit-state definitions already provided in this paper, URM buildings are classified as low, medium, or high seismic design level. This is in contrast to the two categories that are used for URM buildings in HAZUS (FEMA 2003).

The proposed method for categorizing the structures into appropriate seismic groups involves a combination of force demand and force resistance of the URM buildings. To determine seismic force demand, the natural period for each individual building is calculated using the International Building Code (ICC 2006) equation based on material, type of structural system, and height. The equation referred
Supply and Demand

The value obtained and then used in determining force demand. To estimate the expected event, the more reliable the resulting analysis and assessment will be. The more precisely the set of records can match the expected demand with a manageable number of records. Variability in ground motion will introduce high levels of uncertainty into fragility analysis when compared with variations in capacity or uncertainty due to modeling. It is therefore critical that appropriate ground motion records are selected for structural response assessment. The more precisely the set of records can match the expected event, the more reliable the resulting analysis and assessment will be.

Source characteristics of the CEUS intraplate region include low levels of attenuation with ground motions that affect large areas. Due to the low probability nature of the region, there are no natural earthquake records of large magnitude available. As a result, synthetic accelerograms developed by Fernandez (2007) based on the ductility of URM buildings. This is unlike similar applications in the literature, including the study by Gencturk (2007) on wood buildings, where this differentiation is based on the ductility of flexible buildings.

Earthquake Demand

The second component of fragility analysis is the earthquake demand imposed on the building stock. There are several methods of representing the lateral forces imposed on structures due to strong ground motion. The most accurate and rigorous of these methods is the use of accelerograms. Accelerograms are used in this study because they are capable of reflecting features of earthquakes such as source distance, depth, site condition, and type of fault rupture. The use of accelerograms also allows for an accurate representation of earthquake demand with a manageable number of records.

In the study performed by Fernandez (2007), probabilistic models of the CEUS intraplate region include low levels of attenuation with ground motions that affect large areas. Due to the low probability nature of the region, there are no natural earthquake records of large magnitude available. As a result, synthetic accelerograms developed by Fernandez (2007) based on the stochastic method by Boore (2003) are utilized.

In the study performed by Fernandez (2007), probabilistic ground motion records were synthetically generated for seven cities.
located within the Upper Mississippi Embayment. The motions developed for Memphis, TN, are employed in this study because records corresponding to two different site conditions are available. The classifications of “lowlands” and “uplands” represent soft soils and competent rock, respectively.

In this study by Fernandez (2007), the effects of uncertainties in the source, site, and path characteristics, along with nonlinear soil behavior, were incorporated in developing ground-motion attenuation relationships. These relationships were derived using regression analysis of the spectral accelerations from a point-source-based ground-motion model, though directivity effects were not accounted for. Both epistemic and aleatoric uncertainties were considered. The process included the weighted average of three attenuation relationships put forth by Atkinson and Boore (1995), Frankel et al. (2000), and Silva et al. (2003). Probabilistic ground motions corresponding to hazard levels of 10%, 5%, and 2% probability of exceedance in 50 years were developed. These correspond to return periods of 475, 975, and 2,475 years, respectively. Each set of ground motions contains 10 acceleration time histories for both lowlands and uplands soil profiles. The set of synthetically derived accelerograms representing an event with a 975-year return period is selected for use in this study. The acceleration response spectra for lowland and upland records are shown in Fig. 5.

The peak ground acceleration (PGA) of the ground-motion records are scaled at intervals of 0.05 g up to the maximum structural resistance of the most resilient buildings in the database. These scaled records are utilized in the methodology for structural assessment as described in the following section.

**Structural Assessment Methodology**

A database has been developed to accurately represent the structural capacity of URM buildings. In addition, a set of input motions that adequately characterize the seismicity in the CEUS is selected. Thus, we can use a methodology for structural assessment to obtain an accurate prediction of displacement response. As shown in Fig. 1, the building capacity and earthquake demand are used to obtain the structural response results. These results are then statistically evaluated to generate fragility relationships.

Since building capacity is represented by pushover curves that have been converted to equivalent capacity diagrams, a method similar to CSM can be used for the assessment of structural responses. CSM was first proposed by Freeman (1978). After appearing in ATC-40 (ATC 1996), it generated enough interest to spark several additional studies and a variety of proposed improvements. An overview of four previously developed versions of CSM was conducted and an advanced CSM developed by Gencturk and Elnashai (2008) was selected for use in this study. The advanced CSM incorporates the use of nonlinear time-history analysis and ensures convergence. The results from this method were compared with other available versions of the CSM and found to be more desirable for use in the proposed fragility-development framework. The advanced CSM was validated using experimental data from testing of wood-frame structures. However, the CSM is applicable to any structural type for which the structural capacity can be represented with a pushover curve, as suggested by ATC-40 (ATC 1996) and ATC-55 (ATC 2005).

**Fragility Curve Generation**

Fragility curve generation is a statistical analysis performed on the results obtained from the structural response assessment. The data generated represent the variance in building capacity under numerous ground motions. This procedure is the final component of the proposed framework for fragility analysis. The results yield the desired relationship between damage probability and ground-motion input.

It is the objective of this study to introduce an improved method for generating fragility relationships of URM building stock in a format that can be applied to future earthquake-hazard and loss-assessment studies. The most common form of expressing fragility relationships is to display exceedance probabilities of certain damage thresholds as a function of ground-motion intensity. Ground-motion intensity is most often represented in terms of parameters such as peak-ground acceleration, peak-ground velocity, or spectral parameters such as acceleration or displacement at a specific period. Exceedance probability related to ground-motion intensity will be referred to as “conventional” format in this paper. Conventional fragility curves aim to calculate closed-form equations that relate seismic excitation parameters at a certain period to the damage state of a building. In this study, PGA is selected as the parameter for use in defining the hazard input. Ground-motion records are scaled according to PGA due to the influence of acceleration on the behavior of short-period structures such as URM buildings (Elnashai and Di Sarno 2008). The methodology presented by Wen et al.
(2004b) is adopted for fragility curve derivation in conventional format.

A second and less prominent format of representing vulnerability relationships is considered due to its use in HAZUS loss-assessment software (FEMA 2003). In the HAZUS-compatible format, exceedance probabilities are plotted as a function of the structural response of the building. The probability of exceeding a limit-state threshold value is related to a structural response variable. Uncertainty is modeled through a convolution procedure of the building capacity and earthquake-demand uncertainty. A log-normal distribution curve is fitted to the data points for each damage state by using the median and SD as distribution parameters. Probability is plotted against structural response, which is represented in terms of spectral displacement. Therefore, an increase in design level does not always affect the limit-state threshold reportedly achieved by the structure. This is due to the fact that the seismic-design level of URM buildings is predominately defined by strength parameters rather than ductility.

It is important to note that for most conventional fragility relationships, there are only three limit-state threshold values defined. This is different from the four values used in HAZUS-compatible fragility relationships (FEMA 2003). Three values are conducive to the three society-level consequences that result from earthquake hazards (Elshafi and Di Sarno 2008). These society-level consequences are socioeconomic concerns regarding serviceability and continued use of facilities, limited economic loss, and life-loss prevention. If fragility relationships developed in conventional format should require the use of three limit states for application to specific studies or loss-assessment software packages, three appropriate limit states out of the four defined in this study could be chosen. In this case, it would be most appropriate to combine extensive and complete damage-limit states to represent the final socioeconomic limit state of life-loss prevention.

Results

The results from the procedure of assessing building capacity, representing seismic demand, performing structural assessment, and generating fragility curves are presented in this section.

The parameters that are required to generate the fragility curves (for use in loss-assessment software such as HAZUS) are provided in Table 5 for generic soil profile and conventional format. For the full set of parameters, i.e., for both soil profiles (lowlands and uplands) and both formats (conventional and HAZUS compatible), one is referred to Frankie (2010).

The fragility relationships are described by

\[ P(\text{Exceedance} | IM) = \Phi \left[ \frac{1}{\beta_{\text{tot}}} \ln \left( \frac{IM}{LS_i} \right) \right] \]

where the left-hand side = probability of exceedance of limit state \( i \) given the intensity measure, \( IM; \Phi(x) = \text{standard normal cumulative distribution function; } LS_i = \text{threshold value for the } i\text{th limit state; and } \beta_{\text{tot}} = \text{log SD that represents total uncertainty.} \]

This term includes the coupled uncertainty of capacity and demand, the uncertainty in defining the limit-state threshold values, and the uncertainty in structural response assessment. The demand component accounts for the aleatoric uncertainty, which is naturally accounted for by using a set of ground motions. The capacity term includes the uncertainty due to variation in structural capacity (this is also referred to as the modeling uncertainty). The combined uncertainty of capacity and demand is obtained through a convolution process, which is described in more detail in Frankie (2010). The uncertainty in structural response evaluation and selection of limit-state threshold values is represented with a separate term whose value is selected as 0.3 based on previous work (Wen et al. 2004a). The values \( LS_i \) and \( \beta_{\text{tot}} \) are denoted as mean and SD in Table 5.

Conventional fragility relationships are compared in Fig. 6 for low- and high-code buildings for both soil profiles. The probability of reaching limit-state thresholds is plotted against the ground-motion intensity, which is represented in terms of PGA. It is noted that the lowlands soil profile is more demanding than the uplands profile for all fragilities derived in conventional format. Results confirmed that buildings of higher seismic-design levels require more intense ground-shaking to reach a particular limit state when compared with those of lower seismic-design levels. It should also be noted that, although the fragility curves represent the susceptibility of an entire building stock, the brittle behavior of URM building typology is discernible from these two figures. This is most evident in the conventional format, where the complete limit state follows the extensive limit state after a very small increase in PGA. This is due to the low levels of ductility attainable in each of the analytical and experimental capacity curves of URM buildings.

HAZUS-compatible fragility relationships are shown in Fig. 7. It is critical to examine the set of curves derived by this procedure. It is also natural to compare these with the curves currently implemented in the HAZUS (FEMA 2003) software, since it is the most commonly used tool to perform loss assessments for the CEUS. To observe the effect of structural capacity on the fragility curves generated, the capacity diagrams from HAZUS are considered. The methodology of the present paper is applied to these opinion-based capacity diagrams to derive fragility curves. This procedure is performed with the same seismic demand as the curves.

Table 5. Fragility Curve Coefficients for Conventional Format and Generic Soil Profile (in mm)

<table>
<thead>
<tr>
<th>Building category</th>
<th>Slight</th>
<th>Moderate</th>
<th>Extensive</th>
<th>Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>( \beta )</td>
<td>Mean</td>
<td>( \beta )</td>
</tr>
<tr>
<td>One-story, low code</td>
<td>3.50</td>
<td>10.55</td>
<td>7.37</td>
<td>4.63</td>
</tr>
<tr>
<td>One-story, medium code</td>
<td>4.45</td>
<td>10.07</td>
<td>9.10</td>
<td>4.07</td>
</tr>
<tr>
<td>One-story, high code</td>
<td>5.52</td>
<td>10.56</td>
<td>10.67</td>
<td>4.85</td>
</tr>
<tr>
<td>Two-story, low code</td>
<td>3.40</td>
<td>12.30</td>
<td>5.23</td>
<td>9.00</td>
</tr>
<tr>
<td>Two-story, medium code</td>
<td>3.50</td>
<td>9.05</td>
<td>6.35</td>
<td>5.74</td>
</tr>
<tr>
<td>Two-story, high code</td>
<td>3.38</td>
<td>9.51</td>
<td>7.48</td>
<td>5.53</td>
</tr>
<tr>
<td>Three-story, low code</td>
<td>1.31</td>
<td>9.96</td>
<td>4.17</td>
<td>5.58</td>
</tr>
<tr>
<td>Three-story, medium code</td>
<td>1.63</td>
<td>8.29</td>
<td>5.06</td>
<td>4.29</td>
</tr>
<tr>
<td>Three-story, high code</td>
<td>3.19</td>
<td>10.93</td>
<td>6.00</td>
<td>8.80</td>
</tr>
</tbody>
</table>
developed from the database in this study. Fig. 8 compares the resulting fragility curves for the extensive damage state for two-story buildings. It is observed that the median values at each level of seismic input are not exceptionally different. However, much larger values of uncertainty are present for the HAZUS-based curves, as indicated by the lower slope of the fragility function.

Lower levels of uncertainty for the relationships derived in this study are the result of developing curves based on capacity and demand data for a specific region. Utilizing curves with higher levels of uncertainty for this particular region has the potential to overestimate damage exceedance levels at low shaking intensity. However, it is important to note that in the more critical regions of high ground-motion intensity, this same uncertainty may lead to underestimating the damage states reached. This means that a loss-assessment study would likely yield much higher levels of estimated damage for a significant seismic event if the curves developed in this study were used in place of the HAZUS-defined curves. It should be noted that these differences in uncertainty are not related to issues of reliability of the curves. Reliability is a function of how well the curves model the earthquake demand and building capacity, which is improved due to the careful use of simulation-based methods.

It is also important to compare these results with some of the most recent developments in fragility curve generation for masonry structures available in literature. Park et al. (2009) performed seismic fragility analysis for a two-story URM building representative of essential facilities in the CSUS. The fragility analysis demonstrated that the seismic performance of URM buildings was poorer than the level recommended by current seismic codes. This indicates high vulnerability of URM buildings within the CSUS region. The simulation-based fragility curves developed in this study are compared with those of HAZUS (FEMA 2003) in Fig. 8. The results display an improvement in variation of seismic response. It is noted that many of the observations made in the comparison of HAZUS curves in the work of this paper are also shared by Park et al. (2009).

For one case from Park’s study, the out-of-plane walls were modeled in such a way that they are fixed at the top and bottom of the walls only. The connection to the in-plane walls along the side was ignored. Basic bending theory was applied for calculation of
the out-of-plane wall stiffness. In Fig. 9, the high-code building results from Park et al. (2009) are compared with the fragilities developed for high-code, two-story buildings from this study. It is acknowledged that the complete limit-state threshold from Park et al. (2009) is much larger than any observed in this study. The other limit states are defined by very similar sets of parameters, and it is thought that the effects of out-of-plane walls affect the complete collapse-damage limit state. The authors note that the consideration of sound connection between the in-plane and out-of-plane walls results in an increase in seismic capacity—a tendency that is more pronounced for higher limit states, and which can be seen in this comparison.

The second study from literature used for comparison with the curves generated in this study is the work by Rota et al. (2010). In this study, a prototype for a three-story masonry building typical of southern Italy was analyzed. The masonry bearing structure was built of tuff units, while floors were reinforced concrete. RC tie beams were used to guarantee the connection between the floors and masonry walls. Mechanical properties were taken as variables within an appropriate range of values and Monte Carlo simulations were performed to generate input variables. Nonlinear static pushover analyses were used to determine the probability density function of the displacement demand corresponding to different levels of ground motion. Convolution of the cumulative distribution of demand and probability density function of each damage state allowed for the derivation of the fragility curves. A comparison of the fragility curves developed from this prototype structure and those from the work presented here is made in Fig. 10. It is shown that the resulting fragility curves are similar to the medium-code, three-story curves realized from the literature database developed in this study. The procedure implemented by Rota et al. (2010) represented a wide set of building types for three-story buildings by varying mechanical properties and other variables. These properties varied within buildings with flexible diaphragms and out-of-plane failure limited by RC floor beams. This makes it natural for the results to match well with the set of curves derived for three-story URM buildings, despite the differing seismic hazards applied. This comparison is useful since the building capacity models selected have similar structural characteristics.

It should be noted that these are all well-executed methods for generating fragility curves. Comparison with the current study is not meant to determine whether one set is superior to the other. Each is derived for a specific building typology and seismic hazard in consideration. The discussion of how results relate to other sources in literature serves only to make general observations about the curves developed in this study and those of HAZUS and other regions. Thus, it is a very broad validation procedure rather than direct comparison. The objective of these other studies also differs. The curves in these studies are developed using one particular experimental or analytical method to assess the behavior of an individual structure. Although efforts were made, particularly in Rota et al. (2010), to provide curves to represent the diverse properties that can exist within a particular building category, there was only one methodology for assessing structural capacity. In contrast, the procedure presented in this paper reflects the breadth of the database used to model structural capacity. The data are selected from a variety of sources implementing different analytical and experimental methods that represent a variety of URM buildings within a particular region. The comparisons with the fragility curves from the literature confirm that the results presented in this paper provide reasonable levels of exceedance of damage-limit states for URM buildings in the CEUS. The full set of fragility curves derived for each of the formats discussed in this paper, along with further details on procedure and comparison with existing relationships, can be found in Frankie (2010).

Conclusions

Improvements are made to an existing framework for relating ground-motion intensity to the probability of reaching discrete structural-damage levels for URM buildings. The importance of the presented development is derived from the prevalence of URM buildings in the CEUS, a region subject to a high-consequence seismic risk. The framework includes careful selection and definition of building capacity and seismic demand, use of reliable tools for structural assessment, and rigorous processing of the response data to derive fragility relationships.
Care is exercised to realistically represent the behavior of URM buildings. A significant strength of the method presented in this paper is that the database is rigorously gathered from a variety of sources that report analytical and experimental investigations. These sources are used to obtain capacity estimations and to represent classes of URM buildings specific to the CEUS. To provide a comprehensive set of fragilities, building types are classified according to three seismic design levels: low, medium, and high. The methodology used by Gencturk (2007) is improved for application to URM buildings by distinguishing seismic design levels based on a seismic coefficient developed specifically for this study. Earthquake demand on buildings is evaluated using synthetic accelerograms that are representative of the New Madrid Seismic Zone. An advanced CSM is utilized to determine the structural response under the selected ground motions.

Fragility curves are generated by probabilistic analysis of structural response data. They are presented both as a function of ground-motion intensity and as structural demand to comply with the format requirements of different loss-assessment software packages. The results are compared with fragility relationships for URM buildings in literature and an assessment of validity is made. Curves developed from the database are compared with those based on HAZUS-defined capacities. This comparison reveals that the displacement ductility of URM buildings evaluated in this study is lower than the opinion-based capacity curves currently utilized for the region. Additionally, it is postulated that the reduction in uncertainty in these fragility relationships is a result of using a specific set of capacity curves and ground motions. When appropriate ground motions and a representative building database are employed alongside a reliable structural assessment methodology, this is an improvement over applying opinion-based models to individual loss-assessment studies.

The curves generated in this study are based on ground motions generated for the CEUS and applied to a building stock representative of the same region. The use of these curves is suggested for loss assessment to this specific region. Separate ground motion records would need to be applied or generated for other seismic zones. If the URM building stock of a region differs significantly from that of the database developed in this study, particularly in terms of irregular structures that can develop local mechanisms, then a database of pushover curves including out-of-plane failures and nonglobal box-type behavior should be included to perform more accurate loss-assessment studies.

The framework proposed in this paper is amenable to rapid and efficient updating with additional pushover curves and ground-motion records as necessary. The outcome of the work presented herein is a set of simulation-based fragility relationships—a set that is more reliable than those generated by opinion-based methods. Owing to the rigorous models, limit-state definitions, and input motion used, the relationships are only recommended for use in impact assessment software for earthquake loss-assessment studies of regions within the CEUS. The new fragility curves are of interest to researchers, due to the derivation approach from the existing literature. They are also beneficial to risk modelers and managers, due to the reliability of impact assessments obtained from their use.

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References


