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To cite this article: K A A Latiff *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **476** 012057

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3D Numerical modelling on the thermal performance of reinforced concrete encased wide-flanged steel column

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Abstract. This paper presents the development and verification of a three-dimensional (3D) numerical modelling to predict the thermal performance of reinforced concrete encased wide-flanged steel (RCEWFS) column. The numerical model was developed using finite element software, ABAQUS. Then, the verified model was used to determine the suitable value for heat transfer conductance, time step and mesh size that provide the most reliable prediction against the experimental results. The parametric studies were also conducted to study the effect of rising time of fire exposure, section size, and flange width of I-section on the thermal performance of the RCEWFS column. From this study, it can be concluded that the predictions by the 3D numerical model are reliable and accurate. The study on the contour of the model shows that the thermal behaviour of concrete is non-linear

1. Introduction

Column is one of the most important structure in buildings. In the context of strength and stability, they should be the second strongest structural component next to the underlying foundation. In fire research, the mathematical-based study, which is carried out using finite difference method, on the temperature performance of composite column is tedious, complicated, and error-prone [1]. Therefore, extensive studies have been carried out to develop the three-dimensional (3D) numerical models for predicting thermal performance and fire resistance of concrete filled steel tube column [2-4].

At present, there is only one study recorded on the 3D numerical model for reinforced column which is by Xu & Sun [5]. In the study, the numerical model for steel tube reinforced concrete (STRC) column was developed, followed by a parametric study to investigate the factors that influence the thermal performance of the column. Therefore, this paper is aimed at extending the study by investigating the input parameters that may influence the accuracy of the numerical results.

In this research, a 3D numerical model of reinforced concrete encased wide-flanged steel (RCEWFS) column was developed by using finite element software, ABAQUS 6.13. The numerical results were verified by using experimental data by Alham [6]. Then, the verified numerical model was used to determine the suitable value for heat transfer conductance, time step and mesh size that provide the most reliable prediction against experimental results. Lastly, the parametric studies to investigate the effects influencing the thermal performance of the column were presented.



2. Materials and Methods

2.1. Development of the 3D Numerical Model

The 3D numerical model consisted of three individual parts which include steel reinforcement, wide-flanged steel and concrete. The model was developed according to the sizes from the experimental data from Alham [6] as shown in Table 1. Then, the individual parts were assembled into a reinforced concrete encased wide-flanged steel column model as shown in Figure 1. The meshes used for the model were three-dimensional eight-node continuum (DC3D8) heat transfer elements for both concrete core and steel tube.

Table 1. Summary of test specimen.

Column Number	Dimension (mm)	I-Flange Steel Section	Length (mm)
Column 1	425 x 449	W250 x 167	3810
Column 2	425 x 449	W250 x 167	3810
Column 3	370 x 389	W200 x 100	3810

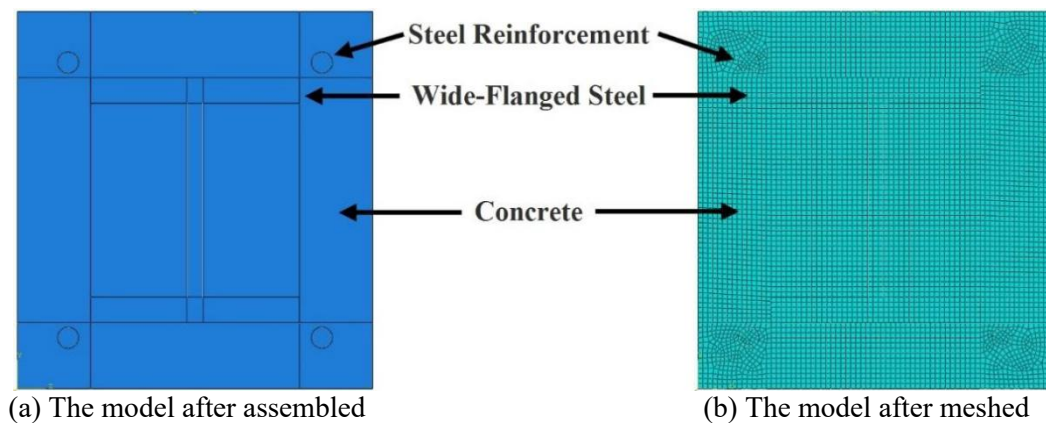


Figure 1. 3D Numerical model of the RCEWF column.

2.2. Thermal Properties

The density for steel and concrete were taken as 7850 kg/m^3 and 2300 kg/m^3 , respectively. Meanwhile, the specific heat and thermal conductivity for both materials were adopted from Eurocode 4 [7]. The thermal properties employed in this paper is similar to studies by Md. Tahir [2] and Rizalman et. al. [3-4].

2.3. Thermal Analysis

In this research, a standard fire ASTM E119 [8] was employed to define the time-temperature heating curve for the model. The standard was also used in the experimental work done by Alham [6].

The heat transfer for the RCEWFS column occurred in three stages. The first stage was the heat transfer from the fire source to an outer concrete surface. In this stage, convection and radiation were involved. The second stage was the heat transfer at the concrete-steel interface. And lastly, the third stage was the heat transfer occurred within the steel and concrete material. The input parameters to define all the heat transfer involved were taken from Eurocode 1 [9], and presented in Table 2 below:

Table 2. Parameters of the heat transfer.

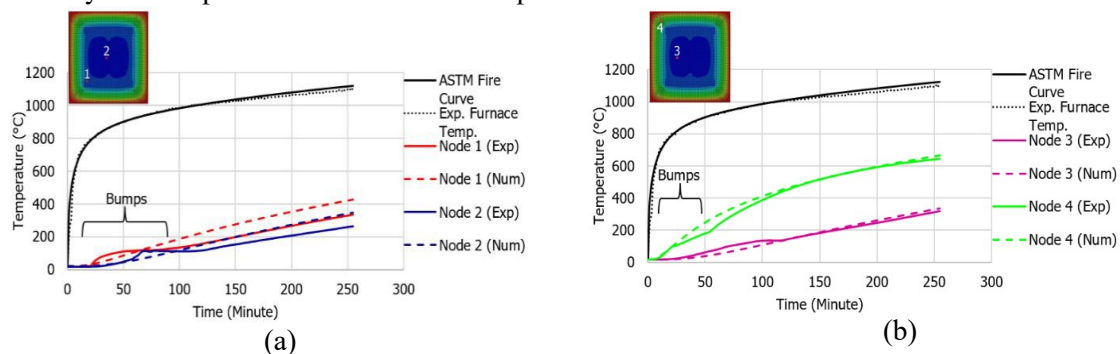
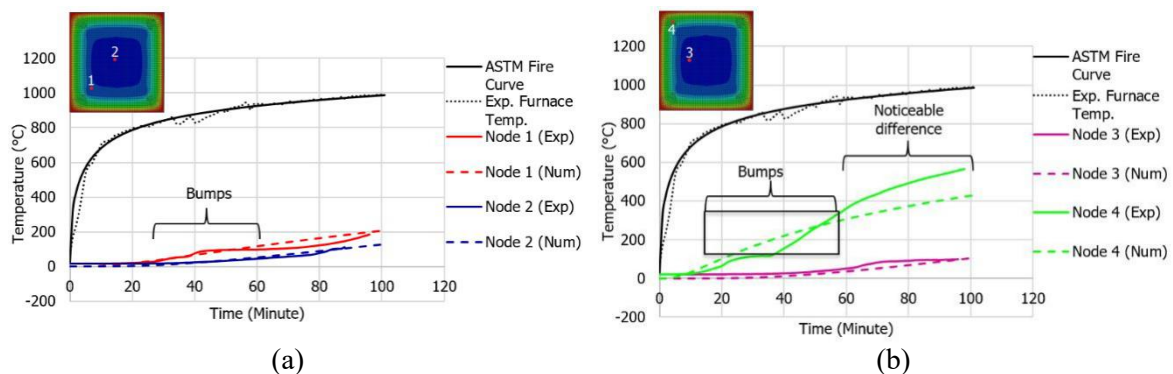
No.	Parameters	Values
1	Conductive coefficient	25 W/m ² K
2	Emissivity of steel and concrete surface	0.7
3	Thermal conductance	200 W/m ² K
4	Thermal conductance	20 °C
5	Stefan-Boltzman constant	5.67 x 10 ⁻⁸ W/m ² K ⁴

3. Verification of the 3D Numerical Model

Figure 2 to 4 show the results comparison between experimental and numerical model for Column 1, 2, 3, respectively. From these graphs, it is observed that all the temperature-time curves obtained from the numerical model followed the trend in the standard fire ASTM E119 [8].

Generally, the difference in the temperature-time curves between the experimental and numerical model is somewhat insignificant for all columns. This indicates that the proposed numerical model is able to predict the temperature performance of the RCEWFS columns and can be used as an alternative tool to the experiment test.

However, there are small bumps observed in every node of the experimental curves (as shown in the figures) occurred between 50°C to 200°C. These bumps, however, are not observed in the numerical curves. The reason is the numerical model is unable to predict the temperature profile in the boiling point of water at 100°C. Similar observations were also made by Md. Tahir [2] and Rizalman et. al. [3-4]. There are also noticeable differences between the experimental and numerical results observed in Node 3 of Column 2 (Figure 3(b)) and Node 3 of Column 3 (Figure 4(b)). The mismatch between these two results may be due to the external disturbances, instruments, and etc. from the experimental tests. But overall, it can be said that the proposed 3D numerical model is able to give sufficiently reliable predictions on the thermal performance of the RCEWFS columns.

**Figure 2.** Comparison between experimental and numerical results for Column 1.**Figure 3.** Comparison between experimental and numerical results for Column 2.

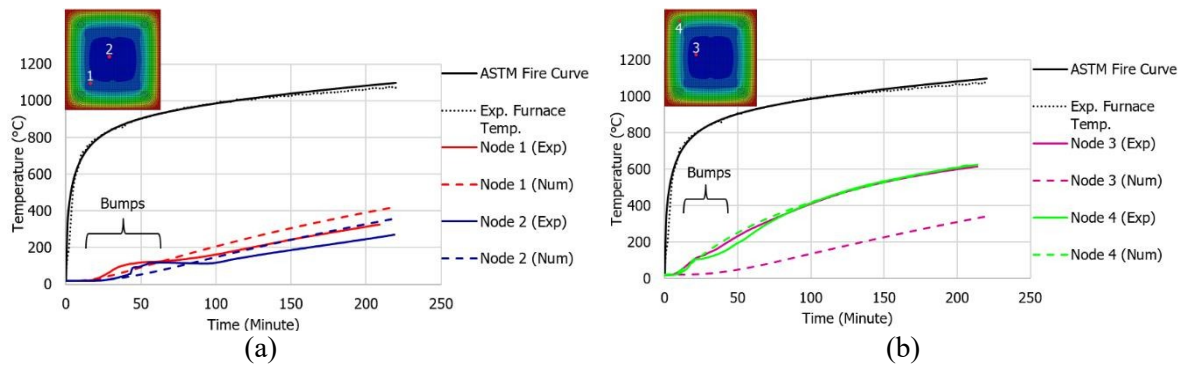


Figure 4. Comparison between experimental and numerical results for Column 3.

4. Regression Analysis

By using the verified 3D numerical model, regression analysis on the parameters was conducted. The purpose is to determine the most suitable value for each parameter that provide the most reliable predictions against the experimental results. In this analysis, Column 2 was selected and the locations of the points to be studied are presented in Figure 5.

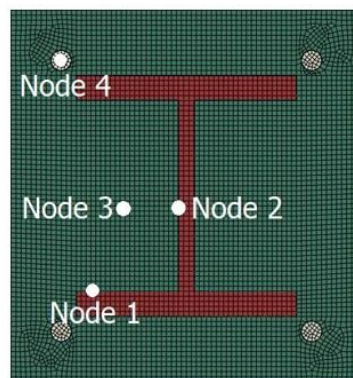


Figure 5. Location of the points of Column 2.

The parameters investigated in this study include heat transfer conductance, time step, and mesh size. Table 3 shows the comparison between the experimental and the numerical temperature for all parameters investigated in this study. It should be noted that all temperatures were obtained at 60 minutes of fire exposure.

Table 3. Comparison between experimental and numerical temperature.

Node	Experimental	Heat Transfer Conductance (W/m ² K)			Time Step (seconds)		Mesh Size (mm)		
		100	200	500	1	120	1	3	6
1	98	110	113	116	115	116	115	115	116
2	47	49	51	52	51	52	52	52	52
3	49	33	35	36	34	36	38	38	36
4	361	295	300	307	309	307	306	307	30

4.1. Heat Transfer Conductance

There were three (3) different values of heat transfer conductance including 100 W/m²K, 200 W/m²K, and 500 W/m²K. These values were used by various researchers in their numerical modelling for concrete-filled steel tubular columns [10-12] and needed to be determine for RCEWFS column. The numerical temperatures for all heat transfer conductance are tabulated in Table 2.

The regression analysis of the numerical results for different heat transfer conductance is presented in Figure 6(a). It shows that all three R² values are close to 1. The difference between the lowest and highest R² value, however, is insignificant with 0.0003 only.

4.2. Time Step

The two (2) values of time-step examined in this study were 1 second and 120 seconds. This study was conducted to determine if larger time-steps can have detrimental effects on the convergences of the simulation and the numerical results. This analysis was also previously performed by O'Neill for timber floors [13]. The numerical temperatures for different time step are presented in Table 2.

Figure 6(b) shows the regression analysis of the numerical results for different values of time step. The R² value for both time steps is close to 1 and difference between the two is only 0.0002, which is negligible.

4.3. Mesh Size

Selecting the mesh size of a numerical model is an important task because it has a major influence on the run time of the simulation as well as accuracy of the results. In this paper, three mesh sizes were studied including 1 mm, 3 mm and 6 mm, which were previously investigated by O'Neill [13]. The numerical temperatures for all mesh sizes are depicted in Table 2.

As for the regression analysis, the graphical presentation is shown in Figure 6(c). It shows that the R² value for all mesh sizes are near to 1, with mesh size of 3 mm is the closest to 1, followed by 1 mm and 6 mm. However, the difference between the three is inconsequential.

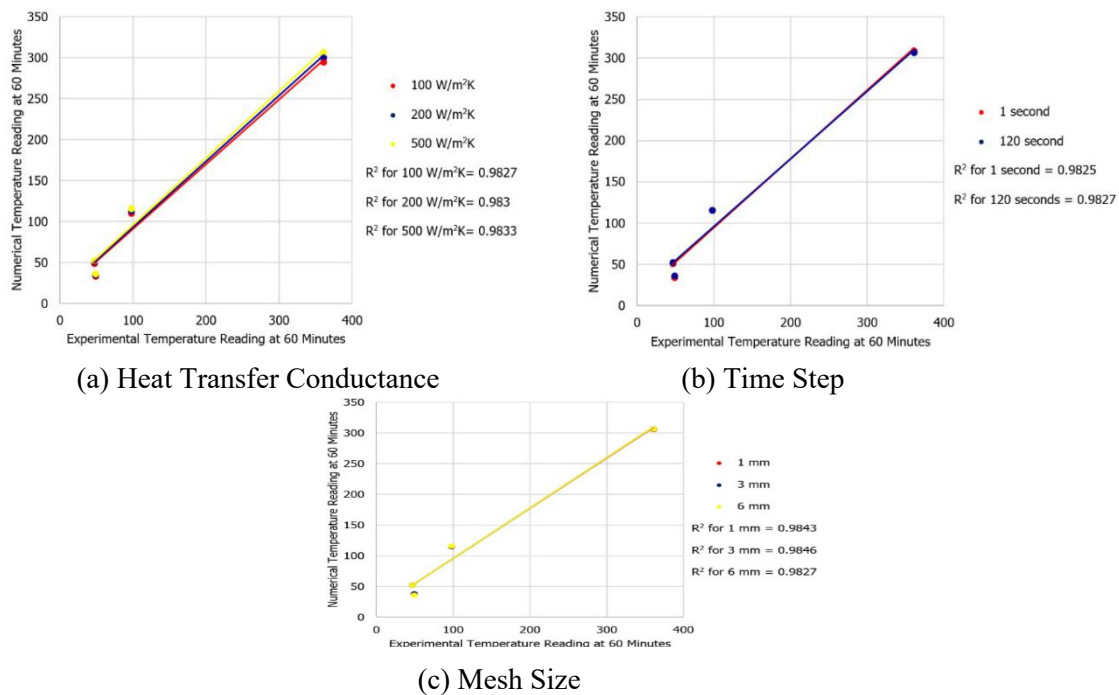


Figure 6. Regression analysis graph for time-step.

5. Parametric Studies

In the parametric studies, the effect of rising time, section size, and the flanged width of the I-section of RCEWFS columns were investigated by using the verified 3D numerical model.

5.1. Effect of Rising Time of Fire Exposure

The temperature distribution across the cross-section of RCEWFS column is shown in Figure 7. The temperatures were measured at four (4) points at 30 minutes, 120 minutes, 360 minutes and 720 minutes of fire exposure. The sequence of the contour colours starts from blue (the lowest temperature), light blue, green, yellow, orange to red (the highest temperature).

As can be seen from the figure, the temperatures of the cross-section increase as the time increases. However, the temperatures of the cross-section are varied from each other, with the outer part is at the highest temperature while the inner part is at the lowest. This shows that the thermal behavior of concrete is non-linear.

The temperature distribution of the concrete at 120 minutes and 360 minutes shows a transition in contour shape from square (Figure 7(b)) to twin oval (Figure 7(c)). This is because steel has higher thermal conductivity than the concrete. Therefore, the heat transfer occurs faster in the steel web than the steel flanges which are surrounded by the concrete.

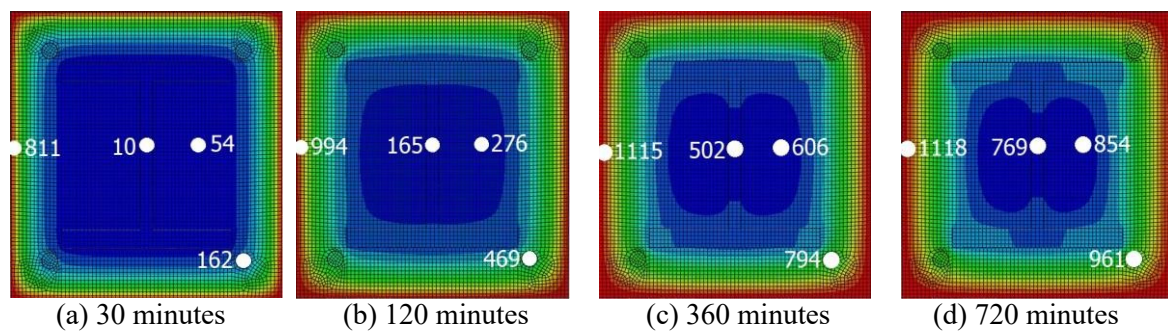


Figure 7. Temperature distribution of column at different exposure time.

5.2. Effect of Section Size

Figure 8 shows a graphical presentation of the temperature distribution of RCEWFS columns between two cross-section sizes which are 425 mm x 425 mm and 400 mm x 400 mm. The temperatures were taken at four (4) locations after 180 minutes of fire exposure.

It shows that the bigger column (as shown in Figure 8(a)) has lower temperatures than the smaller column (as shown in Figure 8(b)) for all measurement points. Hence, it can be concluded that the section size has significant influence on the thermal performance of the column.

On the other hand, it is also observed that the temperature at the outer concrete is similar between the two sizes with only 1°C difference. Thus, it can be said that the maximum temperature for concrete is around 1050°C for this numerical model.

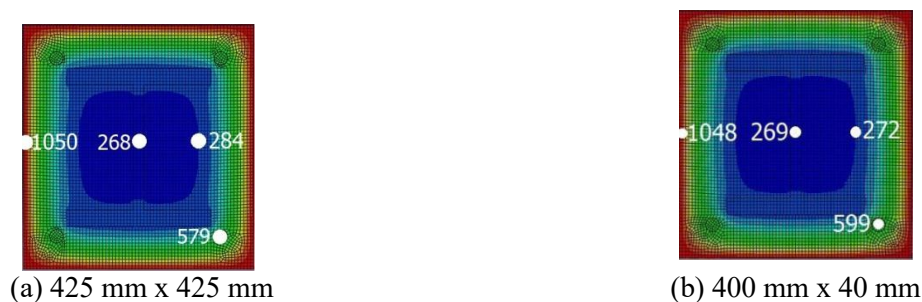


Figure 8. Temperature distribution of column for different section size.

5.3. Effect of the Flange Width of I-Section

Figure 9 shows comparison of the temperature distribution of column with different flange width of I-section. The size of the column was fixed at 425 mm x 425 mm. The temperatures were obtained at four (4) points after 180 minutes of fire exposure.

From the figure shown, the temperature at the centre of the steel web are 254 °C, 261 °C and 269 °C for flange breadth of 200 mm, 225 mm and 250 mm respectively. This shows that the temperature at the centre of the steel web increases as the flange width increases. Due to low thermal conductivity of steel, larger width transfers more heat to the steel web than the smaller width, hence higher temperature.

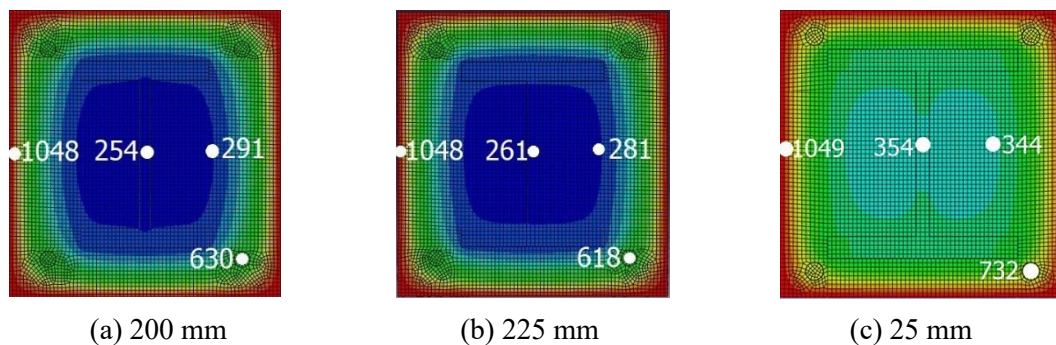


Figure 9. Temperature development of column for different flange width of I-section.

6. Conclusion

Based on the observed results, the following conclusions are drawn:

- The 3D numerical model of the RCEWFS column using ABAQUS 6.13 provides reliable and accurate prediction of the temperature-time curve of the experimental tests. Therefore, the model can be used as an inexpensive and rapid tool to study the thermal behavior of the column. It can also replace finite difference method in the structural design to calculate the temperatures of composite column in fire.
- The study shows that the regression analysis for heat transfer conductance, time step and mesh size is insignificant. But it is recommended to extend the analysis for different time of fire exposure to 120 minutes, 180 minutes, and etc.
- Increasing the time of fire exposure, section size, and flange width of I-section have significant influence on the temperatures of the column. The study also shows that the thermal behavior of concrete is non-linear where the highest temperature occurs at the outer core and decreases as it moves to the inner core.

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