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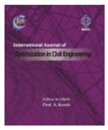

APPLICATION OF NEURAL NETWORK IN EVALUATION OF SEISMIC CAPACITY FOR STEEL STRUCTURES UNDER CRITICAL SUCCESSIVE EARTHQUAKES

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ABSTRACT

Depending on the tectonic activities, most buildings subject to multiple earthquakes, while a single design earthquake is suggested in most seismic design codes. Perhaps, the lack of easy assessment to second shock information and sometimes use of inappropriate methods in estimating these features cause successive earthquakes mainly were ignored in the analysis procedure. In order to overcome to above deficiencies, the learning abilities of artificial neural networks (ANNs) are used in two steps to evaluate the seismic capacity of steel frames consisting moment-resisting frames, ordinary concentrically, and buckling restrained brace (BRB) under critical consecutive earthquakes. For this purpose, peak ground acceleration of second shock (PGA_a) is estimated based on the first shock features in the first step. Next, second ANNs estimate the decreased capacity of the damaged structure for LS and CP performance level according to the proposed PGA_a from the previous step and some seismic and structural features. The results indicate that ANNs are trained to generalize the unseen information very well and reflect good precision in predicting target results in both steps. Finally, the effect of different parameters and repeated shocks is investigated on the seismic performance of mentioned frames. The results show the proper performance of BRB frames in the case of real and repeated earthquakes.

Keywords: seismic sequence; artificial neural networks; buckling restrained brace; ordinary concentrically braced; incremental dynamic analysis; seismic capacity.

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1. INTRODUCTION

Lateral force of earthquake is one of the most important factor that has long been considered by civil engineers in the design of buildings. Earthquake evidence proves that the seismic performance of buildings is strongly dependent on the residual damage caused by previous shocks, and the design assumption based on *single design earthquake* is not very accurate. Because this seismic philosophy does not consider the effect of strong successive shocks on the accumulated damage of structures into account. In recent year, effect of seismic sequence on the behavior of steel moment resisting frames (SMRFs) is investigated in technical literature of structural and earthquake engineering. For example, the cumulative damage of beams is selected as the main damage index by Tenderan et al., (2019) to evaluate the seismic performance of SMRFs under multiple strong ground motions. In this regard, one equation is generated based on the experimental results of the steel beam-to-column connection test considering the ductile fracture [1].

Seismic performance of three SAC steel MRF buildings with deterioration of strength and stiffness are studied by Farivarrad and Estekanchi (2020) under seicmic scenarios consist of mainshock-aftershock. The response of MRFs is estimated using endurance time method in several hazard levels. Comparison of collapse fragility curves indicates that the residual seismic response caused by the mainshock and the direction of applied aftershocks are highly significant factors in evaluation of damaged buildings [2].

Fragility of steel moment frames with masonry iniflls is studied by Di Sarno and Wu (2021) through considering the damage accumulation. The results showed that the steel frames will be higher vulnerability under mainshock-aftershock sequences rather than the mainshocks. Comparison between fragility curves for successive and single scenarios reveals that the medians of studied limit states decreses about 10% with considering sequence of mainshock and aftershocks [3].

In steel structures, ordinary braces are also proposed as a lateral force resisting system. The performance of this system is studied in different forms such as concentric, eccentric brace under single and successive earthquakes. Strongback bracing system (SBS) is one of these braces which promotes uniform story drifts over the height of a structure. This system is studied under consecutive earthquakes by Toorani et al., (2020). This study shows that SBS can postpone the soft-story phenomenon [4]. Eccentrically braced steel frames with energy-absorbing links are evaluated by Mohsenian et al., (2020) under sequential earthquakes. In this regard, the fragility curves are compared for different damage levels, before and after the main earthquake. The performance levels of the Iranian Seismic Code are meeted well by eccentric braced frames with vertical links under successive earthquakes [5]. Seismic behavior of steel eccentrically braced frames which have been founded on soft-soil is studied by Garcia et al., (2018). When first link fails, strong aftershocks which have been generated based on artificial narrow-band methods, could strongly increase interstory drift demands. Against the design philosophy, surrounding members behave nonlinearly [6].

In recent years, buckling restrained brace are proposed to overcome buckling as one of the conventional braces weaknesses. Tall pier bridges with double-column bents retrofitted with buckling restrained braces are investigated by Chen and Li (2021) subjected to near-fault motions. This study reveals that the BRB could considerably decrease the seismic vulnerability. Also the performance of the prototype bridge is improved [7].

Reinforced concrete (RC) frames with buckling-restrained braced as one of the best lateral-force resisting and suitable energydissipating components are analyzed by Du et al., (2020) under near-fault ground motions with fling step and forward directivity effects. Significant insights to the behavior quantification is achieved by using BRB in RC frames under near-fault ground motions. In fact, the high energydissipation is occurred by dual system (BRB and RC frames) under near-fault ground motions with or without velocity-pulse [8]. Since multiple earthquakes can effect the capacity of BRBs by accumulation of plastic strains, Morfuni et al., (2019) evalated the seismic performance of dual systems with BRBs under mainshock-aftershock sequences. This study reveals that as-recorded aftershock do not significantly increase the cumulative ductility demands in BRBs [9]. Probabilistic collapse risk assessment of BRB based on mainshock-aftershock showed that the aftershock can highly amplify the structural response especially when the structure tolerates large residual drifts during the mainshock [10].

In order to determine the effects of artificial multiple earthquakes on essential buildings which have been founded on the soft soil of Mexico City, numerical study is proposed by Guerrero et al., (2017). This study show a suitable design based on the concept of dual systems could decrease the aftershock effects [11].

In addition to above studies, steel structures are investigated by other researchers [12-16] under multiple earthquakes. In most studies, artificial successive earthquakes have been used because of the lack of as-recorded aftershocks. Due to the high potential of successive earthquakes to increase the structural damages, seismic sequence phenomenon should be considered in the design procedure. Moreover, the uncertainty in (1) identifying the characteristics of second shocks and accordingly (2) estimation of structural capacity after the first shock and (3) the ability of damaged structures to withstand subsequent shocks, causes the necessity of more comprehensive study is felt for evaluation of structural capacity against successive earthquakes and estimation of the seismic intensity criteria corresponding to the performance levels consist of life safety (LS) and collapse prevention (CP). In this regard, learning abilities of artificial neural networks as computing systems inspired by the biological neural networks that constitute animal brains is useful.

This technic is used in various aspects such as evaluation of structural behavior [17-20], damage detection [21], generation of artificial earthquakes [22]. Therefore, in order to overcome the first problem – lack of easy access to the most characteristics of the second shocke in design procedure – an ideal artificial neural network is first trained based on the features of the first shock to predict the maximum acceleration of the second shock. This output will be introduced to the next ANNs as input. In order to solve the second and third problems, the second series of artificial neural networks are designed in the next step. These ANNs are trained based on the estimated outputs by previous ANN in the first step and the results of incremental dynamic analysis (IDA) for steel moment-resisting frames, ordinary concentrically braced frames, and steel frames equipped by BRB under as-recorded earthquakes with/without seismic sequence. Decreased capacity of steel frames for LS and CP performance level, equivalent to intensity measures corresponding to the inter-story drift ratio (IDR) associated with the desired level, is estimated by ANNs in the second step. Finally, the effect of some parameters and the use of the artificial consecutive records through repetition of first shock as second’s is investigated in the results process using the designed ANNs in both steps.

2. RESEARCH METHODOLOGY

2.1 Steel Frames

In this paper, three sets of steel frames with 3, 7, and 11 story containing SMRF, ordinary concentrically, and buckling restrained brace are investigated, which have been founded on soil II in Tehran. These frames are selected as residential buildings and designed based on Iranian earthquake design code standard No. 2800, Fourth Edition by Rouzrokh et al. [23] and Atyabi et al. [24]. The geometry of these frames is shown in Fig. 1. All frames are implemented in *Opensees* software for nonlinear analyses. In SMRFs, beams are modeled by concentrating the plasticity, and inelastic deformations at the end of the elements by a zero-length element, and the element between the two concentrated hinges is considered linear using the Elastic Beam-Column element. The deterioration Ibarra-Krawinkler model is used, and the hysteresis behavior of plastic hinges is simulated with bilinear materials. The distribute plasticity model using the NonlinearBeamColumn element with fiber sections is applied for columns. In ordinary steel concentrically braced frames, a distributed plasticity, plastic hinge with numerical integrations across the cross-sections, and fiber method are used for modeling the inelastic behavior of the beam, column, and brace elements. Moreover, eccentricity equal to one-thousandth of the element length is considered in the middle of the brace members to provide conditions for the occurrence of geometric nonlinear behavior. The bilinear model of Steel02 material with a strain hardening ratio equal to 2% on the strain stress diagram is assigned to all elements [23].

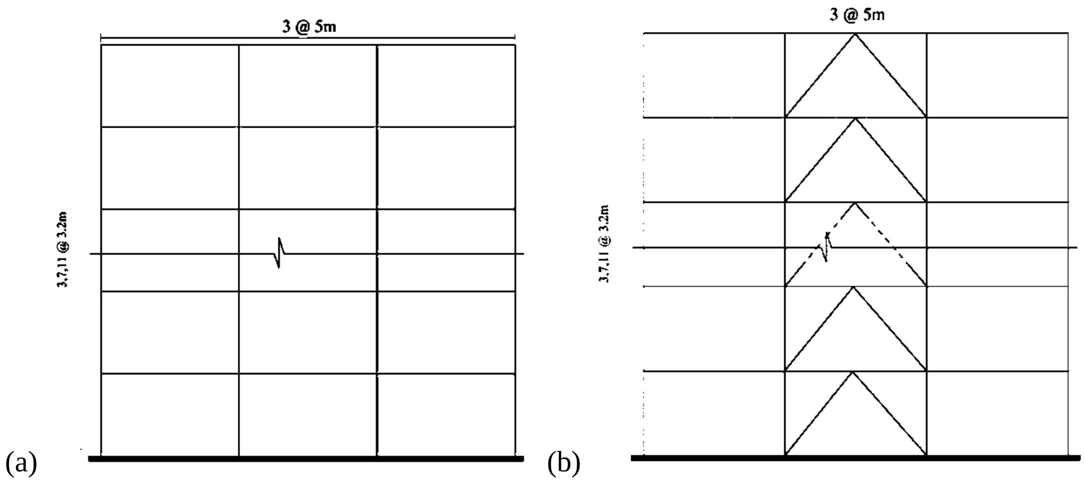


Figure 1. The geometry of selected steel frames (a) SMRF, (b) Ordinary and BRB brace [23-24]

In steel frames with BRB, *truss element* is selected for BRB element because of considering the same nonlinear behavior of the materials in tension and pressure (Fig. 2) using the hardening coefficient. Beams and columns are modeled with *Nonlinear beam column* element. Steel02 is assigned to elements [24]. It should be noted that damping is considered in all three steel frames using the Rayleigh model. SMRFs, ordinary and BRB braced fames are verified based on [16, 25-26], respectively.

2.2 Critical Seismic Scenario with/without seismic sequence phenomenon

In this paper, as-recorded strong ground motions are used for first and second shocks in successive earthquakes because of the insufficient accuracy of methods for the generating of artificial ground motions. Critical single and successive scenarios are selected based on [27] according to effective peak acceleration (EPA). This parameter includes the frequency content of earthquakes, and these records are available in PEER and USGS. For critical successive scenarios, the first and second shocks are recorded at the same station, in the same direction, and have the maximum EPA among the ground motions recorded for the same event by other stations. It should be noted that the selected earthquakes are not necessarily in the state of the mainshock and aftershocks, and both consecutive shocks in the region in the form of foreshock-maishock or mainshock-aftershock also include seismic sequence phenomenon. Details of these records are available in Ghodrati Amiri and Rajabi [27]. All steel frames are analyzed under these records in [23-24].

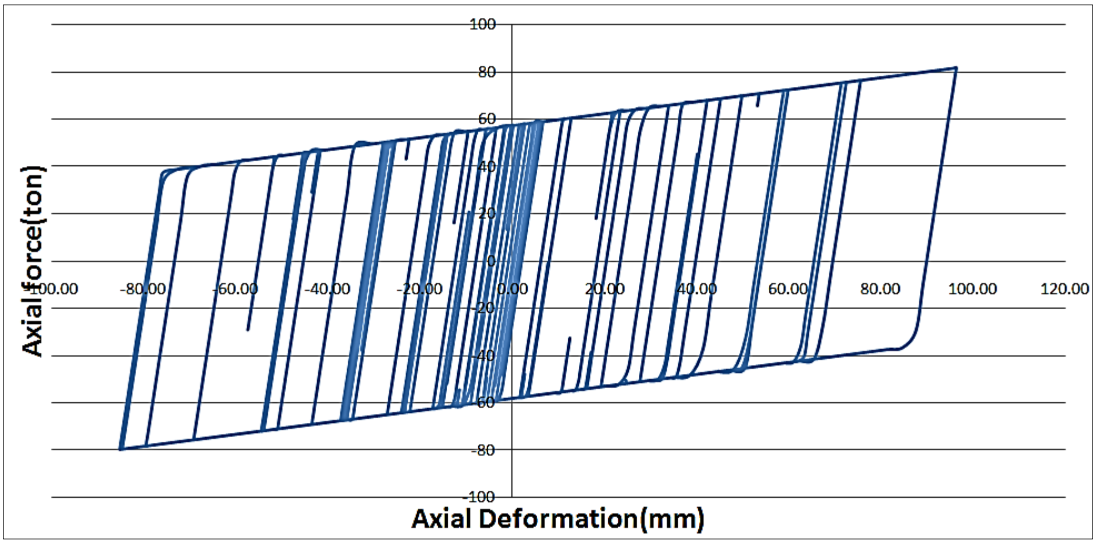


Figure 2. Hysteretic behavior of 7 story BRB frames [24]

3. INCREMENTAL DYNAMIC ANALYSIS (IDA)

The behavior of the structures can be observed in a wide range of different earthquake intensities using incremental dynamic analysis. This method has dynamic nature, and it is preferable to other analysis methods in terms of considering nonlinear behavior for materials.

In this regard, the structure is exposed to scaled earthquakes to different intensity levels, and its behavior can be traced from the elastic to the collapsed state. IDA curves are extracted using Hunt and Filled method in [23-24]. For this purpose, spectral acceleration in fundamental period ($S_a(T_1)$) and maximum inter-story drift ratio (IDR) are selected as intensity measure (IM), and Damage intensity (DM), respectively. Collapse prevention level is equivalent to IDR equal to 0.1, and according to standard 2800, life safety level is determined based on IDR equal to 0.025 and 0.02 for structures up to 5 stories and more, respectively [23-24]. IDA curves for three story SMRF under critical single and successive earthquakes are shown in Fig. 3.

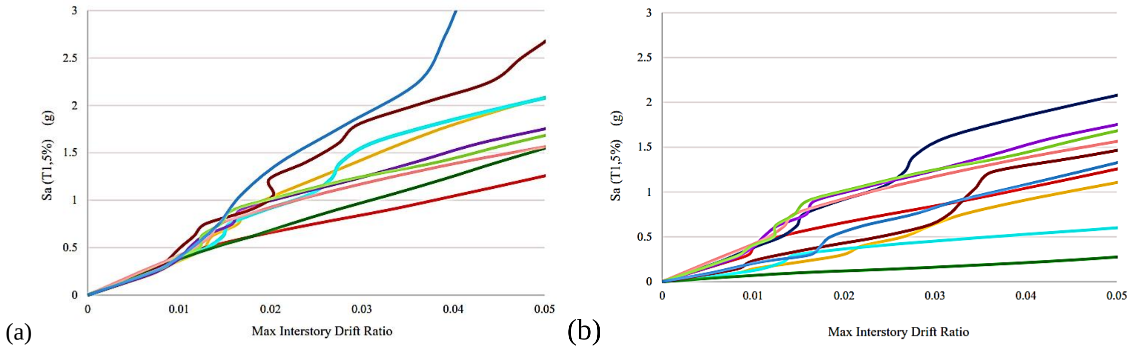


Figure 3. IDA curves for 3 story SMRF under critical single and successive earthquakes [28]

4. ARTIFICIAL NEURAL NETWORKS

Artificial neural networks are computing systems inspired by the biological neural networks that constitute animal brains. ANNs consist of several layers, and each layer consists of neurons. The number of neurons in the input and output layer is equal to the input and output vector dimensions, respectively. In fact, the structure of a neural network is determined by the number of layers and corresponding neurons. Generally, the neurons in each layer are connected to all the neurons in the adjacent layer through a directional relation. So that information is transmitted between neurons through these connections which, each of them has its weight characteristic that is multiplied by the information transmitted from one neuron to another. In order to output values, each neuron applies an excitation function which is usually nonlinear, to the inputs as a weighted set of information. Also, some training series are used to train the artificial neural network which each of them includes an input vector and a corresponding output vector. Since there is no specific law to calculate the number of hidden layers and related neurons, the trial and error method is used. Therefore, The artificial neural networks can learn the process in the patterns using the received information from its inputs, and similarly to the brain, the learning process in the neural network is also inspired by human models. For this, the network can change the weights and finally determine the desired output by providing several examples [29].

In this paper, multilayer feed-forward neural networks with a back-propagation error-algorithm are used in two steps to estimate the peak ground acceleration of second shock (PGA_a) in the first step and decreased intensity measure corresponding to LS and CP levels due to the incidence of consecutive shocks in the second step. These networks include Bias, sigmoid middle layers, and a linear output layer to estimate any function with a limited number of discontinuity points. As shown in Fig. 4, input data for training, testing, and validation of the first ANN are peak ground acceleration of first shock (PGA_m), the magnitude of the first shock (M_m), and expected magnitude of the second shock (M_a). In the next step, in addition to the network output in the first step (PGA_a), the inputs contain the PGA_m, period of frames (T), and frame ID (Tag: 1 for SMRFs, 2 for ordinary concentrically braced frames, and 3 for BRB frames). Estimated outputs in this step are the ratio of intensity measure for the sequence to single case (IM Ratio) for two desired performance levels.

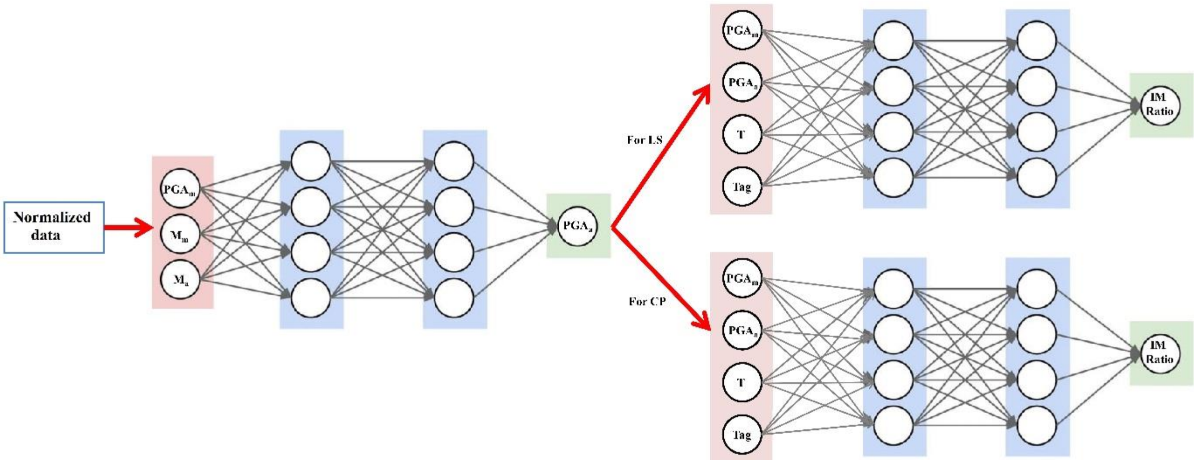


Figure 4. Artificial neural networks in this study

Since the sigmoid transmission function which behaves between 0 and 1, is used in hidden layers, data should be normalized before training the networks according to Fig. 4. In each step, data is randomly selected for training, testing, and validation. In this regards, the values of 60%, 35%, and 5% are randomly selected to obtain the most efficient distribution sets of data and prevent the overfitting issue. The training process is stopped for minimum mean square error (MSE). On the other hand, regression values or correlations between network outputs and the targets (R) equal to one means a complete correlation. Therefore, two criteria, MSE and R, are selected to determine the ideal neural network.

5. EVALUATION OF ESTIMATED OUTPUTS BY IDEAL ANNS

As mentioned earlier, multilayer feed-forward ANNs with back propagation error algorithm are used in two steps. Firstly, PGA_a is estimated based on PGA_m, M_m, and M_a. Next, depending on the selected performance level (LS or CP), decreased intensity measure is predicted based on obtained PGAa from the previous step, PGAm, T and Tag (to separate the SMRFs, ordinary concentrically and BRB frames). The statistical properties of inputs and targets are listed in Table 1. The neuron number in each hidden layer is determined using the trial and error method. In this regard, 1 to 20 neurons are selected for each hidden layer, and the best ANN is selected with the highest R and lowest MSE, among others. Ideal ANN in the first step has 7 and 20 neurons to predict PGA_a with R equal to 98%. In the second step, outputs are estimated for LS level with R equal to 98.6% and ten neurons in each hidden layer. Ideal ANN corresponding to CP level has 18 and 16 neurons in hidden layers, and the correlation coefficient between targets and outputs is 98.2%. A comparison of actual and estimated values by ANN in each step is shown in Fig. 5. As shown in this figure, simulated values in each step by ANN sets spread around the 45-degree line, which implied neither overestimation nor underestimation.

Table 1. Statistical specifications of input parameters.

Input	Min	Max	Average
PGA_m	0.034	1.662	0.277
M_m	4.370	6.690	5.706
M_a	4.370	6.200	5.575
PGA_a	0.056	0.921	0.261
T	0.268	1.994	0.855
Tag	1	3	

In the following, the effect of some parameters such as PGA_m is investigated for LS and CP levels to evaluate the seismic capacity of studied steel frames under as-recorded successive records. For this purpose, other input parameters need to be constant. Among the statistical specifications, the reported average in Table 1 is considered as a representative of the constant data. For example, decreased intensity measures corresponding to LS for SMRFs and CP for ordinary concentrically braced frames are shown with different values of PGA_m in Fig. 6. As shown in Fig. 6-a, the change process is more uniform for SMRFs with increasing the PGA of the first shock. As the PGA_m increases, the SMRFs exceed the life safety limit under critical second shock for lower values of the seismic intensity criterion, while steel frames containing ordinary concentrically braces do not follow a specific process to exceed CP by increasing the PGA_m.

As mentioned in previous sections, the use of repeated shocks that have been generated based on back to back method can lead to non-conservative results. Due to the training of ideal networks, it is possible to investigate the results without performing incremental nonlinear dynamic analysis by introducing the first shock instead of the second's.

Fig. 7 shows IM Ratio corresponding to LS for back-to-back model to real, regardless of the type of steel frames. With increasing the height of the steel frames or increasing the T, the difference between the results caused by real and back to back model is intensified. This difference also emphasizes the necessity of real consecutive earthquakes instead of repeated shocks. Comparison between IM Ratio corresponding to CP level in real and repeated shocks is shown in Fig. 8. The difference between results is severe for relatively tall steel frames.

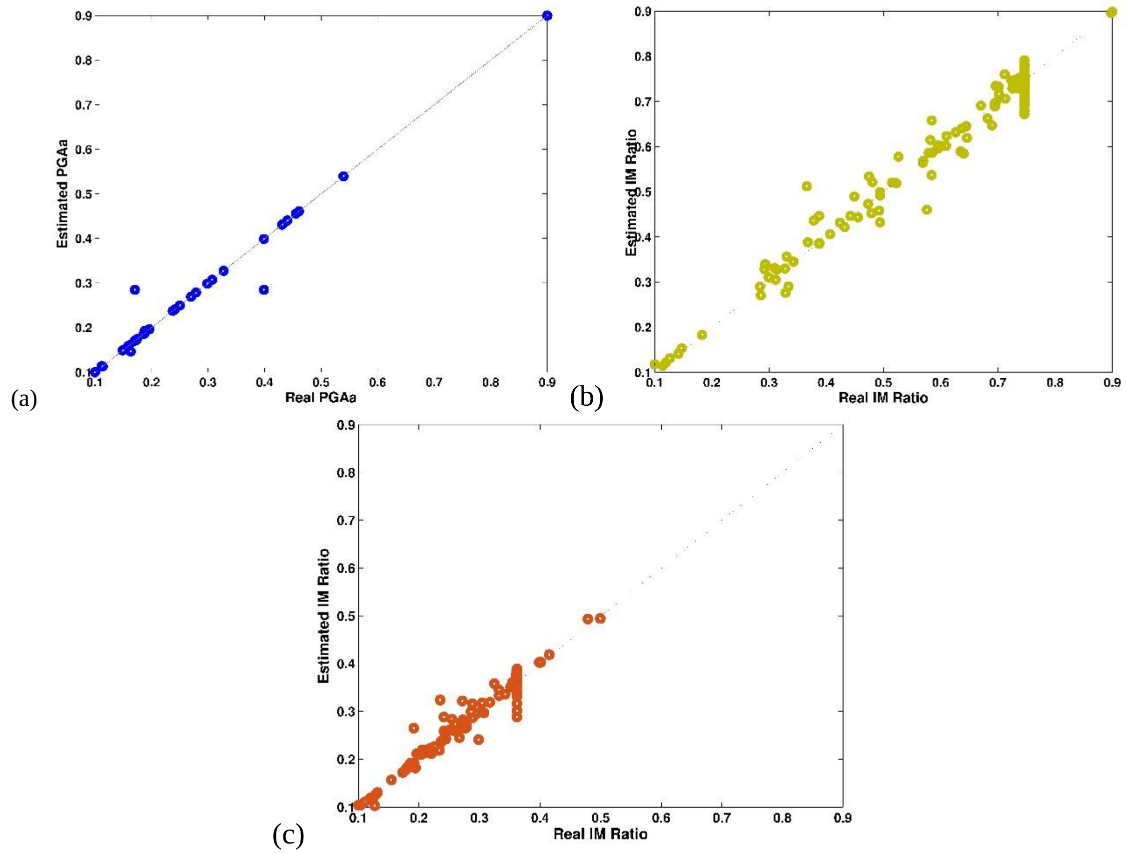
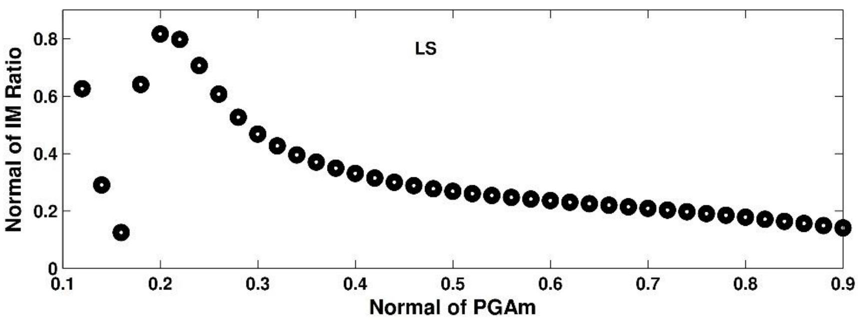
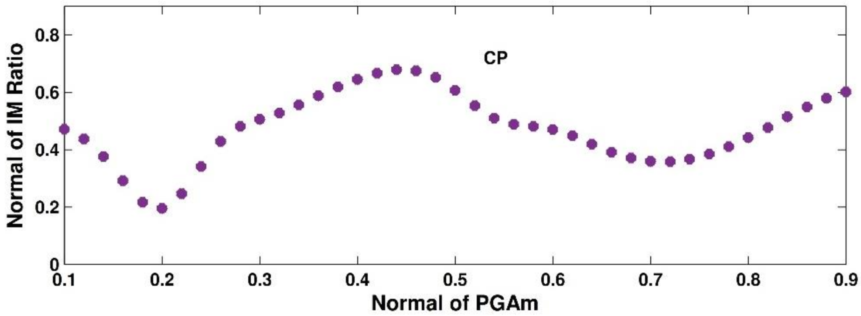


Figure 5. Comparison of actual and estimated values by ideal ANN in (a) 1st step, (b) 2nd step for LS level and (c) 2nd step for CP level



(a)



(b)

Figure 6. Decreased intensity measure corresponding to (a) LS for SMRFs and (b) CP for ordinary concentrically braced frames

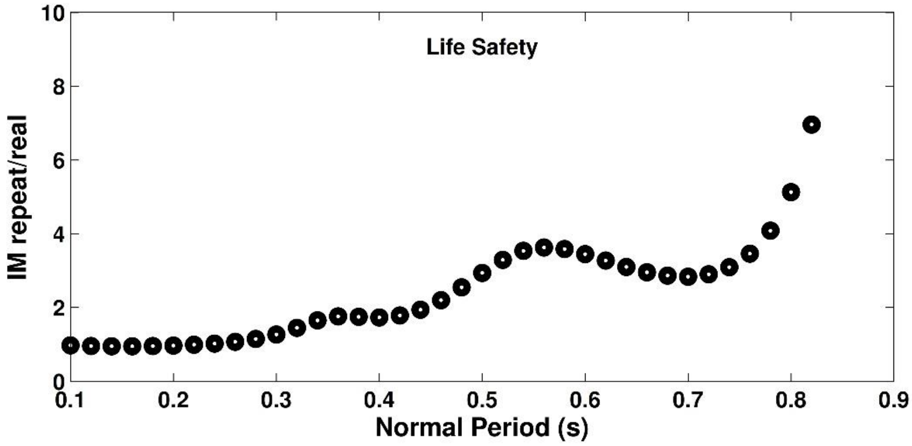


Figure 7. IM Ratio corresponding to LS for back to back model to real, regardless of the type of steel frames

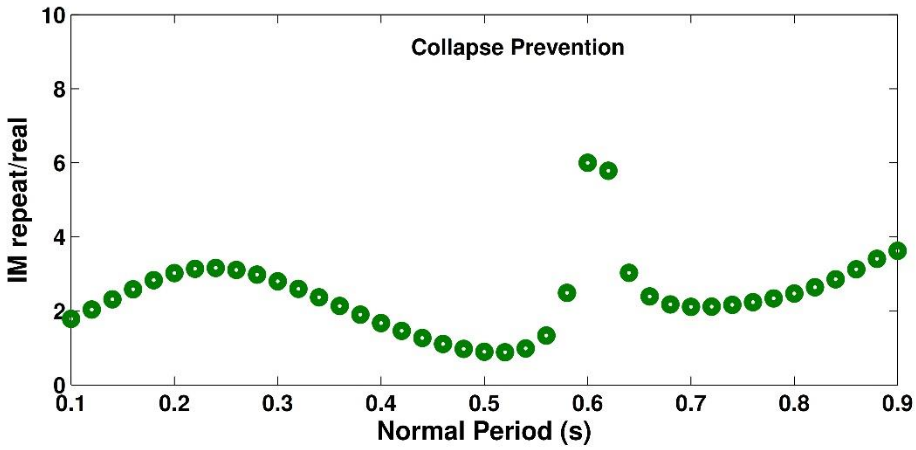


Figure 8. IM Ratio corresponding to CP for back to back model to real, regardless of the type of steel frames

In order to compare the performance of SMRFs and BRB frames in the face of real and repeated consecutive shocks, IM Ratio corresponding to LS level for back-to-back model to real is shown in Fig. 9. The amount of change for the BRB system is less than the SMRFs. The ratio of decreased seismic intensity measure in BRB frames corresponding to LS and CP is compared for repeated to real in Fig. 10. For short to relatively tall buildings, the BRB brace has a similar performance against real and artificial successive earthquakes, and ratio is close to one. This seismic system has eliminated most weaknesses of a conventional bracing system by overcoming buckling under pressure.

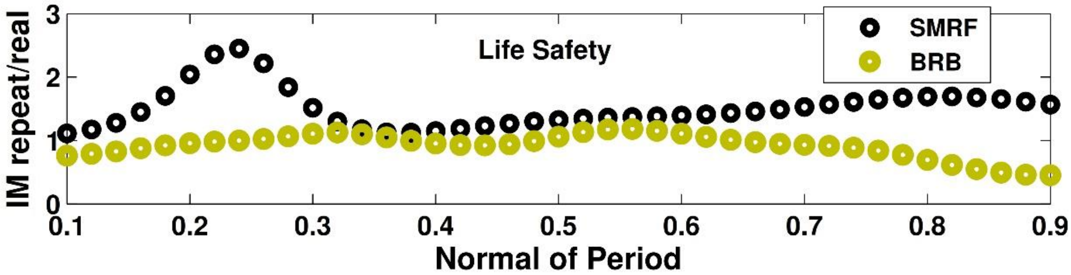


Figure 9. IM Ratio corresponding to LS level for back to back model to real

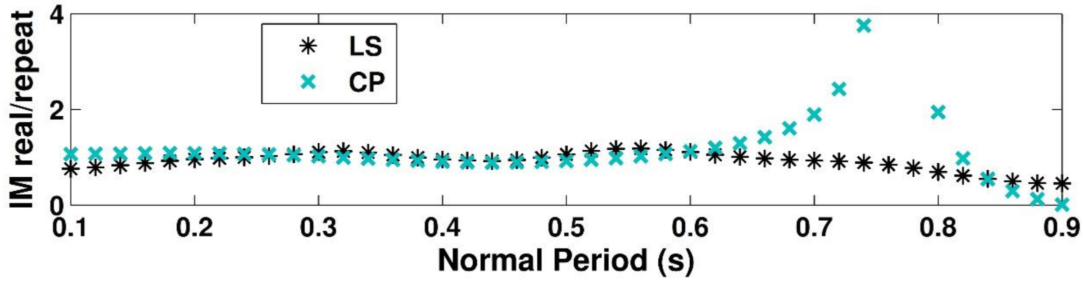


Figure 10. Ratio of decreased seismic intensity measure in BRB frames corresponding to LS and CP for repeated to real

6. RESULT

6.1 Discussion

Consecutive earthquakes lead to accumulation of damage in the structure and collapse before the requirements of seismic design codes. Therefore, it is necessary to consider the successive earthquakes in the structural design procedure. In this paper, in order to overcome some uncertainties, such as identifying the characteristics of second shocks and accordingly estimation of structural capacity after the first shock, the abilities of artificial neural networks have been used in training and estimating results. In this regard, after identifying and selecting the critical seismic scenarios based on Ghodrati Amiri and Rajabi's study in 2017, peak ground acceleration of the first shock - PGA_a - is estimated as one of the most important features of earthquakes by ideal ANN in the first step. According to Fig. 4, this ANN is trained based on first shock characteristics with R > 98%. In the second step, decreased intensity measures for steel frames are predicted with adequate precision based on estimated PGA_a from the previous step, PGA_m, T and Tag of frames for LS and CP levels. These predicted results are compared with real values in Fig. 5. In the following, the effect of some parameters such as PGA_m, period of frames has been investigated on the decreased capacity using ideal ANN in Fig. 6, 7 and 8. Finally, by introducing repeated shocks – by introducing the first shock as the second's – the performance of steel moment-resisting frames and steel frames equipped by BRB is evaluated without performing IDA in Fig. 9 for life safety level. In the last step, Fig. 10 compares the efficiency of BRB frames in the face of real and repeated shocks for life safety and collapse prevention levels.

6.2 Conclusion

This paper evaluates the seismic capacity of steel structures with/without bracing under real and artificial critical successive earthquakes using ideal neural networks. Some results are as follows:

- The proposed *single design earthquake* in seismic design codes may not be a good representative of as-recorded successive earthquakes, and the actual seismic performance of the structures will be very different from the assumption of codes. Because the structures will collapse under real successive earthquakes earlier than what is often expected in codes.
- The structural response under artificial consecutive earthquakes by repeating the first shock as the second's is different from the real scenarios. This difference proves the inadequacy of back-to-back method in the generation of successive earthquakes.
- The change process is more uniform for SMRFs with increasing the PGA_a. As the PGA_m increases, the SMRFs exceed the life safety limit under critical second shock for lower values of the seismic intensity criterion while steel frames containing ordinary concentrically braces do not follow a specific process to exceed CP by increasing the PGA_m.
- Regardless of the type of steel frames, with increasing the height of the steel frames or increasing the T, the difference between the results caused by real and back-to-back model is intensified. This difference also emphasizes the necessity of real consecutive earthquakes instead of repeated shocks.
- For short to relatively tall buildings, the BRB frames have a similar performance against real and artificial successive earthquakes, and the ratio is close to one. This seismic system has eliminated most weaknesses of a conventional bracing system by overcoming buckling under pressure.

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