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Seismic Reliability Assessment of Confined Masonry Walls

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Abstract**:** *Masonry buildings are one of the most vulnerable structures against earthquakes, and therefore their seismic response should be evaluated to mitigate casualties in the future. To assess vulnerability and select retrofit approach, fragility curves can be utilized as powerful tools. Conventional methods for showing building fragilities are based on statistical analysis on the building models. Consequently, these analyses can be shown as fragility curves. These diagrams show the probability of exceeding a specific state of damage versus seismic intensity parameters. One of the most important parts of seismic assessment of building by using fragility curves is distribution function selection. In this paper, the vulnerability of Confined Masonry (CM) walls, evaluated based on Park-Ang damage index by using the model developed in OPENSEES software in previous studies, has been used. The damage index values have been selected based on nonlinear dynamic analysis under thirty earthquake records to reduce the uncertainty of ground motion. Also, the goodness of fit of some distribution functions like normal, lognormal, Gumbel, etc. to the damage indices has been assessed. Finally fragility curves are obtained for two soil types B and C based selected distribution. The results show that the lognormal distribution has better fit in low levels of intensities. However, Gumbel distribution is better in higher levels. Fragility curves show the damage probability for various earthquakes intensities. In low intensity levels damage probability on soil type B is dominant. However, in higher intensities CM walls are damaged on soil type C severely.*

Keywords: *Statistical Analysis, Confined masonry building, Fragility curves, distribution functions.*

1. Introduction

Quantification of the seismic damage is essential, particularly for the buildings. Before the occurrence of earthquakes, predicting damage scenarios may address the planning of strengthening and upgrading. After a destructive earthquake, measurement of damage on individual buildings may result in declaring their immediate functionality or the need for abandoning them. Post-earthquake damage assessment may also suggest the choice among repairing, retrofitting, or demolishing and rebuilding. The damage measure depends on the ground motion, both the response and the capacity of the building itself, and the damage index. Many uncertainties affect them, thus a probabilistic assessment seems to be proper. Basically, such an approach involves two quantities: the hazard at the site and the vulnerability of the building. This paper deals with the second one only. Vulnerability is characterized by analytical fragility curves conditional on the earthquake intensity. A number of methods exist for deriving the fragility curves. Aim of this work is using some distribution functions such as normal, lognormal, Gumbel, etc. to find the best fitting to Park-Ang damage index of CM walls. Also, Nonlinear dynamic analyses of CM walls under thirty ground motions have been done based on the simple single-strut (compression-only) element by using OPENSEES software [1].

2. Numerical Modeling of Masonry Walls

The nonlinear analysis program, OPENSEES 2.4 [2], is used to model the buildings and calculate the damage indices. Reinforced concrete buildings, steel buildings can be modeled using this program. But, the models for masonry buildings cannot be generated directly using OPENSEES. By comparing brick and concrete, it can be recognized that both have similar properties. With respect to shear dominated damage of masonry wall, the simple single-strut (compression-only) element model has been used. The model of confined masonry wall without opening is shown in Figure 1 [1].

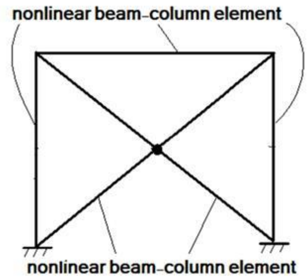


Fig. 1: Model of confined masonry wall without opening [1].

The models shown in Figure 1, have been calibrated in In-Plane direction based on Khanmohammadi-Nahvinia [3]. By comparing relations of width of struts represented by Paulay and Priestley [4], Eshghi and Pourazin [5] and FEMA-356 [6] and calculating lateral stiffness, the relation of FEMA-356has the closest result to Khanmohammadi-Nahvinia [3]. Also, the best relation of strength of wall has been chosen based on Riahi et. al. study[7]. The results of calibrated model are shown in Figure 2.

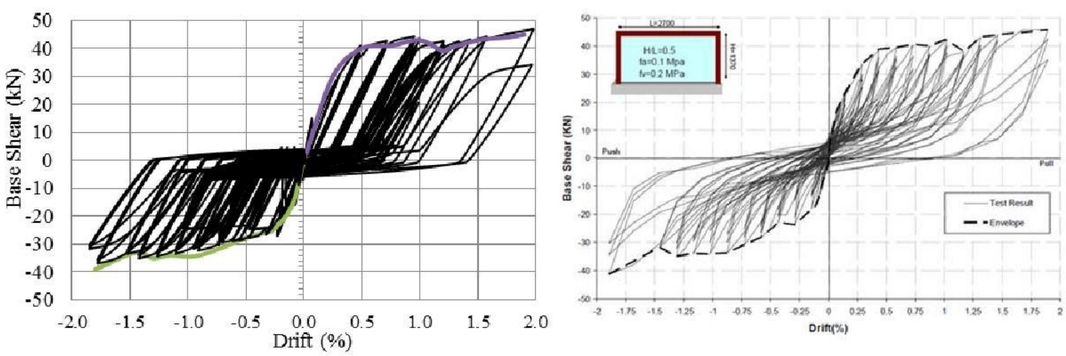


Fig. 2: Calibrated model on In-Plane direction without opening (a) analytical model and (b) experimental [1]

3. Nonlinear Dynamic Analysis

All analyses have been selected based on nonlinear dynamic analysis of 13 CM walls with the same geometry and different materials under thirty earthquake records in [1]. Half of earthquake records are on soil type B and the rest of them on soil type C. Among seismic parameters, EPA has strong correlation with damage index in low-rise building [1, 8].

4. Damage States and Damage Indices

When buildings are subjected to earthquakes, various states of damage occur. Damage index used in [1] is Park-Ang which is common in damage evaluation of building by considering displacement and energy parameters. In this paper, five damage states are considered nonstructural damage, slight structural damage, moderate structural damage, severe structural damage and Collapse. These damage states are defined, using the damage index proposed by Park-Ang [9,10]. The Park and Ang damage index for a structural element is defined as follows [10]:

$$DI_{PA} = \frac{u_{max}}{u_{min}} = \frac{\beta}{F_y u_{mon}} \int dE \qquad (1)$$

Park has proposed β = 0.15 for concrete structures. So this value has been used for calculating damage index of confined masonry wall in this study. The range and best-estimate values of the building damage index, DT, corresponding to various states of damage, are shown in Table 1.

TABLE I: Damage States Based On Park &Ang Damage Index [10]

Damage State		DT	
		Range	Best Estimation
1	Nonstructural damage	0.01 - 0.10	0.05
2	Slight structural damage	0.10 - 0.20	0.15
3	Moderate structural damage	0.20 - 0.50	0.35
4	Severe structural damage	0.50 - 0.85	0.67
5	Collapse	0.85 - 1.15	1.00

5. Distribution Functions

5.1. Normal Distribution

Normal distribution, which likes bell curve, is known with two parameters mean (μ) and standard deviation (σ). Thus, by calculating these parameters the probability can be calculated. The probability density function is recognized as follows:

$$f(x, \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{2}$$

5.2. Lognormal Distribution

Lognormal distribution is a continuous probability distribution of a random variable whose logarithm is normally distributed. Thus, if the random variable X is lognormally distributed, then Y=log(X) has a normal distribution. A random variable which is log-normally distributed takes only positive real values. This distribution is known with two parameters mean (μ) and standard deviation (σ). The probability density function is recognized as follows:

$$f(x, \mu, \sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}} \quad , x > 0 \tag{3}$$

5.3. Gumbel Distribution

Gumbel distribution is used to model the distribution of the maximum (or the minimum) of a number of samples of various distributions. This distribution is known with two parameters (u) (α). The probability density function is recognized as follows:

$$F_y = \alpha e^{[-e^{\alpha(u-y)} + \alpha(u-y)]} \tag{4}$$

$$\alpha = \frac{\pi}{\sqrt{6}\sigma}, \; u = \mu - \frac{0.577}{\alpha} \tag{5}$$

6. Test of Goodness of Fit

The issues of hypothesis testing and confidence intervals relating to fragility curve development have not been addressed in the literature until 2001. This appears primarily because of the fact that the earthquake engineering community has never had the opportunity to collect damage data of a sufficiently large sample that can be used to develop fragility curves on the basis of legitimate statistical analysis [11]. Sarabandi et al. have shown empirical fragility functions from recent earthquakes.

Data from the 1994 Northridge, California and the 1999 Chi-Chi, Taiwan earthquakes are aggregated and analyzed in order to develop these relationships. Resulting empirical fragility curves are introduced for steel moment frame, concrete frame, concrete shear wall, wood frame and rehabilitated unreinforced masonry buildings. [12]. Figure 3 shows the relationship among damage probability matrix, probability distribution fit, and fragility curve for hypothetical data. Based on this figure, lognormal distribution has a good fitness. However, it does not show the goodness of fit in details. In this paper, the visual, Chi-squared and Kolmogrov-Smirnov method was used for test of goodness of fit to select the best distribution and finally show the fragility curves based on it.

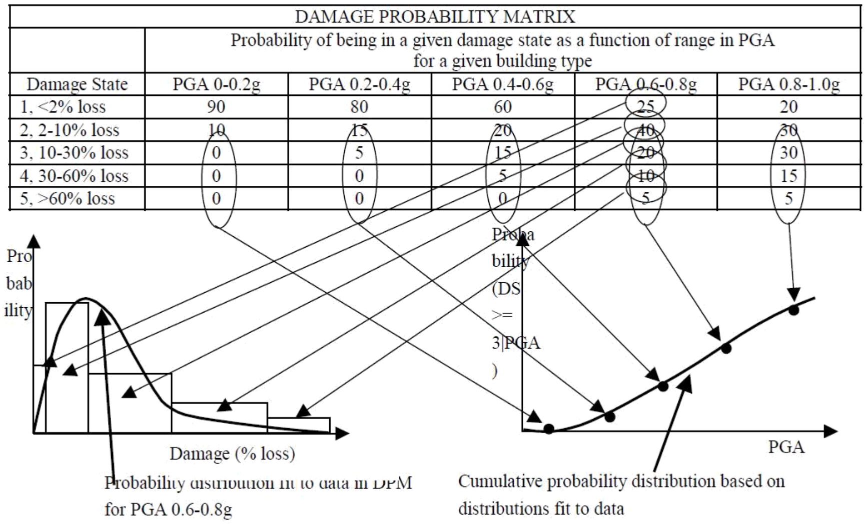
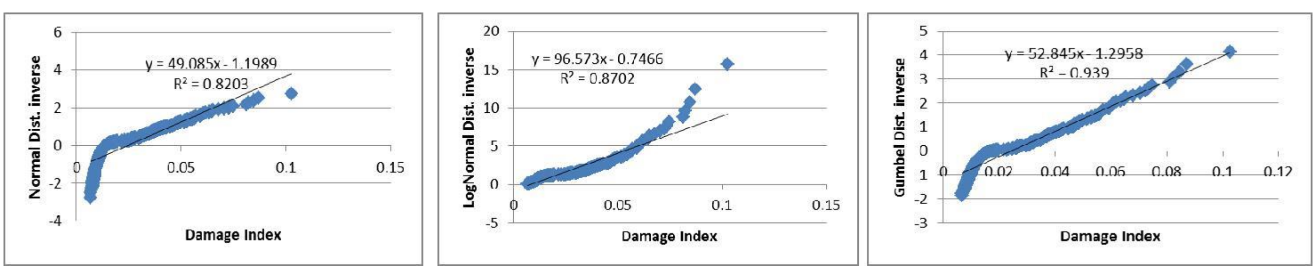


Fig. 3: Illustration of relationship among damage probability matrix, probability distribution fit, and fragility curve [12].

6.1. Method 1: Visual Method

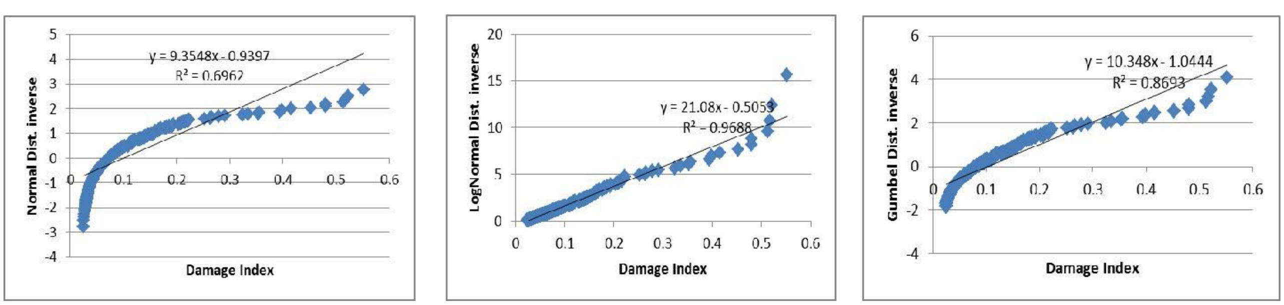
One branch of this method is using the histograms. If the selected distribution function drawn on histogram well, it will be suitable. A good method is drawing data and inverse of cumulative distribution on the same horizontal and vertical axes. If produced curve has a good trend line with a straight line, selected distribution will be suitable.

In this paper, visual method has been used to show whether selected distribution is suitable or not. To use this method, data are arranged in ascending order and specify a number. Then the probability is calculated based on relation: p=i/(n+1). Where i is number of each data and n is number of all data. Finally, draw a curve which data is horizontal axis and inverse of cumulative distribution of probability is vertical axis. Regression of the curve and linear trend line shows the goodness of fit. The data of damage index of CM walls, under earthquake loads in 3 levels of intensity have been evaluated. Each level contains 338 damage indices. The results of EPA=0.2g, EPA=0.4g and EPA=0.6g are shown in Figure 4, Figure 5 and Figure 6 respectively.

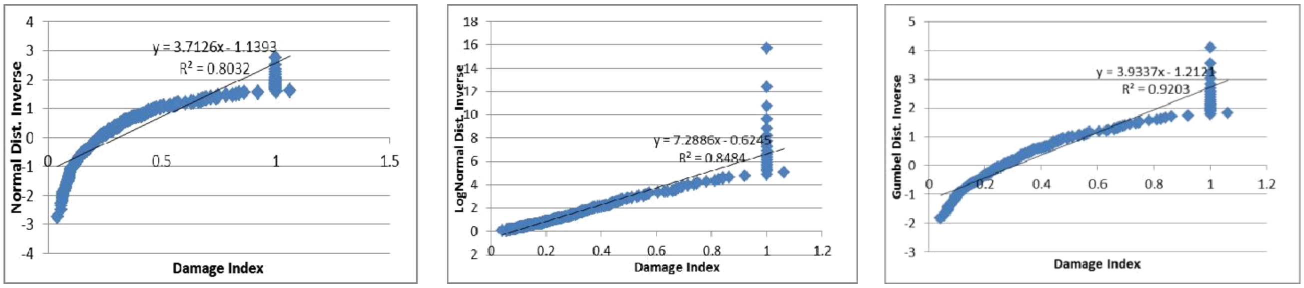


(a) (b) (c)

Fig. 4: Goodness of fit of (a) Normal Dist. (b) Lognormal Dist. (c) Gumbel Dist. (EPA=0.2g)



(a) (b) (c) Fig. 5: Goodness of fit of (a) Normal Dist. (b) Lognormal Dist. (c) Gumbel Dist. (EPA=0.4g)



(a) (b) (c)

Fig. 6: Goodness of fit of (a) Normal Dist. (b) Lognormal Dist. (c) Gumbel Dist. (EPA=0.6g)

6.2. Method 2: Chi-squared Method

This method is based on Chi-squared distribution:

$$f_X(x) = \frac{1}{2^{\frac{n}{2}}\Gamma\left(\frac{n}{2}\right)} x^{\frac{n}{2}-1} e^{-\frac{x}{2}}, \qquad x > 0 \tag{6}$$

Where n is degree of freedom:

N=k-np-1

n_p is two (for distribution with two parameters) and k is number of data. To test the goodness of fit, delta can be calculated as follows and compared with significance level. The results of goodness of fit are shown in table 2 to 4.

$$\Delta = \sum_{i=1}^{n} \frac{(k_i - e_i)^2}{e_i} \tag{7}$$

TABLE II: CHI-SQUARED TEST FOR EPA=0.2G

0.2 g		
Normal	LogNormal	Gumbel
254.340	113.122	84.901

TABLE III: CHI-SQUARED TEST FOR EPA=0.4G

0.4 g		
Normal	LogNormal	Gumbel
582.119	79.768	98.047

TABLE IV: CHI-SQUARED TEST FOR EPA=0.6G

0.6 g		
Normal	LogNormal	Gumbel
73.490	32.170	32.514

6.3. Method 3. Kolmogrov-Smirnov Method

This method is more useful than the other approaches for data with small frequency. To calculate the goodness of fit with this method some functions will be defined. The results of goodness of fit are shown in table 5 to 7.

$$S_n = \begin{Bmatrix} 0 & x < x_1 \\ \frac{i}{n} & x_i < x < x_{i+1} \\ 1 & x > x_n \end{Bmatrix} \tag{8}$$

TABLE V: KOLMOGROV-SMIRNOV TEST FOR EPA=0.2G

0.2 g		
Normal	LogNormal	Gumbel
0.225	0.181	0.186

TABLE VI: KOLMOGROV-SMIRNOV TEST FOR EPA=0.4G

0.4 g		
Normal	LogNormal	Gumbel
0.191	0.075	0.182

TABLE VII: KOLMOGROV-SMIRNOV TEST FOR EPA=0.6G

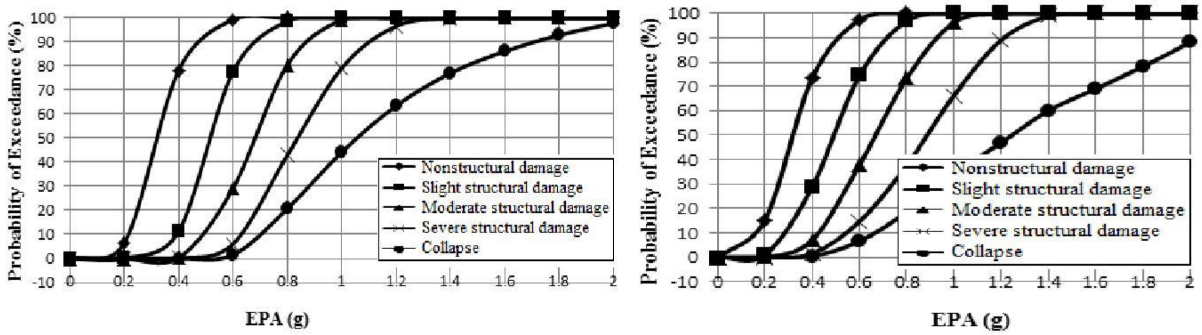
0.6 g		
Normal	LogNormal	Gumbel
0.165	0.043	0.111

7. Fragility Curves

The probability PF_{ij} , that the damage exceeds the i^{th} damage state, given the occurrence of an earthquake with PGA equal to a_j , can be determined as follows:

$$F_i(im) = P\left(DI > d_i \mid IM = im\right) = 1 - P\left(DI \leq d_i \mid IM = im\right) = 1 - \Phi\left(\frac{\ln(DI_i) - \ln(\overline{DI})}{\sigma_{\ln(DI)}}\right) \quad (9)$$

The fragility curves in In-Plane direction include wall without opening on soil type B and C (based on USGS). Park-Ang damage index for all walls has been calculated based on the maximum story drift and the reaction of the wall base. It should be mentioned that by considering 13 models and 30 earthquake records 3900 nonlinear dynamic analyses have been done to obtain all fragility curves. Fragility curves of wall without opening in In-Plane direction are shown in Figure 7.



(a) (b)

Fig. 7: Fragility curves of wall without opening on (a) soil type B, (b) soil type C

8. Conclusion

Fragility curves provide a powerful tool for anticipating the damage to structures in future probable earthquakes. Also, the effect of different parameters on the seismic behavior of these structures can be investigated through using fragility curves.

This paper presents some distribution functions for confined masonry fragility curve development on the basis of statistical analysis. Damage data used in this study, have been calculated in nonlinear analysis of CM wall under thirty earthquake records for three Effective Peak Acceleration (EPA) levels (0.2g, 0.4g and 0.6g). 338 damage indices for each intensity level have been considered. As usual lognormal distribution is used to obtain fragility curves. However, there is not any research in goodness of fit for CM buildings. By considering three distribution functions, Normal, Lognormal and Gumbel, this test has been done. Also, three method, visual, chi-squared and Kolmogrov-Smirnov have been used. The results show that the best fit belongs to lognormal distribution. The first method is simple. However, it shows that lognormal and Gumbel distributions are better than normal distribution. In this method, in level of EPA=0.2g, lognormal and Gumbel distribution are nearly the same and about 0.93 and 0.97 respectively as correlation coefficient. In EPA=0.4g, lognormal distribution is the best one and about 0.98. In high levels Gubmbel is better than lognormal distribution. In second method lognormal is the best one except in EPA=0.2g. Finally, in Kolmogrov-Smirnov method lognormal distribution is the best distribution in all levels. In addition, in third method, when EPA=0.2g the lognormal and Gumbel distribution are the same. Generally, lognormal distribution is the best method especially in lower intensity levels. After this distribution, Gumbel defined exponentially is better than normal.

For low values of EPA, the nonlinear effect of the soil type B becomes dominant and increases damage indices. However, as EPA increases, the structural damage on the soil type C becomes predominant. There is no significant difference between the fragility curves and damage indices of confined masonry walls on two types of soils, since the nonlinear effect of soil would not greatly influence short buildings.

9. References

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