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ENHANCEMENTS IN IDEALIZED CAPACITY CURVE GENERATION FOR REINFORCED CONCRETE REGULAR FRAMED STRUCTURES SUBJECTED TO SEISMIC LOADING

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Abstract. The designing of R/C framed structures subjected to seismic excitation generally is performed by linear elastic method, while current trend of codes of practice is moving toward increasing emphasis on evaluating the structures using non-linear static pushover (NSP) approaches. Recently, several NSP approaches, with varying degree of vigor and success, have been proposed. In this study, initially a comparative study has been made among different non-linear static methods for adopting the most suitable method of extracting the capacity curve of R/C framed structures. Then, a program was developed to overcome the difficulties of graphical iterative procedure of idealization proposed by FEMA-356. Subsequently, the comparative tool, which is a combination of the detected superior NSP method and the developed program, was used to investigate the effects of significant structural variables on idealized parameters of capacity curves of population of R/C framed structures. Eventually, the applicability of replacing the time-consuming NSP procedure by ANN for deriving the capacity curve was tested. The outcomes demonstrated the outperformance of interstorey-based scaling adaptive pushover in addition to high precision of the developed program. Furthermore, the distinct effects of each of the considered structural variables on idealized parameters were unveiled. Finally, an acceptable performance of ANN as an alternative to NSP procedure was certified.

Keywords: pushover analysis, capacity curve, R/C framed structures, idealization parameters, neural network, earthquake, NSP.

1. Introduction

The seismic analysis and design procedures have evolved significantly through the last decade. Nowadays, based on the structural characteristics, different approaches ranging from simple equivalent static analysis to non-linear dynamic analysis are available in literature. As a result, equivalent static analysis is a common approach in practice to determine pseudo-capacity to resist prescribed lateral force for regular R/C frames. Owing to this fact, this approach does not provide insight into the actual capacity of structures. Hence, distinguishing the actual capacity of structures through the procedure of "Performance-Based Design Engineering" (PBDE), has been frequently highlighted (Shattarat *et al.* 2008; Chandler, Lam 2001; Freeman 2005). In response to this a non-linear static pushover (NSP) analysis, as a compromise between simplified linear static and complex non-linear dynamic methods, has been developed. Nowadays, this method found its way to seismic guidelines. One of the fundamental uses of this method relies on the extraction of non-linear force-displacement relationship between base shear and the displacement of control node by applying a graphical iterative bilinearization procedure according to FEMA-356 (2000).

In spite of its many deficiencies, the conventional code-based method is the most well-known method utilized in academic works. It neglects higher modes contribution, stiffness degradation and period elongations (Menjivar 2004). In recent decades, several methods have been proposed to overcome the deficiencies of the conventional method. Some of these methods include: modal pushover analysis "MPA" (Chopra, Goel 2001), Incremental Response Spectrum Analysis, IRSA (Aydinoglu, Celep 2005), Method of Modal Combination, MMC (Kalkam, Kunnath 2004) and Adaptive Pushover Analysis, APA (Antoniou, Pinho 2004; Pinho *et al.* 2005). A majority of them have cumbersome conceptual background and involve computationally intensive procedures. It has been reviewed that APA is one of the most rational novel approaches that overcame these limitations (Seifi *et al.* 2008).

Parallel to the studies in favour of increasing the accuracy of NSP approaches, some of the researchers focused on reducing excessive computational cost and making the PBDE domain viable for real-life engineering applications. Hence, the use of Artificial Intelligence (AI) is incorporated into this realm of knowledge. As a result, ANN has been successfully applied by some researchers (Correno *et al.* 2004; Tsompanakis *et al.* 2005; Gonzalez, Zapico 2007). However, no attempt has been made to employ ANN as an alternative to NSP procedure in favour of predicting the capacity curve. Hence, based on

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the above-mentioned shortcomings, the present study aims to:

i. Choose the most suitable NSP method by means of a comparative study among various types of conventional and adaptive procedures.
ii. Propose a suitable alternative to the graphical iterative procedure of FEMA-356.
iii. Study the effects of tangible geometric and material variables of R/C frame parameters on idealized curve parameters.
iv. Test the applicability of ANN as a replacement for pushover procedure in favour of minimizing expertise, time and efforts of extracting the idealized parameters of a structure.

2. Domain of the selected R/C frame population

First, to facilitate differentiation among the adopted models, "$x_1fx_2sx_3lx_4bx_5r$" has been implemented as a reference point where *f*, *s*, *l*, *b* and *r* refer to the storeys, spans, length of spans, distance between frames and reinforcement type respectively. Also, x_1 to x_5 indicate their corresponding values.

The scope of the present study is confined to R/C regular frames with 2 to 7 stories, 2 or 3 spans by lengths in range of 3.5 to 5 m by 0.5 m increments. The distance between frames was assumed to be constant and equal to 4 m. Two types of longitudinal reinforcement of yield strengths equaling 294.3 MPa and 392.4 MPa have been considered which will be referred to as 3 and 4 with respect to the reference point. Based on the above selected variables, 96 different structures could be possibly modelled. In order to cover the whole range of possible differences among structures, 30 well-distributed models were selected to be considered as structural samples (Table 1).

Table 1. Modelled structures for comparative study

2f2s3.5l4b3r	4f2s4l4b3r	5f3s4l4b3r
2f2s5l4b3r	4f3s3.5l4b3r	6f2s3.5l4b4r
2f3s3.5l4b4r	4f3s3.5l4b4r	6f2s4l4b4r
2f3s4.5l4b4r	4f3s4.5l4b4r	6f3s4.5l4b3r
3f2s3.5l4b4r	4f3s4l4b3r	6f3s4l4b3r
3f2s4.5l4b3r	5f2s3.5l4b3r	7f2s3.5l4b3r
3f3s4.5l4b4r	5f2s4.5l4b3r	7f2s4l4b3r
3f3s4l4b4r	5f2s4.5l4b4r	7f3s3.5l4b3r
3f3s5l4b3r	5f2s5l4b4r	7f3s4l4b3r
3f3s5l4b4r	5f3s4.5l4b4r	7f3s5l4b4r

3.1. Preliminary modelling, analysis and detailing procedure

At this stage, the concrete nominal 28-day compressive strength and modulus of elasticity were assumed equal to 27.458 MPa and 24.787 GPa, respectively. Furthermore, nominal yield strengths of transverse reinforcement were considered equal to the aforesaid values for the longitudinal one. The 30 models of R/C regular frame were created with the aid of SAP2000 program (CSI 2006). Stories and roof were subjected to 6.278 kN/m^2 and 5.788 kN/m^2 as dead loads in addition to 1.962 kN/m^2 and 1.471 kN/m^2 as live loads respectively. By assuming the high seismic region (seismic hazard zone indicator is 0.3 g), linear static analysis procedure, based on UBC-97, was employed for preliminary analysis of models. In all the models P-Δ effect as well as the "cracked sections" was taken into consideration. Confining the storey drift into a 0.025 storey height was a controlling criterion during the analysis procedure (Uniform Building Code 1997).

Afterward, the models were all designed based on ACI 318-99 code load combinations and the "weak beam/strong column" strategy (ACI 318-99 2000). Practical aspects, including bending and curtailment criteria, minimum allowable amount of the longitudinal and transverse reinforcement, existing bar size etc. were controlled manually for each and everyone of the designed frames.

3.2. Finite element modelling

After attaining the logical beams and columns sections, finite element modelling has been carried out. The most relevant package, "SeismoStruct 4.0.2" (2007), has been employed. Via fibre element modelling the program is capable of considering geometric non-linearities as well as material inelasticity. Moreover, precise modelling of bars by defining their location in cross-section was performed. At physical modelling level, 3D inelastic beam-column fibre element models were employed. To represent the beams and columns, 6 and 5 elements were used, respectively. The lengths of each element are determined based on the distribution of reinforcement and expectation of larger level of inelasticity in the vicinity of beam-column connections (Table 2). T-sections and rectangular sections were used to model beams and columns, respectively (Fig. 1). Due to the scope of the study and introduction of negligible confined height in slab, the slab effective width was chosen equal to the beam width. Also, based on a trial and error process, it was found that about 200 fibres are optimum for modelling R/C sections (SeismoStruct user Manual 2007).

Table 2. Assumed element lengths

Member	Elements length (m)					
Beam	0.125L	0.175L	0.2L	0.2L	0.175L	0.125L
Column	0.15L	0.22L	0.26L	0.22L	0.15L	

To account for material non-linearity, the "Uniaxial constant confinement concrete" (con-cc) model was chosen for unconfined and confined concrete (Martinez-Rueda, Elnashai 1997; Powanusorn 2003). In addition, the modified "Menegotto-Pinto" model proposed by Filippou *et al.* (1983) was adopted for reinforcement (Colson, Boulabiza 1992; Byfield *et al.* 2005; Monti *et al.* 1993).

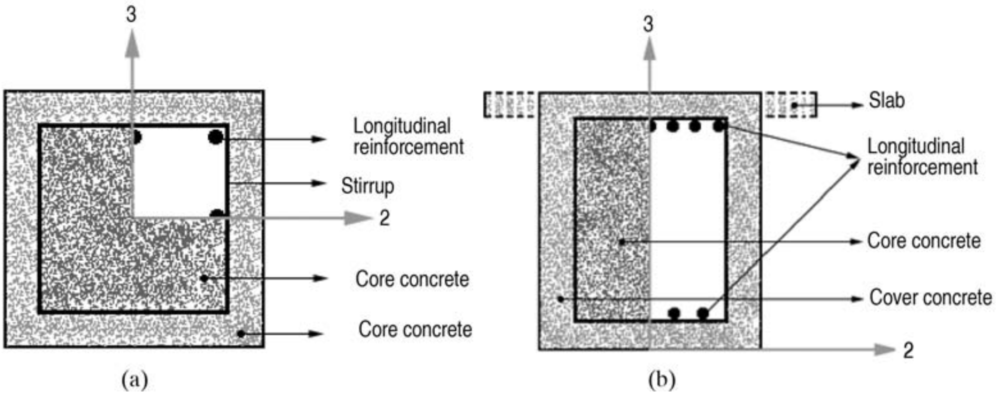

Fig. 1. Adopted R/C (a), T-section and (b) Rectangular section

4. Distinguishing the qualified capacity curve type

4.1. Description of seismic analyses procedures

With the aim of properly identifying the simplest type of NSP method capable of estimating the capacity curve, a comparative study has been performed for one of the relatively large produced models addressed as "6f3s4l4b3r". This model covers all concerning issues including higher mode effects, whiplash effect and so on. Consequently, the outcome of this study was applied as a quantifiable approach for other created models in the next stages of investigation.

After the distribution of gravity loads among the crossing points of beam elements, with respect to the length of their adjacent elements, five types of lateral load distributions were imposed on analogous structures. On the one hand, concerning the conventional prevalent approaches, the "Triangular" method, proportional to the linear static procedure and "Uniform" method consistent with the weight of stories and regardless of their height were utilized (FEMA 2000; SeismoStruct user Manual 2007). On the other hand, adaptive pushover approaches put forward by Antoniou and Pinho (2004), were implemented. In these methods, a variable distribution of lateral loads was utilized. These loads are updated at every predefined step, namely by "Incremental updating procedure" with respect to the modal shapes and participation factors of modes. The participation factors and modal shapes are extracted by eigenvalue analysis.

Depending on whether forces or displacements are applied, two variants of the method exist: *force-based adaptive pushover* (FAP) and *displacement-based adaptive pushover* (DAP). DAP by itself is classified into *displacement-based scaling* and *interstorey drift-based scaling* methods. The major difference between the DAP options refers to the fact that in displacement-based scaling method the storey displacement patterns are calculated from the eigenvalue vectors directly, while in interstorey drift-based scaling technique, the eigenvalue vectors are utilized to determine the inter-storey drifts of each mode (Menjivar 2004).

In line with applying adaptive methods, initially, the inertia mass of the building was modelled at each beam-column joint. In addition, a nominal uniform load P_0 was introduced along the height of structure. Thereupon, for a "force-based" method the base shear was distributed uniformly among all of beam-column joints, while for the "Displacement-based" and "Interstorey-drift based' techniques, target displacements were imposed on joints (Fig. 2).

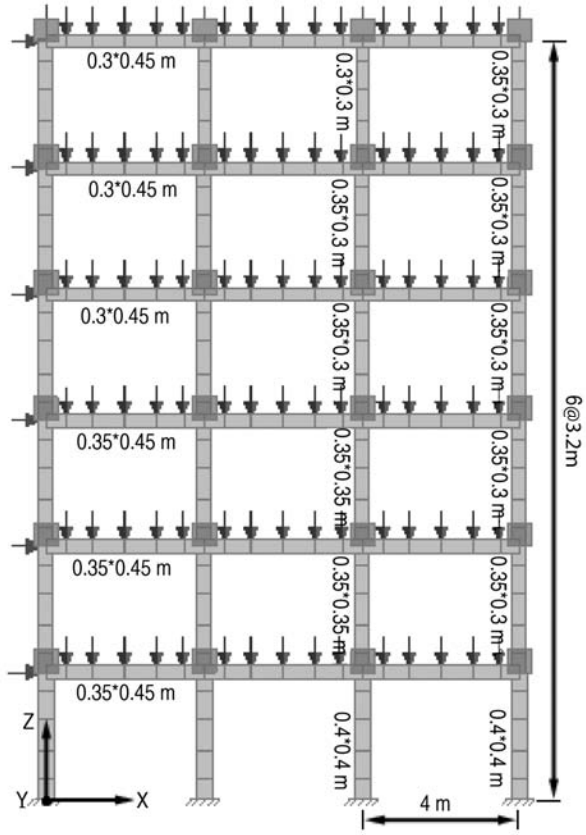

Fig. 2. Geometrical data of finite element model of *6f3s4l4b3r*

The magnitude of the load vector P at any given analysis step is given by the product of its nominal counterpart P_0, and the load factor λ at that step:

$$P = \lambda P_0 \,. \tag{1}$$

During analysis the load factor λ varies between zero and the target load multiplier value (1.0) (SeismoStruct user Manual 2007).

In order to achieve uniformity among various applied pushover methods, the analysis was performed until the control node displacement on the roof reached 2% drifts of the frame height (FEMA 2005). Furthermore, with the aim of improving the accuracy of adaptive methods, spectral amplification was employed and equivalent viscous damping (ξ) was assumed to be 5% as inherent viscous damping (Chopra 1998). A detailed description of the adaptive approaches can be found in (Pinho *et al.* 2006).

Consequently, in order to justify the NSP methods, *"Incremental Dynamic Analysis"*, IDA, was performed for another similar created model. *"Stepping algorithm"* was employed during the study and the model was subjected to a broad range of scaled normalized excitation with the PGA ranging from 0.1 g to 0.8 g with a distinct incremental scaling factor of 0.05 (Vamvatsikos, Cornell 2001). Only the horizontal component of earthquake in a plane of model was imposed on all restraints.

4.2. Earthquake input

The ground motion used during the study was a horizontal north-south component of El-Centro 1940, which caused considerable human and economic losses. The rationale of using this record was the consistency between the seismic zone indicators (0.3 g) exploited for preliminary design and the PGA of the record. The record utilized for APA and IDA analysis, is illustrated in Table 3 and Fig. 3 (Online Reference Documentation 2007).

Table 3. El-Centro earthquake characteristics

Earthquake	Magnitude	Site	Component	PGA (g)	PGD (cm)	Normalization factor
El Centro 18.05.1940	7.1	Imperial valley	North-South	0.318	13.32	3.13

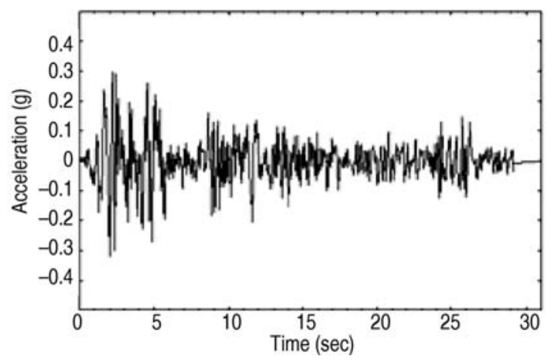

Fig. 3. Time-acceleration of El-Centro record

5. Extracting the idealized parameters of capacity curve

5.1. Idealization criteria

It is worth mentioning that the capacity curve by itself is not meaningful. Therefore, it must be idealized for extraction of important parameters which describe the structural behaviour (FEMA 2000). Although miscellaneous techniques have been proposed for NSP analysis, there is an agreement among researchers that the bilinear idealization method that has been proposed by FEMA-356 is the most acceptable (Chopra, Goel 2001; Akkar, Metin 2007). FEMA-356 idealized capacity curve (Fig. 4) must be computed under these circumstances: (i) it must be bilinear with an initial slope K_e and post yield slop αK_e; (ii) the effective lateral stiffness, K_e, shall be taken as the secant stiffness calculated at a base shear force equal to 60% of the yield strength of the structure; (iii) the post-yield slope αK_e shall be determined by a line segment passing through the actual curve at the calculated target displacement; (iv) effective yield strength V_y shall not be taken as greater than the maximum base shear at any point along the actual curve; (v) an "approximate" balance between the area, which is confined between the bilinear and actual curve, is compulsory (FEMA 2000).

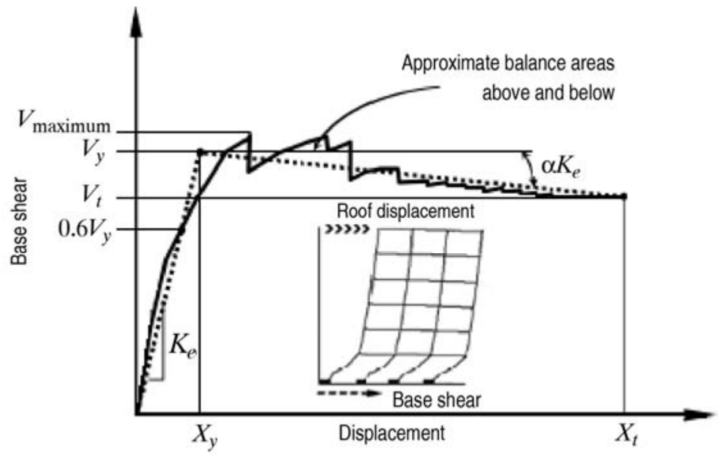

Fig. 4. Capacity curve vs. its idealization

5.2. Alternative proposed for FEMA-356 graphical procedure

In order to generate an idealized capacity curve, FEMA-356 has suggested a graphical iterative procedure. Tackling such an approach manually could not be exempt of error. Also simultaneous fulfillment of all of the above-mentioned 5 criteria seems to be impractical. Furthermore, none of the packages are able to perform the FEMA-356 procedure and predict the precise idealized capacity curve directly. Hence, the vital role of extracting the accurate idealization parameters through the next stage of investigation necessitates the development of a program capable of idealizing the capacity curve precisely. Accordingly, the present work attempts to write a computer code namely '*BLestimator"* under *MATLAB*® environment capable of precisely fulfilling the bilinearization criteria. The concise flow chart of generating the bilinear capacity curve has been presented in Fig. 5 (Seifi *et al.* 2007; MATLAB 2006).

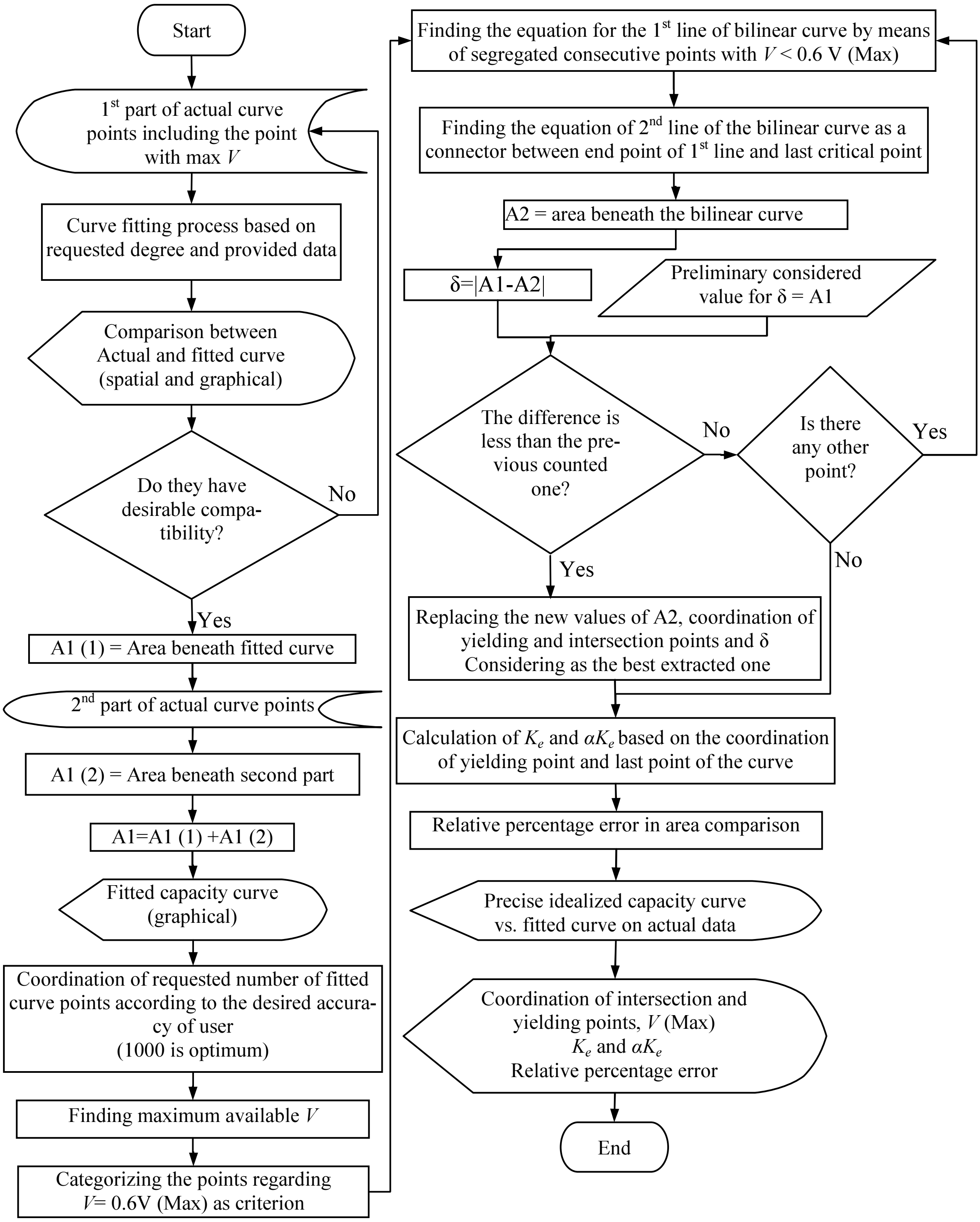

Fig. 5. Flow chart of the developed program for precise bilinearization

6. Influence of structural variables on idealized capacity curve

By assessing the different previously mentioned NSP method and revealing the most suitable one, this method together with "*BLestimator"* generated a well thought-out comparative instrument which is applied to each and every of gravitational-loaded finite element models of Table 1. The course of action required for extracting the idealized parameters is illustrated in Fig. 6. Its use will produce the data required to study the influence of the considered geometric and material variables on idealized parameters of structures including K_e, αK_e, V_y and X_y within the scope of work.

7. Prediction of idealized capacity curve via A.N.N

In recent years neural network has been applied as an alternative to conventional techniques in the realm of PBDE (Correno *et al.* 2004; Gonzalez, Zapico 2007). Moreover, extracting the idealized parameters is a cumbersome and time-consuming procedure which includes specialized steps, while, the non-linear parameters of the structure are easily extractable by means of training appropriate networks.

7.1. Designing

Among different neural network types the one which is widely used is the *feed-forward back propagation* network. This network consists of *input layer*, one or several *hidden layer* and an *output layer*. All nodes called *neuron* are connected with weighted links to each neuron of the next layer (Fig. 7). The output of each neuron is computed through a feed-forward procedure by imposing *activation function* (*f(x)*), on input values with different *weights* (*w*). *Tangent hyperbolic function* was used for hidden layer(s) and *linear function* for output layer. The output of a single neuron is computed by:

$$y_j(p) = f(x)\left[\sum_{i=1}^{m} x_i(p).w_{ij}(p) - \theta_j\right], \tag{2}$$

where m is the number of inputs, θ_j – the threshold on neuron j and w_{ij} – the preliminary weight of input i for neuron j. By computation of *actual outputs*, $y_k(p)$ for the last layer and comparing them with *desired outputs*, $y_{d,k}(p)$ by means of *performance function*, error is computed and back propagated through the network. Then, by calculation of *error gradient* the weights are adjusted and this cyclical procedure is repeated until achieving a prescribed error (MATLAB 2006; Schalkoff 1997). Comprehensive description of the method could be found in (Schalkoff 1997).

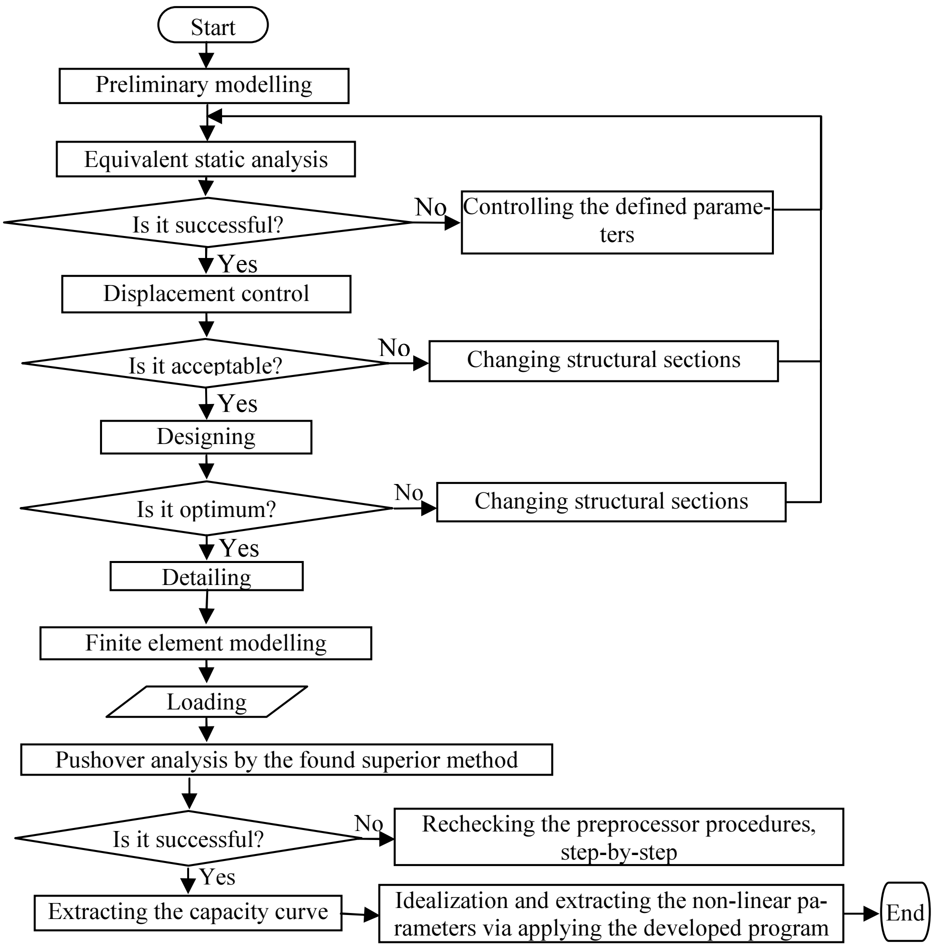

Fig. 6. Flow chart of the procedure passed for each of the 30 models

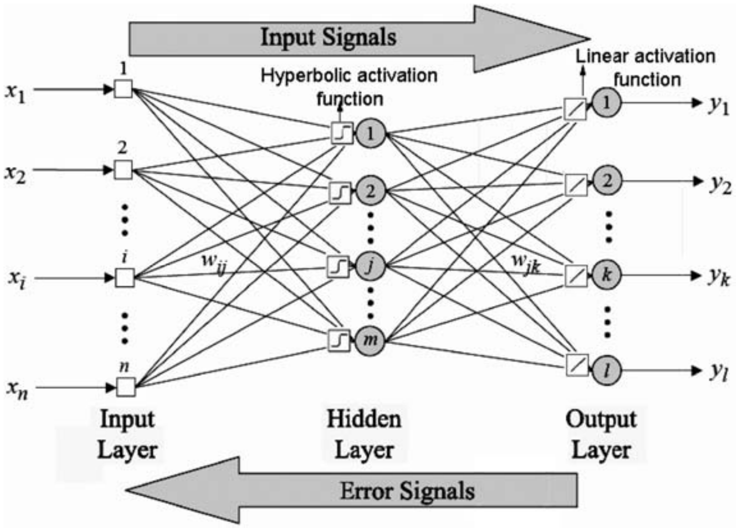

Fig. 7. Feed-forward back propagation network with one hidden layer

7.2. Phases of developing ANN in the present study

a) *Learning process.* This stage is started by defining structural variables as network input and respective idealized parameters obtained analytically as output. To represent to the network all input and output vectors are normalized to the range of [0, 1] by:

$$a_{i,s}(p) = \frac{a_i(p) - a_{\min}}{a_{\max} - a_{\min}}, \quad (3)$$

where a_i is the value of the specific variables for p^{th} model, a_{min} and a_{max} are the minimum and maximum values of the specific variables among all models, and $a_{i,s}$ is the standardized variable value for p^{th} model.

b) *Training the network*. This is the next stage which consists of error minimization. "Mean Square Error", MSE is selected as "performance function" for all networks where:

$$f_{MSE} = \frac{1}{n}\sum_{i=1}^{n} e_k^2(p) = \frac{1}{n}\sum_{i=1}^{n}(y_{d,k}(p) - y_k(p))^2, \quad (4)$$

where n is the number of datasets.

c) *Testing the network.* After training a network of 27 prepared datasets, *testing* was performed on the remaining 3 datasets selected randomly. Testing step reveals the efficiency of trained network by comparing the predicted values with the desired one. Based on the accuracy of testing results, necessity of testing another ANN configuration could be judged.

8. Results and discussion

The outcomes include: (i) Selection of the superior NSP techniques, (ii) Application of the *"BLestimator"* program, (iii) Effects of structural variables on idealized parameters (iv) Testing the applicability of neural network as an alternative to the NSP method.

8.1. Comparison of different NSP techniques

In line with assessing the static capacity curves extracted by the aforesaid NSP methods, they have been compared to the dynamic capacity curve achieved by IDA as in Fig. 8. Afterwards, by tracing the numerical results of different static capacity curves, corresponding base shear for each step of the IDA analysis was determined until it reached the predefined target displacement. By putting the outcomes alongside each other (Table 4), credibility of different NSP approaches were revealed. It was shown that:

- Except for the FEMA-Triangular method that conspicuously underestimated the capacity curve of the structure, the outcomes of other techniques had acceptable estimation of dynamic capacity curve.
- Scrutinizing Table 4 shows that among all of the methods, "DAP Interstorey based" is the unique method that follows the upward trend of the base shears of IDA analysis (especially in the last states, where the structure experiences post-yield behaviour). This fact is of great importance since it has an unmistakable effect on judgment of post-yield stiffness behaviour of the structure.

Due to these facts, "DAP Interstorey based" was adopted as the qualified method to be applied for the other models and in the next steps of the study.

8.2. Estimation of precise idealized parameters using "BLestimator"

Due to the findings so far, only the application of the developed program for DAP-interstorey based capacity curve of 6f3s4l4b3r is presented here.

a) *Actual capacity curve against fitted one.* The curve fitting procedure is performed by importing the first part of coordinates with respect to different degrees imported by the user. After each attempt, for all of the incremental displacement steps, the difference between the corresponding actual and computed (fitted) base shear will be presented numerically and graphically (Fig. 9). After few iterations that just took a few seconds, the predicted polynomial curve of order six was concluded as the best "fitted curve" (Fig. 9, gray line vs. Black line). A critical examination of 100 numerical output datasets unveils that, while in a majority of steps, the absolute difference between the actual base shear and its corresponding computed one is less than 1.50 kN; the maximum difference is also confined to 7.94 kN. The polynomial curve equation is:

$$-19.111\times10^5x^6+23.900\times10^5x^5-11.454\times10^5x^4+26.897\times10^4x^3-36.781\times10^3x^2+43.180\times10^2x-7.417. \quad (5)$$

b) *Area under the estimated capacity curve.* It is major parameter that must be measured to satisfy the fifth-mentioned criteria of FEMA-356. The confined area beneath the capacity curve of 6f3s4l4b3r is equal to 110.4715 kN.

c) *Idealization process and extraction of significant parameters.* At this stage based on the user-defined number, all generated cases of idealization are compared to each other. Evaluation of the final results for 6f3s4l4b3r is summarized in Table 5. They certify the fact that the idealization process FEMA-356 has been performed as precisely as possible, while the computational time has been minimized to less than a minute.

Table 4. Numerical comparing the static capacity curves with IDA results

IDA (Reference)			Non-linear Static Pushover (NSP) method				
Scaling Factors	Roof Displacement (m)	Base Shear (kN)	FEMA Triangular	FEMA Uniform	FAP	DAP Displacement based	DAP Interstorey based
			Base Shear (kN)				
–	0	0	0	0	0	0	0
0.10g	0.053	179.698	124.751	169.370	156.907	170.403	155.817
0.15g	0.105	283.082	193.597	264.776	244.174	273.909	234.162
0.20g	0.147	319.766	233.003	310.602	291.720	342.049	295.365
0.25g	0.178	296.725	251.354	327.949	322.962	370.884	331.951
0.30g	0.216	325.242	263.163	336.546	339.176	383.228	355.698
0.35g	0.249	352.936	268.834	337.997	350.207	385.040	367.590
0.40g	0.280	363.903	272.909	337.356	354.085	379.184	375.400
0.45g	0.385	370.697	277.232	321.070	335.115	343.542	382.077

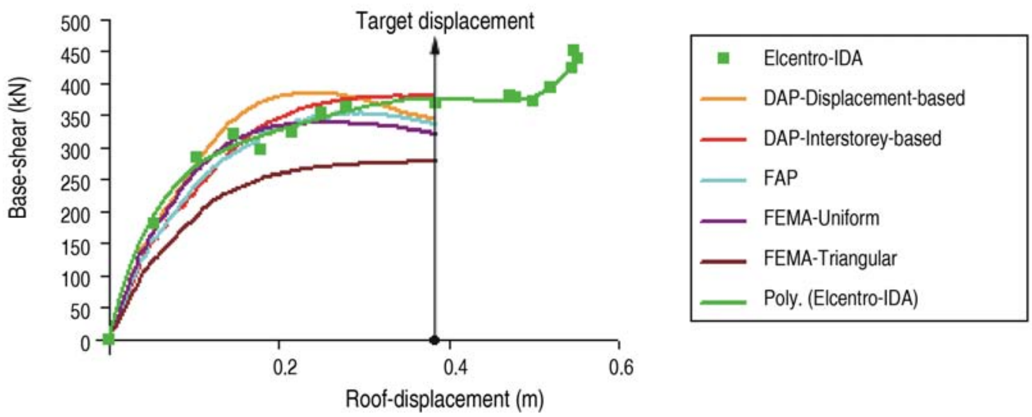

Fig. 8. Static capacity curves vs. dynamic capacity curve

Table 5. Final results of applying idealization program for 6f3s4l4b3r

Parameter description	Sign	Value	Unit
Maximum base shear of the fitted curve	V_{maxim}	382.3963	kN
Coordination of the "effective yield strength point"	X_y	0.1295	m
	V_y	327. 981	kN
Coordination of the intersection point between idealized and the main curve	$X_{intersect}$	0.0777	m
	$Y_{intersect}$	196.7886	kN
Effective lateral stiffness of the building	*Ke*	58.207	Degree
Post-yield stiffness of the building	*alphaKe*	7.8052	Degree
Relative percentage error of area comparison	RPE	0.0015	–

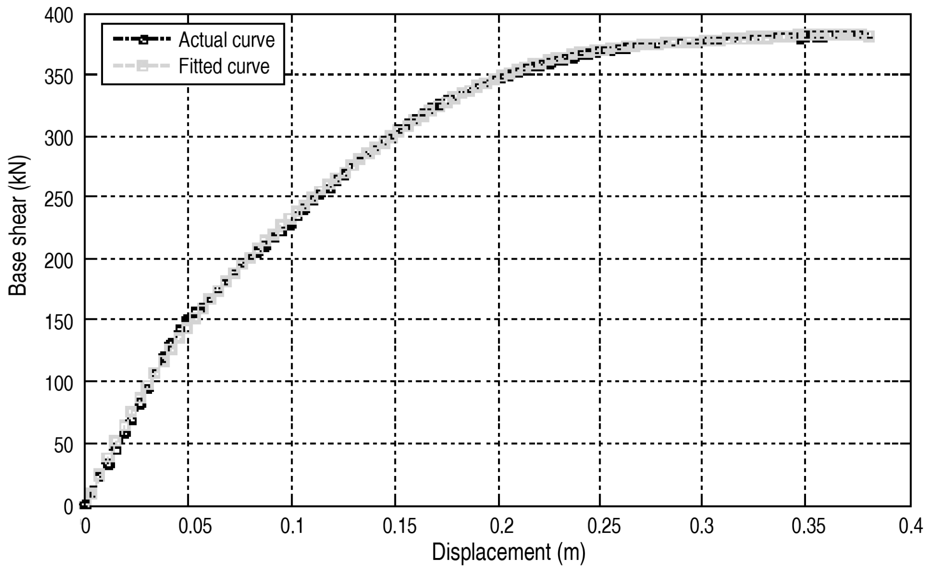

Fig. 9. Actual curve vs. fitted curve by applying the developed program

8.3. Study of the effects of structural variables on an idealized capacity curve

By arranging the contents of Table 6 with respect to different structural variables it could be found that:

- Juxtaposition of similar couples with difference in the number of spans indicates that the more are the spans, the greater is $|\alpha K_e|$. This observation is also true for negative post-yield stiffness models (e.g. *7f2s3.5l4b3r* vs. *7f3s3.5l4b3r*). The number of spans has negligible effect on K_e as well as X_y.
- Grouping the models which are only dissimilar in the length of spans, reveals increments in spans length lower K_e while enhancing the amount of αK_e (e.g. *4f3s3.5l4b3*r vs. *4f3s4l4b3r*).
- In positive post-yield stiffness frames, increase in length of spans results in larger value of X_y (e.g. *4f3s3.5l4b3r* vs. *4f3s4l4b3r*). Negative post-yield stiffness models do not follow this regulation and show unexpectedly higher X_y compared to their corresponding models with longer spans (e.g. *7f3s3.5l4b3r* vs. *7f3s4l4b3r*).
- Use of low strength bars (f_y = 294.3MPa) in narrow span structures is not suggested because it has unsatisfactory effect on αK_e. Redesigning these models by employing reinforcements with higher strength (*fy* = 392.4 MPa) causes improvement in value of αKe(*4f3s3.5l4b3r* vs. *4f3s3.5l4b4r*).
- Increments in number of stories and the subsequent emerging of the whiplash effect deteriorate the unsatisfactory effect on αK_e in narrow span frames with low strength bars. This causes undesirable negative post-yield stiffness (e.g. *7f2s3.5l4b3r* or *7f3s3.5l4b3r*).

8.4. Application of A.N.N

This study was initially aimed at designing a general model for predicting all idealized parameters. However, owing to the use of the entire structural variables as inputs, the outcomes for some parameters were completely deviated. Thus, it was concluded that for the prediction of each idealized parameter, an especial purpose neural network should be designed. This is achieved by keeping an eye on the most influential parameters made known in the former stage of study.

Consequently, the most influential number of inputs in achieving accurate results was selected. The number of neurons and hidden layers were chosen by trial and error. Eventually, for all of the ANNs, the *i+2:Ni:Ni:1* architecture is concluded to be the superior one. Configurations of all networks, influential inputs and corresponding outputs are shown in Table 7.

Finally, by means of the inverse trend of Eq. 3 the predicted values for all of the idealized parameters are converted to the real ones and are compared to the desired values by calculating their absolute relative percentage error, ARPE, as shown in Table 8. Based on that table, it is observed that the difference between the predicted non-linear parameters and the desired values for all of the parameters, excluding the X_y, are negligible. Nonetheless, it should be noticed that for this specific parameter and even in the worst conditions, these straightaway predicted values by ANN is undoubtedly preferable to the one which is manually extractable, through the time consuming FEMA-356 procedure. This procedure apparently could not be exempt of error without utilizing "BLestimator".

Table 6. Structural variable vs. corresponding extracted idealized parameters

Model Name	Structural variable				Idealized parameter			
	No. of stories	No. of spans	Length of spans (m)	F_y (kN/m ^{2})	K_e (degree)	αK_e (degree)	V_y (kN)	X_y (m)
2f2s3.5l4b3r	2	2	3.5	294300	64.930	7.280	107.200	0.032
2f2s5l4b4r	2	2	5	294300	56.473	8.564	158.039	0.045
2f3s3.5l4b4r	2	3	3.5	392400	59.939	10.247	164.806	0.037
2f3s4.5l4b4r	2	3	4.5	392400	52.450	10.170	202.960	0.052
3f2s3.5l4b4r	3	2	3.5	392400	59.011	8.690	134.020	0.061
3f2s4.5l4b3r	3	2	4.5	294300	56.516	9.021	184.075	0.068
3f3s4l4b4r	3	3	4	392400	54.215	11.988	220.114	0.069
3f3s4.5l4b4r	3	3	4.5	392400	51.061	12.095	247.066	0.078
3f3s5l4b3r	3	3	5	294300	54.916	9.896	317.276	0.072
3f3s5l4b4r	3	3	5	392400	49.033	13.718	283.970	0.082
4f2s4l4b3r	4	2	4	294300	57.279	5.744	187.940	0.093
4f3s3.5l4b4r	4	3	3.5	392400	58.450	8.440	234.840	0.085
4f3s3.5l4b3r	4	3	3.5	294300	61.189	5.390	257.678	0.079
4f3s4l4b3r	4	3	4	294300	57.260	6.607	283.890	0.091
4f3s4.5l4b4r	4	3	4.5	392400	52.257	12.626	295.390	0.098
5f2s3.5l4b3r	5	2	3.5	294300	60.220	1.927	191.940	0.110
5f2s4.5l4b4r	5	2	4.5	392400	54.190	11.650	231.010	0.119
5f2s4.5l4b3r	5	2	4.5	294300	57.460	7.646	249.260	0.114
5f2s5l4b4r	5	2	5	392400	53.980	12.365	272.777	0.129
5f3s4l4b3r	5	3	4	294300	58.240	5.029	328.843	0.112
5f3s4.5l4b4r	5	3	4.5	392400	54.315	14.465	309.717	0.106
6f2s3.5l4b4r	6	2	3.5	392400	57.548	9.280	189.650	0.127
6f2s4l4b4r	6	2	4	392400	56.404	10.320	222.281	0.132
6f3s4l4b3r	6	3	4	294300	58.210	7.805	327.980	0.130
6f3s4.5l4b3r	6	3	4.5	294300	57.908	8.630	376.910	0.136
7f2s3.5l4b3r	7	2	3.5	294300	60.837	-2.767	240.471	0.158
7f2s4l4b3r	7	2	4	294300	57.96	9.499	249.290	0.144
7f3s3.5l4b3r	7	3	3.5	294300	60.553	-5.281	367.582	0.160
7f3s4l4b3r	7	3	4	294300	59.520	11.290	361.350	0.131
7f3s5l4b4r	7	3	5	392400	55.070	13.320	411.087	0.151

Table 7. Superior trained networks, influential input and corresponding output

Considered parameter	Network structure	Considered inputs
K_e	3-12-12-1	Length of spans
αK_e	6-12-12-1	No. of stories, No. of spans, Length of spans, F_y
V_y	5-10-10-1	No. of stories, No. of spans, Length of spans
X_y	4-12-12-1	No. of stories, Length of spans

Table 8. Final results of ANNs application for testing datasets

Model name	Desired values				Predicted values by ANNs				ARPE (%)			
	K_e (deg.)	αK_e (deg.)	V_y (KN)	X_y (m)	K_e (deg.)	αK_e (deg.)	V_y (KN)	X_y (m)				
4f3s3.5l4b3r	61.19	5.39	257.68	0.08	60.19	6.09	234.83	0.10	1.64	13.06	8.87	25.86
6f2s4l4b4r	56.40	10.32	222.28	0.13	57.53	11.40	220.66	0.16	1.99	10.48	0.73	18.25
5f2s4.5l4b4r	54.19	11.65	231.01	0.12	54.71	11.96	249.27	0.13	0.96	2.67	7.90	9.88
MARPE (%)									1.53	8.74	5.83	18.00

9. Conclusions

In this paper a method for identifying idealized capacity curve parameters including K_e, αK_e , V_y and X_y has been proposed. The method is tested for finite element models of R/C 2D regular frame structures modelled as closely as possible to those of actual structures. In order to generate different models, geometric variables, including number of stories, number of spans, length of spans, in addition to yield strength of reinforcement as material variables, has been considered. The process includes 4 successive stages. Starting with a comparative study among different conventional and adaptive pushover approaches, all of the methods were applied for a 6-storey frame by comparing them to dynamic capacity curve as an outcome of IDA. It was concluded that "DAP interstorey based" outperforms the other approaches. The second step was codifying the procedure for fulfilling FEMA-356 idealization criteria. The *"BLestimator"* program overcame the deficiencies of the graphical iterative procedure. By means of applying the program, exact idealized parameters are attainable in a fraction of a minute. In the third step by applying DAP interstorey accompanied with the aforesaid developed program (an efficient comparative tool) the influence of the structural variables on idealized parameters were investigated. As a consequence, the most influential parameters and their effects on each idealized parameter have been made known. Prepared datasets have been utilized as an input of the last stage for training feed forward back propagation ANNs. By training the networks, the idealized capacity curve converts to a handy tool for neophytes to be informed about structural behaviour. Also, professionals will be able to effortlessly achieve it for the next stages of their study.

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SEISMINE APKROVA VEIKIAMŲ GELŽBETONINIŲ RĖMINIŲ KONSTRUKCIJŲ LAIKOMOSIOS GALIOS IDEALIZUOTOS KREIVĖS GENERAVIMO TOBULINIMAS

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S a n t r a u k a

Seismine apkrova veikiamų gelžbetoninių rėminių konstrukcijų analizė paprastai atliekama taikant tiesinius tampraus skaičiavimo metodus. Vis dėlto daugelyje šiuolaikinių praktinio taikymo rekomendacijų šiai analizei atlikti siūloma taikyti netiesinius statinius skaičiavimus. Pasaulyje pasiūlyta keletas tokių netiesinių algoritmų. Darbe atlikta lyginamoji šių metodų analizė. Gelžbetonių rėminių konstrukcijų laikomosios galios kreivei gauti parinkta labiausiai tinkanti metodika. Idealizavimo grafinei iteracinei procedūrai realizuoti sukurta kompiuterinė programa taikant FEMA-356. Taikant pasirinktą netiesinio statinio skaičiavimo algoritmą ir sukurtą programą, atlikta konstrukcinių veiksnių, lemiančių gelžbetoninių rėminių konstrukcijų laikomosios galios kreivės formą, parametrinė analizė. Parodyta, kokią įtaką kiekvienas veiksnys turi idealizuotos kreivės parametrams. Papildomai išnagrinėtos alternatyvaus dirbtinių neuroninių tinklų procedūros taikymo galimybės. Atlikta analizė parodė didelį sukurtos kompiuterinės programos tikslumą. Taip pat parodyta, kad dirbtinių neuroninių tinklų modelis gali būti taikomas kaip alternatyva netiesiniam statiniam metodui.

Reikšminiai žodžiai: seisminė analizė, laikomosios galios kreivė, gelžbetoninės rėminės konstrukcijos, idealizavimo parametrai, neuroninis tinklas, žemės drebėjimas, netiesinė statinė analizė.

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