Parametric Study of Fire Performance of Concrete Filled Hollow Steel Section Columns with Circular and Square Cross-Section

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Abstract. Concrete filled hollow steel section column have been widely accepted by structural engineers and designers for high rise construction due to the benefits of combining steel and concrete. The advantages of concrete filled hollow steel section column include higher strength, ductility, energy absorption capacity, and good structural fire resistance. In this paper, comparison on the fire performance between circular and square concrete filled hollow steel section column is established. A three-dimensional finite element package, ABAQUS, was used to develop the numerical model to study the temperature development, critical temperature, and fire resistance time of the selected composite columns. Based on the analysis and comparison of typical parameters, the effect of equal cross-sectional size for both steel and concrete, concrete types, and thickness of external protection on temperature distribution and structural fire behaviour of the columns are discussed. The result showed that concrete filled hollow steel section column with circular cross-section generally has higher fire resistance than the square section.

1 Introduction

Studies have shown that the fire performance of steel hollow section column can be improved by filling the hollow area of the steel section with concrete [1]. Other advantages of concrete filled hollow steel section column include higher strength, ductility, energy absorption capacity, and good structural fire resistance.

Recently, the research methods for fire studies on concrete filled steel hollow section (CFHSS) columns have shifted to the numerical modelling due to the cost and time constraint for conducting the fire testing. Many studies all over the world have been carried out towards the development of the numerical models to predict the fire performance of CFHSS columns [2-4]. However, there has been limited studies done on the numerical models to cater various shapes of steel hollow sections and external fire protection.

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In this paper, an extensive study of the fire performance of slender CFHSS columns at elevated temperature was carried out using the verified 3D numerical models developed by Rizalman and Md Tahir using finite element software, ABAQUS [5,6]. The aim of this research is to establish a fire performance comparison between circular and square CFHSS columns subjected to different variables including cross-sectional shapes, types of concrete, and thickness of fire protection. Thus, the fire resistance and critical temperature of the CFHSS columns for circular and square shapes are discussed in this paper.

2 Methodology

2.1 Material Properties at Elevated Temperature

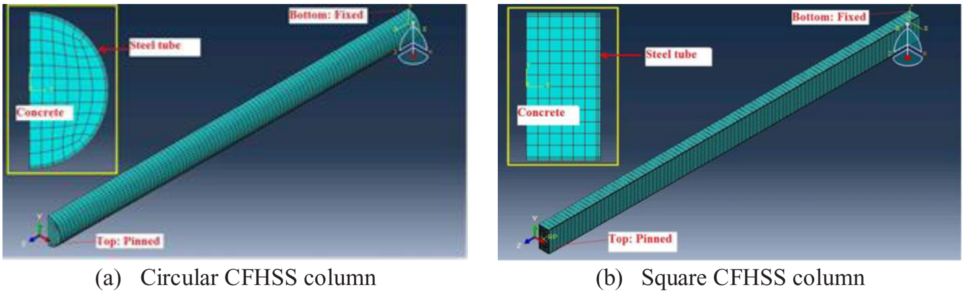
In this study, the mechanical and thermal properties of the materials employed in the 3D numerical model are temperature-dependant. For the mechanical properties of steel, the yield strength (f_y) was assumed to be 350 MPa and the Elastic Modulus (E_s) was taken as 210000 MPa. The stress-strain relationship of steel material at elevated temperature was defined in accordance to the Eurocode 3 model [7]. The Von Misses yield surface was used to define the plasticity behaviour of the steel elements in the numerical model.

For the mechanical properties of concrete, the compressive strength (f_c) of 30 MPa was adopted and the corresponding strain (ε_s) was assumed as 0.0025. The stress-strain relationship of concrete material at elevated by Lie was defined according to the Lie Model [8]. The linear Drucker-Prager yield surface was used to define the plastic behaviour of the concrete elements in the numerical model. The thermal properties provided in BS EN 1994-1-2 [9] were employed to define the thermal properties for both steel and concrete, correspondingly.

2.2 Description of the Selected CFHSS Columns

In this study, a series of slender CFHSS columns with circular and square cross-sections were used to examine the effect of cross-sectional shapes and sizes, concrete types and the thickness of fire protection, on the structural fire behaviour of CFHSS columns. The selected CFHSS columns were divided into five cases: sectional strength at room temperature, cross-sectional area of steel, cross-sectional area of concrete, types of infill, and fire protection thickness.

All selected slender columns were 3600 mm length with steel tube thickness of 5 mm. The column was subjected to standard fire ISO-834 [10]. Fig. 1(a) and 1(b) show the basic three-dimensional finite element model of slender CFHSS columns for circular and square cross-section, accordingly.



(a) Circular CFHSS column (b) Square CFHSS column

Fig. 1. 3D finite element model for circular and square CFHSS columns.

In this study, there were three different load levels applied to each column specimen calculated as 20%, 40% and 60% of their axial design load N_y at room temperature. The axial load was obtained using the following expression:

$$N_y = A_a f_y + A_c f_c + A_s f_s \tag{1}$$

where A_a, A_c, and A_s are cross-sectional area of steel, concrete and reinforcing bars, respectively. Moreover, f_y, f_c, and f_s are the characteristic material strengths of steel, concrete and reinforcing bars, correspondingly.

As previously mentioned, each column was subjected to three levels of axial loads including $0.2N_y$, $0.4N_y$, and $0.6N_y$. The gravitational load, 9.8 N, was also applied to the numerical model.

The basic geometrical and mechanical characteristics of the selected slender CFHSS columns are presented in the table below.

Table 1. Case A - Columns with Equal Compressive Strengths, N_y at Room Temperature.

Features	Group 1			Group 2		
	CHS1	SHS1	CHS1/SHS1	CHS2	SHS2	CHS2/SHS2
Size(mm)	177 x 5	150 x 150 x 5		234.4 x 5	200 x 200 x 5	
A_s (mm^2)	2702	2900	0.932	3603	3900	0.924
A_c (mm^2)	21904	19600	1.118	39549	36100	1.096
N_y (kN)	1603	1603	1.000	2448	2448	1.000

Table 2. Case B - Columns with Equal Cross-Sectional Area of Steel, A_s.

Features	Group 3			Group 4		
	CHS3	SHS3	CHS3/SHS3	CHS4	SHS4	CHS4/SHS4
Size (mm)	189.6 x 5	150 x 150 x 5		253.3 x 5	200 x 200 x 5	
A_s (mm^2)	2900	2900	1.000	3900	3900	1.000
A_c (mm^2)	25334	19600	1.293	46392	36100	1.288
N_y (kN)	1775	1603	1.107	2760	2448	1.127

Table 3. Case C - Columns with Equal Cross-Sectional Area of Concrete, A_c.

Features	Group 5			Group 6		
	CHS5	SHS5	CHS5/SHS5	CHS6	SHS6	CHS6/SHS6
Size (mm)	189.6 x 5	150 x 150 x 5		253.3 x 5	200 x 200 x 5	
A_s (mm^2)	2560	2900	0.883	3446	3900	0.884
A_c (mm^2)	19607	19600	1.000	36103	36100	1.000
N_y (kN)	1484	1603	0.926	2289	2448	0.935

Table 4. Case D – Columns with Different Types of Infill.

	CHS7	CHS8	CHS9	SHS7	SHS8	SHS9
Size (mm)	234.4 x 5			200 x 200 x 5		
Concrete types	None	Plain concrete	Reinforced concrete	None	Plain concrete	Reinforced concrete
A_s (mm^2)	3603			3900		
A_c (mm^2)	39549			36100		
A_a (mm^2)	298			298		
N_y (kN)	2448			2448		

Table 5. Case E – Columns with Different Thickness of Fire Protection.

	CHS2	CHS10	CHS11	SHS2	SHS10	SHS12
Size (mm)	234.4 x 5			200 x 200 x 5		
Thickness of fire protection	None	10 mm	25 mm	None	10 mm	25 mm
A_s (mm^2)	3603			3900		
A_c (mm^2)	39549			36100		
A_a (mm^2)	298			298		
N_y (kN)	2448			2448		

2.3 Thermal and Structural Analysis Procedure

In this paper, the slender CFHSS columns were exposed to standard fire ISO-834 [10] for 120 minutes. In a fire, the heat was transferred from the fire source to an exposed steel outer surface by convection and radiation. The conductive coefficient of 25 W/m^{2}k proposed by BS EN 1991-1-2 [11] was employed. Meanwhile, the emissivity of the exposed surface and the configuration factor for radiation at the exposed surface was assumed as 0.8 and 1.0, respectively. It was also assumed that gap conductive and gap radiative were formed between the steel tube and concrete core interface during fire. The gap conductive was taken as 200 W/m2K whereas the gap radiative was defined by employing the surface emissivity of 0.8 and the configuration factor of 1.0.

The structural analysis was governed by two steps. First, the axial load was applied to the column via the loading plate at room temperature. Then, the load was kept constant during the second step where the thermal loads was applied by extracting the temperature distribution results from the thermal analysis. The normal and tangential interaction at the steel and concrete interface was defined as “hard” contact and friction coefficient of 0.3, respectively. The accuracy of both thermal and structural analysis adopted in this paper have been validated in the works done by Rizalman and Md. Tahir [5,6]

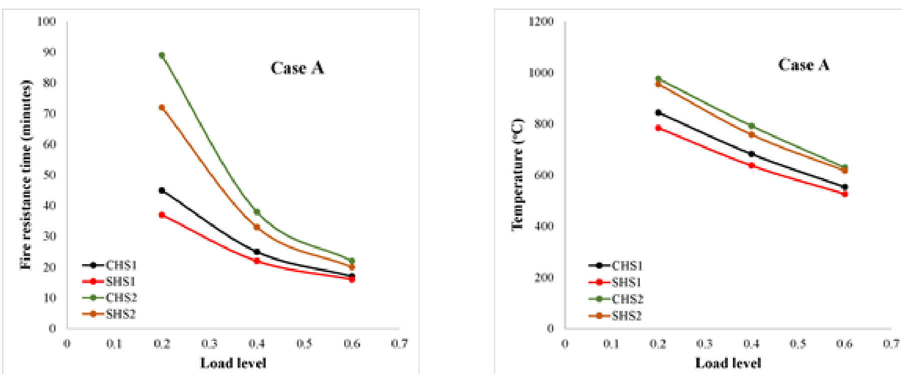
3 Results and discussions

The following sections discussed the comparison of fire resistance and critical temperature between circular and square CFHSS columns.

3.1 Column with Equal Compressive Strength at Room Temperature

Fig. 2 shows the relative comparison of fire resistance and critical temperature between circular and square CFHSS columns with equal compressive strength at room temperature. The comparison indicates that the circular column has longer fire resistance than the square column as illustrated in Fig. 2(a). The same trend was observed for higher load levels but with lower fire resistance. The figure also shows columns with larger cross-section (CHS2 and SHS2) have higher fire resistance than the smaller ones (CHS1 and SHS1).

A similar pattern was also observed on the critical temperature of the selected CFHSS columns (as shown in Fig. 2(b)) where it decreases with increasing load levels. However, higher critical temperatures were observed in circular columns than the square columns because of longer fire resistance.

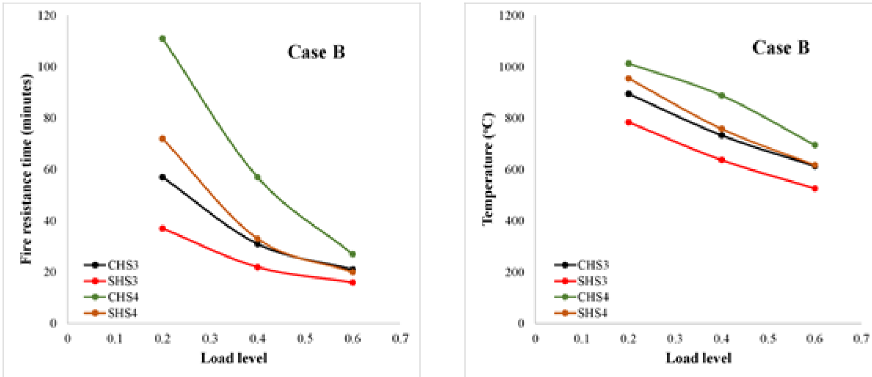


(a) Fire resistance (b) Critical temperature

Fig. 2. Relationship of load ratio to fire resistance and critical temperature for Case A.

3.2 Column with Equal Cross-Sectional Area of Steel

Fig. 3 shows the relative comparison of fire resistance and critical temperature for columns with equal cross-sectional area of steel. As expected, the analysis produced similar results as Case A where circular column has longer fire resistance than the square column (Fig. 3(a)). However, the difference in the fire resistance between circular and square shapes were more noticeable compared to Case A. This is because the difference in the cross-sectional area of concrete in Case B was larger than in Case A. This indicates that the size of concrete has significant role in increasing the fire resistance of the column. A similar trend was observed for the critical temperature for the columns in Case B, as illustrated in Fig. 3(b).

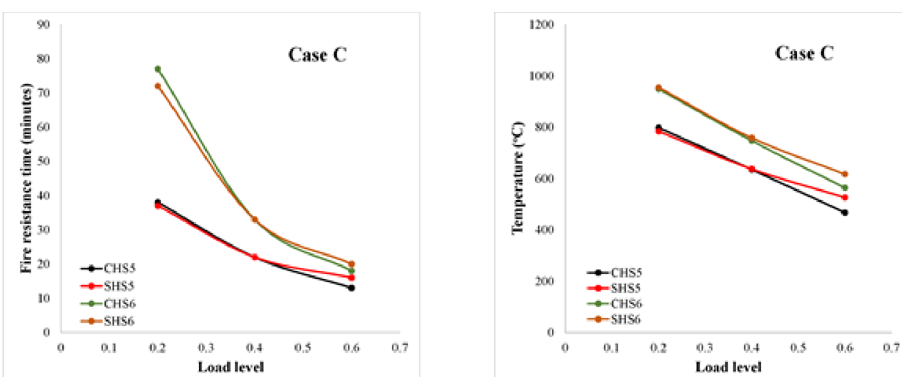


(a) Fire resistance (b) Critical temperature

Fig. 3. Relationship of load ratio to fire resistance and critical temperature for Case B.

3.3 Column with Equal Cross-Sectional Area of Concrete

Fig. 4 shows the relative comparison of the fire resistance and critical temperature for columns with equal cross-sectional area of concrete. Fig. 4(a) shows that the fire resistance in circular columns is slightly higher than the square columns for load level of 0.2. However, both columns failed around the same time for load level of 0.4. Then, it was found that the square column has longer fire resistance than the circular column at the load level of 0.6. Nevertheless, the results difference between the two shapes are almost negligible, thus it can be assumed that the influence of concrete on the fire resistance and critical temperature of the CFHSS columns are more prominent than the steel tube.



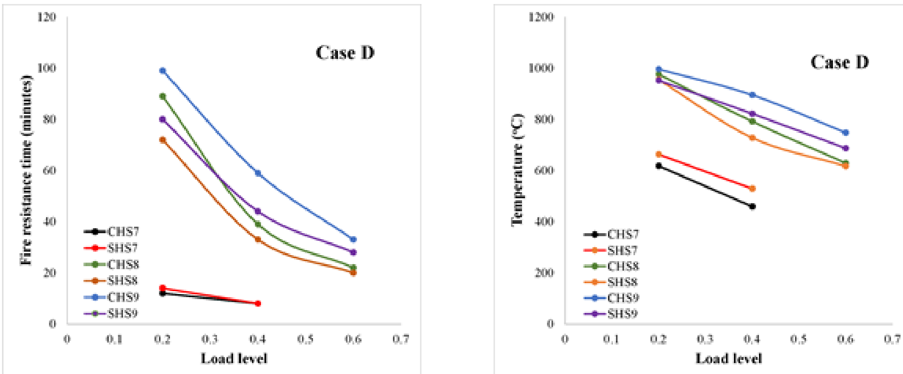
(a) Fire resistance (b) Critical temperature

Fig. 4. Relationship of load ratio to fire resistance and critical temperature for Case C.

3.4 Column with Different Types of Infill

Fig. 5 shows the effect of different types of infill on the fire resistance and critical temperature of between circular and square CFHSS columns. The results show a vast improvement on fire resistance for steel tube columns with concrete infill (CHS8 and SHS8) compared to void columns (CHS7 and SHS7). In addition, both void columns failed at the load level of 0.6 before they were subjected to fire. This indicates that presence of concrete towards the structural performance of hollow steel section column is prominent.

Moreover, the addition of reinforcing bars to concrete infill (CHS9 and SHS9) has also increased both fire resistance and critical temperature of the columns in which the reinforced effect increases with larger load levels.



(a) Fire resistance (b) Critical temperature

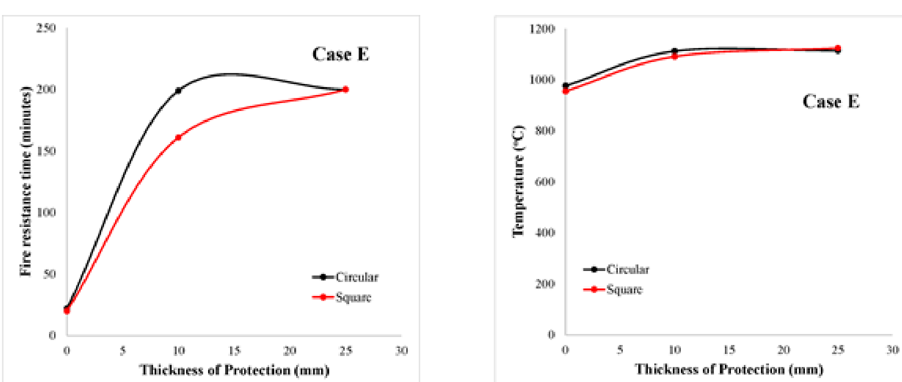
Fig. 5. Relationship of load ratio to fire resistance and critical temperature for Case D.

3.5 Column with Different Thickness of Fire Protection

Fig. 6 shows the fire resistance and critical temperature of the CFHSS column with different thickness of fire protection. In this study, only load level of 0.6 was applied to the column. The results show that when the thickness of the fire protection is 10 mm (CHS11, and SHS11), it can delay the fire resistance of the unprotected CFHSS column (CHS10 and SHS10) by eight times. A similar trend was observed for the critical temperature for the columns in Case E, as illustrated in Fig. 6(b).

It should be noted that the fire resistance of the CFHSS columns with 25 mm protection thickness (CHS12 and SHS12) was actually greater than 200 minutes, which is the maximum fire exposure time fixed in this study. Thus, the fire resistance for CHS12 and SHS12 were set to 200 minutes for the recording purpose, as illustrated in Fig. 6(a).

This study indicates that the effect of fire protection on the fire resistance of the CFHSS column is evident. However, it is also important to consider the practicability of using fire protection especially when it involves the overall costs of a construction.



(a) Fire resistance (b) Critical temperature

Fig. 6. Relationship of load ratio to fire resistance and critical temperature for Case E.

4 Conclusions

From the analysis, the following conclusions are drawn: (a) Circular column generally has higher fire resistance the square column. (b) Concrete has significant influence on the fire performance of the CFHSS columns compared to the steel tube. (c) The use of reinforcing bars on the concrete fill has improved the fire resistance and critical temperature of the CFHSS columns especially at larger load levels. (d) The application of fire protection has slowed the temperature development of the steel section, hence higher fire resistance on the protected CFHSS columns.

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