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Probabilistic methods for the estimation of potential seismic damage: Application to reinforced concrete buildings in Turkey

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ABSTRACT

Three probabilistic methods, for the prediction of potential seismic damage to low and mid-rise reinforced concrete buildings in Turkey, are presented. As the first method, "best estimate" damage probability matrices for each seismic zone are developed by combining expert opinion and the damage statistics compiled from the recent earthquakes occurred in Turkey. Second method involves a reliability-based model, which treats the earthquake force and seismic resistance as random variables. This model expresses potential seismic damage in the form of a damage ratio distribution, which is a function of modified Mercalli intensity or peak ground acceleration. As the third methodology, discriminant analysis technique is utilized to carry out a statistical analysis on the damage data compiled during recent earthquakes that occurred in Turkey. Based on the classification procedure involved in this technique, the damage state probabilities corresponding to different modified Mercalli intensity levels are obtained. These three methods are applied on the building damage databases compiled in the aftermath of several recent earthquakes in Turkey: 1992 Erzincan, 1995 Dinar, and 1999 Duzce earthquakes. The probabilistic damage profile obtained according to these three methods is expressed in terms of damage ratios and the results are compared with each other.

1. Introduction

Earthquakes are natural hazards with high damage potential. However, by utilizing several principles, it is possible to identify and minimize the resulting social and economic losses, which mainly involve loss of human lives, damage to major industrial facilities, civil engineering structures and lifelines.

In general, earthquake loss estimation methodologies involve the following steps: identification of seismic hazard, vulnerability assessment and risk analysis. Major earthquakes occurred all over the world during the past decades increased the number of studies on seismic vulnerability assessment techniques. Majority of these studies focus on empirical and theoretical techniques for estimation of seismic risk for buildings by incorporating the uncertainties related to structural capacity under the assumption of perfectly spatially correlated seismicity (e.g. [1–9]). However, for realistic loss estimations, it is important to take into account the uncertainty related to ground motion variability. Recently several studies have proposed loss models that include spatial variations of seismicity parameters (e.g. [10–12]).

Similarly, in Turkey, where 91.4% of the total area is located in seismically active regions and 95.1% of its population being under earthquake threat [13], many recent methodologies on seismic hazard analysis and damage prediction are developed (e.g. [13–18]). At this stage, in order to estimate and reduce possible future losses, immediate assessment of the seismic resistance of existing structures is quite important. A large number of the studies on damage prediction are deterministic. However, due to aleatory and epistemic uncertainties involved both in seismic demand and seismic capacity, damage prediction procedures should be carried out based on statistical and probabilistic concepts [13].

The objective of this study is to present three different probabilistic approaches in order to estimate the possible future damage to buildings due to earthquakes. These methods are damage probability matrices, reliability-based damage rate model and discriminant analysis. All of the three methods are developed by utilizing statistical and probabilistic techniques, which can be applied on any building group in a certain region, in order to obtain potential damage profile. Both the reliability-based model and the implementation of the discriminant analysis technique are novel approaches for the vulnerability assessment of existing reinforced concrete buildings in Turkey. We note that in all three methods implemented in this study, hazard is assumed to be perfectly spatially correlated.

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2. Damage probability matrices

2.1. Definition and general form of a damage probability matrix

Introduced by Whitman [1] in 1973, a damage probability matrix (DPM) expresses the damage experienced by a particular type of building, designed according to some particular set of requirements, during earthquakes of various intensities. An element of this matrix, $P(\mathrm{DS}, I)$ gives the probability that a particular damage state (DS) occurs when the structure under consideration is subjected to an earthquake of intensity, I. The sum of the probabilities in any column of this matrix is 1.0. In a damage probability matrix, level of damage is described in terms of damage states, whereas the earthquake intensity is generally represented by the modified Mercalli intensity (MMI) scale. The general form of a DPM is given in Table 1. The intensity scale used in the damage probability matrix is the MMI scale since the historical records of past major earthquakes are expressed in terms of MMI. Though in recent studies the damage rates can be expressed in terms of the ground motion parameters, there is a strong correlation between MMI and observed building damage for groups of buildings whose fundamental periods lie within an intermediate range, which makes the quantification of empirical DPMs more convenient.

A damage state in a DPM defines the degree of structural and non-structural damage that would result to a typical building of a specific construction type under an earthquake of a specific intensity. Each damage state is described either qualitatively by a set of words or quantitatively in terms of a damage ratio. Damage ratio (DR) is defined as the ratio of the cost of repairing the earthquake damage to the replacement cost of the structure. In case information regarding actual cost of damage is not available, the verbal description is used. In order to use numerical values in DPMs, quantitative descriptions corresponding to each damage state are defined. On the other hand, even under the same seismic excitation, the damage that may result in a certain type of buildings may vary due to differences in soil conditions, material properties, workmanship and duration of excitation. Thus, DR takes values in between 0% and 100%. In order to set a consistent relationship between damage states and damage ratios and to make calculations easier, the range of the damage ratio corresponding to each damage state is represented by a single damage ratio which is called as the central damage ratio (CDR).

Different design strategies and damage distributions all around the world result in different correlations between damage states and damage ratios. In Turkey, currently the damage states are expressed as No Damage (N), Light Damage (L), Moderate Damage (M), Heavy Damage and Collapse (H, C) states. Based on interviews with damage assessment experts and examining similar studies, Gurpinar et al. [19] estimated the ranges of damage ratios and CDRs corresponding to the five damage states which are shown in Table 1.

2.2. Construction of damage probability matrices

Existing three methods for constructing DPMs are named as empirical, theoretical and subjective methods. *Empirical method* is the assessment of the damage observations of the past earthquakes and evaluation of the relative frequencies of damage states in order to estimate the likelihood of possible damage states. Ideally, when subjective biases are minimized, empirical method is the most reliable way to obtain damage state probabilities. *Theoretical method* consists of dynamic analysis of structures [1]. *Subjective method* involves the subjective judgment of experts depending on their past experience on seismic damage assessment. In this study, the empirical method is conducted using the damage databases of the recent major earthquakes that occurred in Turkey to augment the existing DPMs for reinforced concrete buildings.

Each value in a DPM, $P(\mathrm{DS}, I)$ represents the probability of occurrence of the specific level of damage for a given type of structure, under a certain intensity of ground motion. Using the post-event observational data of past earthquakes, $P_k(\mathrm{DS}, I)$ values can be calculated from:

$$P_k(\mathrm{DS},I) = \frac{N(\mathrm{DS},I)}{N(I)} \tag{1}$$

where $N(I)$ is the number of kth-type of buildings in the region subjected to an earthquake of intensity I and $N(\mathrm{DS}, I)$ is the number of buildings which are in damage state DS, among the $N(I)$ buildings.

It is preferable to express the damage state probabilities involved in each column of the matrix by a summarizing single statistics, called mean damage ratio (MDR), which is defined as follows:

$$\mathrm{MDR}(I) = \sum_{\mathrm{DS}} P_k(\mathrm{DS},I) \cdot \mathrm{CDR}(\mathrm{DS}) \tag{2}$$

where $\mathrm{MDR}(I)$ is the mean damage ratio corresponding to the intensity level I, $P_k(\mathrm{DS}, I)$ is the damage state probability defined in Eq. (1), CDR(DS) is the central damage ratio corresponding to damage state DS. MDR values are generally presented in the last row of a DPM to express the damage ratios in a compact manner.

In the next sections, first the existing DPMs for the active seismic zones in Turkey are examined and then the updated DPMs are presented.

2.3. Existing DPMs for reinforced concrete building stock in Turkey

The development of DPMs for Turkey was first considered by Gurpinar et al. [19] and Gurpinar and Yucemen [20]. In these studies, due to the limited amount of evaluation records from the previous earthquakes, damage state probabilities were estimated by making use of the subjective judgment of experts. The "subjective" DPM corresponding to seismic zone 1, where the seismic hazard is the highest, is presented in Table 2. In this DPM there are two sets of subjective damage probabilities: The first set corresponds to buildings that are designed and constructed in conformance with the specifications designated in the Code (AC), and in the second set it was assumed that the earthquake resistant design provisions are violated (NAC). In that study, the "Code" refers to "Specifications for Structures to be Built in Disaster Areas" which was prepared and put into regulation in 1975 [21]. Later, Yucemen and Bulak [13] developed a set of new DPMs based on the damage

Table 1
General form of a damage probability matrix with central damage ratios as given by Gurpinar et al. [19].

Damage state (DS)	Damage ratio (%)	Central damage ratio (%)	MMI = V	MMI = VI	MMI = VII	MMI = VIII	MMI = IX
None	0–1	0	Damage state probabilities, $P(\mathrm{DS}, I)$				
Light	1–10	5					
Moderate	10–50	30					
Heavy	50–90	70					
Collapse	90–100	100					

Table 2
"Subjective" damage probability matrix for seismic zone 1 (after [19]) AC: according to the Code; NAC: not according to the Code.

Damage state (DS)	CDR (%)	MMI									
		V		VI		VII		VIII		IX	
		AC	NAC	AC	NAC	AC	NAC	AC	NAC	AC	NAC
None	0	1.0	0.95	0.95	0.70	0.70	0.50	0.50	0.20	0.30	0.05
Light	5	0	0.05	0.05	0.15	0.20	0.20	0.20	0.20	0.30	0.20
Moderate	30	0	0	0	0.10	0.10	0.15	0.20	0.40	0.20	0.40
Heavy	70	0	0	0	0.05	0	0.10	0.10	0.10	0.20	0.20
Collapse	100	0	0	0	0	0	0.05	0	0.10	0	0.15
MDR (%)		0	0.25	0.25	7.25	4	17.5	14	30	21.5	42

statistics of the major earthquakes occurred in Turkey after Gurpinar et al.'s [19] study.

2.4. Damage probability matrices formed in this study

After the above studies were conducted, four major earthquakes have occurred in Turkey which caused widespread damage to existing building groups. These are 1995 Dinar, 1998 Ceyhan, 1999 Marmara and 1999 Duzce earthquakes. Due to the high intensities of the mentioned earthquakes and many construction defects involved in the existing building stock, a considerable level of damage was observed. In this study, available earthquake damage reports prepared by the General Directorate of Disaster Affairs and Middle East Technical University (METU) are used to introduce revised damage state probabilities and to complement the empirical DPM given in Yucemen and Bulak [13]. The empirical DPM given in Table 3a is formed by using the damage assessment reports of METU for 1995 Dinar earthquake [22] and reports of the General Directorate of Disaster Affairs for 1999 Marmara and Duzce earthquakes [23,24]. Ceyhan 1998 earthquake data is not utilized herein due to the bias towards the lower damage states involved in the damage database. It also should be mentioned that in Dinar damage database, it was possible to classify the structures as AC and NAC as seen in Table 3a. However, for the rest of the damage databases, related information was missing and the structures are considered to be as NAC structures. We note that in this study, NAC marker is used whenever it is possible to detect that the design or construction of the building is not carried out in accordance with the code [25]. In cases of buildings where there was not sufficient information to identify whether the code is followed or not, the date of construction is used a reference and the buildings prior to the 1998 Code is regarded as NAC buildings. For instance, for the Dinar 1995 earthquake, even though the earthquake occurred before the 1998 code appeared, it was possible to divide the buildings into groups of AC and NAC buildings based on the existing information on buildings. However, for most of the buildings in the Duzce and Erzincan databases, there was insufficient information regarding the individual buildings and most of them were built before 1998, thus we classified them as NAC.

Combining damage state probabilities obtained in this study with the empirical DPM presented in Yucemen and Bulak's [13] study, an updated DPM is constructed for the seismic zones 1 and 2 by relating the cities to the seismic zones. The damage probabilities corresponding to the same zone and intensity such as the case of 1999 Adapazari and 1999 Duzce earthquakes are combined by taking weighted averages with respect to the number of buildings involved. Table 3b shows the empirical damage state probabilities for seismic zones 1 and 2 for various MMI values.

2.5. Best estimate DPMs for Turkey

To obtain a complete set of DPMs for all seismic zones in Turkey and for all possible intensity levels, empirical damage state probabilities given in Table 3b are complemented with the subjective DPMs shown in Table 2. In forming the best estimate DPMs, subjective and empirical damage state probabilities are given weights of

Table 3a
Empirical DPM constructed in this study.

Damage state (DS)	CDR (%)	1.10.1995 Dinar MMI = VIII		17.08.1999 Adapazari MMI = IX	12.11.1999 Duzce MMI = IX
		AC	NAC		
None	0	0.23	0.24	0.04	0.17
Light	5	0.31	0.24	0.34	0.16
Moderate	30	0.38	0.41	0.27	0.28
Heavy	70	0.04	0.05	0.175	0.19
Collapse	100	0.04	0.06	0.175	0.20
Number of buildings		39		79,458 flats	31,800 flats + 119 buildings
MDR (%)		19.75	23	39.6	42.5

Table 3b
Empirical DPM for zones 1 and 2.

Damage state (DS)	CDR (%)	Zone 1 MMI = VI	Zone 2 MMI = VII	Zone 2 MMI = VIII	Zone 1 MMI = VIII	Zone 1 MMI = IX
None	0	0.54	0.45	0.04	0.30	0.08
Light	5	0.34	0.39	0.43	0.45	0.29
Moderate	30	0.11	0.125	0.26	0.13	0.27
Heavy	70	0.01	0.035	0.135	0.07	0.18
Collapse	100	0.00	0.00	0.135	0.05	0.18
MDR (%)		5.7	8.15	32.9	16.1	40.15

Table 4
Best estimate DPM proposed for zone 1.

Damage state (DS)	CDR (%)	MMI = V		MMI = VI		MMI = VII		MMI = VIII		MMI = IX	
		AC	NAC	AC	NAC	AC	NAC	AC	NAC	AC	NAC
None	0	1	0.95	0.95	0.58	0.70	0.46	0.50	0.28	0.30	0.07
Light	5	0	0.05	0.05	0.29	0.20	0.34	0.20	0.39	0.30	0.27
Moderate	30	0	0	0	0.11	0.10	0.14	0.20	0.20	0.20	0.30
Heavy	70	0	0	0	0.02	0	0.05	0.10	0.07	0.20	0.19
Collapse	100	0	0	0	0	0	0.01	0	0.06	0	0.17
MDR (%)		0	0.25	0.25	6.2	4	10.4	14	18.9	21.5	40.7

0.25 and 0.75, respectively. While combining the expert opinion with the observed damage data, we use the weights of 0.25 and 0.75, respectively. These weights are selected in accordance with the number of subjective DPMs versus the empirical DPMs considering that each earthquake produces a single empirical DPM. The damage ratios are not significantly sensitive to the selected weights. For seismic zone 1, when we use even weights of 0.5 for both empirical and subjective data, the individual damage state probabilities vary less than 10%, whereas the mean damage ratios (MDRs) vary less than 3%. For future studies with this approach, we note that, when larger datasets are used from both empirical and subjective sources, the sensitivity of the damage ratios to the weights would be further reduced.

It is worth to mention that in most of the damage assessment reports there was no information on whether the design principles of the building groups complied with the Code [21,25] requirements or not. However, all of the empirical damage state probabilities are assumed to be valid for structures constructed not in accordance with the Code since a wide range of construction defects was observed in the existing building groups. Table 4 shows the best estimate DPM for the Seismic zone 1 of Turkey that is constructed as an outcome of this study. Rather than showing the best estimate DPMs in the form of tables for all seismic zones, we present Fig. 1 to illustrate the MDRs versus MMI to better view the damage state probabilities corresponding to various intensities for all seismic zones and different design strategies. Fig. 1 depicts that regardless of the seismic zone where the structure is located, for all NAC buildings the mean damage ratio versus MMI curves coincide and a single curve is valid for all NAC buildings. This observation is expected since buildings that are not constructed according to the requirements of the code will experience the same mean damage under the same earthquake intensity regardless of the seismic zone. However, for AC buildings, the mean damage ratios are lower in highly seismic zones compared to those in less active seismic zones. This may be related to the fact that, since the expected earthquake forces in seismically active regions are quite high, the design resistances of the AC buildings in these zones are accordingly high. On the other hand, in less active seismic zones the expected earthquake loads are relatively lower and the buildings are designed accordingly with less seismic resistance. Hence, in less active seismic zones, the design seismic capacity is lower and in the case of large-intensity earthquakes, they are expected to experience higher rates of damage compared to those in more active zones.

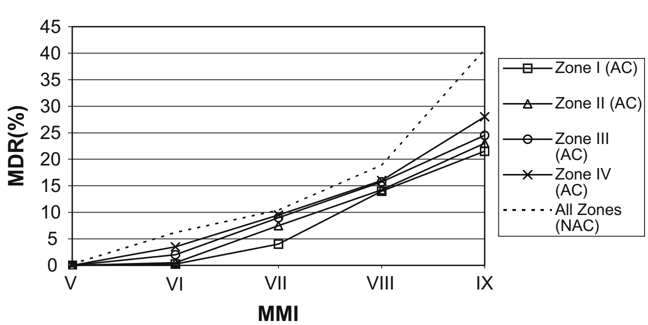

Fig. 1. Variation of MDR with MMI for different zones and design strategies (AC: according to the Code, NAC: not according to the Code).

3. Reliability-based model

An alternative way of defining damage states is to employ simple strength-related damage indices which are straightforward to calculate since they do not require response analysis of the structure. In this study, as the second methodology, we use a reliability-based model similar to that proposed by Shibata [26] which estimates the seismic risk of a building group considering the variation in both the seismic resistance capacity of the existing buildings and the potential seismic force.

3.1. Description of the reliability-based model and definition of the resistance and force indices

This model considers building resistance characteristics and ground motion properties peculiar to Turkey and involves definitions of an earthquake force index and a seismic resistance index. The damage ratio is considered to be a function of ground motion properties and building vulnerability.

It is expressed as the probability of occurrence of a certain level of damage and determined by comparing the force and resistance indices within the framework of classical reliability theory. The basic assumption in this method is that both the seismic resistance and force indices are random variables. Furthermore, statistical analyses of relevant data indicate that both indices are lognormally distributed [18].

The probability of failure in classical reliability theory is defined as follows:

$$P(\text{failure}) = P(\text{Resistance Quantity} \leq \text{Force Quantity}) \quad (3)$$

For the development of a seismic resistance index, the methodology proposed by Shiga [27] is adopted. In that study, the seismic resistance index is defined in terms of the nominal base shear coefficient, i.e. ratio of the total shear force that can be resisted by the structure of interest to the weight of the structure. Similarly, in the search of a nominal value for the total shear force acting on the structures of interest, we identified three indices as follows:

$$\mathrm{WI} = \frac{A_W}{\sum A_f} \quad (4)$$

$$\mathrm{CI} = \frac{A_C}{\sum A_f} \quad (5)$$

$$\tau_{ave} = \frac{F}{(A_C + A_W)} \quad (6)$$

where WI is the wall-area index, CI is the column-area index, τ_{ave} is the average shear stress in walls and columns, in kg/cm^2, A_W is the total area of reinforced concrete walls in one direction in the first floor, in cm^2, A_C is the total area of columns in the first floor, in cm^2, $\sum A_f$ is the total floor area, in m^2, F is the total shear force that can be carried by the structural system and is expressed as $F = cW$ in terms of weight W and base shear coefficient c of the structure. W is the weight above ground level (in kg) and it is taken as $1300 \times \sum A_f$, since the average unit floor weight of the actual buildings in the region was found to be approximately $1300\ \mathrm{kg/m^2}$. The base shear coefficient c is taken to be 0.20 from the recent studies on the seismic performance analyses of low and mid-rise residential structures in the region [28,29].

With the objective of determining nominal shear strength of the building structures of interest, the average shear stress is plotted versus wall and column area indices in order to clearly see the distribution of the damage patterns and states. Using the resulting plots, we identified the two critical values of the average shear stress separating the undamaged and damaged buildings; one value shows the shear stress on the walls and the other on the columns. With these two values, the nominal lateral strength of the structure is calculated as "$10 \cdot A_C + 12 \cdot A_W$", in kg. On the other hand, the nominal lateral force is calculated by multiplying the base shear coefficient by the weight of the structure. Following Shiga [27], we introduced the seismic resistance index C_R through the following equation, where the nominal lateral earthquake force is equated to the nominal strength:

$$C_R \cdot \left(1300 \cdot \sum A_f\right) = 10 \cdot A_C + 12 \cdot A_W \tag{7}$$

Finally, dividing both sides of Eq. (7) by the weight of the structure, the following expression for C_R is obtained:

$$C_R = \frac{10 \cdot A_C + 12 \cdot A_W}{(1300 \cdot \sum A_f)} \tag{8}$$

Physically, the seismic resistance index, C_R, is the ratio of the total shear force exerted on the structure to the weight of the structure. Considering the fact that most of the structural failures observed in recent earthquakes in Turkey were due to shear effects, C_R is an appropriate physical representation of the seismic resistance of the building group under consideration. On the other hand, the earthquake force index C_S depends on the dynamic properties of the buildings (i.e. period and damping effects and soil condition effect), ground motion intensity (i.e. peak ground acceleration or velocity values), and indirectly the return period. It is defined as [18]:

$$C_S = S(T) \cdot \gamma \cdot \frac{A_{\max}}{g} \tag{9}$$

where $S(T)$ is the response spectrum shape given in the Turkish seismic code [25] as a function of characteristic period corresponding to the soil condition type under consideration; $A_{\max}$ is the maximum ground acceleration, g is $9.81\ \mathrm{m/s^2}$; γ is a reduction coefficient which is a function of the damping factor, h and is expressed as follows [26]:

$$\gamma = \left[\frac{1.5}{1 + 10 \cdot h}\right] \tag{10}$$

In this study, a damping factor of 10% is assumed for reinforced concrete buildings.

3.2. Computation of damage state probabilities

According to the reliability-based approach, the rate of seismic vulnerability; in other words the probability of damage exceeding a certain level, is evaluated by comparing the seismic resistance index and earthquake force index. The failure probability is expressed as follows:

$$P(\text{failure}) = P(C_R < \alpha \cdot C_S) \tag{11}$$

where α is the damage state factor defining the level of damage. It is derived by using the energy conservation rule and expressed as:

$$\alpha = \frac{1}{\sqrt{(2 \cdot d - 1)}} \tag{12}$$

where d is the ductility ratio corresponding to the level of damage considered. The values of ductility ratio for different damage states are displayed in Table 5.

Under the assumption of lognormal distributions for the resistance and force indices, the probability of failure is expressed as follows:

$$P(\text{failure}) = 1 - \Phi(\beta) \tag{13}$$

where β is called the reliability index and is to be computed from the following equation:

$$\beta = \frac{\ln\left(\frac{\mu_R}{\mu_S}\right) - \ln\alpha - 0.5 \cdot \ln\left(\frac{1+\upsilon_R^2}{1+\upsilon_S^2}\right)}{\sqrt{(\ln(1+\upsilon_R^2) \cdot (1+\upsilon_S^2))}} \tag{14}$$

In Eq. (14), Φ is the standard normal distribution function, μ_R, μ_S are mean values of resistance and force indices, respectively and υ_R, υ_S are coefficients of variation of resistance and force indices, respectively. In this derivation, it is assumed that C_R is lognormally distributed. This assumption is verified through a series of statistical tests involving Q–Q and P–P plots [18] which are commonly employed probability plots to determine whether the distribution of a variable matches a given distribution. These plots are in the form of a scatter of points along two axes one of which is the observed value and the other is the expected value [32]. If the selected variable matches the test distribution, the data points cluster around a straight line. In particular, Q–Q Plot is a plot of the quantiles of a variable's distribution against the quantiles of the test distribution whereas P–P Plot is a plot of a variable's cumulative proportions against the cumulative proportions of the test distribution.

On the other hand, since $A_{\max}$ is generally assumed to be a lognormal variate [30], it is reasonable to assume C_S to be also lognormally distributed. Utilizing the mean values and the standard deviations of seismic resistance and earthquake force indices of each region, probability of failure under a given intensity is calculated. The resulting failure probabilities are actually cumulative probabilities of damage states and they form the basis for the plotting of the fragility curves, which are shown in Fig. 2a–c for the three damage databases of interest. Using these fragility curves, DPMs for the three damage databases are derived. In this derivation, for a given intensity level, the differences between the cumulative probabilities of the each damage state give the damage state probabilities at that intensity level. The DPMs computed in this way are given in Tables 6a–6c. It should be noted that, since the model does not discriminate the severe and collapse states, CDR corresponding to the damage state "Severe" is taken to be 85% which is the average of CDRs corresponding to "Severe" and "Collapse" damage states. Using the MDRs in Tables 6a–6c, the variation of MDR with MMI is plotted for each damage database in Fig. 3. It is observed that the reliability-based model yields almost the same degree of damage for Duzce and Erzincan whereas the

Table 5
Damage state parameters.

Damage state	Ductility ratio (d)	Damage state factor (α)
Light	0.625	2.00
Moderate	1.00	1.00
Severe	2.00	0.58

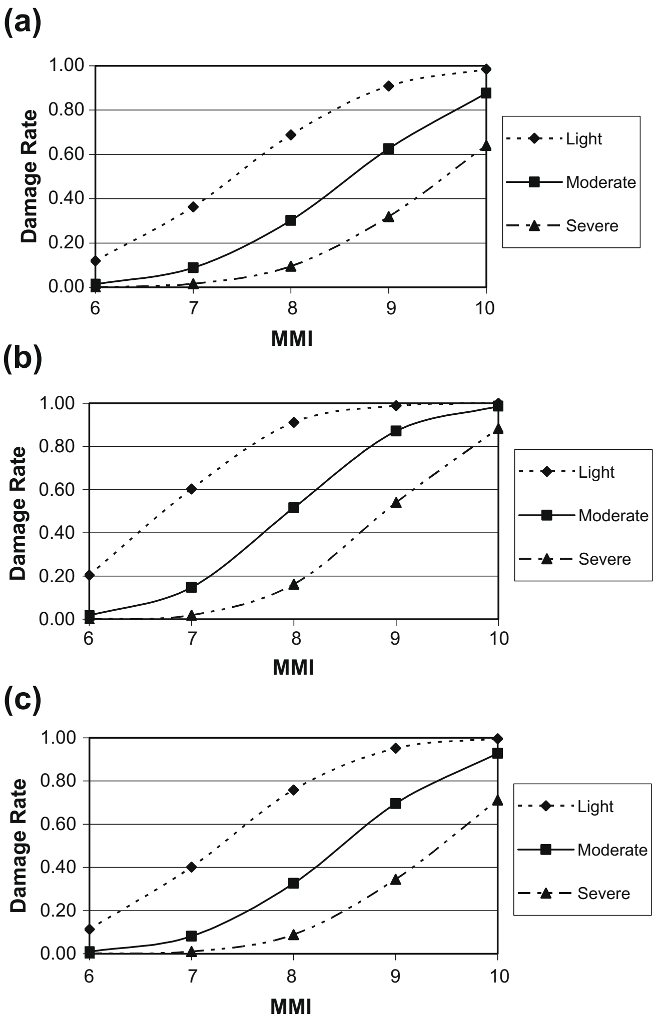

Fig. 2. Fragility curves for (a) Erzincan, (b) Dinar, (c) Duzce damage databases.

Table 6a
DPM for Erzincan damage database as generated by the reliability-based model.

Damage state	CDR (%)	VI	VII	VIII	IX	X
None	0	0.88	0.64	0.31	0.1	0.02
Light	5	0.11	0.28	0.39	0.28	0.1
Moderate	30	0.01	0.07	0.2	0.31	0.24
Severe	85	–	0.01	0.1	0.31	0.64
MDR (%)		0.85	4.35	16.45	37.05	62.1

Table 6b
DPM for Dinar damage database as generated by the reliability-based model.

Damage state	CDR (%)	VI	VII	VIII	IX	X
None	0	0.8	0.4	0.09	0.01	–
Light	5	0.18	0.45	0.39	0.12	0.01
Moderate	30	0.02	0.13	0.36	0.33	0.11
Severe	85	–	0.02	0.16	0.54	0.88
MDR (%)		1.5	7.85	26.35	56.4	78.15

damage estimates for Dinar are higher. This is due to the lower amount of reinforced concrete wall areas in the buildings involved in the Dinar database than that in the other databases [22].

Table 6c
DPM for Duzce damage database as generated by the reliability-based model.

Damage state	CDR (%)	VI	VII	VIII	IX	X
None	0	0.89	0.6	0.24	0.05	–
Light	5	0.11	0.32	0.43	0.25	0.07
Moderate	30	–	0.07	0.24	0.36	0.22
Severe	85	–	0.01	0.09	0.34	0.71
MDR (%)		0.55	4.55	17	40.95	67.3

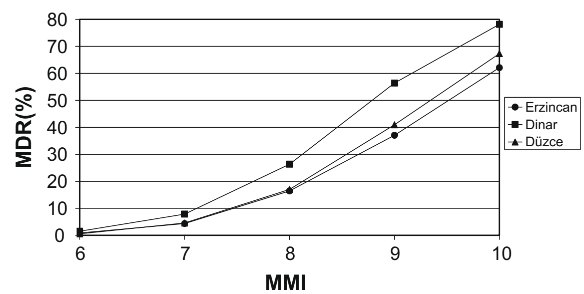

Fig. 3. Variation of MDR with MMI for the three damage databases according to the reliability-based model.

4. Damage ratio estimation based on discriminant analysis

The effects of different parameters on seismic damage vary. In order to make an objective and rational evaluation of damage inducing parameters, a statistical technique known as discriminant analysis is adopted as the third method of the present study. As one of the techniques of the Multivariate Analysis of Variance (MANOVA), discriminant analysis tests group differences due to several dependent variables simultaneously with the investigation of a number of cases [31]. In this study, *groups* are the damage states of the buildings, *cases* are the buildings involved in the damage databases and *variables* are the selected damage inducing parameters. Discriminant analysis in seismic vulnerability assessment aims initially to identify the parameters that discriminate best among the damage state groups; then to develop a function for computing a damage score that will represent differences among the damage states; and finally to develop a rule for classifying future observations, with minimum error, into one of the damage states.

4.1. Definition of damage indices

To perform discriminant analysis, first the estimation variables should be established. The basic assumption is that all of the buildings involved in each inventory are exposed to a specific earthquake and same soil conditions. Assuming that each building stock in itself has faced the same ground motion properties, the damage will be evaluated only on the basis of structural responses. Pay [15] and Yucemen et al. [16] applied discriminant analysis technique on the data compiled from 1999 Duzce earthquake damage assessment reports. The parameters involved in that study were: number of stories, normalized square root of sum of squares of inertias (SRSSI), soft story, overhang and redundancy. In this study, two more parameters; density ratio and floor regularity factor are introduced. All of the seven parameters are applied on the Dinar and Erzincan earthquake damage databases, whereas only six of them are applied on Duzce damage database, since floor regularity factor could not be calculated due to the insufficient information on this parameter. The parameters are defined briefly:

Number of stories (n): This parameter is taken as the number of stories above ground level.

Normalized square root of sum of squares of inertias (SRSSI): It is one of the parameters representing the rigidity of the structure. The lateral rigidity is expressed by a combination of the moment of inertias of all vertical members. SRSSI is a stiffness parameter that involves directional behavior by combining moments of inertia in two directions and it also includes the contribution of masonry walls. SRSSI is defined as follows [15]:

$$\mathrm{SRSSI} = \sqrt{\left(\sum I_x\right)^2 + \left(\sum I_y\right)^2} \tag{15}$$

where

$$\sum I_y = (I_y)_c + (I_y)_s + c \cdot (I_y)_m \tag{16}$$

$$\sum I_x = (I_x)_c + (I_x)_s + c \cdot (I_x)_m \tag{17}$$

In the above equations, I_c is the total moment of inertia of columns in a horizontal direction, x or y; I_s is the total moment of inertia of shear walls in a horizontal direction, x or y; I_m is the total moment of inertia of masonry walls in a horizontal direction, x or y; $\sum I_x$ is the total effective moment of inertia of the members with respect to x axis; $\sum I_y$ is the total effective moment of inertia of the members with respect to y axis; SRSSI is the normalized square root of sum of squares of inertias, and c is the contribution factor of masonry walls and its value is determined based on the results of previous experimental studies [15]. The performance of reinforced concrete (RC) frames with RC infill walls and RC frames with masonry infill walls under reversed cyclic loading are compared and the 'c' is defined to be the relative contribution of the masonry infill walls with respect to RC infill walls. It is calculated as $c = \frac{k_m}{k_{RC}} \cdot \frac{I_{RC}}{I_m}$, where k_{RC} and k_m are the initial stiffness and I_{RC} and I_m are the moments of inertia in the stronger directions of the frames with RC and masonry walls, respectively.

Soft story (ss): Soft story is expressed in terms of the ratio of first story height h_1, to second story height, h_2.

Overhang (oh): This parameter represents the overhang deficiency of a structure. An overhang is defined as the part of a structure where a vertical structural member does not underlie, such as in the case of a balcony. This parameter is expressed by the ratio of footprint area to first floor area and it is denoted by "oh".

Redundancy (r): Redundancy is a measure of the number of continuous frames in two directions. Pay [15] defined a maximum area allowed for the number of frames in two directions. It is derived on the assumption that the distance between the neighboring frames is 5 m. The maximum area, $A^*_{\max}$ is defined as follows:

$$A^*_{\max} = 25(n_x - 1) \cdot (n_y - 1) \tag{18}$$

where n_x, n_y are number of continuous frames in x and y directions, respectively. The redundancy score is defined by comparing $A^*_{\max}$ with the footprint area of the structure as follows:

$$\begin{aligned} &\text{If } A^*_{\max}/A_{\text{footprint}} > 1.0, \quad r = 3 \\ &\text{If } 1.0 > A^*_{\max}/A_{\text{footprint}} > 0.5, \quad r = 2 \\ &\text{If } 0.5 > A^*_{\max}/A_{\text{footprint}}, \quad r = 1 \end{aligned}$$

Density ratio (DR): This parameter is another stiffness expression and it is derived using one of Ersoy's [14] proposals about seismic vulnerability. Ersoy [14] stated that if the ratio of total areas of vertical structural members, i.e. columns and shear walls, is greater than two percent of the typical floor area, the structure can be considered to be seismically safe. The density ratio is defined as follows:

$$\mathrm{DR} = \frac{\sum A_c + \sum A_s}{\sum A_{\text{floor}}} \tag{19}$$

where, $\sum A_c$ is the total column area in first story (m^2); $\sum A_s$ is the total shear wall area in first story (m^2) and A_{floor} is the first story floor area (m^2).

Floor regularity factor (FRF): This parameter represents the deficiencies due to irregularities in plan. It is expressed in terms of the ratio of the sum of projected areas to the floor area.

4.2. Damage state identification based on discriminant analysis

The parameters introduced in the preceding section are the variables whose relative effects on the damage state groups are investigated in the discriminant analysis. Damage states involved in this model are None (N), Light (L), Moderate (M), and Severe (S) states. Severe damage state includes the heavy damage and collapse cases. In this technique, each damage database is investigated separately in order not to lose its own damage characteristics. In implementing the discriminant analysis to the damage databases, numerical computations are carried out by using SPSS-11.0 software [32]. Within the analysis, first, the potential discriminating variables are determined, then the best discriminating variables are identified and finally the discriminant functions, which are linear combinations of the "best" discriminator variables, are derived [33]. The values of discriminant functions, or in other words the discriminant scores, are used for classification of buildings to different damage states [15,18]. The output of the SPSS software is given in two different forms: three sets of unstandardized and standardized discriminant functions for each database. This is a characteristic of discriminant analysis: the number of discriminant functions equals the total number of groups minus one, which corresponds to the damage states in our case. Among these three sets of functions, we identify the most significant discriminant function based on Chi-square tests [18]. Structure coefficients are considered to be the best indicators of the correlation between the discriminating function and the discriminating variables. As they are used to describe how closely a variable is related to a discriminant function, structure coefficients are important in assessing the parameters that matter the most in terms of damage state identification (or classification). Absolute value of a structure coefficient close to ±1 indicates high association [31]. Table 7 shows the structural coefficients for each damage database corresponding to the most significant discriminant function. We note that the structure coefficients of the same parameter can take different signs for each case investigated. The sign of the structure coefficients shows the direction of the relationship of the variable and the discriminant function, such as increasing or decreasing the discriminating score toward a certain damage state. Yet, in cases of multiple groups where number of groups is greater than 2 (multiple damage states in our case), the sign of a structure coefficient may not have a direct physical meaning as different parameters get different signs in different combinations of discriminant functions due to correlations of parameters with each other [16,33]. The structure coefficients in Table 7 indicate that for Duzce database, number of stories is the most significant discriminator variable. This finding confirms the observation in Duzce that the buildings with lower number of stories have gone through smaller damage than the buildings with higher number of stories. SRSSI index as well having a high structure coefficient indicates that the damage states of the buildings in Duzce are influenced greatly by the lateral rigidity of the structure. However, in Dinar and Erzincan, FRF (floor regularity factor) has influenced the damage states more than the other parameters. These findings are consistent with field observations in the cities studied.

Based on the calculated discriminant scores, buildings in the damage databases are classified with respect to their damage states as shown in Tables 8a–8c. In the last row of these tables, the correct classification rates are also given. We note that the best

Table 7
Structure coefficients obtained in the discriminant analysis.

Damage database	*n*	SRSSI	*r*	ss	DR	oh	FRF
Duzce	−0.876	0.674	0.150	0.205	0.283	−0.409	–
Dinar	−0.062	0.187	−0.024	0.004	0.206	0.171	0.790
Erzincan	−0.187	0.036	−0.170	−0.110	0.357	0.110	0.726

Table 8a
Classification results obtained for Duzce damage database.

Original group membership	Predicted group membership				Total
	1	2	3	4	
Count					
1	25	10	5	1	41
2	10	33	9	15	67
3	2	8	5	6	21
4	1	4	4	14	23
%					
1	61.0	24.4	12.2	2.4	100.0
2	14.9	49.3	13.4	22.4	100.0
3	9.5	38.1	23.8	28.6	100.0
4	4.3	17.4	17.4	60.9	100.0

50.7% of original grouped cases correctly classified.

Table 8b
Classification results obtained for Erzincan damage database.

Original group membership	Predicted group membership				Total
	1	2	3	4	
Count					
1	6	1	0	1	8
2	4	10	3	1	18
3	2	1	11	1	15
4	0	0	0	2	2
%					
1	75.0	12.5	0	12.5	100.0
2	22.2	55.6	16.7	5.6	100.0
3	13.3	6.7	73.3	6.7	100.0
4	0	0	0	100.0	100.0

67.4% of original grouped cases correctly classified.

Table 8c
Classification results obtained for Dinar damage database.

Original group membership	Predicted group membership				Total
	1	2	3	4	
Count					
1	8	0	0	0	8
2	2	4	3	0	9
3	4	4	5	1	14
4	0	0	0	2	2
%					
1	100.0	0	0	0	100.0
2	22.2	44.4	33.3	0	100.0
3	28.6	28.6	35.7	7.1	100.0
4	0	0	0	100.0	100.0

57.6% of original grouped cases correctly classified.

classification rate is for Erzincan database. The classification rates improve as one considers less number of damage states [18]. Table 9 shows the damage ratios obtained based on the predicted group memberships shown in the classification results for Duzce, Dinar and Erzincan damage databases.

Table 9
Damage ratios based on discriminant analysis.

Database	Damage states	Damage ratio
Duzce	N	0.25
	L	0.36
	M	0.15
	S	0.24
Erzincan	N	0.28
	L	0.28
	M	0.33
	S	0.11
Dinar	N	0.42
	L	0.24
	M	0.24
	S	0.10

5. Comparison and discussion of results obtained from the different probabilistic models

In Table 10, the mean damage ratios (MDRs) determined from each one of the three probabilistic methods are shown for the purpose of comparison. For relatively low intensities, such as VI and VII, MDRs obtained from the DPM corresponding to AC buildings match closely those obtained from the reliability-based model and the value of MDRs are all below 2% and 5% for MMI values of VI and VII, respectively. (We note that the Dinar database display relatively higher MDR values for the same intensity level for reasons explained in the next paragraph). The MDRs obtained from the DPM for NAC buildings give slightly higher results. Since discriminant analysis method is applied on damage databases of earthquakes with intensities VIII and IX only, there were no results available from this method for intensities VI and VII. For the intensity level of VIII, the MDRs obtained from all three methods are close to each other and they vary between 14% and 20% again with the exception of the reliability-based model results for the Dinar database. The close match of the results obtained from the DPMs and the discriminant analysis model is expected, because in both cases the only source of information is the observed damage records of past seismic activity. While these two approaches can be classified as "empirical" models of damage assessment, the reliability-based model can be considered as a "semi-analytical" model in the sense that it utilizes a code-based earthquake force index and a mean seismic resistance index compared within the classical

Table 10
Summary of MDRs (%) determined from the three probabilistic methods.

Probabilistic method	MMI			
	VI	VII	VIII	IX
DPM/AC buildings (1st seismic zone)	0.3	4	14	21.5
DPM/NAC buildings (1st seismic zone)	6.2	10.4	18.9	40.7
Reliability (1992 Erzincan)	0.85	4.35	16.45	37.05
Reliability (1995 Dinar)	1.5	7.85	26.35	56.4
Reliability (1999 Duzce)	0.55	4.55	17	40.95
Discriminant analysis (1992 Erzincan)	–	–	20.7	–
Discriminant analysis (1995 Dinar)	–	–	16.9	–
Discriminant analysis (1999 Duzce)	–	–	–	26.7

structural reliability framework. Still, reliability-based model gave very close results to the other methods since the seismic resistance index takes into account the observed seismic capacities of the buildings of interests in terms of an average base shear coefficient and wall and column areas, resulting in nominal but realistic lateral force carrying capacities calculated for individual buildings.

When each method is compared within itself for the intensity level VIII, following points are observed:

- As expected, the DPMs compiled from past seismic activity, give higher MDRs for NAC buildings compared to those of AC buildings.
- The MDR value obtained from the reliability-based model for Dinar database is almost 55% higher than those for Erzincan and Duzce damage databases. This is because the mean resistance index for Dinar damage database is lower than those of the other damage databases, due to the less wall areas in the buildings in this database. Thus, when reliability-based model is used, the MDR value computed for the Dinar database would be higher than the other databases under the same intensity of ground motion. This observation is clearly displayed in Table 10.
- When the results of discriminant analysis are compared at the intensity level of VIII for Erzincan and Dinar damage databases, it is seen that the MDRs found from the analysis of Erzincan damage database are 20% higher than those of Dinar. This is due to the fact that in Dinar damage database, the number of moderate and severely damaged buildings is lower than that in Erzincan. Since the damage state distribution of a damage database affects the discriminant scores, the classification made in discriminant analysis tends to the damage states towards which the database is biased.
- When the MDR distribution at the intensity level IX is investigated, it is seen that all of the methods yielded MDRs around 30–50%, except did the DPMs for AC buildings which are expected to perform better since they are designed according to the Code requirements. The slight differences between the results of the methods arise from the points discussed above, for the MMI value of VIII.

6. Concluding remarks

Considering the various uncertainties and random effects, seismic damage prediction should be carried out within a probabilistic and statistical framework. In this study, three alternative probabilistic approaches are presented in order to estimate potential seismic damage to existing reinforced concrete buildings in Turkey. In order to assess the damage estimations obtained from these three methods, the results are expressed in terms of mean damage ratios and compared with each other. The seismic damage estimates obtained from the three probabilistic methods proposed in this study are consistent among themselves and all three approaches appear to be the appropriate methods for seismic damage prediction. In summary, this study provides simple probabilistic procedures, which can be applied on any building group in a certain region, in order to obtain potential damage profile.

For future studies, in order to avoid any bias towards a damage state in the damage databases, the earthquake data collected in the aftermath of earthquakes should be as complete and random as possible. On the other hand, the subjectivity in assigning damage states to structures should be minimized. This might be done by introducing additional parameters to assessment forms in order to check code specifications and by using certain scoring systems in order to decide on the level of damage observed in a structure. Additional damage inducing parameters might as well be developed as input to the discriminant analysis procedure and their significance can be investigated.

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The building damage information for Duzce is from Archival Material from Duzce Database located at website http://www.seru.metu.edu.tr of SERU [Structural Engineering Research Unit], Middle East Technical University, Ankara, Turkey. Erzincan and Dinar building databases are compiled from the archives of Middle East Technical University Earthquake Engineering Research Center.

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