PROGNOSTIC MODELLING OF FIRE RESISTANCE OF RC COLUMNS USING THE CONCEPT OF ANN

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Abstract- The application of artificial neural networks, as an unconventional and innovative method for solving complex civil engineering problems, is very important for modernization of the construction design processes. Many published studies show that neural-based approach can be successfully used in different engineering fields. Neural networks are being used for creating prognostic models mainly in those cases where some prior (numerical or experimental) analyses were already made. This paper presents a neural network prognostic model used for determination of fire resistance of reinforced concrete columns exposed to standard fire from all four sides is presented in the paper. The proposed model relies on the concept of artificial neural networks, in which numerical analysis results are used as input parameters. A brief description of the modelling process is given, and an appropriate example of the neural network prognostic model is presented.

Index Terms- Artificial neural networks, civil engineering, fire resistance,prognostic modeling.

I. INTRODUCTION

The inspiration for establishment and development of artificial neural networks evolved from the human's aspiration to understand the reasoning of human brain, and from the desire to create an artificial "intelligent" system that could be used for data processing applications that are typical for people. Therefore it is very understandable why the concept of artificial neural networks is similar to biological neural networks. Both networks have similar structure, function, data processing technique, and calculation methodology [3, 4]. In short, artificial neural network represent a simplified mathematical model of the human brain.

Nowadays, artificial neural networks are example of contemporary interdisciplinary field offering basic knowledge-based principles for solving various complex engineering problems which could not be solved by traditional modelling and statistical methods [3, 4, 6]. They represent a strong example of sophisticated modelling technique mainly because of their ability for collecting, memorizing, analyzing and processing large number of data.

Number of worldwide researches show that neural networks can be used for creating prognostic models because of their excellent ability for predicting data. A trained neural network serves as an analytical tool for qualified prognosis of results, based on any input data that have not been used in the learning process of the network [5-9].

The prognostic modeling process through artificial neural networks is reasonably simple and easy, yet highly correct and accurate. These positive features fully justify their application, as prognostic models, in a variety of engineering research applications.

This paper presents the application of artificial neural networks for building a prediction model for defining the fire resistance of centrally loaded RC columns exposed to standard fire from four side, using the results of performed numerical analyses as input parameters in the model. A short description of the numerical analyses of columns exposed to standard fire ISO 834, conducted by the computer software FIRE is also presented in this paper. The software is capable of predicting the nonlinear response of reinforced concrete elements and plane frame structures subjected to fire loading, carrying out the nonlinear transient heat flow analysis and nonlinear stress-strain response associated with fire.

II. BASIC CONCEPTS OF ARTIFICIAL NEURAL NETWORKS

Artificial neural networks together with fuzzy logic and genetic algorithms, belong to the group of symbolic methods of intelligent calculations and data processing that operate according to the principles of soft computing. They are developed as a result of many positive features of a several different research areas: data processing, neuro-biology and physics. Some of their basic characteristics are the following: they can analyze large number of data, they can learn from the past data and they can solve problems that are complex, not clear and problems that do not have only one solution.

Artificial neural networks can easily simulate the basic characteristics of the biological nerve system. They represent a simplified mathematical model which is similar and analogous to the biological neural networks. However, processes inside the biological neural networks are very complex and they still cannot

be fully studied and explained. There are hundreds of different types of biological neurons in human brain, so it is almost impossible to create a mathematical model of artificial neuron that will be absolutely the same as the biological neurons. Therefore, the structure of developed models for artificial neurons only looks like the biological ones, with no pretension to copy their real condition [3, 4, 5, 6].

A model of artificial neuron is shown in Fig. 1.

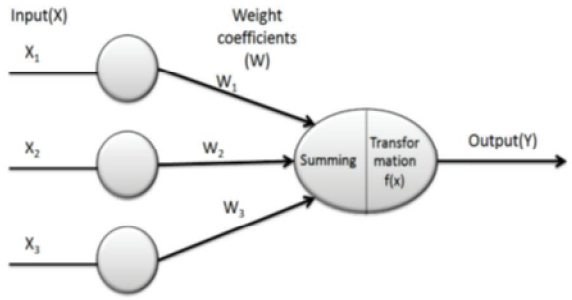


Fig. 1 Model of artificial neuron

The input signals are being collected and processed inside the neuron and the output signals are generated. Every input neuron has its own weight coefficient. In Fig. 1 the input data are marked as X_1, X_2 and X_3, and the appropriate weight coefficients are W_1, W_2 and W_3. The input neuron impulses are W_1X_1, W_2X_2 and W_3X_3. Neuron registers the summed input impulse which is equal to the sum of all input impulses: $X = W_1X_1 + W_2X_2 + W_3X_3$. The received impulse is processed through an appropriate transformation function (activation function), f(x), and the output signal from the neuron will be: $Y = f(x) = f(W_1X_1 + W_2X_2 + W_3X_3)$. One very important characteristic of neural networks is their ability for weight adjustment according to the received history data, which is actually the learning process of the network [3, 4, 6].

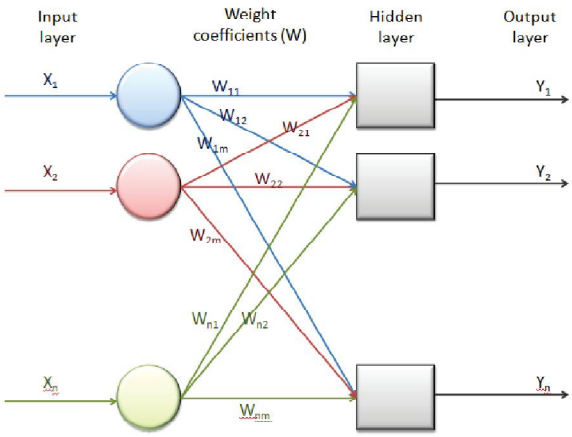


Fig. 2 Model of one layered artificial neural network

An example of the mathematical model of artificial neural network is presented on Fig.2. The network is composed of numerous mutually connected neurons grouped in layers (input, output and one or few hidden layers). The purpose of the input layer is to accept data from the surroundings. Those data are processed in the hidden layers and sent into the output layer. The final results from the network are the outputs of the neurons from the last network layer and that is actually the solution for the analyzed problem.

III. PROGNOSTIC MODELLING OF FIRE RESISTANCE OF REINFORCED-CONCRETE COLUMNS USING THE CONCEPT OF ARTIFICIAL NEURAL NETWORKS

A. General

Fire resistance represents the ability of a construction, a part of a structure or a member of a structure to fulfill its required functions (load bearing function and/or fire separating function) for a specified load level, for a specified fire exposure and for a specified period of time [1]. Generally, the legally prescribed time period in which a structure must remain stable and safe under fire is expressed as time in minutes, and this time represents the fire resistance of a structure. The length of this time period is legally binding in almost every country and it depends on: the height, number of flats, floor area, capacity, content and occupancy of the structure, the distance to fire stations and fire brigades, and the fire protection system of the structure [10]. The legally prescribed fire resistance can be achieved by applying various structural measures (proper form, element's dimensions and static system), or by adopting special protection measures (thermal insulation, etc.). Although many protection measures are currently available, the final choice mainly depends on the type of construction material that needs to be protected. Individual construction materials (concrete, steel, wood) exhibit different behavior under elevated temperatures, which is why they have to be treated in accordance with their individual characteristics when exposed to fire [1, 9, 10].

The fire resistance of a structure can be determined based on the estimated fire resistance of whole structure or of each construction element (columns, beams, slabs, walls, etc.). The fire resistance of a structural element is the time period (in minutes) from the beginning of the fire until the moment when the element reaches its ultimate capacity (ultimate strength, stability and deformability) or until the element loses its separation function [1].

Generally, there are three basic methods for determination of the fire resistance of structural elements and their assemblies. The oldest method is a fire test of loaded elements, in compliance with the national regulations and standards, or comparison of the elements with the results from already performed tests on similar or identical elements. The second method implies the application of empirical formulae obtained from the results of performed fire tests. The third method is an analytically elaborated approach for designing elements with a predefined fire resistance, according to the general principles of structural mechanics and theory of heat transfer [1].

For the last twenty years, particular importance has been given to analytical definition of the problem. The

need for getting answers to many questions in this field implies the application of new, modern and faster, but not less accurate methods for determining the fire resistance of structures. The application of neural networks, as a method for building a prognostic model which can be used for predicting the fire resistance for structural members, is of a huge importance for the design process in construction [3, 4, 5].

The goal of the research presented in this paper was to build a prognostic model which could generate outputs for the fire resistance of centrically loaded reinforced concrete columns for any given input data, by using the results from the numerical analysis as input data.

B. Numerical analyses

The columns as structural elements have an important role in preventing loss of global stability of structures under fire. If these elements do not suffer failure, damages shall be of a local character.

Numerical analyses concerning the behavior of the centrically loaded reinforced concrete columns exposed to standard fire test from four sides are one part of the scientific research work [1]. As a result of this research work the computer program FIRE (FIreREsponse) was developed. This program is capable of predicting the nonlinear response of reinforced concrete elements and plane frame structures subjected to fire loading. The program carries out the nonlinear transient heat flow analysis (modulus FIRE-T) and nonlinear stress-strain response associated with fire (modulus FIRE-S). The solution technique used in FIRE is a finite element method coupled with time step integration [1].

Using the program FIRE, the behavior of centrically loaded columns exposed to standard fire according to ISO 834 (recommended in Eurocode 1, Part 1.2) was analyzed, and the influence of element geometry, concrete cover thickness, type of aggregate, concrete grade, steel ratio, and axial force intensity, was defined. In this case, the support conditions and column length have a negligible influence on fire resistance, and were therefore not varied [5, 10]. The columns were fixed at the bottom side and freely supported at the top side which allowed free expansion in longitudinal direction. The model of the RC columns that were concerned in the analyses is presented in Fig. 3 [1].

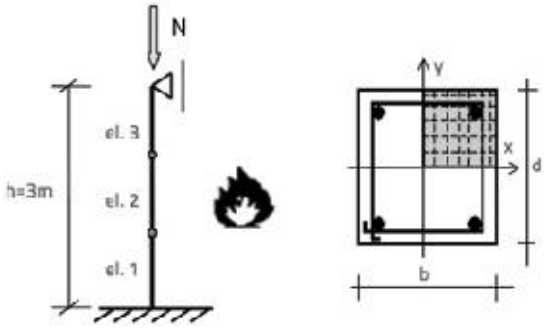


Fig. 3 Reinforced-concrete column exposed to standard fire fromall four sides

The numerical analyses were conducted for different values of the axial force N, and for different dimensions of the cross sections of the columns (20x20, 30x30, 40x40, and 50x50). The thickness of the protective concrete layer varied from 2 to 4 cm, and the loading coefficient a ranged from 0 to 0.5 ($a=N/N_{ult}$, where N is the applied axial force and N_{ult} is the ultimate axial force for the same column). Fire resistance curves, shown on figures 4, 5 and 6, were defined based on numerical analysis results [1]. These curves can be used to determine fire resistance of RC columns which were not previously subjected to numerical analysis. Some of these curves are presented below, and compared to the curves obtained using the neural network prediction model.

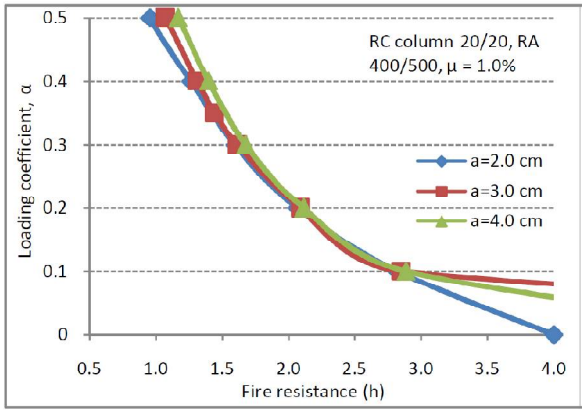


Fig. 4 Influence of the loading coefficient (α) and thickness of the protective concrete layer (a) on the fire resistance of RC columns (20x20 cm)

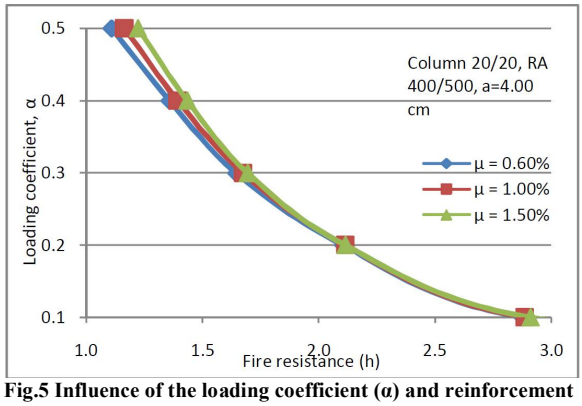


Fig.5 Influence of the loading coefficient (α) and reinforcement percentage (μ) on the fire resistance of RC columns (20x20 cm)

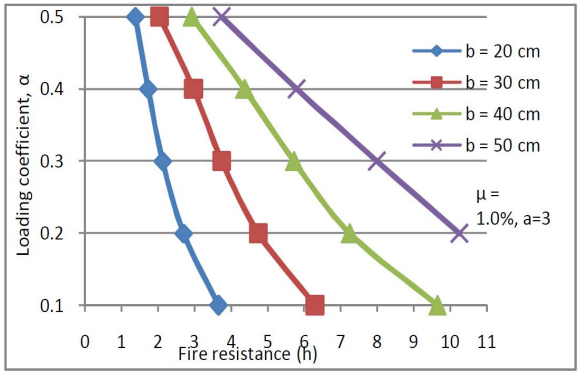


Fig.6 Influence of the loading coefficient (α) and cross section dimensions on the fire resistance of RC columns

C. Neural network prognostic model for centrically loaded RC columns

Using the results obtained by the performed numerical analyses, the goal of this paper was to build a neural network model which can accurately predict the fire resistance of centrically loaded RC columns exposed to fire from all four sides. The results from the numerical analyses were used as input data in order to create and train the artificial neural network so it can provide precise outputs for the fire resistance of RC columns for any other input data.

The neural network prognostic model was developed, trained and tested using the software Neural Tools. Total of 105 cases (data series of input-output data) were analyzed. Out of them, 84 cases (80 %) were used for the training process of the neural network, while the rest of 21 cases (20 %) were used for testing of the network's precision and its ability to accurately predict the value of the fire resistance.

Ten multi-layered free forward neural networks (MLFN) were trained and tested in order to find the optimal architecture of the neural network. This iterative process consisted of training and testing of several neural networks with different architectures until a neural network which provides the best outcomes was selected [2]-[10].

The network architecture (Fig. 7) consisted of three layers: one input layer, one hidden layer and one output layer. The number of neurons in the hidden layer varied from 3 to 12 neurons. The input layer of the neural network had six neurons, one neuron for each independent variable: dimensions of the cross section of the columns (b and d), concrete grade (CG25 or CG35), thickness of the protective concrete layer (a), reinforcement percentage (μ), loading coefficient (α) and the type of the used aggregate (S-silicate and K-carbonate). The loading coefficient represents the ratio between the applied axial force and the ultimate axial force. The output layer had only one variable: the fire resistance of the column expressed in hours (t).

All ten multi-layered free forward neural networks were trained through 1.000.000 learning cycles. One learning cycle consists of determination of weight coefficients for the connections between neurons. The training process of the neural model is actually a smart choice of weight coefficients that give the best predictions [2]-[10]. Training stops at the moment when the error between the actual output (numerically obtained value) and the predicted output (value obtained by the neural network model) reaches the defined error value [11].

The trained MLFN neural networks were tested in order to check their prediction accuracy. The assessment of their prediction accuracy was done by comparing the following parameters: percentage of bad predictions, value of the root mean square error (RMSE) and value of the mean absolute error (MAE). If the percentage of bad predictions is within the allowable limits (less than 30 %), then the optimal neural network is the network that has the lowest value of the root mean square error and mean absolute error obtained by testing [11].

The results from the testing of the analyzed 10 neural networks show that the multi-layered network with 10 neurons in hidden layer gives the lowest prediction error. The value of the RMSE for the MLFN with 10 neurons in the hidden layer was 096, while the value of the MAE was 0,71. Therefore this type of architecture (Fig. 7) is adopted as the optimal for determination the fire resistance of analyzed RC columns.

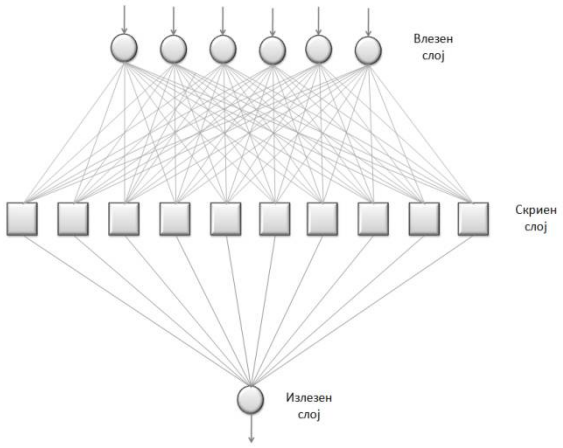


Fig. 7 Neural network model used for determination of the fire resistance of RC columns

The comparison between the predicted values, obtained by the trained neural network, and the numerically obtained values, for the fire resistance of the analyzed RC columns, expressed in hours, is given in Fig. 8.

The results shown in this figure, for all 84 training cases, demonstrate that the neural network prognostic model can generate very precise values for the fire resistance of RC columns exposed to fire from all four sides.

The trained neural network was tested in order to check the network quality and prediction accuracy. The testing was performed by using 21 data series that were different from the data used in the training process. Those 21 testing cases were not used in the process of learning and training of the model. The predicted values obtained by the trained neural network for the testing cases and the corresponding numerically obtained values, are compared in Fig. 9. The testing and comparison of the obtained numerical values for the time of fire resistance of RC columns gave excellent results.

The predicted values obtained by the trained neural network for the 16 cases that were not used for the training, nor for the testing of the neural network, and thecorresponding values calculated with the program FIRE, are compared in Fig 10.

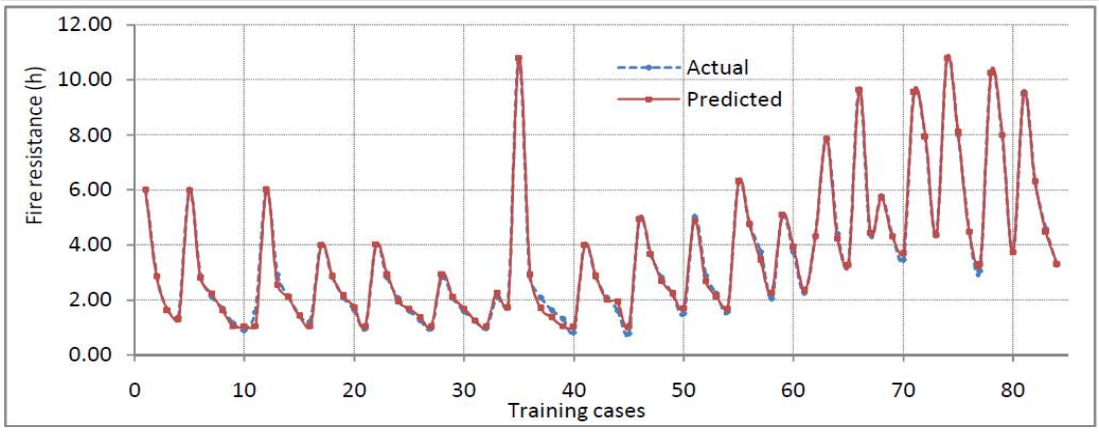


Fig. 8 Comparison of actual and predicted values for the fire resistance of RC columns, used for training of the neural network

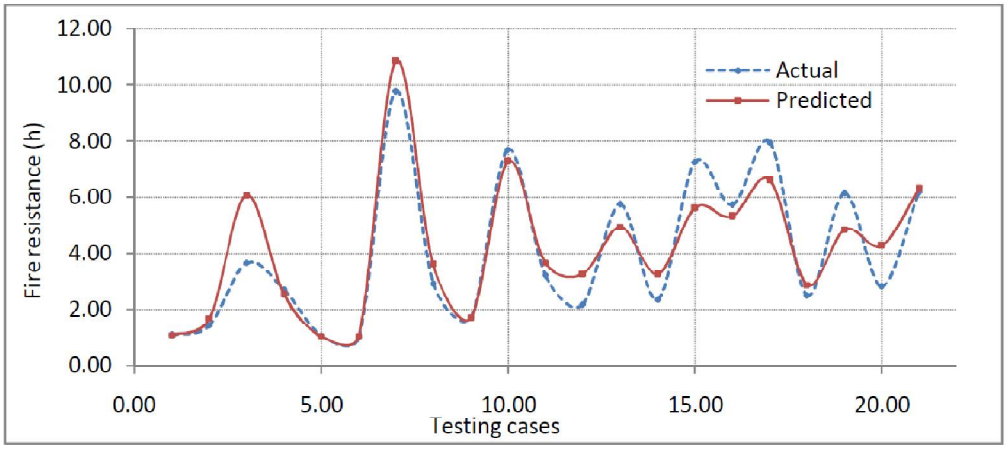


Fig.9 Comparison of calculated and predicted values of the fire resistance of composite columns, used for testing the neural network

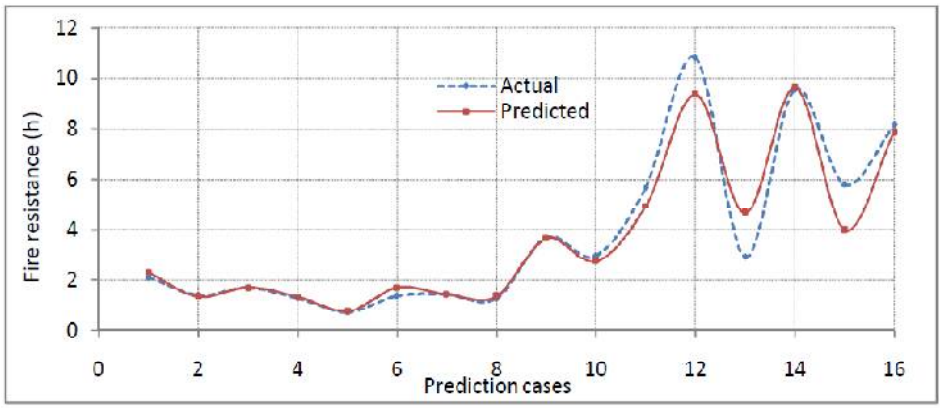


Fig.10 Calculated and predicted fire resistance values for the prediction cases, cases that were not included in the training and testing process

Based on the results obtained from the numerical analysis and the neural network prognostic model, fire resistance curves are constructed [9, 10]. These curves can be used for determination of the fire resistance of RC columns which were not previously analyzed. Comparison of the curves for RC columns with different dimensions of the cross section (20×20 cm, 30×30 cm, 40×40 cm, 50×50 cm), concrete cover thickness a = 2,0 cm and percentage of reinforcement μ = 1 %, constructed by both methods, is presented in Fig. 11. From these curves, depending on the value of the load coefficient, the fire resistance of the column could be defined without any additional calculation.

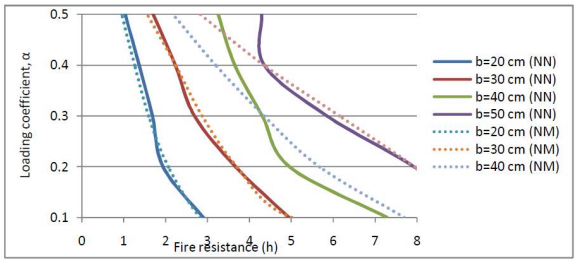


Fig.11 Comparison of calculated (actual) and predicted fire resistance curves for centrically loaded RC columns with different cross section dimensions

It can be seen that the fire resistance curves constructed from the numerically achieved results are

quite similar to the fire resistance curves constructed from the results predicted by the neural network model.

After the comparison of both methods it can be concluded that artificial neural networks present an excellent tool for prognostic modelling and can be used for determination of the fire resistance of reinforced concrete columns, especially in those cases when there are no (or very few) experimental and/or numerical results. This research demonstrates the simplicity and some of the positive aspects for application of the neural networks as prediction models in the engineering area.

CONCLUSIONS

The main goal of this research was to explain the simplicity and the positive aspects of the usage of neural networks for solving engineering problems.

The influence of element geometry, concrete cover thickness, steel ratio and intensity of the axial force, as dominant factors that influence the fire resistance of centrically loaded RC columns, were analyzed and a prognostic model which could generate outputs for the fire resistance of this type of reinforced concrete columns, for any given input data, was build.

Most of the experimental models for determination of fire resistance of RC columns are extremely expensive, and analytical models are quiet complicated and time consuming. That is why a modern type of analyses, such as modelling through neural networks, can help, especially in those cases where some prior analyses were already made.

After the comparison of numerical method and neural network's prognostic model it can be concluded that artificial neural networks present an excellent tool for prognostic modelling and can be used for determination of the fire resistance of reinforced concrete columns, especially in those cases when there are no (or very few) experimental and/or numerical results.

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