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Evaluation of Behavior Factors for Steel Moment Frames under Critical Consecutive Earthquakes using Artificial Neural Network

S. Rouzrokh[1], E. Rajabi[2], Gh. Ghodrati Amiri[1*]

[1] Natural Disasters Prevention Research Center, School of Civil Engineering, Iran University of Science and Technology, Tehran, Iran
[2] Department of Civil Engineering, Tafresh University, Tafresh, Iran

ABSTRACT: Structures that are located in seismic active regions are often subjected to successive earthquakes which occurred with significant PGA in a short time after each other. Studies about different responses of the structures under seismic sequence phenomena, such as structural damage, ductility, displacement, and behavioral factor indicate that the successive earthquakes, depending on their severity, have significant effects on the different demands of structures. For instance, the behavior factor (R factor) is one of the significant parameters in the study of structural response that decreases the lateral forces induced by earthquakes. Therefore, the structure with non-elastic deformations absorbs a great amount of earthquake energy, thus the earthquake energy decreases considerably. Regarding the potential loss of successive earthquakes and the importance of behavioral factors, this paper calculates and estimates this parameter for steel moment frames under critical successive earthquakes. Thus, three steel moment frames with 3, 7, and 11 stories are designed according to Iranian seismic codes (standard No. 2800) and modeled in OpenSEES software. After the design of these frames, critical seismic scenarios with/without successive shocks, are selected and the R factors of steel moment frames are calculated from the results of incremental dynamic analysis (IDA(, time history, and nonlinear static analysis (pushover). The results showed about a 12% reduction in the R factor and, also an increment of damages under successive earthquakes comparing to the individual one. Finally, to estimate the R factor, artificial neural networks are designed using frame properties, successive earthquakes, and extracted behavior factors. The comparison of predicted behavior factors with real values indicated the ability of networks for the estimation of results.

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1. INTRODUCTION

The occurrence of several consecutive earthquakes with a short time interval in the same region is called the seismic sequence phenomenon. These consecutive earthquakes have significant acceleration (PGA) and include foreshocks, main-shocks, and aftershocks. Due to the short time interval between the occurrence of two earthquakes, there is often no opportunity to repair and retrofit the structure, and the damaged structure caused by the first earthquake will be suffered more severe damage and even collapse under the next strong earthquake. Nonetheless, most seismic design codes don't consider consecutive earthquakes, and all processes of structural design are based on a single earthquake. Many studies have been conducted on this phenomenon and its effect on responses of SDOF and MDOF structures. The results of some studies [1-2] indicated that in seismic areas, the recurrence of earthquakes in a short time increased the damage of structures. Changes in the ductility demand, inelastic displacement, drift, behavior factors of structures under consecutive earthquakes have been studied by some researchers [3–5]. The behavior factor (*R* factor) is one of the significant parameters in the study of structural response that decreases the lateral forces induced by earthquakes. As a result, the structure with non-elastic deformations absorbs a great amount of earthquake energy and structures are designed for less force than the amount of elastic behavior in the structure.

Therefore, in this paper, the *R* factors of steel moment frames have been calculated by considering the seismic sequence phenomenon. Since the calculation of the *R* factor requires long-term analyses, the ideal artificial neural network has been designed using the results of analyses. The results show that in all cases, the average of *R* factors under consecutive earthquakes decreases compared to the single earthquake state. Also, the neural network estimates the *R* factors of steel frames under critical successive earthquakes, and with the proper performance, can estimate *R* factors with an error of less than about 6%.

2. METHODOLOGY

2.1. Critical successive earthquakes

In this study, the critical seismic scenarios are selected based on the maximum effective acceleration parameter

*Corresponding author's email: ghodrati@iust.ac.ir

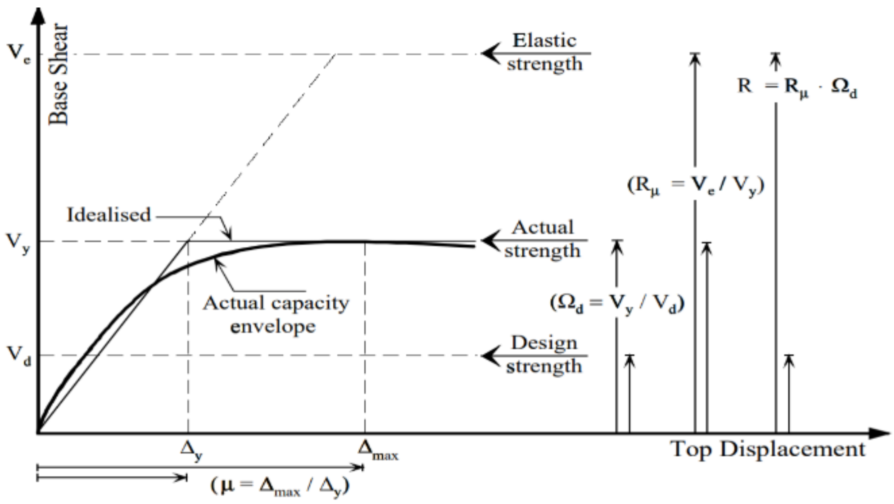

Fig. 1. Proposed force-displacement relationship in Yang method [7]

(EPA) which is one of the parameters of earthquake frequency content [6]. 10 as-recorded consecutive earthquakes containing main-shock with foreshock or aftershock are obtained from the PEER center. Also, a time interval of 100s is used between the first and second earthquakes.

2.2. *R*-factor

As shown in Fig. 1, the Yang method is used for calculating the *R*-factor.

According to Eqs. (1) to (3), ductility, over strength Factor, and finally, the *R*-factor is calculated. In the following equations, V_e is the maximum base shear of structure assuming the linear behavior during an earthquake. Parameters of V_d and V_y are also base shears of the first plastic hinge and maximum nonlinear base shear in structure, respectively.

$$R\mu = \frac{Ve}{Vy} \tag{1}$$

$$\Omega = \frac{Vy}{Vd} \tag{2}$$

$$R = R\mu \times \Omega \tag{3}$$

2.3. Steel frames

In this paper, 2D frames with the structural system of intermediate moment frame (IMF) with 3, 7, and 11 stories are studied. All frames consist of three spans with 5 meters in length, the height of the floors is 3.2 meters, and beams and steel ST37-type of columns. After applying gravity and earthquake loading according to Iranian standard No. 2800, sections of beams and columns are designed in SAP2000. For modeling frames in OpenSEES, the nonlinear behavior of the beams is modeled by concentrating the plasticity and inelastic deformations at the end of the elements. Plastic hinges are applied with the zero-length element and the element between the two concentrated hinges is considered linear by using the elastic beam-column element. For assigning the moment-rotation relationship to plastic hinges, the deterioration Ibarra-Krawinkler (IK) model that represents the deterioration of stiffness and strength is used. The hysteresis behavior of plastic hinges is simulated with bilinear materials and it is allocated to steel beams. To consider the effect of axial force, bending interaction and because of more accurately modeled, the distribute plasticity model using the nonlinear beam-column element with fiber sections is applied for columns. Afterward, assuming the damping ratio of 5%, nonlinear static analyses, incremental dynamics analysis (IDA), and nonlinear time history analyses are performed to calculating the *R* factors of frames under the aforementioned critical single and consecutive ground motion records.

3. ARTIFICIAL NEURAL NETWORKS

From the mathematical point of view, the artificial neural network (ANN) is a "vector mapper" that maps an input vector to an output vector. With known combinations of input and target data, ANN can be "trained" to extract the underlying characteristics and relationships from the data. In this paper, *R* factors are estimated by ideal ANN with optimum neurons in two hidden layers based on the period, PGA, EPA, and magnitude of successive earthquakes. For this, 400 ANNs are designed with a different number of neurons in each hidden layer from 1 to 20 and the ideal ANN is determined with the minimum value of mean square error (MSE) and maximum value of regression (*R*) among all networks. Also, input vectors and target vectors are divided into three sets including training, validation, and testing [8].

Here, the values of 60%, 35%, and 5% are randomly selected for training, testing, and validation, respectively, to obtain the most efficient distribution sets of data and prevent the overfitting issue. The precision of *R*-factors is examined with real ones showed good agreement. So that the average error of the ANN model for predicting the *R*-factors is lower than 6% and more than 90% of the simulated results were

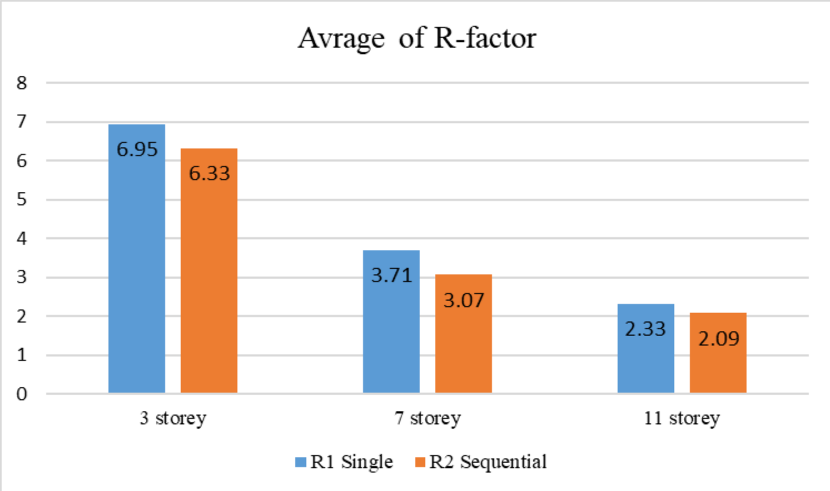

Fig. 2. Force-Displacement relationship in Yang method

within ±15% of the real values for ANN models. The obtained results indicated that the networks were learned to generalize the information well.

4. RESULTS AND DISCUSSION

As mentioned in section 3, nonlinear static analysis is implemented for calculating V_d for each frame. Also, V_y and V_e are obtained based on IDA and time history analysis. As shown in Fig. 2, the results display that the average of *R*-factors of each frame under consecutive earthquakes record has decreased compared to the single seismic records. Because of successive earthquakes, the level of damage caused by the first earthquake increases, and the capacity of the structural members is decreased. As a result, members can tolerate less axial force rather than before, and the linear and nonlinear base shears and subsequently *R*-factor of the structure is reduced.

5. CONCLUSION

The purpose of this paper is to investigate the *R*-factor of intermediate moment frames under critical single and consecutive seismic scenarios and estimate these factors using an artificial neural network. Thus, the *R* factors of steel moment frames with 3, 7, and 11 stories were calculated from the results of analyses under these scenarios. The obtained results are as follow:

· In all-steel moment frames, the average of the *R*-factors showed a reduction rate under critical successive earthquakes comparing to the individual ones.

· Artificial neural networks were a good technique for estimating these coefficients. In this paper, the neural network estimated the *R*-factors of steel frames under successive seismic earthquakes with an average error of less than 6%.

· Iran is located in a seismic region and it is essential to study the seismic sequence phenomenon and its effect on the behavior of structures, especially structures whose performance is important after the earthquake.

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