EXPERIMENTAL STUDY ON BEHAVIOR OF UNPROTECTED FOAMED CONCRETE FILLED STEEL HOLLOW COLUMN UNDER FIRE

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Abstract — Reduction in self-weight and achievement of full fire resistance requirements are some of the important considerations in the design of high-rise structures. Lightweight concrete filled steel tube (CFST) column provides an alternative method to serve these purposes. Recent studies on lightweight CFST columns at ambient temperature have revealed that foamed concrete can be a beneficial and innovative alternative material. Hence, this study investigates the potential of using foamed concrete in circular hollow steel columns for improving fire resistance. A series of nine fire test on circular unfilled hollow and foamed concrete filled hollow section column were carried out. ISO 834 standard fire exposure test were carried out to investigate the structural response of these columns under fire. The main parameters considered are load level and foamed concrete density; foamed concrete density used are 1500 kg/m^3 and 1800 kg/m^3 at 15%, 20%, and 25% load level. All the columns tested are without any external fire protection, with concentrically applied load under fixed-fixed boundary conditions. The columns dimension was 2400 mm long, 139.7 mm diameter and steel tube thickness of 6 mm. The fire test result showed that foamed concrete increases the fire resistance of steel hollow column up to an additional 16 minutes. The improvement is more at load level above 15%, and the gain in fire resistance is about 71% when 1500 kg/m^3 density foamed concrete is used. Generally, foamed concrete filled steel hollow column demonstrate a good structural fire behavior, based on the applied load and foamed concrete density. Also, inward local buckling was averted by filling the steel hollow column with foamed concrete. General method for composite column design in Eurocode 4 adopted to calculate the axial buckling load of 1500 kg/m^3 foamed concrete filled columns. These type of columns can be used for structures like airports, schools, and stadiums; taking the advantage of exposed steel for aesthetic purpose and high fire resistance. It can also be used for high rise structures; taking advantage of high fire resistance and reduction in self-weight of a structure.

1.0 INTRODUCTION

Unprotected structural hollow steel columns resist fire for only limited amount of time. Depending on the applied load on the column and shape factor of steel hollow column, a 15 to 20 minutes fire resistance usually achievable; Fire resistance of 30 minutes can only be achieved in a rare cases[1–2].

For a hollow structural steel sections to resist fire for a longer period of time, certain protective measures must be done to slow the temperature rise in the steel. External insulation, water cooling, and concrete filling are among the fire protections for hollow structural steel sections. However, filling with concrete is very attractive and easiest method of enhancing the fire resistance. Temperature development in the bare steel outer shell increases rapidly, making it to loses strength and stiffness, as the steel can no longer carry the load, it will then be transferred to the concrete[3].

Furnace fire tests were carried out on concrete filled steel tube columns exposed to standard fire. A total of 58 columns comprising circular and square cross-section were filled with plain concrete, reinforced concrete, and steel fiber reinforced concrete were then tested under fire at National Research Council, Canada. The outer steel tubes were kept naked without any external fire protection and majority of the columns were tested under concentric load. The results showed that filling steel tube with plain concrete can make the column to resist fire up to 1 to 2 hrs. While filling with reinforced concrete or fiber reinforced concrete, a fire resistance of up to 3 hrs can be achieved. Most of the plain concrete filled columns failed due to buckling, and the failure was sudden contraction. Whereas failure for the reinforced concrete and fiber reinforced concrete filled column was by gradual contraction [4-5].

Extensive researches on concrete filled steel hollow column sections were conducted. Romero et al. [6] investigated the behavior of axially loaded slender concrete filled steel tube columns using normal and high strength concrete at elevated temperature. Sixteen steel tube columns were tested with the plain concrete, reinforced concrete, or fiber reinforced concrete; nominal concrete strength of 30 MPa for normal concrete and 80 MPa for high strength concrete were used. Applied axial load level were 20% and 40%, under fixed-pinned boundary condition. All the columns tested had an external diameter of 159 mm, 6 mm wall thickness and 3180 mm long. The result showed that addition of fiber reinforcement in concrete filled hollow structural steel column under fire does not improve the column fire resistance, but addition of steel reinforcing bars produce a reasonable increase in the fire resistance of the column.

Fire resistance test was carried out on axially and eccentrically loaded circular concrete filled steel tube slender columns. A total of 36 columns were tested using grade 30 and 90 concrete, the load level and the infill concrete type was the same as in [6]. Also similar conclusions were made as in [6] above [7].

A study on the fire behavior of continuous axially loaded concrete filled steel tubular columns was conducted, 10 specimens of square cross-section were tested with plain, reinforced and steel fiber reinforced concrete as infill. All the columns tested were 3.2 m long, but only central 2 m length subjected to fire, with applied load levels between 33 to 38%. The authors reported that the steel tube axial elongation was less than 3 mm, which is far less than the axial elongation from the other fire tests on concrete filled column where the whole length was exposed to fire. Also comparison between experimental and calculated results from codes may not be conservative, especially for the columns filled with plain concrete and with fire resistance less than 30 minutes [8].

Fire resistance study on concrete filled steel tube column exposed to non-uniform fire on the column faces was investigated by [9]. The results showed that fire endurance time of the column increase as the slenderness ratio and load level increases. Also, steel and concrete strength have negative effect on the fire endurance time of the column.

Experimental and numerical study on fire behavior of high strength steel circular columns were carried out by [10]. Three high strength steel circular hollow columns and a concrete filled high strength steel hollow column were tested under ISO standard fire exposure with eccentrically applied load. The experimental result showed that high strength steel column resist fire for 20 to 22 minutes with load level between 10.1 to 19.4%. There was no local buckling on the unfilled column; failure was due to global buckling. Filling the high strength steel hollow column with concrete increases the fire resistance to 108 minutes with load level of 12.8%, and it fails due to global buckling. A numerical investigation on concrete filled steel tube column using high strength structural steel was carried out. The parameters investigated include column dimension, strength of steel, concrete strength, load level, aggregate type and concrete moisture content. The result indicated that concrete diameter and strength have much significant effect on fire resistance rating than steel strength. Also at the same load level, the fire resistance decreases with higher steel strength and increases with lower concrete strength [11].

Ghannam [12] investigated the use of stainless steel as an alternative to carbon steel in concrete filled steel tube column. Twelve columns comprising circular and square cross-section were studied for fire and post fire conditions. The columns were 1870 mm long, 200 mm diameter and 3 mm steel tube thickness. The load was

applied axially at 30 and 45% load level. It was concluded that concrete filled stainless steel column have a better performance in fire than concrete filled carbon steel column.

Exposed concrete filled hollow steel section columns in fire have better fire resistance characteristics than reinforced concrete columns exposed in fire, since the steel tube prevents the inner core concrete from spalling. The steel tube serves as a form work, so no form work required, which is an added advantage. These are among the benefits that caused increase in the use of concrete filled hollow steel section column for tall buildings in China [13].

Filling steel hollow sections with normal and higher strength concrete increases the strength, stiffness, and fire resistance of the steel column. However, reducing the self-weight of a structure is another benefit derived from using foamed concrete or light weight concrete as infill material in the concrete filled hollow section columns.

Hunaiti investigated the contribution of foamed and light weight aggregate concrete at ambient temperature. The results showed that circular hollow section filled with foamed concrete resist up to 90% of the squash load [14]. Researches by [15-16] at ambient temperature suggested that it is possible to replace normal weight concrete with light weight concrete. Also, design equations from Eurocode 4 can be used for lightweight concrete filled circular steel tube columns [17].

Ambient temperature test on foamed concrete showed that light weight, ease of fabrication, durability and cost effectiveness are some of its advantages identified by [18–20]. Other advantages include excellent thermal and sound insulation, low density, self-compacting, and high flow ability [21].

A lot of studies were performed on columns filled with normal and high strength concrete at ambient and elevated temperatures. Few researches are available on concrete filled column using foam concrete and lightweight foam concrete at ambient temperature, with very few or no available literature on concrete filled steel tube column using foamed concrete at elevated temperature.

The purpose of this research is to study the possibilities of using foamed concrete to improve the fire resistance of steel hollow column, and to study the behavior of steel hollow section column filled with foam concrete exposed to standard fire. The effect of filling the steel hollow section with 1500 kg/m^3 and 1800 kg/m^3 density foamed concrete under fire were studied. Load levels applied on the columns were 15%, 20%, and 25% of the ultimate compressive load of the hollow steel column at ambient temperature.

2.0 EXPERIMENTAL PROGRAM

The fire resistance tests were carried out at the fire testing laboratory of Universiti Teknologi Malaysia. Nine fire tests were carried out on structural hollow steel section and foamed concrete filled structural hollow steel sections. Three columns were tested hollow without infill foamed concrete, while the remaining six columns were filled with 1500 kg/m^3 or 1800 kg/m^3 density. The aim of this experiment was to investigate the effect of foamed concrete and load level on the fire behavior of structural hollow steel section columns. All the columns tested were 2400 mm long, 139.7 mm outer diameter, and steel tube thickness of 6 mm. The columns were fixed at top and bottom ends, and the loads were applied axially on the columns. Load levels applied on the columns were 15%, 20%, and 25% of the hollow steel section ultimate load at ambient temperature according to Eurocode 3, part 1 [22].

Table 1: Test Properties and Results

Test	Column ID	D (mm)	t (mm)	f_y (MPa)	f_c (MPa)	μ (%)	Axial Load kN	Boundary condition	FRR (mins)
1	CHS15	139.7	6	444.11	-	15	167.9	Fixed-Fixed	27
2	CHS20	139.7	6	444.11	-	20	223.8	Fixed-Fixed	15
3	CHS25	139.7	6	444.11	-	25	279.8	Fixed-Fixed	14
4	FCFHSQ15	139.7	6	444.11	30.62	15	167.9	Fixed-Fixed	36
5	FCFHSQ20	139.7	6	444.11	30.62	20	223.8	Fixed-Fixed	24
6	FCFHSQ25	139.7	6	444.11	30.62	25	279.8	Fixed-Fixed	21
7	FCFHSW15	139.7	6	444.11	11.81	15	167.9	Fixed-Fixed	43
8	FCFHSW20	139.7	6	444.11	11.81	20	223.8	Fixed-Fixed	25
9	FCFHSW25	139.7	6	444.11	11.81	25	279.8	Fixed-Fixed	24

Note: CHS= Unfilled circular hollow steel, FCFHS= Foamed concrete filled hollow steel, Q=1800kg/m³ foamed concrete, W=1500Kg/m³ foamed concrete, 15=15% Load level, 20=20% Load level, 25=25% Load level

μ = load ratio, FRR = fire resistance rating

2.1 Material properties

Hollow steel sections used for these tests were cold formed circular hollow steel sections manufactured in Malaysia. The steel grade was S355JOH, the actual strength of the steel hollow sections were determined from the tensile coupon tests in accordance to BS EN 10002-1 [23]. Material properties of the steel obtained from the coupon test are presented in Table 1.

Foamed concrete cylinders were cast and cured in water for 28 days. The foamed concrete densities used in this research are 1500 kg/m³ and 1800 kg/m³. Cylinder strength for all the densities considered is presented in Table 1.

2.2 Specimens Preparation

The circular steel hollow sections used are 2400 mm long, an outer diameter of 139.7 mm and wall thickness of 6 mm. Two ventilation holes were drilled of 15 mm diameter on each column at 500 mm from both ends; another hole was drilled at the middle of the column length for concrete thermocouples.330 x 330 x 12 mm steel end plates were welded at the bottom end of the columns, 7 days after casting the foamed concrete and curing; other end plates of the same dimension with the bottom plate were also welded at the top end of the columns.

2.3 Experimental setup and Procedures

The furnace used for these tests as shown in Figure 1, was 4.35 m height and 1.2 m width with a hydraulic jack of 1000 kN capacity attached to the furnace. The columns were positioned vertically inside the furnace, and then fixed between the furnace base and the top plunger. The columns were loaded from the top using the plunger from the hydraulic jack. The loads were kept constant throughout for a given load level, and then the furnace gas burners were activated, ISO 834 [24] standard temperature time curve was used.

Figure 1: Furnace
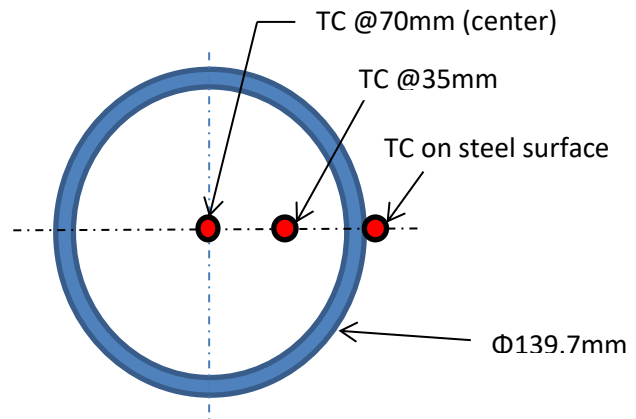
Figure 2: Thermocouple positions

Temperatures of the columns were measured using the type K thermocouple attached on steel surface and inside the in filled foamed concrete as shown in Figure 2. Two thermocouples were attached on the steel surface, another two were attached inside the column at concrete center and at one-fourth of the column diameter. Furnace temperature was obtained from the four thermocouples in the furnace.

Axial displacements of the columns were obtained from the movement of the plunger of the hydraulic jack machine. An ISO 834 failure criterion for axially loaded member under fire condition was adopted in this research, which is based on the amount and rate of axial deformation. The axial contraction should not exceed 0.01L mm or axial deformation rate not exceed 0.003L mm/min, where L is the length of specimen in mm.

3.0 RESULTS AND DISCUSSION

3.1 Effect of Load level

The failure mode was the same for the entire load level considered. Global and local buckling as in figure 3, are the failure observed in the unfilled hollow steel column, the local buckling is inward around the mid-height and bottom of the unfilled hollow steel column. Global buckling was observed for the entire foamed concrete filled column tested, outward local buckling was also observed for 15% load level only as shown in Figure 4.

**Figure 3**: Failed unfilled hollow column

Figure 4: Failed foamed concrete filled column

Figure 5A presents the axial deformation with time for circular hollow steel columns loaded with 15, 20 and 25% load levels. CHS column loaded with 15% load level has higher fire resistance due to the less applied load which will result in less axial stress on the column when compared to CHS columns loaded with 20 and 25% load level. CHS20 and CHS25 experienced more axial stress and less axial expansion when compared to CHS15 column. Increase in load level level significantly decreases the fire resistance of CHS columns. This can be as a result of increase in axial stress over the cross-section of the column as a result of higher load level. Also, the strength and stiffness of the CHS decrease with increasing temperature during the fire exposure. Therefore, CHS15 has 27 minutes fire resistance, which is more than CHS20 and CHS25 that have 15 and 14 minutes fire resistance, respectively.

Figure 5B and 5C presents the effect of load level on FCFHS columns filled with 1800 kg/m^3 and 1500 kg/m^3 foamed concrete density, respectively. Increasing the load level decreases the fire resistance of the columns. It is due to the increase in the axial stress over the cross-section of the column as a result of higher load level. At the same time, the strength and stiffness of steel and foamed concrete decrease with increasing temperature during the fire exposure. It can also be seen that the axial expansion of the column increase with decreasing load level. Considering FCFHS columns loaded with 15% load level in Figure 5B and 5C, the contraction of the columns due to induced stress become less, allowing more thermal expansion to take place with increasing temperature. When the load level increase from 20 to 25% for FCFHS1500, 1 minute fire resistance decrease was observed. This can be due to little increase in load level (5%) as also shown in Figure 5A for CHS columns.

Generally, fire resistance of 30 minutes is obtained for 15% load level. At high load level of 20% and 25%, fire resistances of less than 30 minutes are recorded. The load level affect the axial stress induced in the columns during fire exposure. Between 15% to 25% load level, a substantial decrease on fire resistance time was observed from both CHS and FCFHS columns.
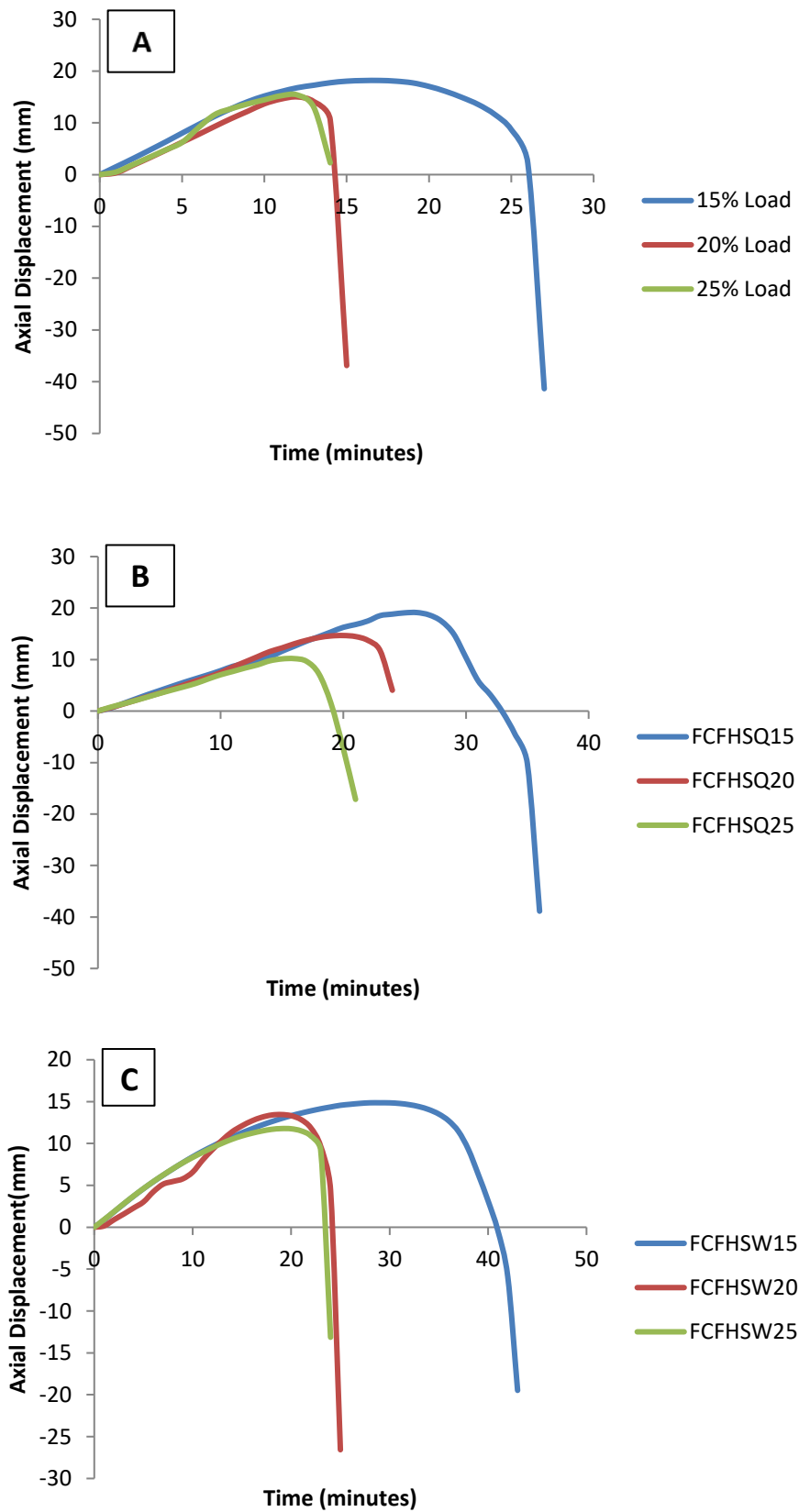
**Figure 5**: Effect of load level on the Columns (A) CHS (B) FCFHS1800 (C) FCFHS1500

3.2 Effect of foamed concrete filling

A comparison was made between circular hollow steel columns and foamed concrete filled hollow steel columns with 15%, 20%, and 25% load level as shown in Figure 6A, 6B, and 6C. Foamed concrete filling improves the fire resistance of steel hollow columns. This is because foamed concrete slows the temperature rise in FCFHS columns, and reduction in strength of steel and foamed concrete is also slow. This will result in additional fire resistance time when compared to CHS columns. At the same time, the foamed concrete prevents inward local buckling of the the steel hollow columns during fire exposure. All these contribute in improving the fire resistance of FCFHS columns.

The axial deformation with time for the columns with 15% load levels in Figure 6A showed a significant difference in fire resistance time. All the columns were loaded with 15% of its design axial buckling load at ambient temperature. FCFHS1500-15 column has highest fire resistance of 43 minutes, this can be due to the low thermal conductivity of 1500 kg/m^3 foamed concrete which cause slow temperature rise in hollow steel and delays the deterioration of the steel and foamed concrete strength during fire exposure.

From Figure 6B and 6C for 20% and 25% load level, respectively; the fire resistance of FCFHS columns is more than that of CHS columns due to foamed concrete filling. FCFHS1500 columns have higher fire resistance than FCFHS1800 columns for all the load levels considered, this is because 1500 kg/m^3 foamed concrete has low thermal conductivity when compared to 1800 kg/m^3. Therefore, foamed concrete deterioration due to fire exposure will be slow and the temperature rise in the hollow steel will be delayed.

Generally foamed concrete filling increase the fire resistance of CHS columns. A fire resistance of CHS is increased from 27 minutes to 43 minutes using 1500 kg/m^3 foamed concrete filling at 15% load level. At 25% load level, it was increased from 14 minutes to 24 minutes using the same fomaed concrete density.
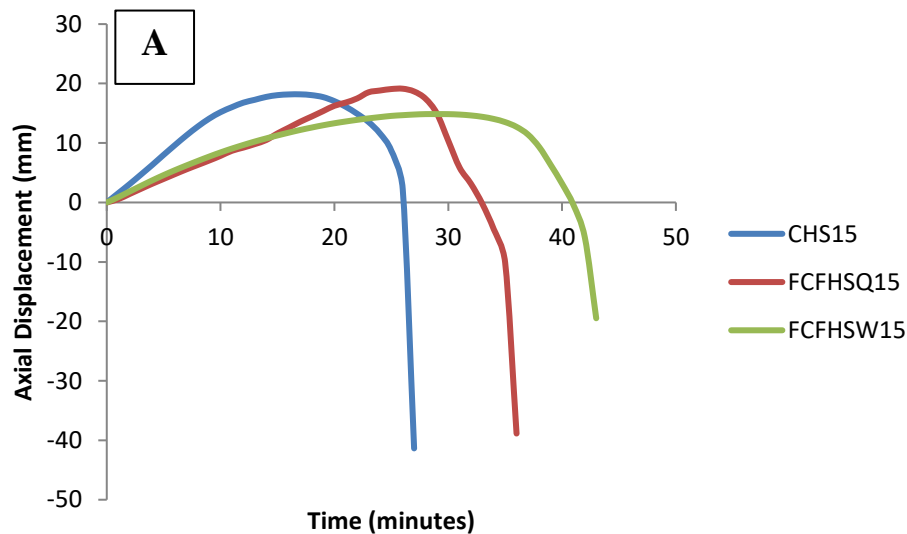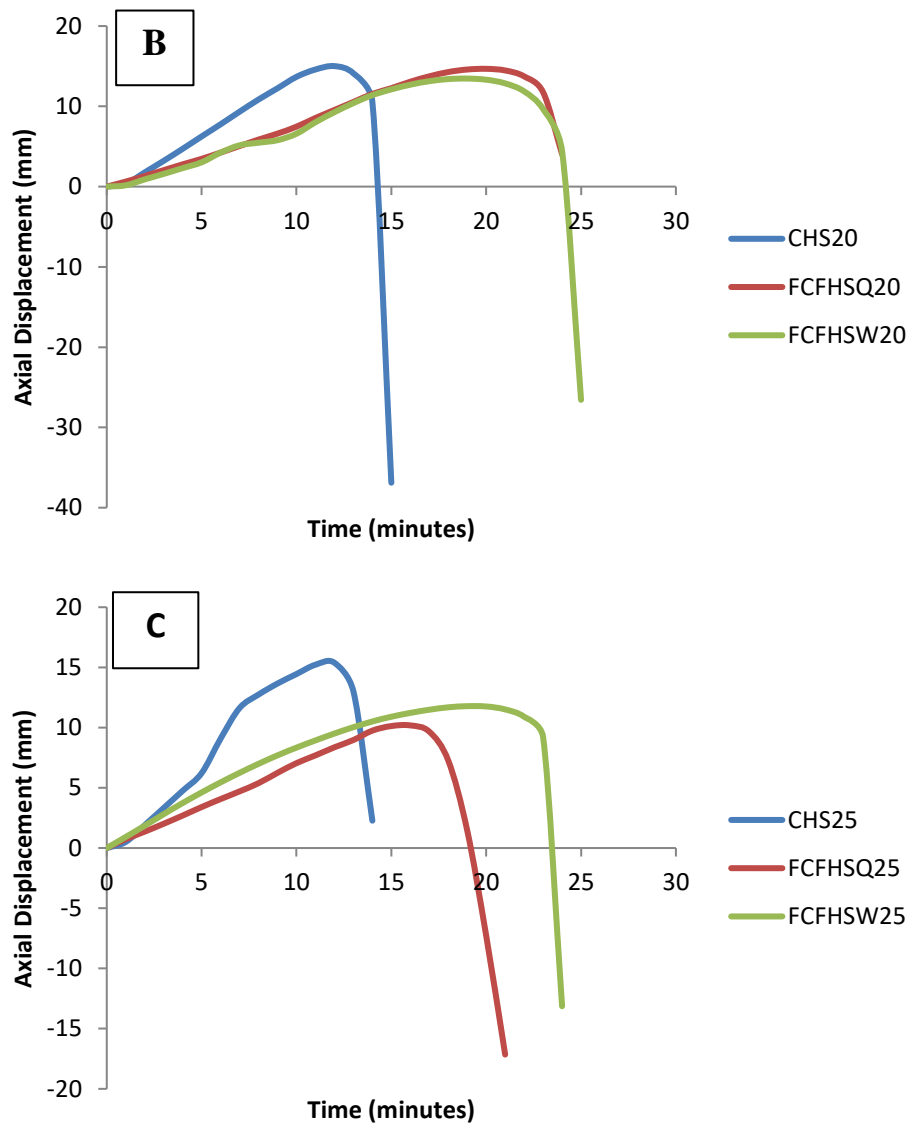
**Figure 6**: effect of foamed concrete filling (A) 15% Load level (B)20% Load level (C)25% Load level

3.3 Temperature Development

The steel hollow section temperature rises more rapidly with time, while the foamed concrete temperature increases gradually with time for all the foamed concrete filled hollow columns tested. This is from the fact that steel has high thermal conductivity than foamed concrete, and the fire is directly applied to the steel surface without any protection; the foamed concrete was being protected by the steel tube. There are wide gap between the temperature on steel and that of foamed concrete.

The temperature rise within the foamed concrete is slow due to its low thermal conductivity, which is as a result of air pores. The air pores inside the foamed concrete make the heat conduction to dominate at a relatively low temperature. A representative sample for FCFHSQ15 showing steel and foamed concrete temperature development against time was plotted in figure 7.
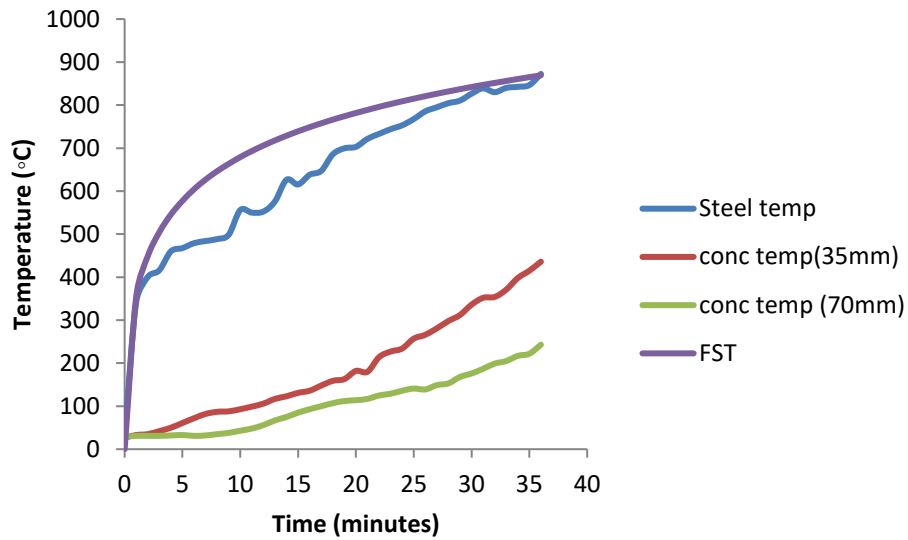
Figure 7: Temperature-Time curve for FCFHSQ15
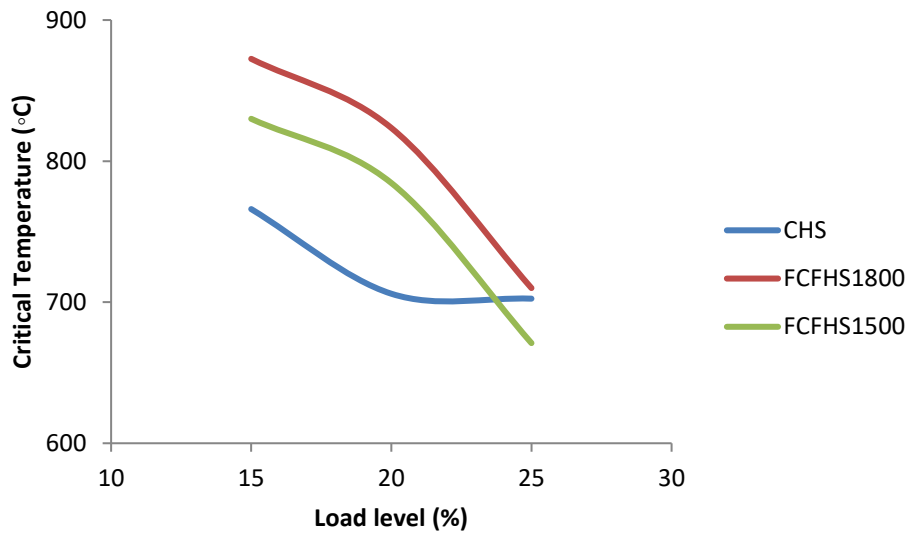
Figure 8: Comparison for critical temperature at different load level.

The steel tube temperature at which the steel tube column failed is called critical temperature. From figure 8, the critical temperature of unfilled hollow steel column was high at 15% load level; it decreases to almost same value for 20 and 25% load level. Critical temperature for foamed concrete filled hollow section columns decreases with increase in load level. A sharp decrease of critical temperature was observed for foamed concrete filled hollow columns. The critical temperature of FCFHSQ was higher than that of FCFHSW for all the load level considered, but critical temperature for FCFHSW drops below that of hollow steel column at 25% load level. Generally, the critical temperature decreases with increase in load level for all the tested columns.

3.4 Fire concrete contribution ratio

Fire concrete contribution ratio (FCCR) can be defined as the ratio between the fire resistance rating of the concrete-filled section and that of the hollow steel section, both subjected to the same axial load [6], [25] as in equation 1.

$$FCCR = \frac{Fire\ resistance\ of\ foamed\ concrete\ filled\ hollow\ section}{Fire\ resistance\ of\ unfilled\ hollow\ section} \tag{1}$$

Table 2: Fire concrete contribution ratio (FCCR)

S/N	Column ID	Load level	FRR FCFHS	CHS	FCCR
1	FCFHSQ15	15	36	27	1.33
2	FCFHSQ20	20	24	15	1.60
3	FCFHSQ25	25	21	14	1.50
4	FCFHSW15	15	43	27	1.59
5	FCFHSW20	20	25	15	1.67
6	FCFHSW25	25	24	14	1.71

It is intended to study the benefit of using the foamed concrete filled hollow column relative to unfilled hollow steel column. Table 2, presents the gain in fire resistance time for using foamed concrete filled hollow section column. It can be seen that the fire resistance time of an unfilled hollow column can be improved depending on the load level applied on the column.

Filling hollow steel column with 1800 kg/m^3 density foamed concrete increases the fire resistance time by 60% at 20% load level. An amount of up to 71% increase in fire resistance of unfilled hollow column was achieved when filled with 1500 kg/m^3 density foamed concrete at 25% load level. It is clearly shown that 1500 kg/m^3 density foamed concrete filling produced more gain in fire resistance time of the foamed concrete filled hollow columns tested at different load levels.

FCFHS1800-20 column has high FCCR compared to FCFHS1800-25. This shows that the steel tube buckles during expansion. The steel tube carries the whole load on CFST column during expansion. Therefore, when the steel tube buckles during expansion, concrete will take part in resisting the load from that time to failure. As such, foamed concrete contribute more in resisting the load under fire for FCFHS1800-20 column.

Contrary to findings by [6] and [25] on CFST columns under fire, the FCCR for FCFHS column is higher for columns subjected to high load level. This is because foamed concrete has low thermal conductivity. Therefore, the material deterioration will be slow due to possible short fire resistance time as a result of high load. As such, greater contribution in resisting load is expected from the foamed concrete. Another reason may be as a result of shorter axial expansion in columns subjected to high load level. Hence, the foamed concrete contribution is expected to be more.

3.5 Comparison with existing Design models

Several simple calculation models are available for calculating specific parameter in concrete filled steel tube column under fire. The existing models have some certain limitations in their application; their validity of applications was checked in foamed concrete filled steel hollow column.

3.6 Axial buckling load comparison

Eurocode 4 provides simple calculation model for concrete filled steel hollow sections, two methods were provided; general method for composite column and Annex H which is specifically for unprotected concrete filled hollow column. General method for composite column was considered in this work. Temperature field measured from the experimental work was used for the calculation. The design axial buckling load was calculated from equation 2,

Fire resistance design equation 3, from Association of New Urban Housing Technology (ANUHT) in Japan was also used to compare with the experimental results.

$$N_{fi,Rd} = \chi \, N_{fi,pl,Rd} \tag{2}$$

$$\frac{N_{fi,Rd}}{A_c f_c} = (5.75 \times 10^{-5} . f_c^{2.63} . t + 1)^{-0.214} \tag{3}$$

Table 3: Axial buckling load comparison

Column ID	Axial buckling load (KN)				
	Test	EC4	ANUHT	Test/EC4	Test/ANUHT
FCFHSQ15	167.9	170.81	211.9	0.98	0.79
FCFHSQ20	223.8	281.04	229.7	0.80	0.97
FCFHSQ25	279.8	349.89	235.8	0.80	1.19
FCFHSW15	167.9	141.67	123.0	1.19	1.37
FCFHSW20	223.8	161.99	131.1	1.38	1.71
FCFHSW25	279.8	233.56	131.7	1.20	2.12
Mean				1.06	1.36
Standard deviation				0.24	0.49

Axial buckling load from the test was compared with the calculated values as shown in table 3. It can be shown that axial buckling calculated using Eurocode simple calculation produces mean value of 1.06 and standard deviation of 0.24. The values of axial buckling load for specimens filled with 1800 kg/m³ foamed concrete density produced unsafe values. While all the specimens filled with 1500 kg/m³ foamed concrete density produced safe results. Therefore base on the test and calculated values, Eurocode 4 general method for composite column can be used to predict the axial buckling load of foamed concrete filled steel hollow column with 1500 kg/m³ foamed concrete density.

From the calculated values of axial buckling load using ANUHT, specimens filled with 1800 kg/m³ foamed concrete density produced unsafe results for 15 and 20% load level; and a safe value for 25% load level. While all the specimens filled with 1500 kg/m³ foamed concrete density produced safe and conservative results. Based on these results, ANUHT method cannot be used to predict the axial buckling load of foamed concrete filled steel hollow column.

3.7 Critical Temperature Comparison

Critical temperature is the temperature at which the column is expected to fail in a steel member; it depends on the applied load level on the member. BS EN 1993-1-1[22] provides an equation for calculating critical temperature. Temperatures measured from the thermocouples at the time of failure were compared with the calculated critical temperature from Eurocode using equation 4, the values are presented in Table 4.

$$\theta_{a,cr} = 39.19 ln \left[\frac{1}{0.9674\mu^{3.833}} - 1 \right] + 482 \tag{4}$$

Table 4: Steel critical temperatures comparison with test result

Column ID	Load level		Critical steel temperature (°C)		
	hollow	Foamed Concrete filled	Test	hollow	Foamed Concrete filled
FCFHSQ15	0.15	0.11	873	768.2	814.9
FCFHSQ20	0.20	0.15	824	725.0	768.2
FCFHSQ25	0.25	0.19	710	691.3	732.7
FCFHSW15	0.15	0.13	830	768.2	789.8
FCFHSW20	0.20	0.18	785	725.0	740.8
FCFHSW25	0.25	0.22	671	691.3	710.6

Two critical steel temperature values were calculated, considering the hollow steel tube only; and when both the steel tube and foamed concrete were considered in calculating the load level. For all the critical temperature values in table 4; the less the load level, the high the critical temperature and vice-versa. It can be seen that the critical temperature for hollow steel tube is less than that of concrete filled column. This shows that foamed concrete contributed in resisting the load at a time the steel can no longer sustain the load. Also, the foamed concrete delays the temperature rise in the steel tube.

All the specimens produced safe result for the critical temperature except FCFHSW25, where the test result is less than the calculated values for hollow and concrete filled specimen. For this case a sensitivity analysis is required to make a reasonable conclusion as suggested by [6].

The critical temperature for values for hollow column was calculated because in some cases failure occurs during the load transfer from the steel tube to foamed concrete core.

4.0 CONCLUSION

The paper presented 9 fire tests on hollow and foamed concrete filled hollow steel column. The work focused on 1800 kg/m^3 and 1500 kg/m^3 foamed concrete density; 15%, 20%, and 25% load level. The work investigated the fire behavior of foamed concrete filled hollow columns by considering the axial deformation, temperature developments, failure modes, and foamed concrete contribution in fire endurance of the columns. From the analysis and comparison of the results, the following conclusions could be made:

1. There is a significant change in fire resistance between 15 to 20% load level for all the columns tested. But between 20 to 25% load level, the fire resistance change was not significant for all the columns tested.
2. Foamed concrete filling slows the temperature rise in the foamed concrete filled steel hollow columns under fire. A highest fire resistance of 43 minutes was achieved at 15% load level.
3. Foamed concrete filling improved strength and stiffness of the column, thereby preventing it from local buckling.
4. Foamed concrete filling decrease the rate of axial deformation of the columns, which is as a result of delay in temperature rise of the steel hollow section.
5. Foamed concrete density of 1500 kg/m^3 was found to be a good in fill material for the concrete filled column, considering its contribution in fire resistance time of the columns when compared with 1800 kg/m^3 foamed concrete density.
6. Simple calculation using general method for composite column in Eurocode 4 can be used to reasonably predict the axial buckling load of foamed concrete filled column with foamed concrete density of 1500 kg/m^3 up to 25% load level.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgement

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Appendix

Notations
D = steel tube diameter
t = steel tube thickness
f_y = yield strength of steel
f_c = 28 days concrete cylinder strength
µ = Load level
BC = Boundary condition
FRR = fire resistance rating
$N_{fi,Rd}$ = design axial buckling load in fire situation
X = reduction or correction coefficient
$N_{fi,pl,Rd}$ = design value of the plastic resistance to axial compression of the total cross-section in fire situation
$\theta_{a,cr}$ = steel critical temperature
t = fire exposure time
A_c = cross-sectional area of concrete