Determining Earthquake Performances of Existing Reinforced Concrete Buildings by Using ANN

Musa H. Arslan, Murat Ceylan, Tayfun Koyuncu

Abstract—In this study, an Artificial Neural Network (ANN) analytical method has been developed for analyzing earthquake performances of the Reinforced Concrete (RC) buildings. 66 RC buildings with four to ten storeys were subjected to performance analysis according to the parameters which are the existing material, loading and geometrical characteristics of the buildings. The selected parameters have been thought to be effective on the performance of RC buildings. In the performance analyses stage of the study, level of performance possible to be shown by these buildings in case of an earthquake was determined on the basis of the 4-grade performance levels specified in Turkish Earthquake Code-2007 (TEC-2007). After obtaining the 4-grade performance level, selected 23 parameters of each building have been matched with the performance level. In this stage, ANN-based fast evaluation algorithm mentioned above made an economic and rapid evaluation of four to ten storey RC buildings. According to the study, the prediction accuracy of ANN has been found about 74%.

Keywords—Artificial neural network, earthquake, performance, reinforced concrete.

I. INTRODUCTION

IN the last century, over than twelve major earthquakes with minimum magnitudes 7 (Ms) caused significant casualties and extensive structural damage in Turkey [1], [2]. According to the studies published after earthquakes, the reinforced concrete (RC) buildings damaged by the earthquakes had many common defects, and a large number of the existing RC buildings did not have sufficient strength, stiffness or ductility because of these defects. In Fig. 1, a typical example of heavy damaged RC buildings in Turkey is given. Although the existing RC buildings are weak, Turkey has an earthquake code (TEC-2007) [3] with strict rules in regions with a high earthquake risk, just like other countries. This situation shows that the main reason for the difference between the code and the existing condition is insufficiencies in both the projects and the control mechanism for the construction process.

The earthquake design criteria in the national earthquake codes are constantly upgraded and improved with the increase in knowledge about the real behavior of structures during earthquakes. Performance of the existing RC buildings in Turkey under earthquake effect is determined according to

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TEC-2007 [3] criteria. By using a series of methods that are developed according to the basic principles of FEMA-356 [4] and ATC-40 [5] and that can be easily adapted to the Turkish building stock; TEC- 2007 [3] enables calculation of the performance of existing RC buildings.

Fig. 1 A seriously damaged RC building in Marmara region [2]

Expected earthquakes and current status of particularly the reinforced concrete (RC) building stock in Turkey require RC buildings to be urgently evaluated. Considering the current building stock and the seismicity of Turkey, this is theoretically and practically very difficult. Due to this difficulty, researchers have developed and continue to develop certain rapid evaluation methods and some structural scoring systems in recent years [6]-[8]. In all methods, cost and time-saving can be achieved during detailed evaluation of thousands of buildings.

In this study, authors studied on an ANN based algorithm that using the parameters obtained from RC buildings projects in computer media. The main aim of the study is to develop a method that can evaluate behaviors and performances of the RC buildings under earthquake loads. The mentioned algorithms were calibrated for the 4-storey or 10-storey RC buildings, general type of residence in Turkey, where a significant part of the existing RC building stock of this type is known to be inadequate. Earthquake performances of the RC buildings were determined and classified on the basis of the obtained results and, building performances were determined with high accuracy by using the recommended method. Thus, it was shown that this ANN based model, which brings innovations for the fast evaluation of earthquake risks of RC buildings, can be developed on a large number of sample buildings and can be used in areas with high earthquake risk.

II. METHODOLOGY OF PERFORMANCE ANALYSIS

Within seismic codes, the earthquake safety of existing RC buildings is determined based on the concept of performance-based design. Generally this takes the form of desired performance outcomes, such as withstanding minor earthquakes undamaged; withstanding medium-scale

World Academy of Science, Engineering and Technology
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earthquakes with limited damage and; withstanding large-scale earthquakes without total collapse. The critical outcome is the prevention of total structural collapse. This means that the upper level withstands total collapse (CP); the sub level, for the crucial structures, may be slightly damaged but remains fit for immediate occupancy (IO). Between the sub and upper levels there is Life Safety (LS) level situation. Multiple performance objectives for these levels, including the seismic transformation periods, have been specified in Table I.

TABLE I
STRUCTURAL PERFORMANCE BASED ON DAMAGE

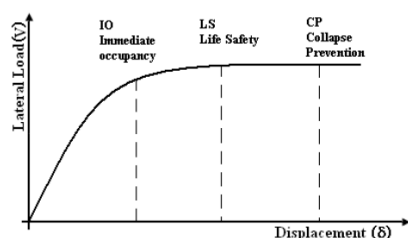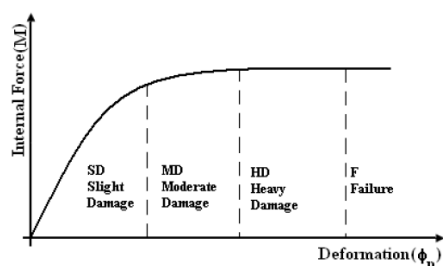| Performance Group	Performance Level	Performance Criteria
S₁	Immediate occupancy (IO)	• The ratio of beams in Slight Damage (SD) and Moderate Damage (MD) shall not exceed 10% in any story. • There must not be any columns beyond Slight Damage (SD). • There must not be any beams beyond Heavy Damage (HD).
S₂	Life Safety (LS)	• The ratio of beams in Moderate Damage (MD) and Heavy Damage (HD) shall not exceed 20%in any story. • In any storey, the shear force carried by columns in Heavy • Damage (HD) shall not exceed 30% of story shear.
S₃	Collapse Prevention (CP)	• The ratio of beams in Heavy Damage (HD) must not exceed 20% in any story. • In any story, the shear force carried by column that passed Slight Damage (SD) must not exceed %30 of story shear force.
S₄	Collapse (C)	• If the failure cannot be prevented, it is under failure condition.

Fig. 2 Performance levels of a structure

Fig. 3 Damage levels of a section

According to TEC-2007 [3], performance of the RC buildings can be evaluated using two methods: linear or non-linear methods. The civil engineer chooses a method to determine the damages and the performance of the building, and there is a four-stage performance scale for both of the methods in TEC- 2007 [2].

Seismic performance of the load bearing system is defined as the sum of seismic damage levels of the structural elements (beam, column, etc.) which form the load bearing system. The damage level of the elements of the load bearing system differs according to the method of analysis. In common with FEMA 356 [4], TEC-2007 [3] states that the seismic performance of buildings can be determined using linear or nonlinear analysis. The design engineer is free to utilize either linear or nonlinear analysis approaches. The seismic codes also include a number of analysis methods, such as "incremental equivalent seismic load method", "incremental mode superposition method" and "analysis method in time domain" which are suitable to be used for both approaches. In the present study, the structures were evaluated using nonlinear analysis with the incremental equivalent seismic load method (static pushover analysis method).

Static pushover analysis is frequently used within the literature as the preferred performance measure. Pushover analysis is a numerical method of calculating a building's lateral load capacity under the influence of increasing lateral loads. Gravity loads are in place during lateral loading.

Structure reaction in pushover analysis is defined by a capacity curve describing the relationship between the base shear force and lateral roof displacement. Load-displacement and moment – rotation (curvature or deformation) curves that show levels of performance of the load bearing system and cross section are given in Figs. 2 and 3, respectively.

The non-linear method is based on plastic hinge hypothesis and performed by analyzing pushover analysis and the capacity curve comprising lateral load – lateral displacement. On the other hand, linear method is much simpler than non-linear method and is based on a linear structural analysis approach. In this method, earthquake load reduction coefficient (R) which is an expression of the ductility of the building, and building safety factor (I), are taken as 1. This method can be applied in two ways; a) equivalent static seismic load method (This can be used in the buildings with a coefficient smaller than 8 and a maximum height of 25 meters where torsion is insignificant) b) mode superposition method (this can be used in all buildings). According to the results of both analyses, effect capacity ratio for each cross section in the load bearing system is calculated according to (1) provided in TEC-2007 [3] and the damage limit of the section is determined (r). In this formula R_s refers to the capacity of the related section, E to the elastic earthquake effect which is expected to be accommodated, G and Q refer to the cross section forces produced by the dead and live load.

$$r = \frac{E}{R_s-(G+Q)} \qquad (1)$$

Fig. 2 indicates force deformation relationship in a ductile RC section. An identified section damage status gives storey damage status which then gives building global damage status. Thus, the global damage and performance level to be recorded in the building in case of an earthquake are determined. General performance outcomes of RC structures are; withstanding minor earthquakes undamaged; withstanding

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medium-scale earthquakes with limited damage; and withstanding large scale earthquakes without total collapse. The critical outcome is the prevention of total structural collapse. This means that the upper level withstands total collapse while the sub-level, for crucial structures, may be slightly damaged but remains fit for immediate occupancy.

Between the sub- and upper-levels, the Life Safety level is required. TEC-2007 [3] divides building performance level into four categories according to number of columns, beams and shearwalls. These are Immediate Occupancy (IO), Life Safety (LS), Collapse Prevention (CP) and Collapse (C), respectively. The criteria given in the Code for these performance levels are listed in Table I. In this study, four different performance levels of the buildings during an earthquake were grouped as S_1, S_2, S_3 and S_4.

III. DATA COLLECTING

In Turkey, most of the residential buildings are constructed having 4-10 floors. In this study, collected total of 66 RC buildings with 4-10 storey, that were thought to represent existing RC buildings in Turkey [9], [10]. Selected RC buildings were modeled with the commercial program (IDE-Statik V.6.0053) program. Performance analysis of the RC buildings was performed according to the linear procedure specified in TEC-2007 [3]. In the analyses, the earthquake, ground motion with 10% probability of exceedance in 50 years, equivalent to a 475-year return period was chosen. TEC-2007 [3] states that under this earthquake, the residence buildings should provide the Life Safety (LS) performance level whose details are given in Table I. The building which provides this performance level will not be severely damaged in the earthquake but retains a margin against onset of partial or total collapse. Some of building models are shown in Fig. 4 with the opinion of providing examples out of 66 residence buildings chosen in the analysis. Earthquake performance of a RC building is based on a lot of parameters. Table II indicates variation intervals of some parameters for the selected 66 buildings. In table, 0 value was entered for PY for the buildings built before 1998 and 1 value for the buildings built after 1998. The reason behind this is that TEC went through a radical change in 1998. Therefore, the buildings designed after the year 1998 are safer than the ones which were designed before 1998. Similarly, for example ST was defined as 1 in hollow-tile floor slab, 2 in plate slab and 3 in beam slab.

Fig. 4 Selected different types of the RC buildings analyzed in the study

TABLE II
USED DATA RANGE

Parameter	Minimum Value	Maximum Value
Number of Storey (NS)	4	10
Building project year (PY)	0	1
Average Column Ratio (ρ_{CA})	0.008197	0.024721
Average Shear Wall Ratio (ρ_{SWA})	0	0.011725
Average Longitudinal Bar Ratio in Columns ($\rho_{\ell\,col}$)	0.00843	0.012828
Average Longitudinal Bar Ratio in SW ($\rho_{\ell\,sw}$)	0	0.010643
Steel Tension Strength (S)	220	420
Concrete Compression Strength (C)	16	20
Average Inertia of Beams (IB)	0.001092	0.0045
Importance Factor (I)	1	1,5
Soil Type (Z)	1	4
Earthquake zone (EZ),	1	4
Earthquake Reduction Coefficient (R)	4	7
Living Load Reduction Coefficient (n)	0.3	0.6
Structural Performance (S_1-S_4)	1	4
Slab types (ST)	1	3

IV. APPLICATION OF ARTIFICIAL NEURAL NETWORK (ANN) TO PROBLEM

The use of artificial neural network (ANN) models may be made to drastically reduce the computational effort in such cases. ANN is a type of artificial intelligence application implemented by engineers to carry out specialized design tasks so far. ANNs have been widely used for the prediction of various structural quantities. ANNs thus have been a powerful tool in solution of various structural engineering problems [11]-[13]. In this study;

1. Three-layered (input layer, hidden layer and output layer) feed-forward artificial neural network (ANN) structure was used and trained with the error back propagation algorithm. The ANN architecture given in Fig 5.

2. In classification of RC buildings under earthquake loads according to their performances, selection of appropriate ANN architecture is very important for the accuracy of the study. As indicated in the literature [11]-[13], optimum number of hidden nodes and learning rate values comprising the architecture of the network were found in training and testing phase of the ANN via experimentation. Firstly, by keeping the learning rate constant, number of hidden nodes was increased from 2 to 100. Optimum number of hidden nodes was determined as 80 because of lowest training and test error. Similarly, 80 hidden nodes which were found as optimum number of hidden nodes were kept constant. After the stepwise increase of learning rate from 0.001 to 5.0, it was found that the value of 2.0 had the lowest training and testing error.

3. In this study, ANN was trained with 11 different algorithms which are commonly used in ANN applications in the literature: BFG, CGB, CGF, CGP, GDA, GDM, LM, OSS, RP and SCG algorithms [11]-[13]. All training procedures were performed by operating the ANN with 10000 iterations. 19 different structural

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parameters were presented to ANN as inputs. Outputs of ANN were labeled as four classes (S_1, S_2, S_3 and S_4) including four different performance levels of the buildings during an earthquake. Training and test errors given in Tables III-V were conducted according to classical equations.
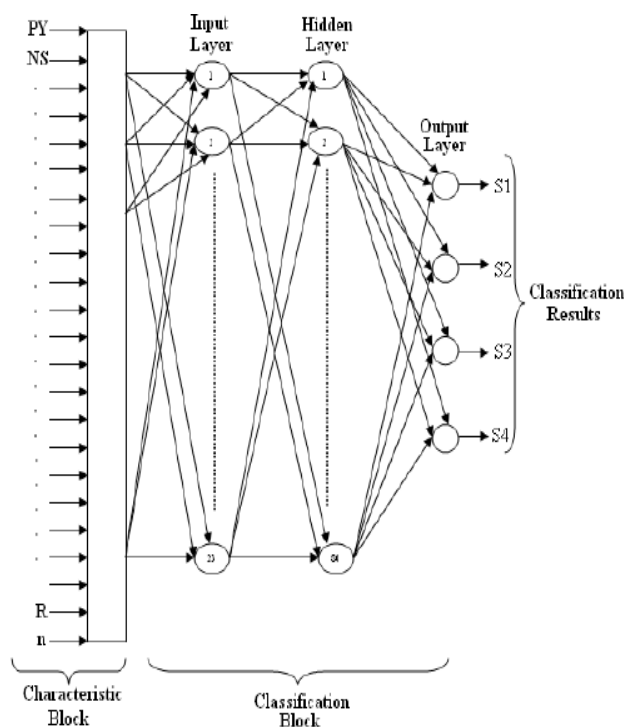

Fig. 5 Selected different types of the RC buildings analyzed in the study

TABLE III
TRAINING AND TEST ERRORS OF ANN WITH PRE-PROCESSING USING ONLY MEAN VALUES OF DATA SET 1

Training Algorithm of ANN	Training Error (%)	Test Error (%)
BFG	4.66	40.15
CGB	3.23	40.85
CGF	2.14	40.67
CGP	1.43	39.61
GDA	5.50	42.46
GDM	8.67	39.35
GDX	4.03	41.13
LM	4.28	40.53
OSS	1.89	40.82
RP	11.33	42.71
SCG	0.71	43.35

In this study, 2-fold cross-validation test was performed to confirm the accuracy of the classification procedure and to test generalization capability of the proposed network. The used data set contains the data of 66 buildings comprised of 4 classes (S_1, S_2, S_3 and S_4). Of these 66 buildings, 7 belong to S_1, 20 belong to S_2, 23 belong to S_3 and 16 belong to S_4. To apply 2-fold cross-validation test, these buildings were divided into 2 data sets. Table VI indicates building classes. In line with the above mentioned test procedure, the ANN was trained with the 1st data set and was tested with the 2nd data set. Then it was trained with the 2nd data set and tested with the 1st data set.

TABLE IV
TRAINING AND TEST ERRORS OF ANN WITH PRE-PROCESSING USING ONLY MEAN VALUES OF DATA SET 2

Training Algorithm of ANN	Training Error (%)	Test Error (%)
BFG	2.42	35.48
CGB	0.80	34.23
CGF	2.44	31.29
CGP	0.80	34.56
GDA	1.69	34.28
GDM	6.45	32.13
GDX	0.93	34.19
LM	7.25	33.06
OSS	0.92	34.27
RP	5.83	36.13
SCG	0.80	35.40

TABLE V
TRAINING AND TEST ERRORS OF ANN WITH PRE-PROCESSING USING ONLY MEAN VALUES OF AVERAGE OF (DATA SET 1 AND DATA SET 2)

Training Algorithm of ANN	Training Error (%)	Test Error (%)
BFG	3.54	37.82
CGB	2.02	37.54
CGF	2.29	35.98
CGP	1.12	37.09
GDA	3.60	38.37
GDM	7.56	35.74
GDX	2.48	37.66
LM	5.77	36.80
OSS	1.41	37.55
RP	8.58	39.42
SCG	0.76	39.38

TABLE VI
DISTRIBUTION OF CLASSIFIED DATA SETS ACCORDING TO GROUPS

Performance Group	DATA SET 1	DATA SET 2
S_1	4	3
S_2	11	9
S_3	12	11
S_4	8	8

V. RESULTS AND FINDINGS

Findings of this study are briefly summarized as follows;

1. According to the data used, the performances of the RC buildings under earthquake loads were determined with an accuracy of 64.26%. Using the ANN, the performances of the RC buildings could be determined in a very short time like 15 seconds. To determine the performance levels of the buildings, among 11 back propagation algorithms, it would be better to use GDM algorithm with high accuracy ratio. When the previous studies performed with the ANN were analyzed, it was observed that success of the algorithm varies according to the selected data set. In evaluation of a RC building, it is known that forming computer model of the load bearing system takes 1-2 days. In this study, evaluation of a building took only 15 seconds using the ANN method.

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2. Procedures such as coring, building survey etc. we're not used in this method; rather, building project data were taken into account. It is known that due to insufficient building inspections and other factors, particularly the RC buildings constructed before the 1999 Marmara Earthquake and till coming into force of TEC-1998 [14] are very poor according to building projects. Thus, according to the method presented in this study, the RC buildings which were found to lack sufficient performance levels on the basis of the evaluations made according their projects will not achieve adequate performance levels also in the on-site measurements. Therefore, the analyzed method can enable fast scanning of all buildings to sort inadequate ones.

3. Especially, when we look in the Table III, it is seen that the performance levels of the 66 RC buildings are 10.61% S_1, 30.3% S_2, 34.85% S_3, 24.24% S_4. In TEC-2007 [3], the RC residence buildings have to provide at least S2 Life Safety (LS) in order to be in the sufficient performance level during the earthquake. According to this statement, 59.09 % of the buildings chosen as examples are the buildings not having sufficient earthquake performance according to the TEC-2007 [3] criteria.

4. In all of the studies numbered [6]-[8] carried out on the evaluation of the present RC buildings, the probability of collapse of the sample buildings under a possible earthquake was detected with different proportions. Here, the variability of the parameters used in the studies, the sample structure group, the analysis methods chosen and the approaches can be seen as the main reason. In addition, TEC-2007 [3] performance criteria have not been taken as the basis in any of these methods, so far. Since the study was carried out on the basis of TEC-2007 [3] norms, structure performance after the earthquake was determined according to the related code criteria. There are not any other studies taken TEC-2007 [3] as the basis and using ANN in the literature.

5. The present study has demonstrated that all of these selected parameters directly affected the seismic performance of building, which is a function of lateral load carrying capacity and earthquake performance.

6. It should be noted that selected ANN models presented above are valid only for the ranges of database given in Table II. Therefore, the estimation capacity and estimation duration of each algorithm will be expected to be lower than calculated in this study, in case of increasing the selecting buildings.

7. With this study, an ANN based algorithm which determines the earthquake performance of residence buildings according to the conditions of the code and can make categorization was achieved.

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