Effect of Uncertainties in Development of Fragility Curves for URBM Building

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Abstract

Seismic fragility analysis of Un-reinforced Brick Masonry (URBM) Buildings is useful for determining the possible extent of damage in the event of an earthquake. It is known that there are uncertainties with respect to both the mechanical properties of masonry and the characteristics of earthquake ground motion. This paper presents sensitivity studies: by considering Weibull distribution as candidate distribution for compressive strengths of brick and mortar and varying the Coefficient of Variation (COV); and by using 12 different earthquakes time histories available in the strong motion atlas of India separately. For this purpose a one room, single storey URBM building has been considered and the fragility curves have been obtained by integrating Improved storey shear modelling, Monte Carlo simulation and Incremental dynamic analysis. From the study, it has been observed that while using the Weibull distribution as candidate distribution for mechanical properties of masonry, fragility curves of URBM buildings are not significantly affected by the COV whereas they are sensitive to the choice of earthquake ground motion. Fragility curves obtained using different earthquake time histories show three bands. For the suite of earthquake time histories considered in this study, the observed fragilities are generally increasing with the epicentral distance. In other words observed fragilities corresponding to the far-field earthquake time histories are generally higher than those corresponding to the near-field earthquake time histories. Thus, for vulnerability analysis, selection of suite of earthquake time histories judiciously is more important than modelling the statistical variations in mechanical properties of masonry.

Keywords: Coefficient of Variation, Incremental Dynamic Analysis, Seismic Fagility Curves, Sensitivity, Unreinforced Brick Masonry, Weibull Distribution

1. Introduction

Masonry is the most important and one of the oldest construction materials. Now a days brick masonry is widely used for low rise building construction, but its heavy weight and high stiffness with the lower tensile strength makes masonry structures prone to damage during earthquakes. Seismic vulnerability analysis of Unreinforced Brick Masonry (URBM) buildings is useful for determining the possible extent of damage in the event of an earthquake. The conditional probability of exceeding prescribed limit states of damage of an element or a set of elements at risk due to a given severity of ground motion is termed as fragility. Certain approaches to characterize uncertainties in ground motion hazard, building response, damage to building components, and losses (i.e., casualties, financial losses, and business interruption) have been proposed by Baker and Cornell1. In order to find out uncertainty in seismic capacity of masonry buildings a two storey unreinforced building wereanalysed and unit weight, uniaxial compressive strength, shear strength at zero confining stress, Young’s modulus, shear modulus, and available ductility in shear are considered as random variables based on statistical characterization2. Analysis of results of the study Parisi and Augenti2 shows a large dispersion in displacement capacity and lower dispersion in spectral acceleration capacity.

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which can directly reveal both design and retrofit solutions depending on seismic capacity predictions. It is known that there are uncertainties in mechanical properties of masonry and in the characteristics of earthquake ground motion and both uncertainties in mechanical properties of masonry and uncertainties in the characteristics of earthquake ground motion for the development of fragility curve for URBM building are included in the study Balasubramanian et al. For handling uncertainties earthquake time histories corresponding to 12 earthquakes are considered for which data is available in the Atlas of Indian Strong Motion Records. But sensitivity analysis of these uncertainties for the development of fragility curves is not included in the paper. In the present study Weibull distribution is used for considering uncertainties in mechanical properties and characteristics of ground motion in the development of seismic fragility curves of URBM buildings. In the study a single storey building URBM building is chosen from literature for the development of seismic fragility curves. Building is discretized into different piers and capacity curve of building is obtained and the method is called improved storey shear modelling. Damage grades are defined in the capacity curves based on structural performance characteristics. Incremental dynamic analysis is carried out to obtain fragility curves, through performing multiple non-linear dynamic analysis of a structural model under a suite of ground motion each scaled to several levels of seismic intensity. Scaling levels are appropriately selected to force structure through the entire range of behaviour from elastic to inelastic and finally to global dynamic instability, where the structure essentially experiences collapse. In the present study sensitivity analysis is carried out in order to find out the influence of coefficient of variation of compressive strengths of brick and mortar and characteristics of ground motion in the development of fragility curves.

2. Methodology

The methodology integrates Improved Storey Shear Modelling, Incremental Dynamic Analysis and, Monte Carlo Simulation (MCS) for handling uncertainties. Development of fragility curves for a one roomed, single storey URBM building of size 3.03m x 2.76m x 3.19m with opening in walls is done in FORTRAN using the methodology given in literature in which sensitivity of coefficient of variation of compressive strengths of brick, mortar using Weibull distribution and characteristics of earthquake is done. Damage grades are classified into three based on the structural performance characteristics as in the literature than fixed limiting values. Damage Grade 1 (DG1) corresponds to 33% of yield displacement, Damage Grade 2 (DG2) corresponds to yield point of building and Damage Grade 3 (DG3) corresponds to collapse of building. Compressive strengths of brick, mortar, and bed-joint friction coefficient are statistically independent random variables whereas compressive strength, elastic modulus, shear strength and tensile strength of masonry are dependent random variable which depends on the independent ones. Mean values of compressive strength of brick and mortar above lintel and below lintel are taken from the literature. Equation of compressive strength of masonry, elastic modulus, shear strength and tensile strength are taken from literature. Coefficient of variation of compressive strength of brick and mortar are varied (Table 1.) and Multi-Record IDA has been carried out to find the influence of coefficient of variation in seismic fragility. Similar work by using lognormal as candidate distribution for compressive strength of brick and mortar are done in CSIR-SERC.

Sensitivity of uncertainty in the characteristics of earthquake time histories is carried out by separately using Single-Record IDAs for the 12 earthquake time histories available in the literature. For sensitivity of uncertainty in coefficient of variation of compressive strength of brick and mortar a suite of earth quake time histories are selected randomly which include both near field and far field earthquakes whose response spectrum shows a uniformly dispersed band which is given in the literature.

2.1 Estimation of Parameters used in Weibull Distribution

The Weibull distribution is used for modelling instances of failure of individual components of large systems. Weibull distribution is a continuous probability distribution with a scale parameter and shape parameter.

Table 1. Coefficient of variation of compressive strength of brick and mortar used in the study

| Brick COV | Mortar COV |
|-----------|------------|
| 0.1       | 0.05       |
| 0.15      | 0.1        |
| 0.2       | 0.15       |
| 0.25      | 0.2        |
Density function changes drastically with value of shape parameter. Moreover the skewness and coefficient of variation depends only on the shape parameter. In this study Weibull distribution is used as distribution used for considering the uncertainties in material properties of masonry with compressive strength of brick and mortar are random variables whose coefficient of variation is changed in each simulation for understanding its sensitivity in generation of fragility curves.

Distribution function for Weibull distribution is:

\[
F(x) = 1 - \exp \left( -\left( \frac{x}{\sigma} \right)^\eta \right)
\]

Mean, \( \mu = \sigma \Gamma(1 + 1/\eta) \)

Variance = \( \sigma^2 [\Gamma(1 + 2/\eta) - (\Gamma(1 + 1/\eta))^2] \)

Coefficient of Variation
\[
\Omega = \frac{[\Gamma(1 + 2/\eta) - (\Gamma(1 + 1/\eta))^2]^{0.5}}{\Gamma(1 + 1/\eta)}
\]

Where \( \eta \) = shape parameter and \( \sigma_b, \sigma_m, \mu_b, \mu_m \) are scale parameters and \( \mu_b, \mu_m \) are mean values for compressive strengths of brick, mortar below lintel and mortar above lintel. The computed values of scale and shape parameters for compressive strengths of brick and mortar are presented in Tables 2 and 3.

Shape parameter corresponding to the selected COV is determined using trial and error method and it will decrease with increase in coefficient of variation of compressive strength. Scale parameter is found out from obtained shape parameter corresponding to COV, and it varies depending on the change in mean value of compressive strength of brick and mortar.

### 2.2 Suite of Earthquake Time Histories

The details of the earthquake time histories considered in the study are presented in the Table 4.

### 3. Results and Discussions

Suite of earthquakes are selected and whose PGA is scaled to different levels of seismic intensity to study the entire range of behaviour of the considered building from elastic to inelastic range and finally at the collapse level or the point at which fragility becomes 1. DG1, DG2, DG3 are

**Table 2.** Scale parameters and shape parameters corresponding to the selected COV for compressive strength of brick

| \( \Omega \) | \( H \) | \( \mu_b \) (in MPa) | \( \sigma_b \) |
|---|---|---|---|
| 0.1 | 12.5 | 24.2 | 25.2155 |
| 0.15 | 7.905 | 24.2 | 25.7120 |
| 0.2 | 5.79 | 24.2 | 26.1372 |
| 0.25 | 4.542 | 24.2 | 26.5041 |

**Table 3.** Scale parameters and shape parameters corresponding to the selected COV for both the mortars below and above lintel

| \( \Omega \) | \( H \) | \( \mu_b \) (in MPa) | \( \mu_m \) (in MPa) | \( \sigma_b \) | \( \sigma_m \) |
|---|---|---|---|---|---|
| 0.05 | 24.9 | 5.9 | 2.1 | 6.0305 | 2.1464 |
| 0.1 | 12.5 | 5.9 | 2.1 | 6.1476 | 2.1881 |
| 0.15 | 7.905 | 5.9 | 2.1 | 6.2686 | 2.2312 |
| 0.2 | 5.79 | 5.9 | 2.1 | 6.3723 | 2.2681 |

**Table 4.** Earthquake time histories considered in the study

| Earthquake designation | Earthquake | Date | Recording station | \( R \) (in km) | NF/FF | PGA (in g) | Magnitude \( (m_b) \) |
|---|---|---|---|---|---|---|---|
| EQ1 | Dharmsala Earthquake | 26/04/1986 | Shahpur | 9.98 | NF | 0.248 | 5.5 |
| EQ2 | North-East India Earthquake | 10/09/1986 | Saitsama | 44.79 | FF | 0.139 | 5.2 |
| EQ3 | India-Burma Border Earthquake | 18/05/1987 | Diphu | 105.03 | FF | 0.086 | 5.7 |
| EQ4 | India-Bangladesh Border Earthquake | 06/02/1988 | Nongkhlaw | 116.27 | FF | 0.114 | 5.8 |
| EQ5 | India-Burma Border Earthquake | 06/08/1988 | Diphu | 189.94 | FF | 0.337 | 6.8 |
| EQ6 | India-Burma Border Earthquake | 10/01/1990 | Berlongfer | 230.01 | FF | 0.145 | 6.1 |

(Continued)
3. Results and Discussions

A suite of earthquakes are selected and whose PGA is scaled to different levels of seismic intensity to study the entire range of behavior of the considered building from elastic to inelastic range and finally at the collapse level or the point at which fragility becomes 1. DG1, DG2, DG3 are three damage grades corresponding to 33% of yield point of building, yield point of building, and collapse of building respectively as per literature.

(a) against DG1  (b) against DG2  (c) against DG3  
(d) against DG1  (e) against DG2  (f) against DG3  
(g) against DG1  (h) against DG2  (i) against DG3  
(j) against DG1  (k) against DG2  (l) against DG3

Figure 1. Fragility curves for the URBM building considered. (a)-(c) for brick COV 0.1; (d)-(f) for brick COV 0.15; (g)-(i) for brick COV 0.2; (j)-(l) for brick COV 0.25; M-0.05, M-0.1, M-0.15, M-0.2 refers to COV of mortar 0.05, 0.1, 0.15, 0.2 respectively (X-axis is PGA and y-axis is fragility).

| Earthquake designation | Earthquake            | Date           | Recording station | R (in km) | NF/FF | PGA (in g) | Magnitude (m_b) |
|------------------------|-----------------------|----------------|-------------------|-----------|-------|------------|-----------------|
| EQ7                    | Uttarkashi Earthquake | 10/10/1991     | Uttarkashi        | 32.52     | FF    | 0.309      | 6.5             |
| EQ8                    | Chamba Earthquake     | 24/03/1995     | Chamba            | 8.2       | NF    | 0.146      | 4.9             |
| EQ9                    | India-Burma Border    | 06/05/1995     | Diphu             | 215.91    | FF    | 0.102      | 6.4             |
| EQ10                   | India-Bangladesh      | 10/05/1997     | Jellalpur         | 24.45     | FF    | 0.138      | 5.7             |
| EQ11                   | Chamoli Earthquake    | 29/03/1999     | Gopeshwar         | 8.70      | NF    | 0.359      | 6.4             |
| EQ12                   | Kachchh Earthquake    | 26/01/2001     | Ahmedabad         | 238       | FF    | 0.106      | 7               |

Note: R - Epicentral distance; NF-Near-Field earthquake; FF-Far Field earthquake; m_b-Body wave magnitude. For 12 different earthquakes time histories the response spectra corresponding to the near field and far-field earthquake time histories are not separated significantly and they form a uniformly dispersed band.
three damage grades corresponding to 33% of yield point of building, yield point of building, and collapse of building respectively as per literature. Fragility curves corresponding to constant COV for compressive strength of brick and varying COV of compressive strength of mortar is plotted in the Figure 1 (a)-(l) for DG1 and DG2 and DG3. Fragility curves for brick COV 0.1, 0.15, 0.2, 0.25 is having the almost similar graph for all the three damage grades. Figure 2 (a)-(c) shows the fragility curves obtained for 12 earthquakes for three damage grades with x-axis PGA and y-axis fragility. Curves corresponding to 12 earthquakes are attaining the fragility value 1 at different PGA values and the fragility curves of these earthquake time histories show three bands for all three damage grades. Following are the observations made from the fragility curves plotted:

- PGA corresponding to that fragility curves against DG1 (Figure 1(a), (d), (g) and (j)) has attained a value of unity at 4.5 m/sec², 4.75 m/sec², 5.0 m/sec² and 5.0 m/sec² for mortar COVs of 0.05, 0.1, 0.15 and 0.2 respectively. Whereas, for attaining the values of fragility 0.25, 0.5, 0.75 there is no change in PGA.

- PGA corresponding to that fragility curves against DG2 (Figure 2(b), (e), (h) and (k)) has attained a value of unity at 10.25 m/sec² for mortar COVs of 0.05, 0.1, 0.15 and 0.2 respectively.

- PGA corresponding to that fragility curves against DG3 (Figure 2(c), (f), (i) and (l)) has attained a value of unity at 11 m/sec² for mortar COVs of 0.05, 0.1 and at 11.25 m/sec² for mortar COVs of 0.15 and 0.2.

- From Figure 2, fragility curves corresponding to the single record IDA of 12 different earthquake time histories considered in this study damage grades show three band formation.

- Earthquake EQ3, EQ5, EQ6, EQ9 and EQ12 form first band for all the three damage grades whereas EQ1, EQ2, EQ4, EQ7 and EQ8 form second band, EQ10 and EQ11 form third band.

- In first band all earthquakes are far field earthquakes whose epicentral distance (R) is more compared to other earthquakes.

- For the second band of fragility curves in all the three damage grades epicentral distance is less compared to first band and it include both near field and far field.

- Earthquake time histories with very less epicentral distances are found to fall in the third band.

- Thus, in general, the observed fragilities are increasing with the epicentral distance of the earthquake time histories considered and observed fragilities corresponding to the far-field earthquake time histories are generally higher than those corresponding to the near-field earthquake time histories.

Figure 2. Fragility curves obtained from single record incremental dynamic analysis of 12 earthquake time histories (a) for DG1; (b) for DG2; (c) for DG3 (x-axis is PGA (m/sec²) and y-axis is Fragility).
4. Conclusions

Sensitivity analysis of fragility curves considering both uncertainties in mechanical properties of masonry and uncertainties in characteristics of ground motion is carried out in the present study. Study reveals that coefficient of variation of compressive strength of brick and mortar is not significantly affecting the fragility curves of the considered single stored URBM building. On the other hand fragility curves are significantly sensitive to the characteristics of earthquake time histories. For the suite of earthquake time histories considered in the study, the observed fragilities are generally increasing with the epicentral distance and observed fragilities corresponding to the far-field earthquakes are generally higher than those corresponding to the near-field earthquake time histories. Thus, for vulnerability analysis selection of suite of earthquake time histories judiciously is more important than modelling the statistical variations in mechanical properties of masonry.

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