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ANALYTICAL DAMAGE ASSESSMENT OF LOW-CODE BUILDINGS EXPOSED TO THE 2023 KAHRAMANMARAŞ EARTHQUAKE SEQUENCE

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Abstract: *M7.8 Pazarcık, Kahramanmaraş occurred on February 6th has a devastating impact on eleven provinces, resulting in the collapse of numerous buildings and affecting millions of people. After that, a series of strong aftershocks of M6.6 (Nurdağı, Kahramanmaraş), M7.7 (Elbistan, Kahramanmaraş), and M6.4 (Yayladağı, Hatay) struck sequentially. The earthquake sequence causes an increase in the extent of damage and also an increase in the number of collapsed buildings. In this study, the seismic responses of low-code (designed as per TEC 1975) low- and mid-rise buildings located in eleven affected provinces are evaluated under sequential strong ground motions recorded at selected AFAD stations that are close to each city center. The two most damaging events have been chosen by comparing recorded peak ground velocities at the particular station site. Nonlinear dynamic analyses are performed with sequentially recorded ground motions on equivalent single-degree-of-freedom systems based on compiled capacity curves from the literature. The results of the analyses were evaluated in terms of drift ratio to determine the observed ratio of exceeding the prescribed damage limit states. Subsequently, fragility curves were derived separately for the investigated building classes. The findings contribute to a better understanding of the structural vulnerabilities and seismic performance of low-code buildings in the affected regions.*

Introduction

In the aftermath of the devastating earthquake sequence beginning with the M7.8 Pazarcık, Kahramanmaraş earthquake, 35.355 buildings collapsed, 17.491 buildings need to be collapsed urgently, 179.786 buildings were severely damaged, 40228 buildings were moderately damaged, 431.421 buildings were slightly damaged, and 860.006 buildings were undamaged, according to the damage assessment report of the Ministry of Environment and Urbanization dated March 6, 2023. In the earthquake sequence, thousands of aftershocks were recorded, including three major earthquakes which are M6.6 Nurdağı, Kahramanmaraş (ten minutes after the mainshock), M7.7 Elbistan, Kahramanmaraş (nine hours after the mainshock), and M6.4 Yayladağı, Hatay (February 20th). These earthquakes led to further structural damage and the collapse of heavily affected buildings. Therefore, it is crucial to consider the impact of the earthquake sequence on the damage state of the buildings.

Low-code reinforced concrete (RC) frame buildings designed as per the Turkish Earthquake Code of 1975 (TEC 1975) constitute a large portion of residential building stock and are known to be vulnerable to catastrophic seismic events due to structural deficiencies and non-compliance with the code requirements. This study focuses on analytically evaluating low-code low-rise (up to 4 stories) and mid-rise (5-8 stories) residential buildings using ground motions recorded during the earthquake sequence. AFAD network stations close to each of the city centers where the population is dense were selected. Peak ground velocities (PGV) recorded at each station for the four major seismic events mentioned above were utilized. Records with the two highest PGV values from four seismic events were combined separately for components in two horizontal directions for dynamic analyses. The reason to prefer PGV to compare the characteristics of the records is that PGV has a good correlation with structural damage for building-height classes used in this study (Akkar et al. 2005) and also simply-calculated intensity measure. Structural responses were evaluated based on drift ratio obtained from nonlinear dynamic analyses with equivalent single-degree-of-freedom systems (SDOF) based on capacity curves in spectral acceleration-displacement format obtained from the literature.

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Ground Motion Selection

In this study, the records for the four largest earthquakes in the earthquake sequence (M7.8 Pazarcık, Kahramanmaraş (mainshock), M7.7 Elbistan, Kahramanmaraş, M6.6 Nurdağı, Kahramanmaraş, M6.4 Yayladağı, Hatay) were considered. Stations close to city centers in eleven cities were selected to evaluate the PGV values of the ground motions. Then, two major earthquakes were identified for sites nearby a particular station by comparing recorded PGV values. For all provinces except Hatay, the first two largest earthquakes that affected the regions were the mainshock and M7.7 Elbistan earthquake, as expected. Recorded PGV values for the M7.7 Elbistan earthquake are even greater than those for the M7.8 Pazarcık earthquake at certain stations. After the mainshock, it is known that Hatay was locally affected mostly by M6.4 Yayladağı in the earthquake sequence, which caused heavily damaged buildings to collapse.

Recordings for all earthquakes were not available at each selected station. For example, since ground motion data for the M7.7 Elbistan, Kahramanmaraş was not available at some selected stations (4619, 4620, 4621, 6305), the ground motion data of the M6.6 Nurdağı, Kahramanmaraş was considered for those stations. Interestingly, the M6.4 Yayladağı earthquake was recorded at only one of the selected stations in Hatay. Also, only one station was found near Kilis, and there is no record for the M7.8 Pazarcık earthquake at this station. Consequently, records of the M6.6 Nurdağı and M7.6 Elbistan earthquakes were used for Kilis. Table 1 displays the selected stations in each province and the two highest recorded PGV values in the earthquake sequence, which are calculated as the geometric mean of those in two orthogonal directions. In Table 1, the listed PGVs for the first earthquake in all provinces except Kilis are obtained from the M7.7 Pazarcık earthquake, while the second earthquake varies based on the effects of the events in the earthquake sequence.

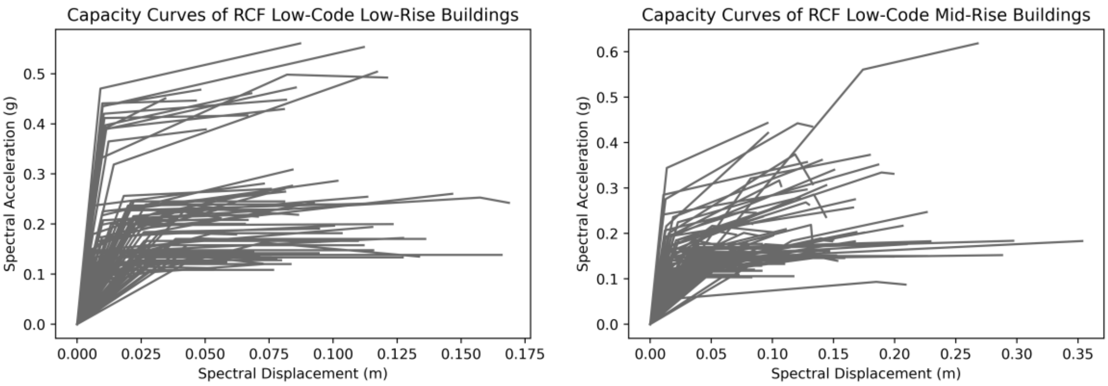
Province	Station Code	First Earthquake PGV (cm/s)	Second Earthquake PGV (cm/s)
Adana	0118	16.50	17.38
Adana	0123	16.33	18.13
Adana	0125	28.64	24.17
Adıyaman	0213	71.97	24.21
Diyarbakır	2101	15.11	7.84
Elazığ	2310	10.10	5.76
Gaziantep	2703	14.70	13.35
Hatay	3123	135.79	
Hatay	3124	104.43	63.78
Hatay	3125	87.89	37.40
Hatay	3126	101.11	11.22
Hatay	3129	114.15	9.20
Hatay	3131	46.48	6.29
Hatay	3132	59.27	8.18
Malatya	4406	18.94	27.33
Kahramanmaraş	4617	27.26	24.88
Kahramanmaraş	4618	24.85	6.64
Kahramanmaraş	4619	30.23	8.26
Kahramanmaraş	4620	34.47	29.11
Kahramanmaraş	4621	37.97	18.60
Şanlıurfa	6305	13.76	1.58
Kilis	7901	4.86	11.94
Osmaniye	8003	28.26	17.80

Table 1. Selected stations and recorded two largest PGV values in the earthquake sequence.

Consequently, two major ground motions in two horizontal components were combined at each station to analyze representative building models. A total of 46 ground motions were utilized for the dynamic analyses.

Nonlinear Dynamic Analyses on Low-Code RC Frame Building Models

Capacity curves are obtained from the results of nonlinear static analyses performed by Sucuoglu et al. (2004), Akkar et al. (2005), Inel et al. (2008, 2016), Silva et al. (2014), Ucar et al. (2015), Guler et al. (2008), Sengoz and Sucuoglu (2009), and Cavdar and Bayraktar (2015). The study included a total of 94 models representing low-rise buildings and 147 models for mid-rise structures. All capacity curves represented in acceleration-displacement response spectra (ADRS) for low-rise and mid-rise buildings compiled from previous studies are given in Figure 1a and Figure 1b, respectively. To represent the seismic behavior of the buildings as equivalent single-degree-of-freedom (SDOF) systems, these capacity curves were idealized as bilinear or trilinear curves. SDOF systems are modeled and analyzed using OpenSeesPy framework. The hysteretic load deformation response of representative SDOF systems was defined using *Pinching4* material. Dynamic analyses were conducted on these equivalent SDOF systems, considering 46 ground motions, to analytically assess the damage state levels of low-code low-rise and mid-rise buildings exposed to the 2023 Kahramanmaraş earthquake sequence. The impact of the increase in structural damage within the earthquake sequence was taken into account, as combined records of two sequential events were used.



(a) (b)

Figure 1. Capacity curves for low-code reinforced concrete buildings complied from literature: a) low-rise b) mid-rise buildings

Spectral displacement demands of each model (Sd_i) obtained from analyses were required to be converted to roof displacement (δ_i) with Equation 1 where Γ_{1i} is the first mode modal participation factor and Φ_{1i} is the roof level amplitude of the first mode. Then, the top drift ratio (θ_i) is calculated using the building height of each model (H_i) with Equation 2.

$$\delta_i = \Gamma_{1i}\, \Phi_{1i}\, Sd_i \tag{1}$$

$$\theta_i = \delta_i / H_i \tag{1}$$

The threshold levels of damage states are determined based on the drift ratio for each building class, following the guidelines provided in the HAZUS MR4 technical manual (Table 2). It is important to note that in this study, the extensive and complete damage states are not differentiated from each other. This decision is made due to the prevailing knowledge that the building stock mostly has irregularities and was not designed as per the code requirements.

Low-Code	Slight Damage	Moderate Damage	Extensive/ Complete Damage
Low-Rise	0.005	0.008	0.02
Mid-Rise	0.0033	0.0053	0.0133

Table 2. Damage limit states defined as drift ratio.

In this study, ground motions containing various PGV levels are used to assess the structural responses. Totally 11.086 top drift ratios obtained from analyses represent the structural responses of low-code low- and mid-rise buildings located in eleven provinces. The overall evaluation of low-code RC frame buildings with an observed fraction of being in a particular damage state is demonstrated in Figure 2. The findings indicate that 20% are undamaged, 22% are slightly damaged, 36% are moderately damaged, and 22% are extensively or completely damaged.

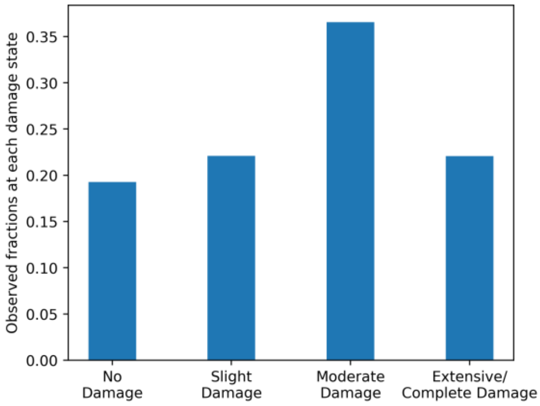


Figure 2. Damage state evaluation of low-code RC frame buildings.

A comprehensive framework developed in the Python environment incorporates the earthquake sequence ground motion dataset, enables the evaluation of the distribution of buildings across various damage states, and ultimately generates fragility curves for each building class.

Derivation of Analytical Fragility Curves

Analytical fragility curves express the exceedance probability of damage states for considered building classes related to the intensity of ground motion (Kircher et al. 1997). Damage states are defined as slight damage, moderate damage, and extensive or complete damage. Threshold levels of these damage states are determined as per the HAZUS MR4 technical manual (Table 2). The top drift ratio is selected as a demand parameter and those obtained from analyses are utilized to evaluate the seismic performance of the investigated building classes in the affected provinces.

Fragility curves were developed using PGV as a ground motion intensity measure, which provides a strong correlation with structural damage (Akkar et al. 2005). To derive the fragility curves, the maximum PGV values observed in each province during the earthquake sequence were utilized. Figure 3 presents the distribution of the maximum observed PGV values in each province obtained from the selected stations.

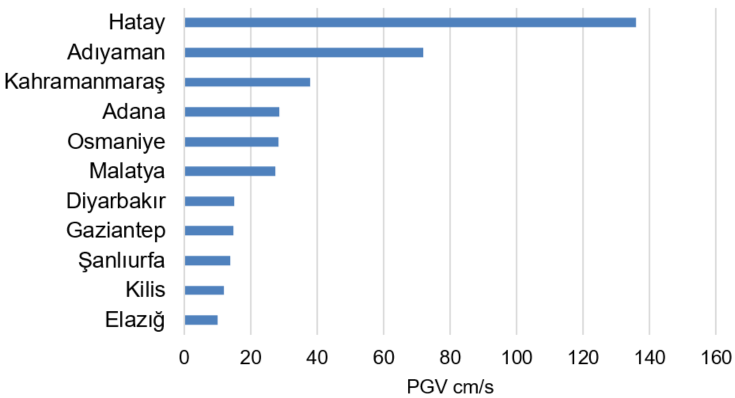


Figure 3. Distribution of maximum PGV values.

In order to derive the fragility curves, the initial step involves determining the number of top drift ratios that exceed the damage limits over the total number of analysis results in each province.

These values are then used to calculate the fractions of observations. Fragility curves fitting to the observed fractions for three damage states are represented in Figure 4.

Lognormal cumulative distribution function is used to derive the fragility curves, and its parameters are estimated using the maximum likelihood estimation method, as suggested by Shinozuka et al. (2000) and Baker (2015). Figure 4 displays the fragility curves derived for the building classes situated near the selected stations.

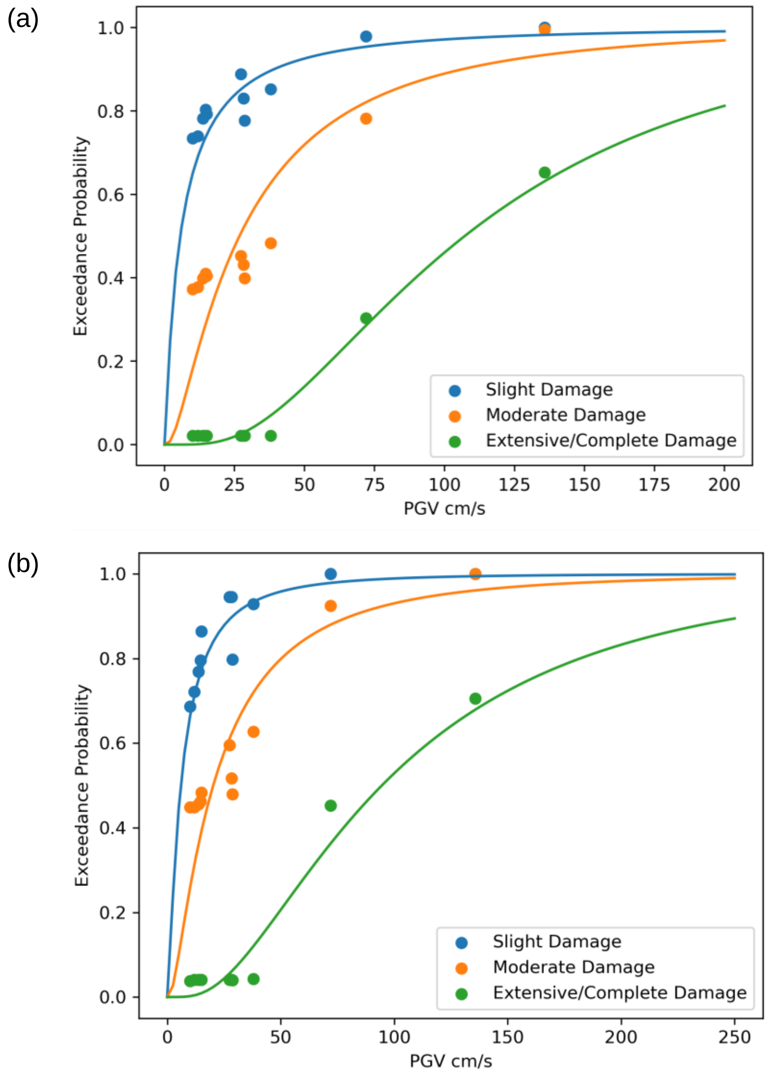


Figure 4. Fragility curves for low-code RC frame buildings a) low rise b) mid rise

Conclusion

The earthquake sequence that occurred in Kahramanmaraş in 2023 resulted in the collapse or damage of numerous buildings. This study focused on assessing the damage caused by the earthquake sequence to low-code low-rise and mid-rise buildings. These types of buildings, which constitute a significant portion of the residential building stock, are known to be vulnerable to seismic events due to structural deficiencies. The analysis utilized ground motion records obtained from AFAD stations located in densely populated areas near city centers, and peak ground velocities (PGV) were used as a measure to evaluate the structural damage. Nonlinear dynamic analyses were conducted using equivalent single-degree-of-freedom systems, considering capacity curves obtained from previous studies.

The evaluation of the dynamic analysis results in terms of the damage limit states revealed that approximately 20% of the investigated building classes were extensively or completely damaged. The TCIP (Natural Disaster Insurance Institution) has reported that as of May 22nd, 2023, 20% of the insurance claims received were for heavily damaged or collapsed buildings. Given that the majority of the damaged buildings are expected to fall within the building classes examined in this study, it can be concluded that a reliable estimation has been made, despite several parameters that hinder direct comparison.

Fragility curves were developed to represent the probability of exceeding different damage states for the considered building classes based on the maximum PGV values observed in each province.

Overall, this study provides valuable insights into the seismic performance of low-code residential buildings in the affected areas following the Kahramanmaraş earthquake sequence. The findings underscore the importance of improving building design and ensuring compliance with seismic codes to mitigate the vulnerability of structures to future seismic events.

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