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Finite element analysis and neural network investigation of box columns under climate change

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ORIGINAL RESEARCH PAPER

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ABSTRACT

The behavior of box-shaped columns under heating is investigated. For this purpose, the various sections of thin-wall box-shaped columns were modeled and verified in different temperature ranges by ABAQUS software. The results of this research showed that increasing the thickness leads to increase the buckling stability of column under temperature change. Since the behavior of column will be better than thinner columns under climate change because of the increase in the modulus of elasticity. The solid columns have better buckling stability than hollow columns in normal conditions.

KEYWORDS

climate change, column, box-shaped, solid and hollow, buckling, neural network

1. INTRODUCTION

Temperature change is a complex phenomenon to which each structure might be exposed during its life cycle. Regarding the very sensitive performance of steel in high temperature, it seems necessary to study the effect of high temperature and climate change on the performance of steel structures. As the main part of structures in buildings, column has crucial role on the strength of structure. Recently, the guidelines and research consider designing the structures under high temperature conditions, e.g. study on the variations of different types of bolted connection under heating conditions [1]. The aim of this study was to evaluate the performance of bolts at high temperatures. Leston-Jones et al. [2] conducted research with two laboratory tests and examined the overturning moment at high temperatures. Lawson et al. [3] reviewed some laboratory tests on the beam to column connections at the elevated temperatures. The experimental studies on the resistance of Hollow Structural Steel (HSS) with square and circle cross-sections to temperature change were performed by Han and Huo [4]. The loading capacity and fracture mechanism of a square stainless steel (type S304) at high temperatures were investigated during the firing tests to evaluate the mechanical properties of stainless steels. The stress-strain curves, modulus of elasticity, performance, resistance, reduction area, and tensile strength of stainless steels at high temperatures are found and compared with European regulations. Han and Huo [4] investigated the exposure of concrete-filled hollow steel structure to different temperature and evaluated the behavior of this structure under the axial load. Al-Jabr et al. [5] conducted twenty experimental columns on the five different connections at high temperatures. Wang et al. [6] performed an experimental work to determine the resistance and the failure of end-plate connection under high temperature condition. Gomes et al. [7] evaluated the length of buckling in different temperature conditions and used Euro Code 3 Part 1–2 to determine the design load. Kodur

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and Dwaikat [8] used ANSYS Code to analyze the behavior of beam-column under high temperature conditions and determined the factors influencing the behavior of column. Li et al. [9] studied the behavior of restrained steel column in fire conditions. For this purpose, the axial and rotational restraints were applied. A Finite Element Method (FEM) model was built to simulate the temperature test. Fan et al. [10] performed laboratory tests on eight square sections to study the resistance of stainless-steel box columns under high temperature.

Neural network is a new method that has been applied for elaborating heat data, but it never has been used for predicting the results of FEM heating. Some scientists used this method for thermal interpretation. Žmak and Filetin [11] worked on the conductivity of steel at 700 °C and used neural network to predict this value at elevated temperatures. Lazarevska et al. [12] studied the resistance of concrete composite column using neural network. They evaluated the performance of hallow steel sections filled with concrete under high temperature conditions. The effects of the shape and size of cross sections and the intensity of the axial force were investigated in this research. Hozjan et al. [13] worked on a real-coded Genetic Algorithm (GA) as a new method to estimate the behavior of steel between 250 °C, 600 °C and compared this method with Artificial Neural Networks (ANNs). Podgornik et al. [14] studied the potentials and possibilities of artificial neural network-based modeling to select and optimize vacuum heat treatment and also predicted the mechanical properties of steel tools. MATLAB was employed as practical software to estimate the behavior of materials under different heat conditions [15]. Marcsa and Kuczmann [16] employed numerical methods to evaluate the nonlinear system of formulas with using Newton–Raphson technique as well as the fixed-point method. Finite element analysis and neural network were employed together to predict the structural performance in some recent research like the study of Jafari et al. [17] on the performance of sandwich panel under earthquake conditions. Badarloo and Badarloo [18] studied the behavior of steel shear wall under static load with ABAQUS software. At the end of this study, neural network method as well as fit toolbox of MATLAB was employed to estimate the FEM results.

Since common design and construction projects mostly use the columns with box sections, this type of column was used in this research. The novelty of this study pertains to the discussion on the partially restrained box columns with either hollow or solid section, while other studies are conducted on solid columns. Furthermore, the application of neural network for estimating the finite element results from variable inputs like stress, temperature, thickness, and size is considered as another novelty in this research. For this purpose, firstly, a finite element model of a steel column is developed and loaded similar to practical experiments. After the validation of results, several box columns with different width to thickness ratios are subjected to simultaneous thermal and pressure tests. In the present study, the ratio of width to thickness of column plates is variable and investigated at different temperatures.

2. METHODOLOGY

The main aim of this study is the assessment of the performance of steel box columns with different boundary conditions (hinged on one side and cantilever on other side). The axial buckling load applied to the column on the hinged side as an axial load as well as temperature is considered as variable parameter. Different variables are introduced as input parameters in ABAQUS (Hibbett and Sorensen, [19]) and MATLAB (Grant and Boyd [20]). Finally, the critical load and ultimate stress are obtained at the end of the analysis. These values (critical load and ultimate load) are assumed as output values for neural network to be predicted when using MATLAB software [15].

2.1. Procedure of modeling with ABAQUS software and MATLAB

ABAQUS as finite element software is used for modeling steel columns under different conditions and for obtaining critical loads at various temperatures. The following steps are considered for modeling steel columns in the software:

- The critical load is applied to one side of the column and the value of critical load is obtained from the guidelines and the resistance of the column is examined under the axial load. All of the columns have a suitable resistance to the design buckling load suggested by guidelines;
- In the next step, the data from mechanical properties of steel (stress-strain curve, modulus of elasticity and compressive strength) was used to determine the behavior of steel at different temperatures. Other research concentrated on the high-temperature characteristics of steel was been used for this purpose;
- Afterward, the load and boundary condition were used to determine the boundary conditions of the column using the hinged connections on the both sides of column, which was used in other research. However, there is no general research on the hinged and cantilever columns. The length of column in all samples is constant and equal to 3.8 m;
- Finally, neural network was used to develop ABAQUS software for this purpose, the author should determine the input variables and the predicted output values. In this research, the variables are temperature, dimensions of column, and ultimate tensile strength, and the output is the critical load.

2.2. Dimensions and boundary condition of columns

Table 1 shows different columns chosen for analyzing and obtaining critical load and ultimate tensile strength after taking the steps mentioned in Table 1. Five groups of sections were analyzed under five temperatures (5, 10, 20, 400, 800 °C) as well as it is shows in Table 1.

2.3. Using ANFIS to interpret results

Adaptive Neuro-Fuzzy Inference System (ANFIS) [21] is a type of artificial neural network that relies on Takagi-Sugeno

Table 1. Sample and characteristic of them

Boundary condition	Thickness (mm)	Length (m)	Dimension (mm)	Temperature (C°)					Section
				5	10	20	400	800	
Fix	2	3,800	SHS 80 × 80	1	2	3	4	5	Hollow (1&
Fix	20	3,800	SHS 80 × 80	1	2	3	4	5	Hollow (2&
Fix	0	3,800	SHS 80 × 80	1	2	3	4	5	Solid (3&
Fix	2.2	3,800	SHS 120 × 80	1	2	3	4	5	Hollow (4&
Fix	0	3,800	SHS 120 × 80	1	2	3	4	5	Solid (5&
				Group (1&1, 2, 3, 4, 5),. . .., (5&1, 2, 3, 4, 5)					

fuzzy inference system. The technique was presented in the early 1990s [22]. Since, it combines the neural networks and fuzzy logic principles together; it is used to take advantage of the both methods in a single framework. The inference system corresponds to a set of fuzzy If-Then rules that have learning capability to approximate nonlinear functions. Therefore, ANFIS is a universal predictor, which has been used in different engineering problems. In order to use ANFIS method in this research, the value of critical load obtained from ABAQUS software is considered as output layer and other input variables like dimensions are the inputs to the ANFS Graphic tools in MATLAB software.

2.4. Verification

Fan et al. [10] conducted a research on the box column under different temperature conditions. In this research, six columns with different dimensions were chosen and underwent heating and axial load in furnace for laboratory tests. Finally, ABAQUS software was used for analyzing axial buckling load and temperature load conditions and the FEM method was compared with experimental test. Stress-strain curves were obtained for each column according to heat load (5 °C–800 °C) and these data was used to make FEM models in this study. Figure 1 depicts the temperature variation, temperature-time curve and boundary condition of box column, which was obtained by ABAQUS software in this study and experimental test in Fan et al.

The dimensions of the samples are listed in Table 1 and the values of critical load are obtained from FEM analyses in different temperatures 5, 10, 20, 400 and 800 °C.

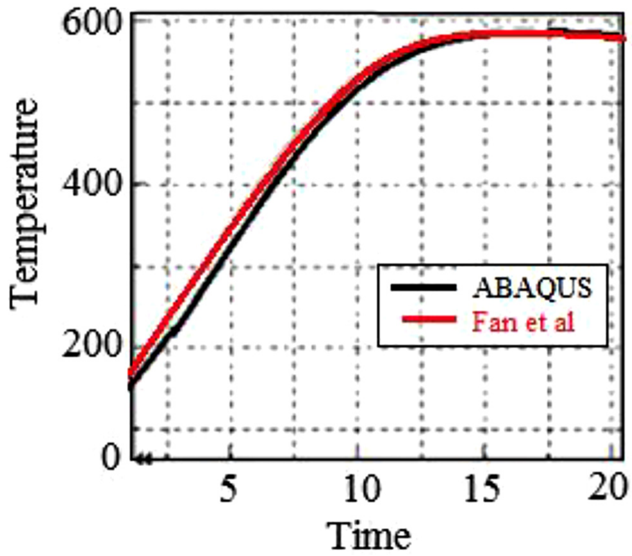

Fig. 1. Verification of column with ABAQUS software

3. RESULTS

3.1. Elaborating FEM results with ANFIS software

The overall results are interpreted and the graphs obtained from software indicate the performance of column at critical loads and high temperatures. As it can be seen in Figs 2–6 the load reduction percentage (ABAQUS LOAD/GUIDE LINE LOAD) will be decreased by increasing the thermal loads on columns. The percentage of reduction in buckling loads equals to the ratio of the load obtained from ABAQUS to the load mentioned in guidelines at low temperature. Figure 2 illustrates that this load for a specimen with 80 mm × 80 mm square section for $K = 1$ at temperatures between 0 and 10 °C shows a value quite close to one, while between 20 and 800 °C temperature range, this ratio is reduced. Figure 4 shows that at high temperatures, the column does not have any stability against buckling loads and can fairly tolerate 0.4–0.15 times the critical buckling loads specified in guidelines. Therefore, some adjustment should be considered when hollow steel column is used at high temperatures.

Moreover, Figs 4–6 show that the reduction influence of temperature at calculated percentages is higher, because temperature is raised, leading to the decrease in buckling load. In the sections with higher thickness like samples 2 and 3, the reduction of load versus original buckling load is more significant. On the other hand, comparing two important sections of 80 mm × 80 mm and 120 mm × 80 mm indicates that the increase in section size results in the increase in critical buckling load at ambient temperature and also applied temperatures. The buckling load obtained from ABAQUS is reduced more than the buckling load from the guidelines. It means that at larger cross sections or greater thicknesses, it is not possible to meet the guideline's expectations.

As it is mentioned above, the only way to investigate the buckling load under the applied temperatures is the

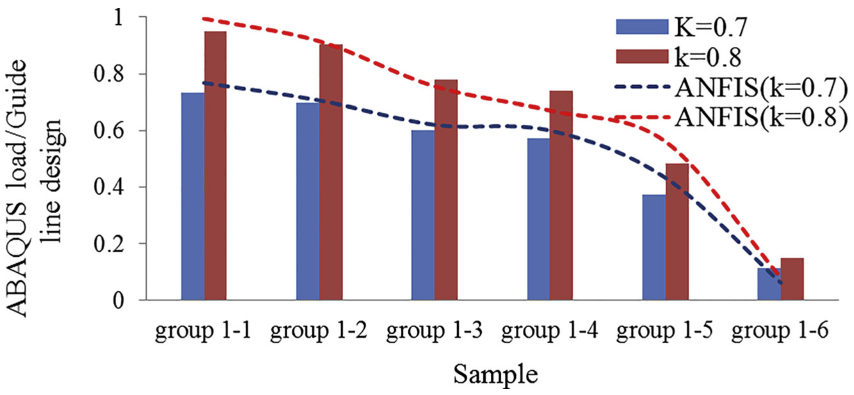

Fig. 2. Reduction in buckling loads in group 1 (final step: fracture state)

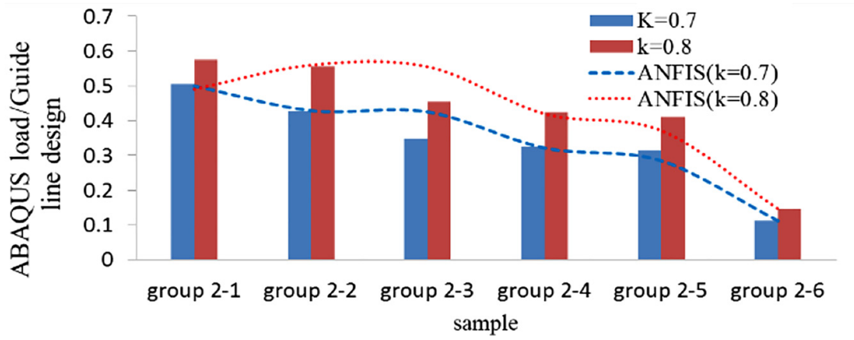

Fig. 3. Reduction in buckling loads in group

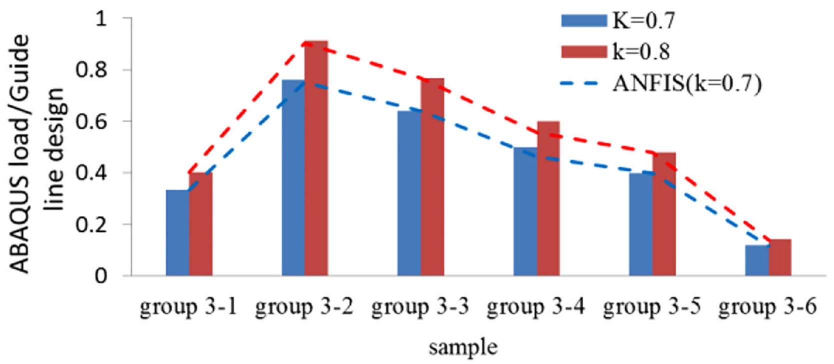

Fig. 4. Reduction in buckling loads in group

evaluation of real columns in experiments (heat test) and finally compares the results with finite element results, and this study was conducted to this aim. In the samples in this research, the following results can be mentioned:

- The increase in size and thickness of section leads to increase the critical buckling loads in temperatures between 0 and 300 °C. It might be possible to produce columns capable of tolerating 0.4–0.7 times the buckling loads specified in the guidelines. Furthermore, if it is mandatory to use these kinds of columns, the hollow sections must be insulated and the maximum buckling load is enhanced with the increase in thickness;
- The stability of columns at temperatures between 0 and 20 °C has appropriate conditions and increasing the analysis time (i.e. 360 minutes) results in dropping the buckling load up to 0.7 times the values in guidelines;
- Using columns with hollow or solid sections at high temperatures as 800 °C to manufacture industrial structures like furnaces is not recommended at all and it is suggested to evaluate the stability of these columns when they are insulated;
- The results in this study and amount of reduction in percentage of load according to stress–strain curves depend on the thermal properties of steel materials, and it

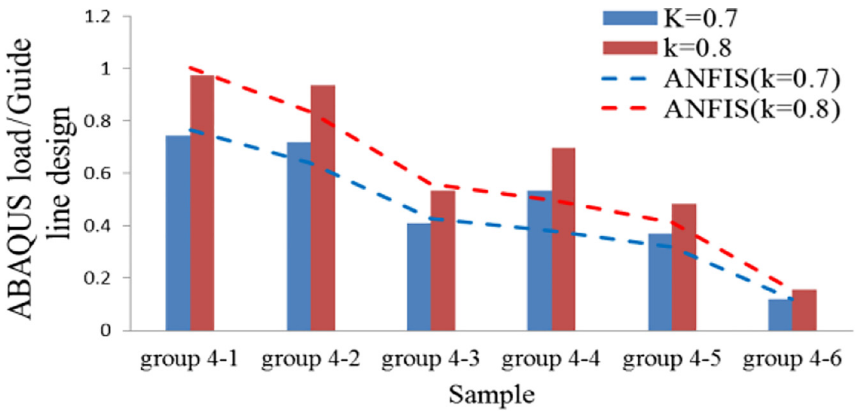

Fig. 5. Reduction in buckling loads in group 4 (final step: fracture state)

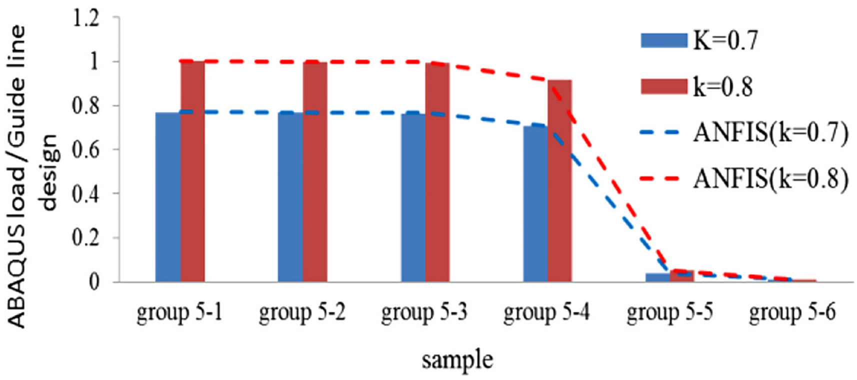

Fig. 6. Reduction in buckling loads in group

is obvious that these parameters will be different when the grade of steel changes;

- The values obtained from MATLAB software is fairly close to the results of finite element analysis. It means that it is possible to apply the neutral network for estimating the maximum ultimate load. According to Figs 2–7, ANFIS can estimate the result of buckling loads near to FEM method.

3.2. Provided design equations and relation between buckling loads in guideline and design load

It is possible to analyze the behavior of columns with inputting variables (size, thickness, and temperature) in neutral network model in a linear equation. Thus, the input values must enter in proposed equations in neutral network models of software and then estimate output values (critical load). Also, the values in finite elements can be calculated. The value of correlation coefficients (R^2) shows mean square error of calculation. As R^2 is closed to 1 indicates that the approximation was more efficient. As it can be seen in Fig. 7, for the current model R^2 is 0.98, which shows highly efficient of performance.

Figure 7 shows how estimated critical load values are closed to those obtained from ABAQUS. Therefore, it is possible to estimate critical loads in columns more accurately when more samples are being used. Also, it is possible to evaluate performance of columns with changing the input parameters like maximum critical stress, thickness, size of column, and heat. Thus, it is required to be familiar with the performance of column by producing more samples and conducting temperature test in the furnace. These values will be compared with practical values and also by entering these values in MATLAB software, a relation between experimental values and finite element parameters will be found. On the other hand, with having high amount of samples in producing a neutral network find a relation between input and output [23]. Therefore, the critical values could be estimated where there is no relation in the guidelines. This can be done by entering new parameters in the MATLAB software. According to Fig. 7 and equation ($Y = 0.98 \times X + 2813.4$) can be used to estimate critical buckling load. Y is estimated value and X is the value obtained from ABAQUS software.

Figure 8 shows the relation between input parameters and variation of critical buckling loads. The results in Fig. 8a illustrates that changes in size and also thickness of column can influence on increasing the capacity of critical buckling load as increase of those lead to increase the critical buckling loads.

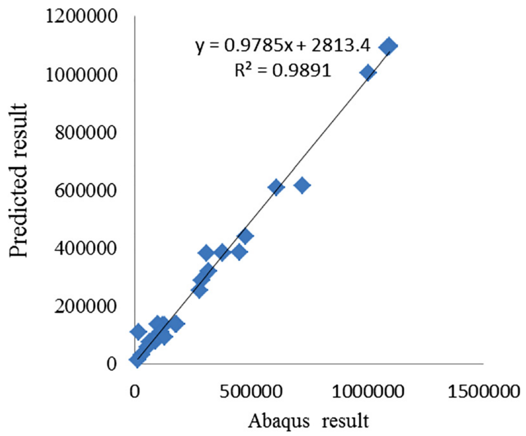

Fig. 7. Relation between calculated critical load obtained from ABAQUS and those values obtained from neutral network

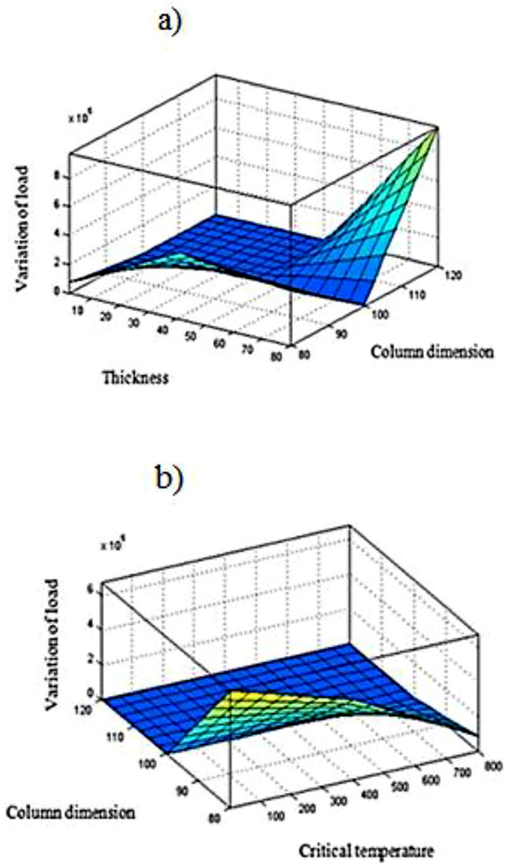

Fig. 8. Variation of critical load, a) size, b) thickness of column

According to Fig. 8b, the maximum changes in buckling loads happen at temperatures between 0 and 300 °C. At higher temperatures, since the buckling load is reduced drastically, the strength of steel drops significantly and no considerable changes could be seen in 3D graphs. It means that in sample groups 1–6 the ultimate load is decreased significantly at temperature ranges between 400 and 800 °C. In this condition, increase in resistance stress of sections

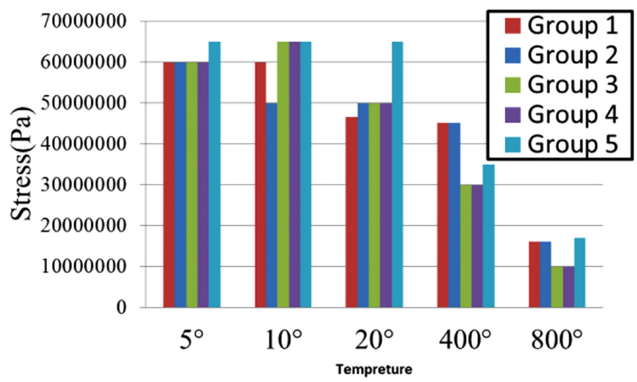

Fig. 9. Stress in samples due to buckling loads (group 1 to group 5)

could not help to increase or change the critical load. In fact, the amount of critical load and its variation is just influenced by temperature and in temperature between 600 and 800 °C changes in critical buckling loads is very low in all section sizes.

However, at lower temperatures, the variation of critical load is more considerable, i.e. changes in engineering parameters like size and thickness of column effect on either increase or decrease of critical load. This graph shows variation of critical buckling loads with input parameters like size and thickness of column as well as critical temperature.

3.3. Maximum stress in columns

The maximum stress for every graph was entered in an Excel spread sheet and Fig. 9 shows this value. As it can be seen in figures, at high temperatures, the amount of applied stress on the column will be decreased with reduction in buckling load.

It means that capacity of column is reduced, and in fact, less stress and displacement is applied on columns and the column cannot stand mechanical loads.

4. CONCLUSION

With the increase in population of the world, the demand for high-rise building, especially those with steel structures, is increased. However, the incapability of steel to tolerate heat makes the design engineer society worried about designing resistant building with steel structures. The guidelines for temperature design (heat loads) usually do not cover some important effects of heat like heat sagging and lack of uniform heat at the height of section. Moreover, these guidelines provide the behavior of structural components individually without the interaction of different components in a structure. For the first time, the neural network was used, which is applied to approximate either experimental or simulation results, for the estimation of critical buckling loads of columns at high temperatures. In other words, there is no study on the partially restrained columns at high temperatures. Therefore, this study could be an appropriate start about heat and steel columns. In this research, the modeling of partially restrained box columns was studied and the results are as follows:

- The size of box columns in all samples was assumed close to previous studies performed on heat loading. In the present study, the behavior of hollow sections is compared with that of solid sections. The buckling load is estimated based on maximum heat and the displacement is estimated during the loading in different temperature scenario;
- The increase in thickness of steel columns leads to stability in their behavior against heat changes;
- The maximum buckling load in steel columns with smaller section sizes is significantly reduced at high temperatures. Therefore they are not recommended at all;
- The performance of column and capability of chosen section extremely depend on stress-strain variations as well as steel modulus of elasticity at high temperatures. Therefore, any factor that causes the increase in the maximum stress of structure would lead to the increase in the strength of column.

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