AN INVESTIGATION ON THE USE OF SIMULATED RECORDS IN DERIVATION OF FRAGILITY CURVES FOR RC BUILDINGS IN DÜZCE

K. Kadaş¹, S. Karimzadeh², A. Askan³, M. A. Erberik³ and A. Yakut³

¹ Graduate Student, Department of Civil Engineering, Middle East Technical University, Ankara
² Post-doctoral Researcher, Department of Civil Engineering, Middle East Technical University, Ankara
³ Prof. Dr., Department of Civil Engineering, Middle East Technical University, Ankara
Email: koraykadas@yahoo.com

ABSTRACT:

Probabilistic assessment of seismic damage for an individual building or a building stock in terms of fragility curves generally requires utilization of ground motion records either seismologically consistent with the probable hazard for the area studied or chosen arbitrarily without considering the seismological characteristics, but covering a range of intensity levels. In both alternatives, the analyst should select several records to be able to perform the probabilistic studies accurately. This condition might not be always satisfied for regions where there are limited number of seismologically consistent records available or for cases when there are less number of records available for high intensity levels. To compensate for this, region-specific stochastically simulated ground motions could be utilized. This study evaluates the suitability of simulated records in development of fragility curves for a typical mid-rise reinforced concrete (RC) moment-resisting frame sampled from existing Düzce buildings. The simulated records have been generated by using stochastic finite-fault methodology with regional seismicity parameters of Düzce. Utilizing a multi-degree-of-freedom model of the selected building, nonlinear time history analyses have been performed and fragility curves considering alternative intensity measures (i.e., PGV, ASI, HI and VSI) have been developed. To test the performance of the simulated records-based fragility curves, a set of ‘real’ records compatible with the seismological characteristics of the region was selected from NGA-West2 ground motion database of PEER, and ‘real’ records-based fragility curves were developed as well. The results have been displayed graphically to present the appropriateness of the simulated records in loss estimation studies.

KEYWORDS: Fragility Analysis, Real Ground Motion Records, Simulated Ground Motion Records, Reinforced Concrete, Düzce

1. INTRODUCTION

Probabilistic seismic loss estimation studies inherently require use of fragility curves to assess the level of seismic damage to the structures. Correspondingly, fragility curves which are developed analytically necessitate utilization of ground motion records either seismologically consistent with the probable hazard for the area studied or chosen arbitrarily without considering the seismological characteristics, but covering a range of intensity levels. In both cases, the analyst should select several records to be able to perform the probabilistic studies accurately. This condition might not be always satisfied for regions where there are limited number of seismologically consistent records available or for cases when there are less number of records available for high intensity levels. To compensate for this, region-specific stochastically simulated ground motions could be utilized. The appropriateness of using simulated ground motions for nonlinear time history analyses has been investigated by various researchers and certain advantages have been displayed along with their shortcomings (e.g.: Galasso and Zareian, 2014; Goda et al., 2015; Karimzadeh et al., 2017a). Recently, Karimzadeh et al. (2017b) examined the suitability of region-specific stochastically simulated ground motions records in determination of nonlinear response of typical moment resisting frames particular to Düzce, which is located in a highly active seismic zone.
of Turkey. The study has shown that ground motion records stochastically simulated for a specific region could be efficiently used to determine the linear and nonlinear dynamic responses of the structures located in that region.

This study takes a step forward and investigates the suitability of simulated records in development of fragility curves based on alternative intensity measures. To test the performance of simulated records in derivation of fragility curves, a set of ‘real’ records compatible with the seismological characteristics of the region was selected from NGA-West2 ground motion database of Pacific Earthquake Engineering Research Center (Ancheta et al., 2013). Under the sets of ‘real’ and ‘simulated’ ground motion records, nonlinear time history analyses have been performed for a multi-degree-of-freedom (MDOF) system of a typical mid-rise reinforced concrete (RC) moment-resisting frame which was selected from existing Düzce buildings (Karimzadeh, 2016). Afterwards, fragility curves for 3 performance states (IO-Immediate Occupancy, LS-Life Safety and CP-Collapse Prevention) have been generated considering alternative intensity measures (i.e., PGV, ASI, HI and VSI). These intensity measures have been recently shown to correlate well with top-drift based seismic damage of structures (Yakut and Yılmaz, 2008; Kadaş and Yakut, 2013; Mazılıgüney et al., 2013; Kadaş and Yakut, 2014). The numerical results of this study have been displayed graphically to present the suitability of the simulated records in loss estimation studies.

2. GROUND MOTION DATABASE

In this study, to investigate the effect of simulated input hazard in development of final fragility curves of typical MDOF RC frames, the research study has been limited to city of Düzce. This region is selected as the study area since the city is located on the seismically very active western segments of North Anatolian Fault Zone (NAFZ). Furthermore, the buildings located within the region represent typical deficient low-to-mid-rise Turkish buildings in rural areas. Two alternative sets of ground motion records are formed: ‘simulated’ and ‘real’ ground motions.

2.1. Simulated Ground Motions

In order to form a regional database of ground motions with distance or azimuthal variability in the Düzce region, a set of scenario events are simulated along the western segments of the strike-slip NAFZ. For this purpose, ground motion simulations are performed for a set of scenario events inside of the Düzce region bounded by 30°- 32° Eastern longitudes, 40°- 41° Northern latitudes. For ground motion simulations, stochastic finite-fault methodology based on a dynamic corner frequency approach proposed by Motazedian and Atkinson (2005) is used.

Scenarios are simulated for different magnitude ranges with moment magnitudes of 5.0, 5.5, 6.0, 6.5, 7.0 and 7.1 (the 1999 Düzce earthquake) considering local source, path and site conditions. Further details corresponding to ground motion simulations in the study area can be found in Ugurhan et al. (2010) and Karimzadeh et al. (2017b). Time histories are generated on a total number of 370 nodes inside the region of interest. For fragility analyses of the selected frame, among the simulated motions, 100 time series with different soil conditions, distance and magnitude values are selected. The selected records are categorized according to primary intensity measure, ASI parameter as modified by Yakut and Yılmaz (2008) (i.e., the period range has been extended to 0.1-2.5s) to a total of 10 intensity levels with intervals of 0.15gs while the maximum ASI value is considered to be 1.5gs. The closest distance of the selected records to the fault plane varies between 0.48 to 47.77 kilometers.

2.2. Real Ground Motions

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, 202 records are chosen with following seismological characteristics: fault type as Strike-Slip, magnitude range as 5.0-7.1, Joyner-Boore distance range as 0-20 km and Vs30 range as 180-760 m/s. Out of these 202 available records,
79 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 100 real records in total considering modified ASI (Yakut and Yılmaz, 2008) for the fragility analyses.

2.3. Main Characteristics of the Ground Motion Database

All selected records are baseline corrected and filtered with a 4th-order bandpass Butterworth filter (within f=0.1-25 Hz). Afterwards, Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Housner Intensity (HI), and modified version of ASI (for the period range of 0.1-2.5s) are calculated via SeismoSignal software (Seismosoft, 2015). Figure 1 compares the 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 ‘real’ and ‘simulated’ records display a close match except for high PGA levels in ‘simulated’ records.

![Figure 1. Distribution of the ground motion parameters for both real and simulated records](image)

3. DESCRIPTION OF THE FRAME ANALYZED

The building typology in Düzce is mostly considered as deficient low-to-mid-rise RC structures and correspondingly, a typical mid-rise RC moment resisting frame has been sampled from Düzce damage database. A five-story-four-bay frame structure, F5S4B, as depicted in Figure 2, was modeled and analyzed in OpenSees software using fiber-based frame elements and nonlinear material definitions yielding dynamic characteristics as
listed in Table 1. Further details regarding modelling of the frame can be found in Karimzadeh (2016) and Karimzadeh et al. (2017b).

Table 1. The total mass and fundamental period of the selected frame.

<table>
<thead>
<tr>
<th>Frame ID</th>
<th>Total Mass (t)</th>
<th>Fundamental Period T₁ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F5S4B</td>
<td>166.02</td>
<td>0.52</td>
</tr>
</tbody>
</table>

4. DERIVATION OF FRAGILITY CURVES

Fragility curves could be derived analytically using mainly two different methodologies (i.e., normal distribution function-based and frequency analysis-based) as investigated basically in Karimzadeh et al. (2017c) particular to masonry structures located in Erzincan. In this study, fragility curves are developed following frequency analysis-based methodology (Equation 1):

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

where, \(n_A\) is the sum of responses equal or above \(i^{th}\) limit state \((LS_i)\), and \(n_T\) stands for the total number of responses, both at the \(j^{th}\) ground motion intensity level \((GMI_j)\). To obtain the final fragility curve, a cumulative lognormal distribution function is fitted to the scattered probabilities using Probit regression (Baker, 2015).

4.1. Limit State Definition

As the fragility curves are generally developed for 3 structural performance levels namely Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP), a nonlinear pushover analysis has been performed to obtain the structure specific pushover curve of the frame structure examined. Based on the global yielding and collapsing points of the structure, IO and CP points are determined, and afterwards, LS point is determined as three-quarters of the CP point. The global drift ratios corresponding to these states are listed in Table 2 and Figure 3 displays the performance levels along with the pushover curve of F5S4B.
Table 2. Global drift ratios corresponding to the limit states IO, LS and CP.

<table>
<thead>
<tr>
<th></th>
<th>IO</th>
<th>LS</th>
<th>CP</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>0.300%</td>
<td>0.785%</td>
<td>1.046%</td>
</tr>
</tbody>
</table>

Figure 3. Pushover curve for F5S4B with corresponding limit states (green for IO, blue for LS and red for CP)

4.2. Dynamic Response of the Frame Structure to the Selected Ground Motion Sets

The primary intensity measure to form uniformly distributed ‘real’ and ‘simulated’ ground motion sets has been selected as ASI (modified by Yakut and Yılmaz, 2008). Thus, the number of records available in each bin of ASI was enforced to be 10. After performing nonlinear time history analyses with the selected records, some of the analyses have been cancelled due to numerical errors as depicted in Figure 4.

It is also noted that for the other intensity measures considered (i.e., PGV, HI and VSI), there is no uniform distribution of results throughout the bins since the ground motion data sets are formed with another intensity measure (i.e., ASI). As observed in Figure 4, there is an accumulation of results in low-to-mid intensity levels, whereas there is lack of sufficient number of results at high intensity levels which might affect the corresponding fragility information. Table 3 summarizes the range of intensity measures resulting from the sets formed considering modified ASI.

Table 3. Range of intensity measures.

<table>
<thead>
<tr>
<th>Intensity Measure</th>
<th>Min</th>
<th>Max</th>
<th># of bins</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASI</td>
<td>0</td>
<td>1.5gs</td>
<td>10</td>
</tr>
<tr>
<td>PGV</td>
<td>0</td>
<td>120cm/s</td>
<td>10</td>
</tr>
<tr>
<td>HI</td>
<td>0</td>
<td>300cm</td>
<td>10</td>
</tr>
<tr>
<td>VSI</td>
<td>0</td>
<td>270cm</td>
<td>9</td>
</tr>
</tbody>
</table>
4.3. Fragility Curves

Using the maximum global drift values extracted from nonlinear time history analyses under ‘real’ and ‘simulated’ record sets, fragility curves for 3 performance levels (IO, LS and CP) have been derived utilizing the code provided by Baker (2015). Figure 5 comparatively displays the fragility curves developed for the intensity measures considered which have been recently shown to be correlating well with top-drift based seismic damage of structures (Yakut and Yılmaz, 2008; Kadaş and Yakut, 2013; Mazılıgüney et al., 2013; Kadaş and Yakut, 2014).

For all intensity measures, it is observed that the ‘simulated’ records show close match with the results of ‘real’ records-based curves for IO limit state. However, a similar performance could not be observed for LS and CP limit states where the difference is reaching to 0.20 in terms of probability of exceedance, with LS for modified ASI as the worst case, ‘real’ records yielding higher values. Yielding of higher probability of exceedance values for ‘real’ records might be attributed to the unavailability of ‘real’ records at high intensity levels and the use of scaled records at these levels.

Close curves are obtained for LS and CP limit states where the basis intensity measure is selected as either PGV, HI or VSI. This could be explained by the fact that there are not sufficient number of records/results available at high intensity levels as discussed before. However, further investigations are necessary for detailed conclusions on this issue.

Figure 4. Number of available results in each bin of alternative intensity measures
Figure 5. Fragility curves for the limit states IO, LS and CP for alternative intensity measures

5. CONCLUSIONS

The objective of this study is to investigate whether the fragility curves generated for a typical mid-rise RC building from alternative ground motion sets, real and simulated records, are consistent with each other. For this purpose, Düzce city, located in western segments of NAFZ, is selected as the study area and ground motion simulations are performed for different scenarios using stochastic finite-fault methodology. On the other hand, real records compatible with the seismological characteristics of the region are selected from NGA-West2 ground motion database of PEER. Then, a 5 story 4 bay MDOF RC building is selected from Düzce damage database for building response evaluation and generation of fragility curves.

Overall, it is observed that in cases of linear elastic responses or structures with low levels of inelasticity (IO limit state), dynamic analyses conducted with real and simulated records yield similar results. For the other limit states (LS and CP), the results are different: At these limit states, the ASI-based fragility curves obtained with real records provide higher probabilities of exceedance compared to the curves obtained based on simulated records. This may be due to the fact that in case of material nonlinearity or higher levels of inelasticity, the ground motion characteristics play an important role due to energy dissipation characteristics of structural systems. However, when the other ground motion intensities (PGV, HI and VSI) are used for generation of fragility curves, the trends can not be generalized due to the limited number of records particularly at higher intensity values.

Finally, numerical results in this study indicate that fragility curves can be derived with simulated data for MDOF structures considering appropriate intensity measures. Further studies should be performed for verification of these fragility curves including loss estimations with curves formed with both real and simulated records.
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