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A study on fragility analyses of masonry buildings in Erzincan (Turkey) utilizing simulated and real ground motion records

Shaghayegh Karimzadeh [a,]*, Koray Kadaş [a], Ayşegül Askan [a], Murat Altuğ Erberik [a], Ahmet Yakut [a]

[a] *Middle East Technical University, Department of Civil Engineering, Universiteler, Dumlupinar Bulvari No:1, Cankaya, Ankara 06800, Turkey*

Abstract

Ground motion records are generally required to develop fragility curves which are utilized in seismic loss estimation studies for earthquake prone zones. These records could be 'real', i.e. recorded acceleration time series or 'simulated' records consistent with the regional seismicity and produced using alternative simulation techniques. This study mainly concentrates on development of fragility curves for masonry buildings located in Erzincan (eastern Turkey) using 'simulated' ground motion records and evaluates the suitability of these fragilities by comparing with the curves developed utilizing 'real' records. To generate a set of scenario earthquakes by using regional seismicity parameters of Erzincan, stochastic finite-fault methodology has been employed as the simulation technique. The 'real' records, on the other hand, are selected from Pacific Earthquake Engineering Research Center's NGA-West2 ground motion database and chosen to be compatible with the seismological characteristics of the region of interest. The records are imposed on a set of masonry buildings (with 1-, 2-, 3-stories and 3 different quality classes) representing the building stock in Erzincan. To assess the dynamic responses of the structures, nonlinear time history analyses utilizing equivalent single-degree-of-freedom systems are performed on OpenSees platform. Afterwards, fragility curves for three limit states (Immediate Occupancy, Life Safety and Collapse Prevention) are generated. This study also investigates the sensitivity of these fragility curves to ground motion variability and two alternative fragility curve generation methods.

Keywords: Fragility analysis, masonry structures, real ground motion records, simulated ground motion records, Erzincan (Turkey)

* Corresponding author. Tel.: +903122105428
E-mail address: shaghkn@gmail.com

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1. Introduction

In order to provide reliable information for decision makers regarding the outcomes of potential earthquakes, seismic risk analysis should be performed with high levels of accuracy. One of the main steps in seismic risk analysis is vulnerability assessment. For an analytical vulnerability assessment, fragility functions should be derived. Regional characteristics of the ground motion set have large impact on the fragility curves. So far, most of the fragility curves in the literature have been derived based on global ground motion databases with records from different parts of the world (e.g.: [1-3]). Recently, Karimzadeh et al. [4] has studied seismic damage estimation of Erzincan (Turkey) region utilizing simulated ground motion records. In that study, only a single approach is utilized for derivation of fragility curves. The main purpose of this study is to develop fragility curves for masonry building stock within a specified area using alternative approaches that utilize regionally 'simulated' ground motion datasets and to compare these fragilities with the curves derived using global 'real' records. Other objectives are to evaluate the sensitivity of these curves to both ground motion variability and alternative fragility curve generation methodologies.

In the first part of this study, the sensitivity of fragility curves to two alternative input ground motion datasets derived for an area with high seismicity is investigated. To consider regional seismicity in the study area, the first group of the records is generated using the stochastic finite-fault ground motion simulation methodology as introduced in Motazedian and Atkinson [5]. For this purpose, a set of scenario events is generated using the regional source, path and site models in the region of interest. The second group of the records is selected based on global ground motion databases with records from different parts of the world. Additionally, for each group of the records, the effects of considering ground motion variability in selection process are investigated. The approach for calculation of the conditional probability of exceedance used to derive fragility functions is the other important aspect that affects the generated fragility curves. In the second part of this study, fragility curves are derived based on two alternative approaches followed by a sensitivity analysis.

The region of interest is selected to be Erzincan which is one the most hazardous regions in Turkey with sparse ground motion networks. The city is located on a deep alluvial basin within a tectonically complicated area, at the conjunction of three strike-slip faults: the right lateral North Anatolian Fault, the left lateral North East Anatolian Fault (NEAF), and the left lateral Ovacik fault [6]. To derive fragility curves with the variety of approaches, local building dataset which are collected from a walk-down survey in the study area are utilized. Since the majority of the existing structures in Erzincan are masonry classes (almost 57%), fragility functions are derived and compared for this type of buildings. In this paper, fragility curves are derived with respect to Peak Ground Acceleration (PGA) since there is a strong correlation in between PGA and nonlinear responses of masonry building stock [7].

2. Ground motion records

The effect of input hazard in the final fragility curves is investigated using two different (simulated and real) ground motion record sets.

To provide regional-specific ground motion dataset in the study area, ground motion simulations are implemented along eastern segments of NAFZ. For this purpose, different scenario earthquakes with Mw=5.0, 5.5, 6.0, 6.5, 7.0, and 7.5 as well as the 1992 Erzincan event (Mw=6.6) are simulated using stochastic finite-fault methodology [5]. Simulations are performed at a total of 123 nodes inside of a rectangular region bounded by 39.45°-39.54° Eastern longitudes, 39.70°-39.78° Northern latitudes. The node spacing is approximately 1 km. In the simulation process, the source, path, and site parameters are adapted from a previous study by Askan et al. [6]. As a result of simulations, a total of 861 records are available including different soil conditions, distance and magnitude values. Further details corresponding to the simulations can be found in Askan et al. [8,9]. To perform fragility analyses, of 861 available records, a database of 200 time histories with maximum PGA of 1g is selected. It is noted that the selected time histories are generated on a strike-slip fault mechanism covering a broad range of magnitudes (Mw=5.0-7.5) and the closest distance to the fault plane varies between 0.26 to 17.55 kilometers. The selected ground motion set is subdivided into 20 intensity levels with intervals of ΔPGA=0.05g so that an even distribution for responses of the structures can be obtained.

Along with the simulated record set generated for the study, a set of real records seismologically compatible with the study area is formed. From the NGA-West2 database of Pacific Earthquake Engineering Research Center, 184 records are chosen with following seismological characteristics; fault type as strike-Slip, magnitude range as 5.0-7.5, Joyner-Boore distance range as 0-20 km and $V_{s,30}$ range as 220-500 m/s [10]. Of these 184 available records, 113 records are randomly selected as the original records where some of them are linearly scaled in the time domain to obtain 10 records at each intensity level yielding 200 real records in total considering the PGA range of 0.05-1g for the fragility analyses.

To display the characteristics of the selected records, these records are baseline corrected and filtered with a 4th-order bandpass Butterworth filter (within f=0.25-25 Hz). Then PGA, Peak Ground Velocity (PGV), Housner intensity (HI), Arias intensity (Ia) are calculated. Figure 1 compares distribution of the mentioned ground motion parameters for both real and simulated record sets. The results in the form of scattered data for both real and simulated records demonstrate that even for a specified PGA, regional variability in selection process is taken into account. It is also observed that in terms of PGV, HI and Ia, a close match is obtained for the sets.

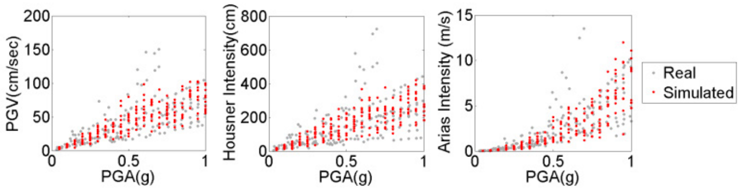

Fig. 1. Distribution of the ground motion parameters for both real and simulated records

3. Masonry building database used in this study

As a result of a walk-down survey in Erzincan, all masonry structures are classified into 9 sub-classes where buildings within each sub-class are believed to exhibit, on average, similar damage behavior under identical seismic intensities. During this classification, two main structural parameters are considered: Number of stories (1-2-3 story) and level of compliance with the seismic design and construction principles (high (A), moderate (B) and low (C)). In definition of the abbreviated names for all sub-classes, 'MU' corresponds to masonry type, the number in the next digit denotes the number of stories, and the letter in the last digit indicates the level of compliance with seismic design codes and construction principles. To assess the dynamic responses of the masonry classes, Non-Linear Time History Analysis (NLTHA) within OpenSees platform is preferred [11]. When dynamic responses of a large population of structures subjected to ground shakings are of concern, it is usually desired to apply simplified and idealized structural models instead of complicated Multi-Degree-of-Freedom (MDOF) models. Accordingly, in this study, each building sub-class is idealized into an Equivalent Single-Degree-of-Freedom (ESDOF) system. For each ESDOF model, a well-known hysteresis model proposed by Ibarra et al. [12], named as "Modified Ibarra-Medina-Krawinkler Deterioration Model with peak-oriented hysteretic response" is defined (Figure 2). Correspondingly, three fundamental structural parameters including period (T), strength ratio (η) and ductility factor (μ) are defined for all building sub-classes. For each subclass a total of 20 samples are simulated using Latin Hypercube Sampling technique. Structural parameters corresponding to the simulated buildings can be found in Karimzadeh et al. [4].

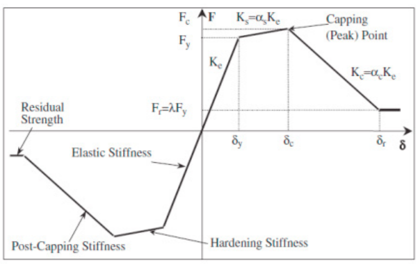

Fig. 2. Backbone curve for hysteresis model (Adapted from Ibarra et al. [12])

4. Fragility studies

In this study, three structural performance levels are considered: Immediate Occupancy (LS1), Life Safety (LS2) and Collapse Prevention (LS3). For generation of all sets of fragility curves, limit states corresponding to these performance levels are taken from Karimzadeh et al. [4]. In this section, first, two alternative ground motion data sets (the first group regionally simulated and the second group global real records) are employed to study the difference of the generated fragility curves to seismic hazard. Then, sensitivity of the generated curves to ground motion variability is evaluated by taking a different number of records for each intensity level inside of each group. In addition, the sensitivity of the fragility analysis is investigated for two alternative fragility curve generation techniques using different probability exceedance functions.

4.1. Study on alternative ground motion datasets (real versus simulated)

In this study, fragility analyses are performed based on real and simulated ground motion datasets as presented in Section 2. To study the effect of variability in seismic demand on the final fragility curves, for each group of records (either real or simulated) two different subgroups with different number of records are considered. The first subgroup consists of 1 set that consists of a total of 200-records for considering ground motion variability (10 records for each intensity level with different soil conditions, distance and magnitude values). The second subgroup involves 10 different sets, each of them containing only 20 records (1 record for each intensity level randomly selected from the first subgroup). In the latter subgroup, variability in seismic demand is ignored within each set.

4.2. Study on alternative fragility curve generation methodologies

In this part, we investigate the sensitivity of fragility curves to two alternative generation methodologies which use different approaches to compute the probability distribution functions. The difference in between two approaches is only on the assumption of the conditional probability of attainment or exceedance of a specified limit state at a certain ground motion intensity level. The first approach assumes a normal distribution function (ND-based) whereas the second approach performs frequency analysis (FA-based) to calculate the probabilities of exceedance. Equation 1 presents the formula used in the first approach whereas Equation 2 corresponds to the formula used for the second approach as follows:

$$P[D \geq LS_i | GMI_j] = a_A \tag{1}$$

$$P[D \geq LS_i | GMI_j] = \frac{n_A}{n_T} \tag{2}$$

where, a_A is the total area in the normal distribution function above the ith limit state (LS_i), n_A is the sum of responses equal or above LS_i, and n_T stands for the total number of responses, both at the jth ground motion intensity level (GMI_j). To obtain the final fragility curve, a cumulative lognormal distribution function is fitted to the scattered probabilities with least squares technique.

5. Discussion of the generated fragility curves

Comparison of the results obtained from simulated and real records reveals a wide range of seismic responses for all masonry sub-classes since they are generally non-engineered structures without any standards regarding the material quality and the construction technique. Figure 3 comparatively displays the fragility curves for both real and simulated records using the 200-record subgroup and FA-based method. For all limit states and subclasses except MU3C-LS3 case, the simulated records provide slightly higher exceedance probabilities than those of real records. When the curves are compared for LS1, a negligible difference is observed between the curves for all subclasses. This observation is much more pronounced for low-story buildings with higher building quality. However, when the results for LS2 and LS3 are of concern, the difference becomes noticeable especially for higher PGA levels. The maximum difference in terms of exceedance probability reaches up to 0.10 where the simulated record-based fragility curves mostly yield higher values than those of real records. This may be attributed to the potential nonlinear responses of structural models at higher intensity (PGA) levels where the responses become more complex due to yielding.

Figure 4.a shows the FA-based fragilities using simulated records for a sample case (MU2B) investigating the sensitivity of the curves for ground motion variability using 200- versus 20-record sets. Comparison of the curves shows that the results from 200-record set almost lie within 1 standard deviation of the mean curves based on 20-record sets. The variation among individual 20-record sets and 200-record set observed for all subclasses demonstrates that the ground motion variability has a significant effect on the final results. Therefore, it seems reasonable to consider ground motion variability in terms of magnitude, source to site distance and soil condition for a certain intensity level in derivation of fragility curves. It is also necessary to compare fragility curves based on the two alternative assumptions for the probability of exceedance. If the curves of a sample subclass (MU2B) from two alternative methods are compared, it can be observed that the exceedance probabilities calculated in according with ND-based method are greater than those of FA-based method (Figure 4.b). This observation is also valid for all subclasses where the maximum difference in terms of exceedance probability is approximately 0.35.

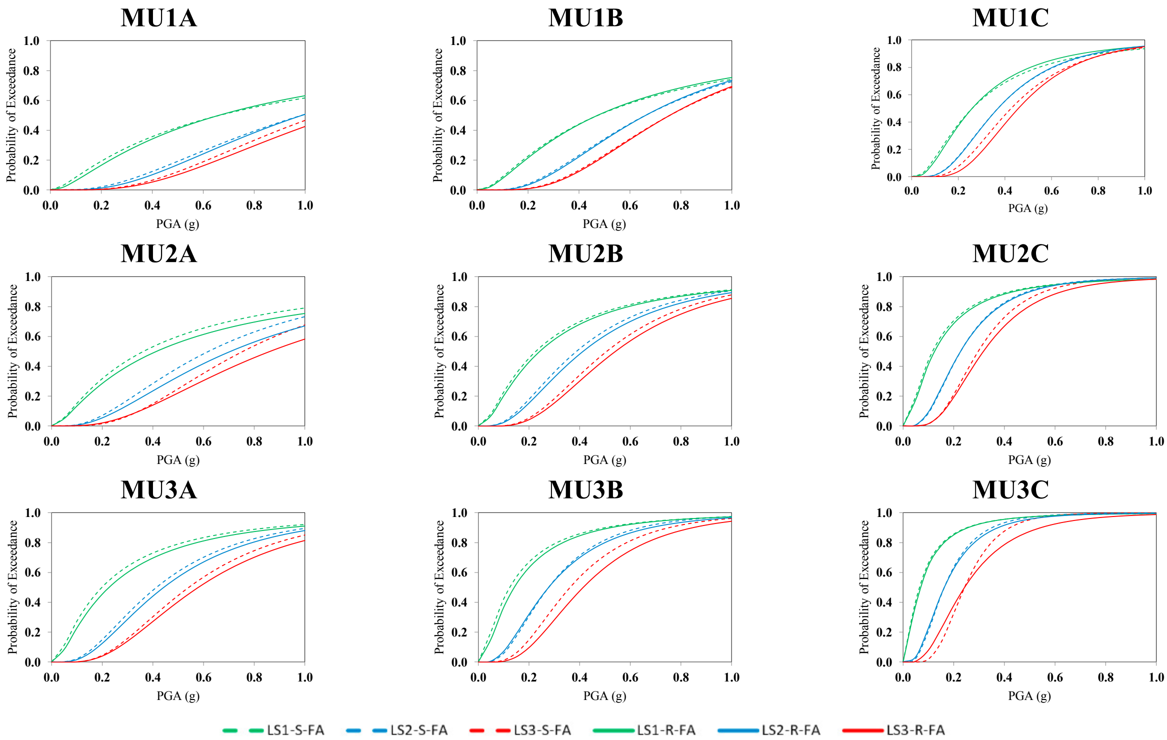

Fig. 3. Comparison of fragility curves for Real versus Simulated Records using 200-record set and FA-based method

6. Conclusions

The focus of this study is to evaluate the sensitivity of fragility curves for masonry structures located in Erzincan, Turkey to alternative ground motion sets (i.e., simulated versus real), ground motion variability (i.e., 200 versus 20 records) and alternative fragility curve generation methods (i.e., FA-based versus ND-based). As it is expected, due to the variability in ground motion records and their dynamic characteristics (e.g.: frequency content, ground motion amplitudes, energy contents), the final fragility curves are influenced by using alternative ground motion set. The level of this influence has been quantified herein. The results from this study show that simulated records can be alternatively used in order to derive regional fragility curves when there is a limited number of ground motion records at high-intensity levels or in regions of sparse seismic networks. Consequently, reliable and conservative fragility curves can be obtained by introducing ground motion variability in terms of magnitude, source to site distances and soil conditions for a certain intensity level through the simulations. This conclusion is valid in the case of ground motion databases that consist of a large number of simulated records such as the presented study. The second part of the study shows that the assumption of either FA-based or ND-based affects the fragility curves particularly when the nonlinear behavior is more likely. Therefore, further evaluation of the methodology is required. The results of this study will be further evaluated in the future, through comparisons of estimated damage levels from the presented fragility curves against the observed damage data obtained after the 1992 Erzincan earthquake.

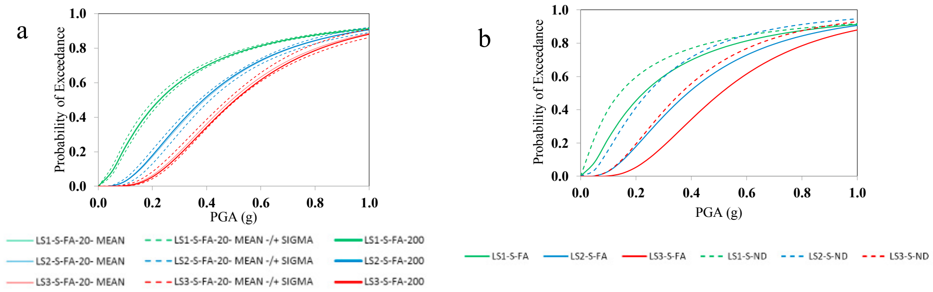

Fig. 4. Comparison of fragility curves for MU2B (a) 200-record set versus 20-record set using FA-based method; (b) FA-based versus ND-based method using 200- record set

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