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Using the Concept of Neural Network in the Evaluation of Fragility Curve of Steel Moment Frame

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ABSTRACT

In order to present fragility analysis, the present research has offered the implementation of Neural Network (NN), which can give accurate estimations of structure responses in a part of the required calculated time by common analysis. The main advantage of using Neural Network (NN) concept is that it can study the issues without having an algorithmic solution or one which is quite hard to find. The proposed methodology has been used for steel moment frame structures. Results show that by implementing the proposed Neural Network (NN), a reduction of one-order magnitude is obtained to have a complete fragility analysis.

KEYWORDS: Neural networks, Time history dynamic analysis, Fragility curves, Harmony research, Steel moment frame.

INTRODUCTION

Structure analysis method is shaped from scientific methods, such as mechanic theory and mathematical methods, resulting in numerical simulation methods. Yet, three decades before, a new group of calculative methods, known as Smooth Computing (SC), were proposed and presented. They were first observed with doubt and skepticism, yet having achieved suitable results. Gradually, their use increased in different areas of engineering sciences. Neural Network (NN), Fuzzy Logic (FL) and metaheuristic method are the most important SC methods (Márquez-Chamorroa et al., 2015). Seismic fragility analysis, which gives a safety limit index for structural systems, is the main factor of danger evaluation. Majd et al. (2012) used trustable fragility curves based on two indices of damage; namely, "inner story drift" and "plastic axial deformation". Özel and Güneyisi (2011) studied the fragility curve of an RC frame, equipped with same-axis buckling brace, as well as normal log distribution functions. Their study showed that fortifying RC buildings with such buckling braces improves their performance against earthquakes. Jong and Elnashai (2005) offered the principles of fragility curve extraction for RB structures with disordered plan and related a damage index in order to describe damage features of disordered structures.

In a limited number of studies, NN method was used to reduce the calculations needed for expansion of fragility curves. In Lagaros and Fragiadakis (2007), a Monte Carlo simulation was suggested by means of NN, which could lead to quick evaluation of the possibility of exceeding a limited state for a certain danger level. Papadrakakis et al. (2008) proposed an NN, based on Monte Carlo simulation, for evaluating huge concrete dams with a non-linear limited element, in order to estimate the dam loading capacity by means of the continuum strong discontinuity approach.

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In this research, four limit cases have been considered; therefore, an 8-parameter improvement problem is to be solved. Harmony research algorithm, which belongs to metaheuristic category, has proven to be a suitable improvement method (Lee and Geem, 2005). Therefore, this method is being used to solve improvement problems. Additionally, in order to expand fragility curves, it is needed to estimate structural responses, which are obtained from time history non-linear dynamic analysis. In order to study the considered myriad of calculative attempts, an approximate structural response NN is proposed, which reduces the greatness of calculation time more than once. In NN-based methodology, it is suggested that uncertainty in request is to be taken into account in a correct state, in which a great source of records could be studied with fewer calculative attempts.

Fragility Analysis

The evaluation of structural earthquake danger requires calculating the possibility for a set of limit states. The aim of finding limit state possibilities is surpassing, done as a danger curve for structural damage. The maximum annual frequency of average inner story drift (θ_{max}), which is bigger than y, is obtained as:

$$\nu_{\theta} = \int p(\theta_{max} \geq \frac{y}{IM} = x)|d\lambda_{IM}(x)| \quad (1)$$

where V_θ is the rate of θ_{max}, bigger than Y. $\lambda_{IM}(x)$ is the annual frequency of average intensity measure, bigger than x. In other words, $\lambda_{IM}(x)$ is the danger curve and $d\lambda_{IM}(x)$ is its inclination. Absolute value is used for the inclination, as it is a negative amount. Based on the above equation, seismic fragility F_R is defined as the possibility of limit state, depending on a seismic intensity measure IM, demonstrated as peak ground acceleration, spectral acceleration, speed range or other controlling variants, compatible with seismic danger characteristics. In this research, the first mode spectral acceleration SA (T_1, 5%) is used to show the intensity of ground seismic shock. Therefore, fragility curves of seismic fragility are defined as:

$$F_R = P(\theta_{max} \geq \frac{y}{IM} = x) \quad (2)$$

According to Shinozuka et al. (2000), it is assumed that F_R curves could be demonstrated as ni-parameter normal log distribution functions (λ average and log, standard deviation β) and the estimation of both parameters is done with maximum possibility method. Possibility function for the current aims is shown as:

$$L(\mu_1, \mu_2, \dots, \mu_n, \beta_1, \beta_2, \dots, \beta_n) = \prod_{i=1}^{N} \prod_{k=1}^{n} F_R(S_{A,i}, y_k)^{x_i k} \quad (3)$$

where F_R is the fragility curve for a certain damage status; $S_{A,i}$ is the spectral acceleration of the first mode; $x_i k$ is equal to 1 or zero; N is the general number of structural realizations after the earthquake; and n is the general number of limit states. Therefore, F_R will be given as:

$$F_R(S_A) = \varphi[\frac{In\left(\frac{S_A}{\mu_k}\right)}{\beta_k}] \quad (4)$$

where φ is the standardized normal distribution function. As proposed in Shinozuka et al. (2000), two parameters of μ_k and β_k in Equation 4 (in which k = 1, 2… n) are calculated as amounts that optimize ln (L) by applying a maximum optimization algorithm. This research uses an optimization metaheuristic algorithm (Geem et al., 2001), in which there is no evaluation of the inclination.

Harmony Research

The optimization algorithm used to solve 2n parameter problem (μ_k, β_k, k = 1, 2…, n) is a harmony search algorithm (HS), as it is a method that spends less time for calculation among other metaheuristic algorithms (Lee and Geem, 2005; Lagaros and Papadrakakis, 2010). Harmony search was originally used by the improvement process of jazz music (Geem et al., 2001). Music harmony in a certain time corresponds with solution vector in a certain interaction, as well as the corresponding audience aestheticism with goal function. Based on the above mentioned algorithm concept, HS algorithm consists of the 5 following steps:

primary parameter initialization, primary harmony memory initialization, partial improvement of the new harmony, harmony memory updating and final index evaluation.

Seismic Need Evaluation with Neural Network

The main purpose of this study is to give an efficient and effective fragility analysis in form of steel moment frame structure calculations. For so doing, two parameters of μ_k and β_k in Equation (4) need to be calculated for each limit state considered. The quality of close fragility analysis depends on the estimation of these two parameters, which are influenced by the size of natural record set. Therefore, a trained NN is used in order to obtain seismic demand level, corresponding to an EDP that is demonstrated based on structure's first period mode (S_A (T_1, 5%)). Seismic records, showing uncertainty in demand, are determined by an NN with the help of an IM vector. IMs show the parameters for each seismic record, thus they are used as an input for the NN.

Choosing Intensity Measures

Strong seismic shocks are quite complicated, demanding lots of data to completely describe and explain them. Definition of some ground shocks, called Intensity Measures (IMs), simplifies the description and explanation of a strong ground shock, relating seismic danger with structural data considered to solve earthquake engineering problems. The most important characteristics of a ground shock in terms of earthquake engineering are the domain, frequency and time length of the quake. Some IMs, related to one of the three ground shock characteristics, are necessary. IMs, related to the effect of more than one characteristic, are more trustable for explaining and describing a ground shock and can be more suitable to reflect the potential damage inflicted by a ground shock in a structural system. The most common IMs are the domain, resultant from an accelerometer of peak ground acceleration (high frequency), peak speed (average frequency), peak movement (low frequency), permanent speed and acceleration, as well as effective design acceleration. Domain IMs are used to calculate the derivative of damping relations in possible danger analysis, because its establishment according to IMs' dependency is related to the earthquake's greatness, as well as to the distance of the site to the source. IMs related to frequency are described *via* different spectra and domain distribution of a ground shock among varying frequencies. IMs are related to the frequency rate, Fourier spectrum and power spectrum corresponding to the ground shock's frequency and low frequency, themselves equivalent to the impact of ground shock on structures with varied essential characteristic periods. Meanwhile, such IMs are spectral parameters, such as: dominant period, band width, central frequency, shape coefficient and V_{max}/a_{max} proportion, which describe a ground shock.

Estimation Program

As aforementioned, the main aim of the presented methodology is to describe a curve by means of the relation between the explained intensity measure and an IM criterion as well as max seismic response of a structural system, explained with an EDP. The aim of design and map is to calculate the training of an NN in order to estimate the seismic demand, demonstrated in accordance to the structure's basic period (S_A (T_1, 5%)) for a certain amount of limit state, itself indicated by the max. inter-story drift. This is the EDP used in the present research. Therefore, NN should be able to correctly calculate S_A (T_1, 5%), resulting from ground shock mapping. Intensity measures for certain intensity should be well-related to seismic demand to be used as input for the NN, so that it could well reflect mapping traits. This research performs a calculation design and map of structural response with training NNs within the framework of structures' fragility analysis. The design's first step is corresponding calculation by defining the training set, in which N vectors of IM are generated *via* Latin Hypercube Sampling (LHS) (Olsson et al., 2003), while structural response is taken into consideration in limit states in a set of ground shocks in Table 1. The amount of N is evaluated by a limited non-linear

dynamic element analysis while referring to its structural performance. NN training phase is carried out in the second stage of the calculation design. This phase includes selecting an appropriate NN structure and training its test. Once training and testing methods are successfully done, the trained NN is capable of calculating whether a new design vector is feasible, based on structural analysis without having any limited non-linear dynamic element analysis.

Table 1. Characteristics of 30 natural records

Record ID	Earthquake Name	Station	PGA (g)	PGV (m/cm)	PGD (m)
P0810	Cape Mendocino	Rio Dell	0.385	43.9	22.03
P0345	Coalinga	Park Field	0.112	14.6	5.69
P0817	Landers	Morongo Valley	0.188	16.6	9.45
P0739	Loma Prieta	Halls Valley	0.134	15.4	3.3
P0889	Northridge	Beverly Hills	0.617	4.8	8.57
P0058	San Fernando	Lake Hughes	0.145	17.3	2.88
P0139	Tabas	Boshrooyeh	0.107	13.7	10.5
P0360	Coalinga	Vineyard Cany	0.23	27.6	6.21
P0352	Coalinga	Gold Hill	0.094	11.0	2.87
P0891	Northridge	Big Tujunga	0.245	12.7	1.12
P0933	Northridge	Sunland	0.157	14.5	4.29
P0166	Imperial Valley	Chihuahua	0.27	24.9	9.08
P0169	Imperial Valley	Cucapah	0.309	36.3	10.44
P0916	Northridge	La Crescenta	0.159	11.3	3.0
P0899	Northridge	Glendale	0.357	12.3	1.94
P0808	Cape Mendocino	Fortuna	0.116	30.0	27.59
P0323	Coalinga	Cantua Creek	0.281	25.8	3.71
P0168	Imperial Valley	Compuertas	0.186	13.9	2.92
P1547	Duzce	Bolu	0.822	62.1	13.55
P0164	Imperial Valley	Calipatria Fire	0.128	15.4	10.91
P0173	Imperial Valley	El Centro Array	0.139	16.0	9.96
P0814	Landers	Desert Hot	0.171	20.2	13.87
P0818	Landers	North Palm	0.134	14.5	5.57
P0747	Loma Prieta	Hollister Diff.	0.279	35.6	13.05
P0743	Loma Prieta	Anderson Dam	0.244	20.3	7.73
P0792	Loma Prieta	WAHO	0.638	38.0	5.85
P0892	Northridge	Canoga Park	0.489	14.2	5.5
P0721	Superstitn Hills	Plaster City	0.186	20.6	5.4
P0722	Superstitn Hills	Wildlife Liquef.	0.408	6.0	3.9
P0914	Northridge	LA - Saturn St.	0.474	34.6	6.55

Numerical Example

Three steel moment frame buildings with three, eight or twelve stories were selected. They were located in one of the high seismic regions of Iran. The buildings were residential and calculated based on Eurocode 8 (2005). All three buildings had similar story plans, but different

heights. Fig. 1 illustrates the floor plan and the considered frames. Gravitational load includes both live and dead loads. The dead load of the stories was 550 $\frac{kg}{m^2}$; the live load 200 $\frac{kg}{m^2}$ and the roof load 150 $\frac{kg}{m^2}$. Other types of loading, such as wind or snow loads, were not taken into account. Moreover, soil-structure interaction was not considered as well and the columns' bases were assumed to be in the floor. The height of stories was 3.2m.

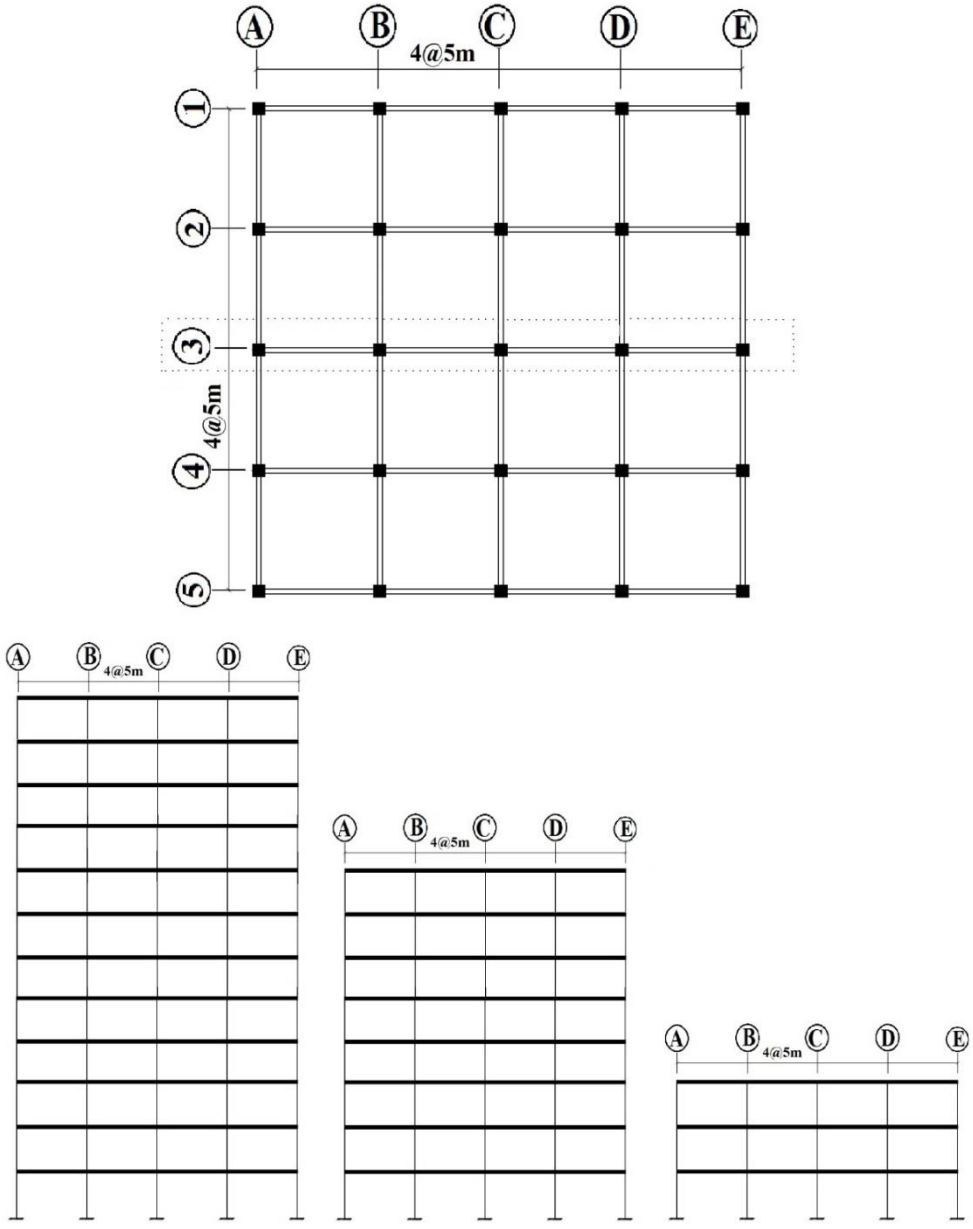


Figure (1): Stories' plan and the frames considered (frame 3) for analysis

Pushing resistance of roof concrete was 210 $\frac{kg}{cm^2}$ and the concrete slab thickness in the stories, 15cm. Table 2 shows the beam and column sections used in this building.

Table 2. Sections used in the structures considered

Story	Column	Beam	Story	Column	Beam
1	2IPE600	IPE450	7	2IPE450	IPE360
2	2IPE600	IPE450	8	2IPE450	IPE360
3	2IPE600	IPE450	9	IPE600	2IPE240
4	2IPE500	2IPE360	10	IPE400	IPE320
5	2IPE500	2IPE360	11	IPE330	IPE270
6	2IPE500	2IPE360	12	IPE300	IPE240

The structures considered were measured by means of a computer software, named SeismoStruct V.6 (SeismoSoft, 2012). Each member was modeled with an individual column-beam element, whereas the frames had rigid connections and constant bases. This element brings a good balance between calculative accuracy and cost (Fragiadakis and Papadrakakis, 2008). The impact of gravitational forces and second-tier effects are considered and studied *via* non-linear geometrical considerations.

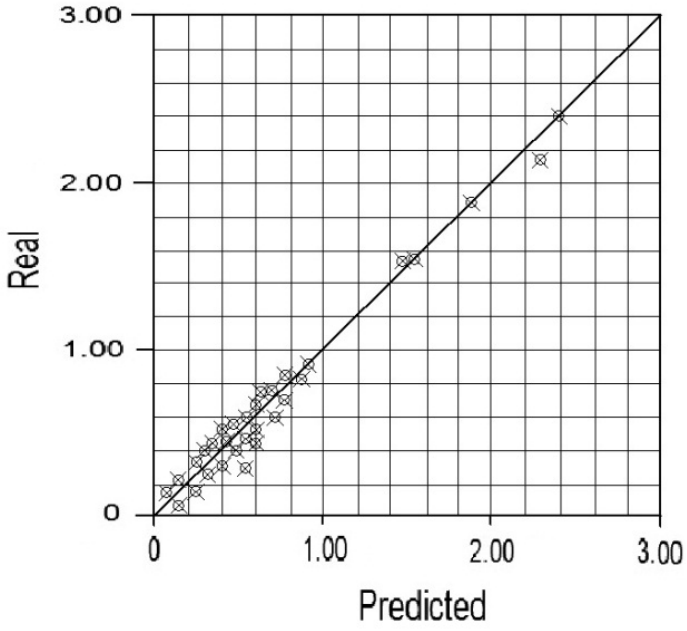
NN Used

The numerical example solved in this study is composed of calculation abilities and NN estimation, development and expansion of fragility curves, calculation of average annual frequency of exceeding the limit state and the required calculative costs. Accordingly, 30 natural mappings have been used. These records are selected from PEER databases of strong shocks (Internet, 2010), in accordance with the following characteristics.

NN Estimation

In this numerical research, the abilities of NN estimation have been taken into consideration. The aim of NN estimation is to estimate and calculate the demand of presenting limit state for different combinations of three IM rates, taken to be more trustable to explain ground shock. Therefore, there are three NN input nodes for each structural model, whereas two curve layers contain 25 nodes. Trial and error method has proven that this number of curve nodes match accurate estimations with efficient and effective calculations. The output layer has four nodes, corresponding with spectral acceleration of basic period (S_A (T_1, 5%)) for the discussed limit state; therefore, an NN combination of 3-45-45-4 is used for each structural model considered.

Normally, there are two network kinds; named complete and patterned attached networks. In a complete attached network, each unit in a layer is attached to all units of the previous layer and next layer. Such a network structure is widely used. Alternatively, there might be some local dependence among the units and some connections will decrease by establishing the patterned attached network. The number of neural cells used in hidden layers is unknown and usually calculated by trial and error. In the first learning phase, gradual increase occurs in the number of hidden units and then optimal integration is suitable for the attempts in removing some of them in order to find the minimum size of the network. After selecting the appropriate NN structure and learning instructions, the network is then used for presenting the estimation of seismic demands presenting the limit state corresponding with different rates of input IMs.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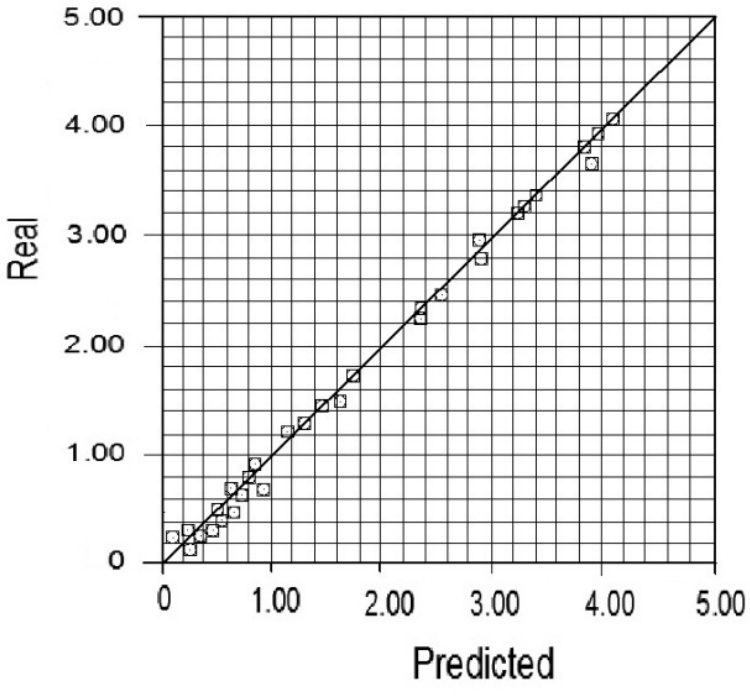
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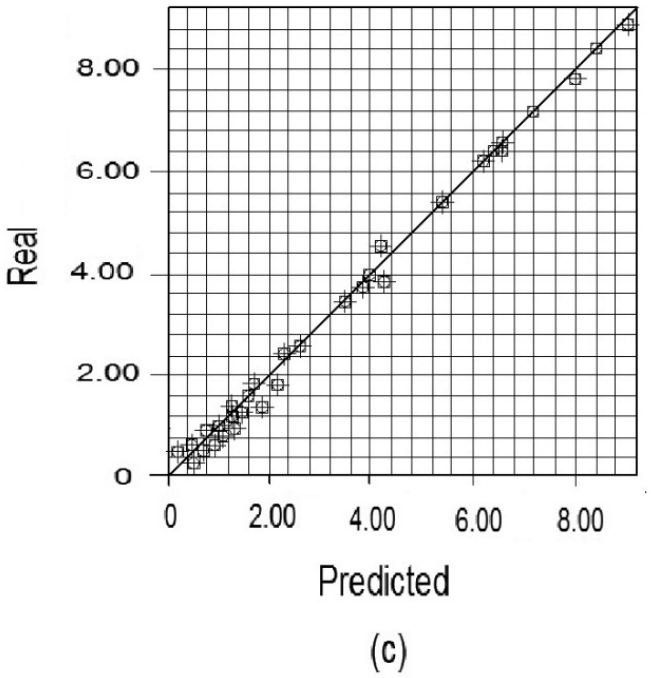


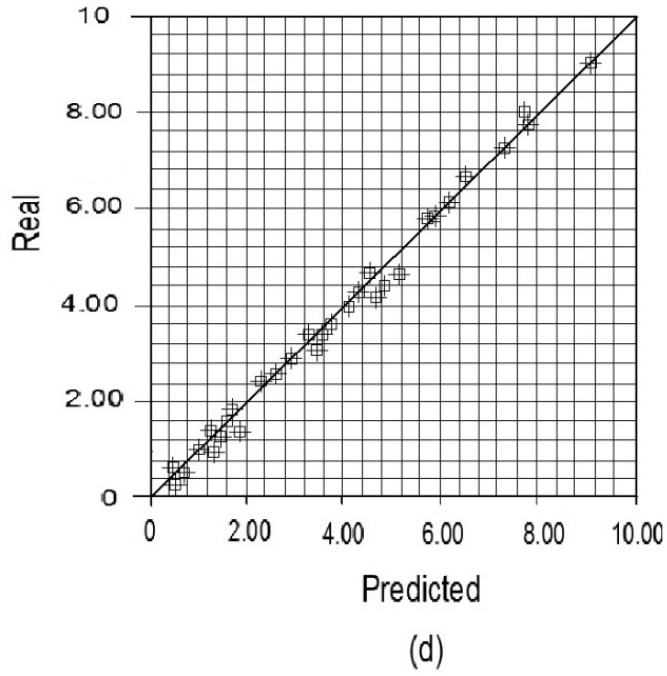


Figure (2): The ability of NN estimation in 3-story frame model: a) low damage limit state (0.3%), b) medium damage limit state (0.7%), c) vast damage limit state (2%) and d) collapse limit state (5.33%)

The abilities of NN extrapolation are proposed to be problematic, which is due to NN features for drawing

each function by regulating its parameters in accordance with the present data. As a result, having efficient and effective training data to prevent NN extrapolation, instead of its interpolation, is very important. The impact of this obstacle decreases through creating training a sample by means of the Latin Hypercube Sampling (LHS) method within IM bounds. Thus, NN always estimates interpolated rates. Figs. 2, 3 and 4 show the performance and efficiency of NN, in which the estimated rates are drawn against the results from a complete non-linear analysis. The set of mappings are selected *via* LHS Method, whereas four corresponding patterns with 30 natural records have been used to study the estimation capabilities of NN.

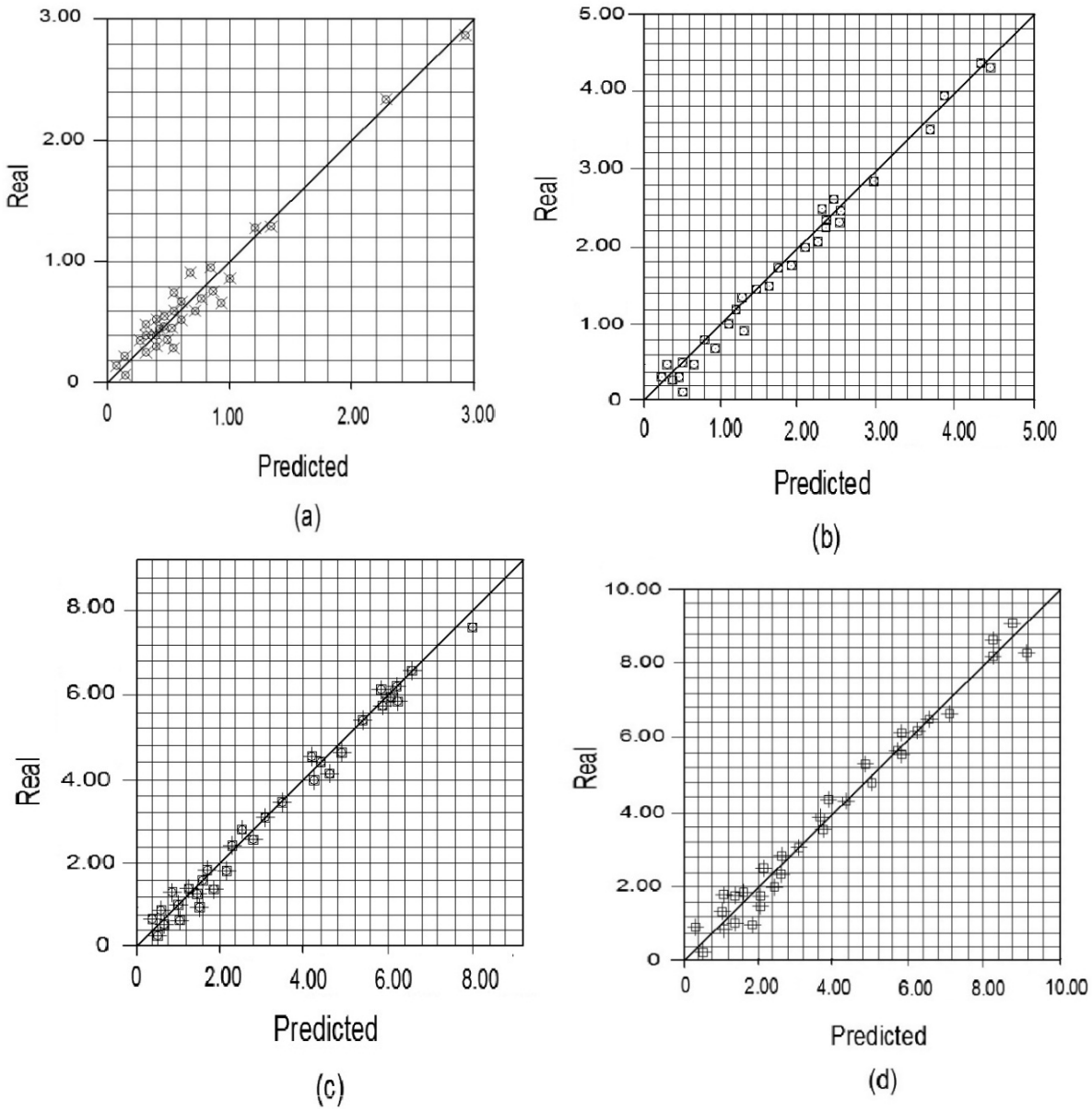
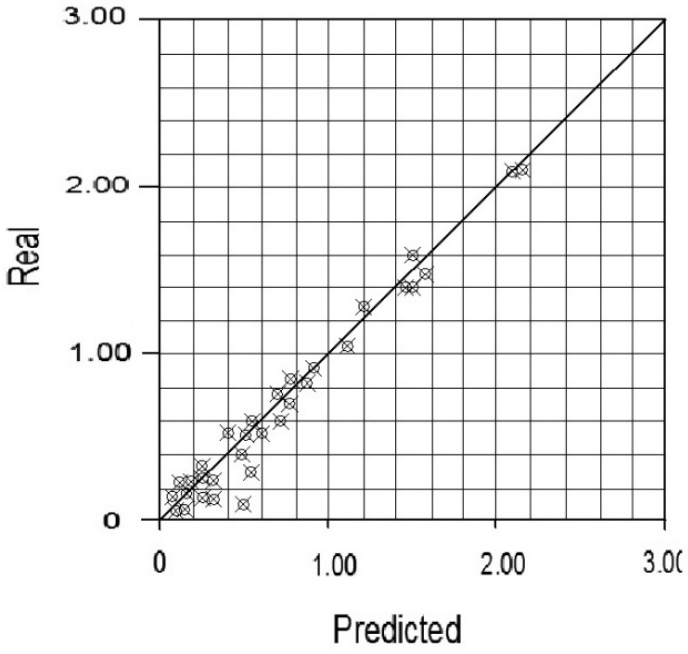


Figure (3): Estimation capability of NN in 8-story frame model: a) low damage limit state (0.25%), b) medium damage limit state (0.5%), c) vast damage limit state (1.5%) and d) collapse limit state (4%)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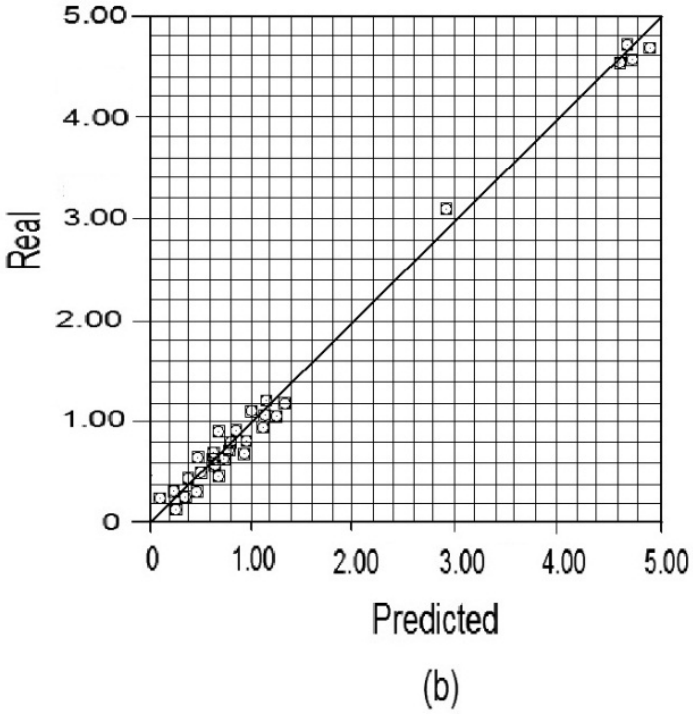
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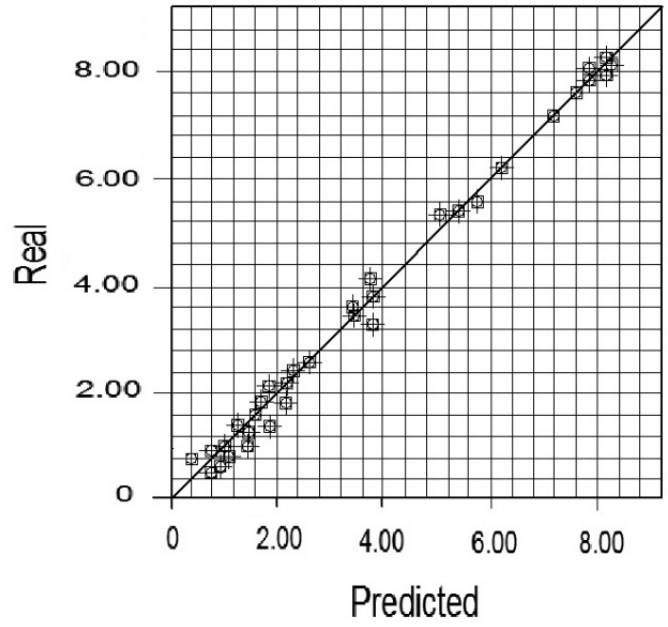

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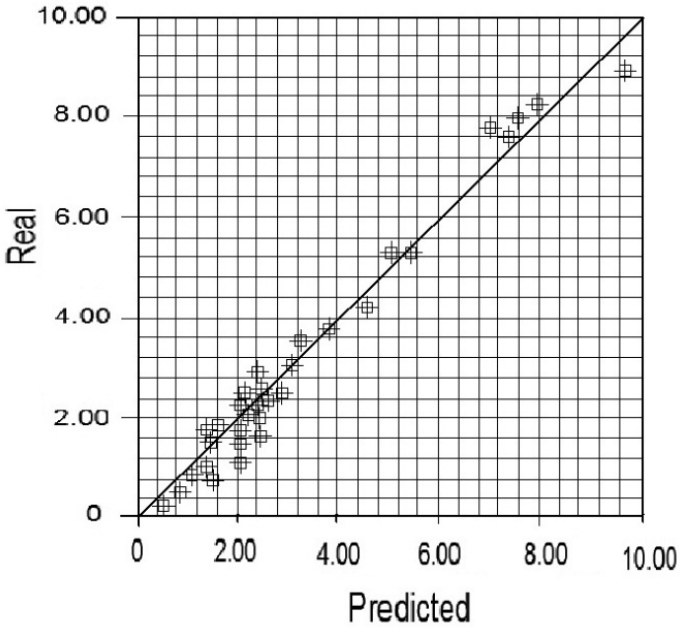

(d)

Figure (4): Estimation capability of NN in 12-story frame model: a) low damage limit state (0.2%), b) medium damage limit state (0.45%), c) vast damage limit state (1%) and d) collapse limit state (3.5%)

Fragility Curves

Figs. 5, 6 and 7 give four fragility curves of limit state for each of the three structural models. The limit states considered are defined by the maximum drift rates, covering the general zone of structural damage. The rates of e_{max} in accordance with HAZUS (2003) for each of the four limit states shown in Figs. 2 to 4, are selected. For each limit state, non-linear analysis as well as vertical statistics are performed to calculate two parameters of μ and β in Equation 4, by carrying out harmony search algorithm (L) maximizing L_n. The parameters used for HS algorithm, based on the parameters recommended in (Mahdavi et al., 2007), are as below:

Harmony Memory Size (HMS) was -100 and Harmony Memory Consideration Rate (HMCR) was -0.9, while the rate of sound tone regulation (PAR) was considered to be 0.35. The optimization method was taken into consideration when the best amount of sound tone regulation (PAR) is 0.2. Vertical statistics for all aforementioned four limit states were made. For the present research's goals, four states have been studied to calculate two parameters (μ_k, β_k, κ = 1… 4). Figs. 5, 6 and 7 demonstrate fragility curves, corresponding to the limit states, which cover the entire zone of structural damage of the three structural models considered. It can be observed that 30 earthquake records offer a good prediction of the two parameters μ_k and β_k. Since the final product of fragility analysis is to calculate a long-term possibility, in which a certain drift increases in a building located in a certain site, the evaluation of the influence of uncertainty sources in accordance with Medium Annual Frequency (MAF) is necessary. Each limit state indicated in Figs. 2 to 4 is signified as follows: a) low damage limit state: LD, b) middle damage limit state: MD, c) vast damage limit state: CD and d) collapse limit state: C.

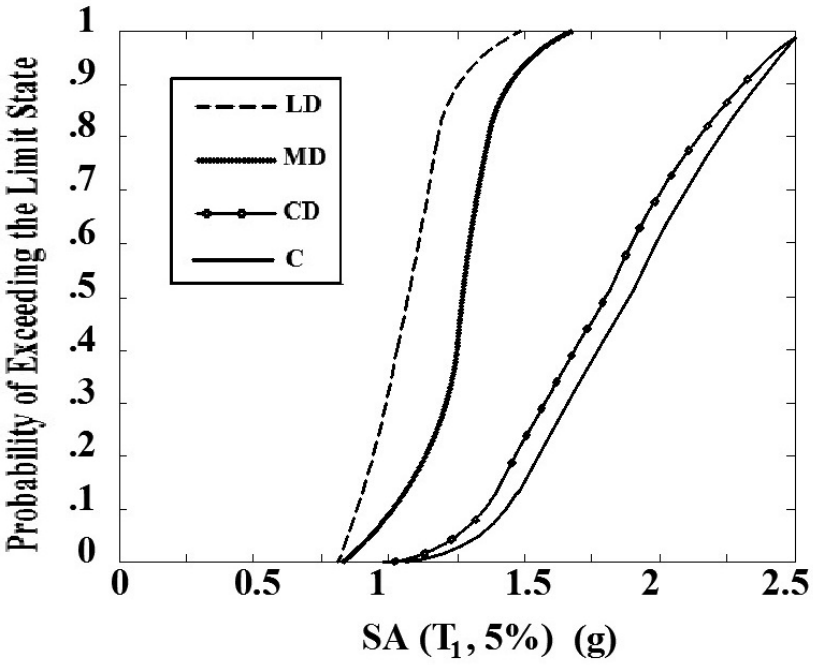

Figure (5): Fragility curve for 4 limit states for 3-story frame

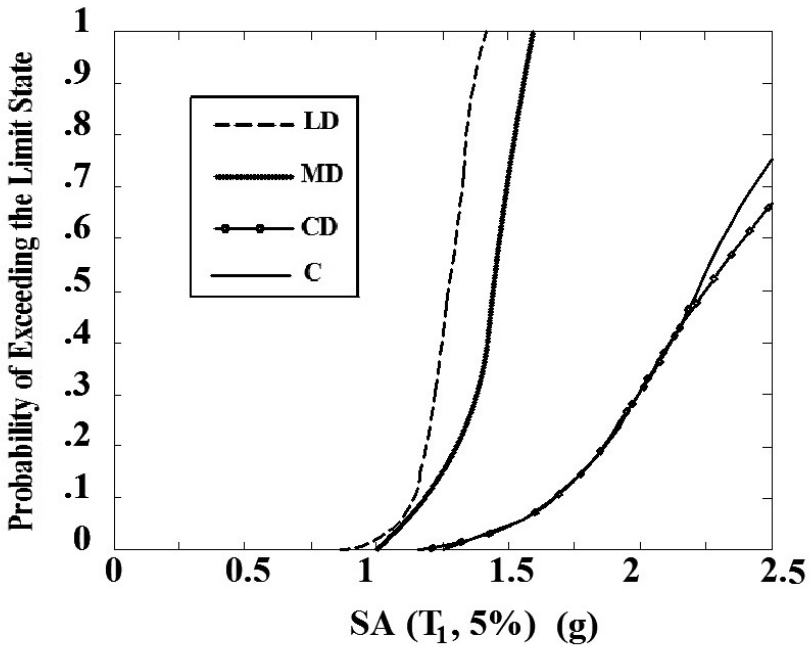

Figure (6): Fragility curves for 4 limit states for 8-story frame

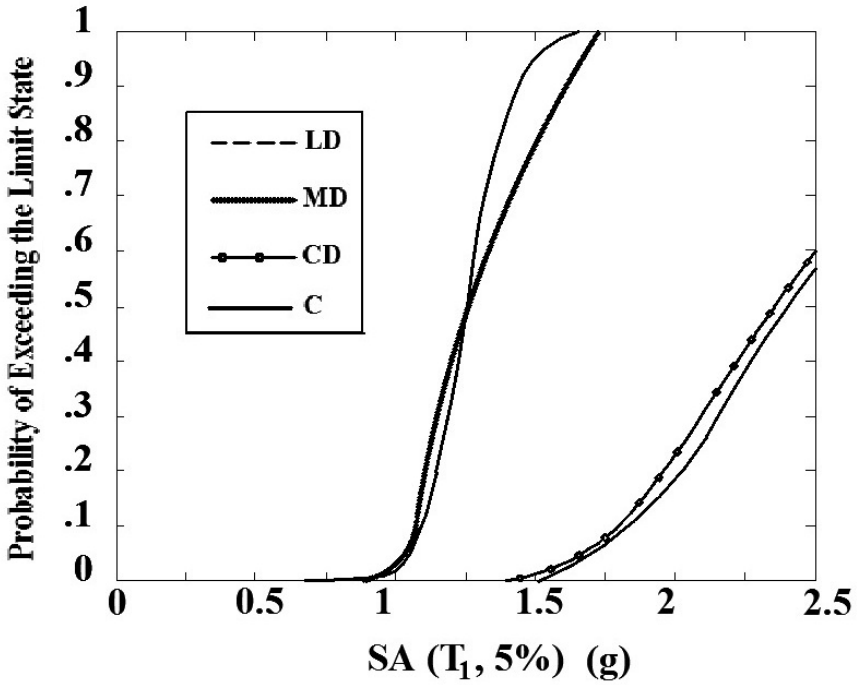

Figure (7): Fragility curves for 4 limit states for 12-story frame

Table 3. Medium annual frequency of exceeding the limit states for different models

	θ ≥LD%	**θ ≥ MD%**	**θ ≥ CD%**	**θ ≥ C%**
3-Story Model	7.23E-03	2.31E-03	6.25E-04	1.97E-04
8-Story Model	3.98E-03	1.24E-03	3.59E-04	4.01E-05
12-Story Model	2.67E-03	0.53E-03	1.61E-04	3.44E-05

CONCLUSION

This research proposed an efficient calculative method to expand fragility curves, depending on different limit states of steel moment frame. Fragility curves are defined with maximum drift rates, covering the entire zone of structural damage. In order to have the fragility analysis, based on time history dynamic analysis, dynamic analysis for different intensity levels should be carried out for a number of ground shocks, sufficient for carrying out statistical analysis of the results. Necessary statistical information for understanding and studying structural systems could be presented in various forms, according to the goal considered (horizontal and vertical statistics). In fragility analysis, in which the designer seeks finding seismic demand, vertical statistics are necessary. In order to calculate optimum rates of the two characteristic parameters of fragility curve function, research harmony optimization algorithm is performed.

NN-based instruction is suggested to make predictions of seismic demand, which offer structural capacity. It is used to evaluate the fragility of steel moment frame in 3, 8 and 12 stories. What is more, the ability of neural calculative prediction method is presented in combination with dynamic analysis.

The main goal is to suggest a method which can present accurate seismic predictions of structural systems at one calculation time, then combined with fragility analysis. Temporal considerations of repetitive analysis, involved in dynamic analysis methodology, cause NN use. Calculative attempts in vertical statistics based on limit states' fragility, become more, due to the fact that the required sample is in the same size. Using NN, in effect, removes any limitation of sample size, resulting in a more accurate expansion of fragilities. Neural networks are trained by means of a set of intensity measures, which can be easily extracted from a source of natural ground shock records.

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