ANALYTICAL FRAGILITY ASSESSMENT OF A LOW-RISE URM BUILDING

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ABSTRACT :

Unreinforced masonry (URM) is one of the most common structural types for low-rise buildings in the United States. Its dynamic behavior is highly nonlinear and generally shows high vulnerability to seismic loading. Despite the need of its seismic risk assessment, the fragility curves of URM buildings based on analytical model is scarce in the field of earthquake engineering. This study performs seismic fragility analysis of a URM low-rise building. Fragility curves are developed for a two-story URM building designed to represent a typical essential facilities (i.e., a firehouse) in the central and southern US (CSUS) region. A structural modeling method is proposed that can be effectively used for fragility analysis without significant computational time, and which maintains an acceptable level of accuracy in representing the nonlinear behavior of the structures.

KEYWORDS: Unreinforced masonry, Seismic fragility, Composite spring model

1. INTRODUCTION

Unreinforced masonry (URM) is one of the most common structural types for low-rise buildings in the central and southern US (CSUS) region. For rational estimation and reduction of the potential seismic losses associated with URM structures, the seismic performance level should be quantitatively measured through risk assessment of such structures. Fragility analysis is an effective tool for risk assessment of structural systems as it can be used for probabilistic estimation of seismic losses and eventually enables decision-making activities for seismic risk reduction. Fragility curves for URM structures are currently available from HAZUS (HAZUS, 1999). However, these fragility curves are subjectively constructed based on expert opinion (Wen et al., 2003). This study performs seismic fragility analysis of low-rise URM building structures using a simplified modeling method that can be effectively used for fragility analysis without significant loss of computation time, and which maintains an acceptable level of accuracy in representing the nonlinear behavior of the structures. The seismic responses of the URM building subject to different levels of earthquake inputs are probabilistically estimated considering the randomness in its material properties to yield the fragility curves. The fragility analysis shows that the seismic performance of URM buildings is well below the desirable building seismic performance level recommended by current seismic codes, indicating high vulnerability of URM buildings within the CSUS region. The model-based analytical fragility curves developed in this study can increase the accuracy and effectiveness of seismic risk assessment of essential facilities of the CSUS region. Moreover, the structural modeling method introduced in this study can be effectively used for development of the fragility curves of an individual URM building with a particular configuration.

2. REPRESENTATIVE URM BUILDING STRUCTURE

A benchmark building is selected as representative of existing URM low-rise buildings in the CSUS region. This particular building has been designed and constructed for an experimental study (Yi, 2004) to determine the lateral load resistance of a URM building (Figure 1). The full-scale 2-story test building has been designed to represent typical construction of an existing URM firehouse in the CSUS region. Four unreinforced masonry walls, referred to as Wall A, Wall B, Wall 1, and Wall 2, define the test structure. The building is 7.3 m (24 ft) by 7.3 m in plan and has story heights of 3.7 m (12 ft) and 3.0 m (10 ft) for the first and second floor, respectively.

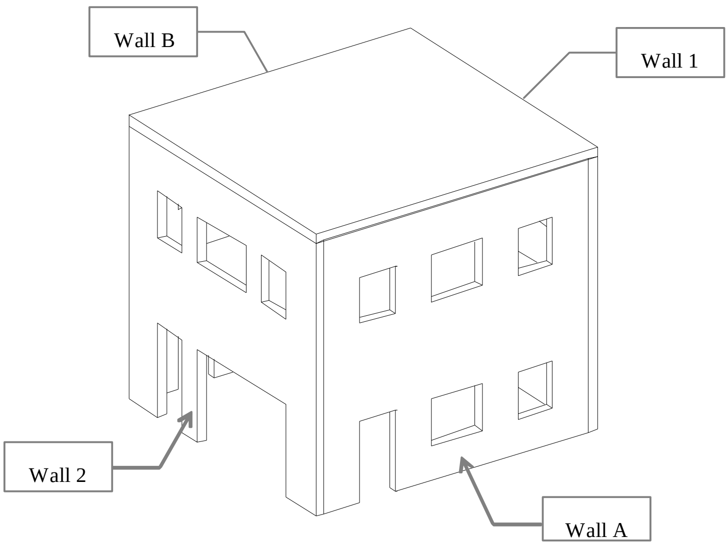

Figure 1: Typical Low-Rise URM Building in the CSUS region

The material properties of the degraded URM buildings are determined based on FEMA guidelines (ASCE, 2000). Values offered for URM structures in "fair condition" are used for determination of the material properties as listed in Table 1.

Table 1: Basic Material Properties for the URM Test Structures

Properties	Degraded URM (from FEMA 356)
Masonry Density (kN/m^3)	18.84
Masonry Compressive Strength (MPa)	5.37
Masonry Elastic Modulus (MPa)	2955
Masonry Bed-Joint Shear Strength (MPa)	0.18

3. MODELING URM BUILDINGS

The most refined approach for analyzing a URM wall is the so-called brick-by-brick approach which models individual masonry brick as a solid element connecting to each other by the interface elements representing the mortar. However, in the interest of achieving a simpler model for dynamic analysis, the models developed in this study are based on two-dimensional behavior only and it is assumed that the earthquake excitation is parallel to Wall A and Wall B of the benchmark URM building (i.e., in the symmetry plane). The 2D model presented in this study is simple enough for repetitive dynamic analyses, yet it is able to capture most of the important nonlinear behavior of the wall components and the diaphragms.

3.1. Modeling of In-Plane Walls

In order to more realistically model the nonlinear behavior of perforated in-plane walls, a simple composite nonlinear spring model is utilized for this study (Craig et al, 2002, Park et al, 2002). The basic approach to develop a composite spring model for the in-plane behavior of a URM wall is to first subdivide the wall into distinct areas or segments, which behave in a similar fashion as a solid URM wall. Each segment of the URM wall is then represented by a nonlinear spring, and the springs are assembled in series and parallel arrangements to match the segment topology for the wall itself. Figure 2 shows the perforated URM wall (Wall A or B) of the benchmark structure on the left side and the schematic view of the corresponding composite spring model on the right. In this composite spring model, each component or segment is treated individually as a solid masonry shear wall, and the stiffness and the strength are determined accordingly from the models in FEMA 356.

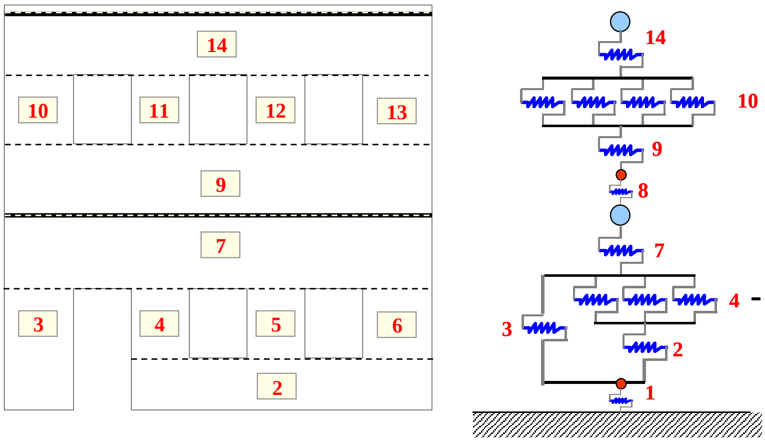

Figure 2: Composite Spring Model of Wall A and Wall B

3.2. Modeling of Out-of-Plane Walls

In this study, an out-of-plane wall is modeled with a single nonlinear spring with bi-linear hysteresis behavior. Properties needed for describing the dynamic behavior of an out-of-plane wall are then its stiffness and strength. The out-of-plane walls are modeled in such a way that they are fixed at the top and bottom only, and the connection to the in-plane walls along the side is ignored. Basic bending theory is applied for calculation of the out-of-plane wall stiffness. This configuration could be used for representing the out-of-plane walls with degraded connection condition. For estimation of the out-of-plane wall strength, it is assumed that a crack is initiated along the top or the bottom of the out-of-plane wall when the maximum tensile stress exceeds the tensile strength of the masonry, which is estimated as 89.6 kPa according to FEMA (ASCE, 2000).

3.3. Modeling of Flexible Diaphragms

Wooden floors and roofs in URM buildings are connected to the bearing walls with simple connections that cannot transmit bending. As a result, these components are modeled as flexible diaphragms with extensional and shear stiffnesses. The shear and extensional stiffness values obtained from the experimental test (Yi, 2004) are modified considering the aging effect. As a result, the shear and the extensional stiffnesses of the diaphragm are determined to be 500 kN/m and 109.0×10^3 kN/m, respectively.

3.4. Modeling of URM Buildings

Computer program DRAIN-2DX is selected in this study for modeling the behavior of the URM test structure. The complete URM test structure is modeled by assembling the composite nonlinear springs for each wall with the lumped wall masses, as illustrated in Figure 3. For illustration purposes, the in-plane walls are represented in Figure 3 by a single spring in each floor. However, the actual model incorporates the nonlinear behavior of in-plane walls at a component-level as displayed in Figure 2.

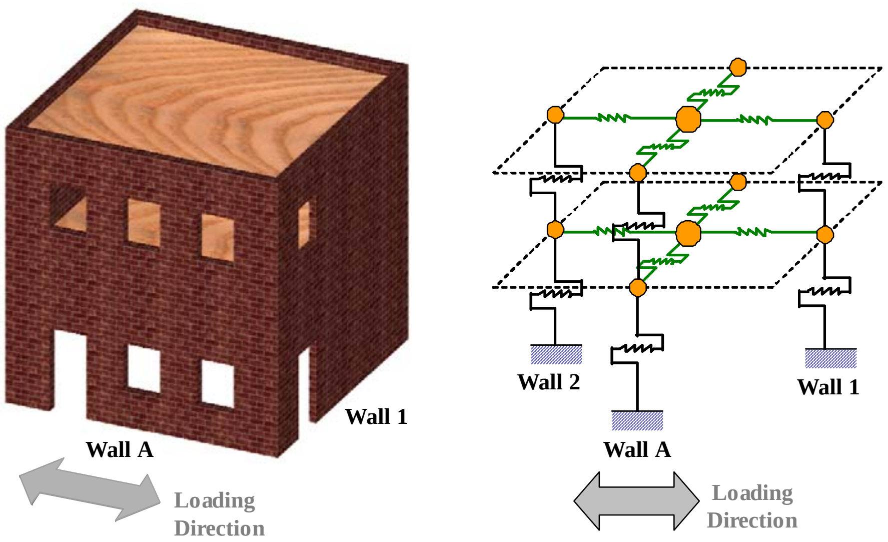

Figure 3: Nonlinear Spring Model Representing a URM Test Structure

4. FRAGILITY ANALYSIS OF THE URM BUILDING

Fragility is defined as the probability of a structure reaching or exceeding a specified limit state under a given earthquake intensity level (Ellingwood, 2001). This probability could be calculated if the probability distribution of the structural damage under a given earthquake level is obtained by accounting for stochastic variations of material properties and the earthquakes mentioned above. Therefore, estimation of the probability distribution of the structural damage for levels of earthquake yields fragility curves. The fragility curves of the URM building is constructed following this concept in the following sub-sections.

4.1. Damage Measure and Performance Levels

Defining a measure for quantifying the building seismic damage is the first important step of a fragility analysis. FEMA 356 and HAZUS use the maximum drift ratio to assess building performance and levels of damage to structural components. In this study, the limit states defined in HAZUS are adopted and the fragility curves are developed accordingly, because the fragility curves to be developed in this study are to be compared with those of HAZUS. The threshold values for the limit states expressed in terms of the drift ratio are defined as 0.2% for slight damage, 0.5% for moderate damage, 1.2% for extensive damage and 2.8% for complete damage.

4.2. Earthquake Inputs

Wen and Wu (2001) developed a suite of synthetic ground motions for three cities in Mid-America. Among them, 10 ground motion records for Memphis with 2% probability of exceedance in 50 years are used for this study. The elastic acceleration spectrum of the input ground motions and the time-history plots can be found in Wen and Wu

(2001).

4.3. Uncertain Variables

Past investigations suggest a number of the URM material properties that exhibit uncertain properties (Abrams et al., 1997, Schueremans et al., 1999, and JCSS, 2001). Referring to the literature, it is assumed that masonry density, compressive strength, bed-joint shear strength, and damping ratio are the major sources of structural uncertainty for the URM structures in this study, and these structural parameters are represented as random variables as presented in Table 2. Uncertainties inherent in the earthquake loading are also considered by using a suite of input ground motions. That is, different earthquakes with the same intensity level might cause different responses of the structure. The spectral acceleration at the fundamental period of the building is considered as earthquake intensity measure in this study, and all ground motions in the suite are scaled such that all have the same spectral acceleration value for each level of earthquake demand.

Table 2: Structural Uncertainties for URM Structures

Random Parameters	Distribution	Mean	COV
Masonry Density (kN/m^3)	Lognormal	18.84	0.05
Masonry Compressive Strength (MPa)	Lognormal	5.37	0.25
Masonry Bed-Joint Shear Strength (MPa)	Lognormal	0.18	0.20
Damping (%)	Uniform	5.0	0.115

4.4. Construction of Fragility Curves

The most direct means of statistical analysis to obtain probabilistic description of the response is running a series of nonlinear time-history analysis through Monte Carlo simulation. However, it requires a relatively large number of simulations in order to obtain a sufficiently reliable estimate for probability of damage. Therefore, Latin Hypercube sampling (LHS) technique (Imam and Conover, 1980) is utilized in this study for efficiency of the simulation process. The region of the probability distribution of each random variable is divided into ten intervals such that all the intervals have equal probability, and a value is randomly generated from each interval and stratified. The ten stratified values are then randomly combined without replacement along with ten ground motions to yield ten combinations of random variables. Taking each combination of random variables as an input, a dynamic time history analysis is performed and the maximum drift ratio is calculated for each combination. The values of the maximum drift ratio calculated for all ten combinations of the random variables are then used for probabilistic description of the drift ratio for a given level of ground motion. This step of calculating the drift ratio is performed over the range of the input earthquake intensity from 0.1g to 3.0g with an increment of 0.1g to obtain necessary data for generation of the fragility curves. Fragility curves are developed for the limit states defined in HAZUS, as discussed earlier. Note that the limit states defined for "pre code" URM low-rise structure in HAZUS is utilized, as it is assumed that the structure is designed without consideration of the seismic loadings. The distribution of the responses, i.e., the maximum inter-story drift ratios, resulted from the analyses with ten combinations of input random variables derived with LHS mentioned above are obtained over the range of the input earthquake intensity. Figure 4 shows the response (i.e., drift ratio) distribution of the URM structure for selected earthquake intensity levels. The dotted horizontal lines indicate the thresholds for the HAZUS limit states, which are corresponding to the complete, extensive, and moderate damage level from the top. According to Cornell et al. (2002), a log-normal distribution for the statistical description of the building response would be a reasonable assumption. Parameters necessary to describe the log-normal distribution, i.e., the log-normal mean ($\mu_{\ln D}$) and the standard deviation ($\sigma_{\ln D}$), can be estimated from the log-normal probability plot of the data points. Figure 5 shows the data points of the maximum drift ratio for the URM structure plotted on the log-normal probability paper along with the fitted lines for selected ground motion intensities. The log-normal mean and standard deviation can then be estimated from the y-intercept and the slope of the fitted line, respectively. The median value of the drift ratio for a given earthquake intensity is also calculated as $\breve{m}_D = e^{\mu_{\ln D}}$.

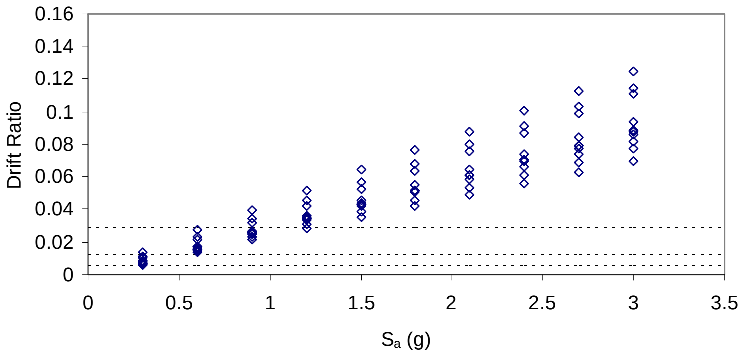

Figure 4: Distributions of Drift Ratio for Selected Input Ground Motion Intensities

The fragility curves of the structures corresponding to different limit states can then be generated by plotting the input earthquake level represented in terms of S_a and the probability of exceeding limit states. Assuming log-normal CDFs for the fragility curves, the fragility corresponding to a given damage state can be expressed as a log-normal cumulative distribution function:

$$F_R(S_a) = \Phi\left(\frac{\ln\left(S_a / \hat{S}_a\right)}{\sigma_{\ln S_a}}\right) \tag{1}$$

where, $\hat{S}_a$ and $\sigma_{\ln S_a}$ indicate the median capacity and the variability of the system, respectively, both being expressed in terms of spectral acceleration. The log-normal parameters can be estimated by plotting the calculated values of the probability of exceedance on log-normal probability sheets as shown in Figure 5. The fitted fragility curves are shown in Figure 6.

The U.S. Geological Survey (USGS) provides an interactive website (http://eqhazmaps.usgs.gov/) where the spectral accelerations of several probabilistic earthquake hazard levels (10%, 5%, and 2% probability of exceedance in 50 years) corresponding to several different period values (0.2, 0.3, and 1.0 second) can be obtained for any particular location within the US by entering the zip code. Based on the resulting spectral accelerations, the site class information for the location is used to construct a response spectrum of an earthquake with an arbitrary probability of exceedance. Using these response spectra, the spectral acceleration values corresponding to two different levels of probability of exceedance – 2% and 10% in 50 years – for the URM building are obtained. The probability of exceeding various limit states can then be read from the fragility curves. Table 3 shows the probability of exceeding limit states for different earthquake levels. The seismic performance of low-rise URM buildings observed from Table 3 and Figure 6 can be compared with the performance level recommended by the current seismic code to measure its relative vulnerability. The seismic performance level corresponding to the Basic Safety Objective (BSO) of building structures suggested by FEMA 356 is to ensure the "Life Safety" level and the "Collapse Prevention" level for the earthquake level of 10/50 PE and 2/50 PE, respectively. The URM building analyzed in this study shows more than 20% probability of exceeding the extensive damage state for the earthquake level of 10/50 PE, and more than 80% probability of exceeding the complete damage state for the earthquake level of 2/50 PE. Overall, these results indicate that the seismic performance of URM buildings is well below the desirable building seismic performance level recommended by the seismic code, indicating high vulnerability of URM buildings within the CSUS region.

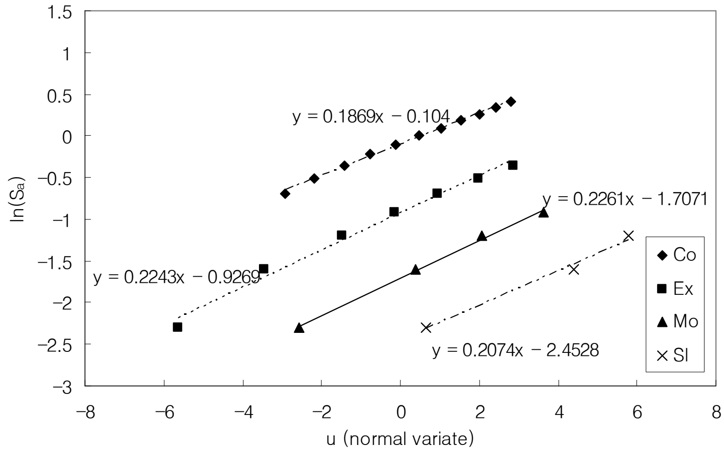

Figure 5: Log-normal Fitting of Fragility

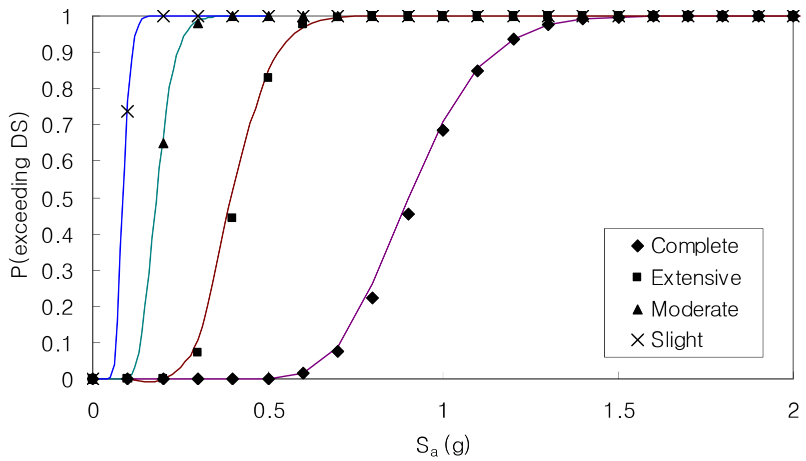

Figure 6: Fitted Fragility Curves

Table 3: Probability of Exceeding Limit States for Different Earthquake Levels

Natural Period (sec)	Earthquake Level (Prob. of Exceed.)	Spectral Acceleration (g)	Probability of Exceeding Limit States			
			slight damage	moderate damage	extensive damage	complete damage
0.450	10% in 50yrs.	0.330	1.000	0.996	0.209	0.000
	2% in 50yrs.	1.057	1.000	1.000	0.999	0.803

6. CONCLUSIONS

Model-based analytical fragility curves for a 2-story unreinforced masonry building typical of the CSUS region are developed in this study. These fragility curves are distinguished from the existing fragility curves in HAZUS in that the HAZUS fragility curves are derived using selected parameters which are based on the subjective judgments of experts. A simplified spring model is developed to describe the highly nonlinear dynamic behavior of URM structures in an effective manner, and a typical URM low-rise building is modeled for the fragility analysis. The fragility curves are then generated for the structure considering the uncertainties in both the seismic demand and the material properties. The fragility analysis shows that the seismic performance of URM buildings is well below the desirable building seismic performance level recommended by the seismic code, demonstrating the high vulnerability of the URM buildings within the CSUS region.

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