Experimental investigation on temperature distribution of foamed concrete filled steel tube column under standard fire

B Kado[1,2], S Mohammad[1], Y H Lee[1], P N Shek[3], M A A Kadir[1]
[1]Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia.
[2]Department of Civil Engineering, Faculty of Engineering, Bayero University Kano, Nigeria.
[3]Construction Research Centre (CRC), Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia

E-mail: bkado.civ@buk.edu.ng

Abstract. Standard fire test was carried out on 3 hollow steel tube and 6 foamed concrete filled steel tube columns. Temperature distribution on the columns was investigated. 1500 kg/m^3 and 1800 kg/m^3 foamed concrete density at 15%, 20% and 25% load level are the parameters considered. The columns investigated were 2400 mm long, 139.7 mm outer diameter and 6 mm steel tube thickness. The result shows that foamed concrete filled steel tube columns has the highest fire resistance of 43 minutes at 15% load level and low critical temperature of 671 ºC at 25% load level using 1500 kg/m^3 foamed concrete density. Fire resistance of foamed concrete filled column increases with lower foamed concrete strength. Foamed concrete can be used to provide more fire resistance to hollow steel column or to replace normal weight concrete in concrete filled columns. Since filling hollow steel with foamed concrete produce column with high fire resistance than unfilled hollow steel column. Therefore normal weight concrete can be substituted with foamed concrete in concrete filled column, it will reduces the self-weight of the structure because of its light weight at the same time providing the desired fire resistance.

1. Introduction

Fire is one of the intense environmental conditions to which when a structure is exposed to, it gradually weakens the structural members, and after sometimes the members will fail, therefore causing the whole or part of the structure to fail.

Structural fire design base on BS EN 1993-1-2 [1] and BS EN 1994-1-2 [2] for steel and steel-concrete composite respectively, provided three design methods namely; simplified models, Advanced models, and testing. The first two methods uses two steps procedure for the design, they are determination of thermal response and mechanical response.

Rodrigues and Moreno [3], presented a simplified procedure for the determination of temperature field in concrete filled columns. Abaqus computer package was used to simulate the distribution of temperature in the columns. Concrete and steel properties provided in EN 1994-1-2 [2], were used for the modeling. It was concluded that the procedure offers a better alternative for the determination of temperature field in concrete filled column.

Numerical analysis on the effect of temperature rising time, section size, steel ratio, and sectional core area was carried out by Xu and Sun [4] on the steel tube reinforced concrete columns under fire.

The results showed that the temperature on the steel outer surface increases rapidly with time, while the inner steel tube and core concrete temperature increases slowly with time. The authors concluded that the section size and sectional core area ratio have significant influence on the temperature development; and the steel ratio has little influence on temperature development of steel tube and sectional center.

Dong et al, [5] investigated the effect of heating time, section diameter and steel tube diameter on temperature distribution of circular concrete filled steel tube reinforced concrete column under fire. Abaqus finite element software was used for simulating the temperature field. The authors reported that the heating time and cross-section diameter have a significant influence on the temperature development on the column, while the steel tube diameter has a very little influence on the temperature rise of the column.

Recent research on thermal properties and heat transfer on reinforced concrete filled steel tube columns under fire was conducted by [6]. Thermal conductivity, specific heat, thermal contact conductance at steel-concrete interface, and density from different researchers were compared. The results showed that there is a wide dispersion between different thermal properties model of steel and concrete, but the dispersion is more in thermal properties of concrete than that of steel. Aggregate type affects the thermal conductivity of concrete; also aggregate and moisture content have some effects on specific heat of concrete. Effect of temperature on density of steel and concrete is minimal.

Experimental and numerical work was carried out on concrete filled steel tube short columns at elevated temperature by [7,8]. Short concrete filled columns were exposed to fire with and without applied axial load. Temperature development in the columns was obtained for 30 and 60 minutes. The steel tube thickness used was 6, 6.3 and 8 mm and an external diameter of 114.3 and 141.3 mm. The authors concluded that significant change in stress-strain behavior was observed for the column exposed to fire for 60 minutes. Also the applied load level has no effect on the concrete final temperature recorded. The diameter of the column influenced the concrete core final temperature.

A lot of studies were carried out on thermal analysis of concrete filled steel tube columns such as [9–12], but there are limited or no available literatures on foamed concrete filled steel tube column. To determine the behavior of concrete filled steel tube column, detail temperature development within the column is required. Design of concrete filled steel tube column using BS EN 1994-1-2 [2] requires the temperature values within the column as the first stage. The temperature values will then be used to obtain the axial buckling load of the column at a certain fire resistance. This paper presents the experimental work on temperature development of foamed concrete filled steel tube column. Six foamed concrete filled steel tube and 3 unfilled hollow steel columns were tested with foamed concrete of density 1800 kg/m^3 and 1500 kg/m^3. The length of the columns was 2400 mm, with external diameter of 139.7 mm and steel tube thickness of 6 mm. The applied axial loads were at 15, 20, and 25% of the ultimate load of the hollow steel tube calculated using Eurocode 3. The test was carried out in a standard furnace following ISO 834 standard Temperature-time curve.

2. Experimental Program

2.1 Material Properties

Steel and foamed concrete used in this research were tested at ambient temperature and reported. For the steel, circular cold formed steel hollow section of grade S355JOH manufactured according to BS EN10219 by Mig-Melewar Company Malaysia was used for this research work. The tube outer diameter is 139.7 mm and wall thickness of 6 mm. Tensile coupon sample was cut along the longitudinal section of the steel tube, and the detail steel characteristic properties obtained from tensile test are presented in Table 1.

Light weight foamed concrete of target densities 1500 kg/m^3 and 1800 kg/m^3 were used in this work. Cement-sand ratio of 2:1 and water-cement ratio of 0.5 was carefully chosen with reference to [13] who found that the above ratios produced foamed concrete with better compressive strength and adequate workability. A total of 12 cylinders of 100 mm diameter and 200 mm height were casted and tested at

28 days. The mix details and characteristic properties of the foamed concrete used were presented in Table 2.

Table 1. Characteristic properties of steel.

Material	Yield stress, Mpa	Ultimate stress, Mpa	Elastic Modulus, Gpa	Poisson's ratio
Circular steel hollow section, S355JOH	444.11	494.73	202.73	0.31

Table 2. Mix details and characteristics property of foamed concrete.

Target dry density (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	Silica fume (kg/m^3)	Fresh density (kg/m^3)	Hardened density (kg/m^3)	Compressive strength at 28 days Mpa	Elastic modulus Gpa	Poisson's ratio
1500	750	375	375	75	1604	1545	30.62	15.10	0.29
1800	900	450	450	90	1909	1850	11.81	22.43	0.24

2.2 Experimental preparation and procedure

The steel tube length was 2400 mm, 139.7 mm external diameter and steel tube thickness of 6 mm for all the specimens. 20 mm diameter hole was drilled at the mid-height of the steel tube for placing the thermocouple inside the tube. Another two ventilation holes of 15 mm diameter were drilled at 500mm from both ends of the steel tube columns.

Steel end plates was welded at the bottom of the steel tube, after casting the foamed concrete and cured for 7 days, another end plate was then welded at the top of the steel column.

Four type K ceramic protected thermocouples were used for measuring the temperature on the specimen. Two thermocouples were attached on the steel surface using binding wire as shown in figure 1; the other two were positioned inside the steel tube at approximately 35 mm and 70 mm from the steel tube outer surface through the drilled hole prior to foamed concrete casting as shown in figure 2. The entire foamed concrete filled columns specimen tested was stored in the laboratory for 6 month before testing.

The specimens were then tested in a standard furnace of 4.35 m height, 1.2 m width and a 1000 kN hydraulic jack capacity for loading. ISO 834 standard fire exposure was used for the tests under axially applied load at 15, 20, and 25% of the ultimate load of steel hollow column calculated using BS EN1993-1-1 [14]. All the specimens were loaded and then heated to failure. Temperature development and fire exposure time was recorded. An ISO 834 failure criterion for axially loaded member under fire condition was adopted for this test, which stated that the axial contraction or axial deformation rate should not exceed 0.01L mm or 0.003L mm/min respectively, where L is the length of the specimen in mm.

Figure 1. Thermocouple on the steel surface

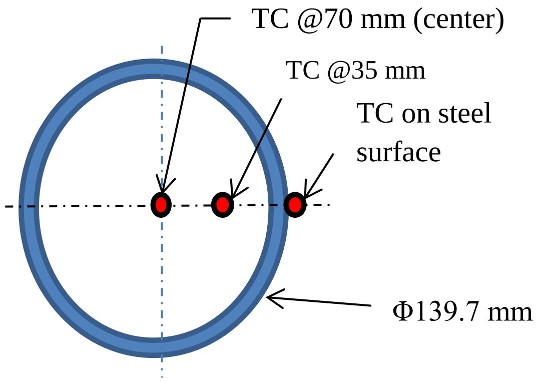

Figure 2. Thermocouples positions

3. Experimental Results

3.1 Effect of foamed concrete filling on steel temperature development

Steel hollow and foamed concrete filled steel columns were tested up to failure. 1500 kg/m^3 and 1800 kg/m^3 foamed concrete densities were used for this research. Figure 3 shows the steel temperature development on the column at 15% load level. Hollow steel tube reached 766 ºC critical temperatures at 27 minutes, while foamed concrete filled columns continue to resist applied load with increase in steel tube temperature. The highest critical temperature attained by 1800 kg/m^3 density foamed concrete filled steel tube column (FCFHS1800) at 15% load level was 873 ºC at 36 minutes, and the highest fire resistance time was 43 minutes attained by 1500 kg/m^3 density foamed concrete filled steel tube column (FCFHS1500). Foamed concrete filling slows the temperature rise in the column especially at temperature above 400 ºC.

When the load level was increased to 20%, the critical temperature decreases for the entire specimen tested as shown in figure 4. Steel hollow column has the lowest critical temperature, followed by FCFHS1500. FCFHS1800 has the highest critical temperature of 824 ºC at 24 minutes. Foamed concrete filled with 1500 kg/m^3 foamed concrete density has slightly high fire resistance time and less critical temperature than the column filled with 1800 kg/m^3 foamed concrete.

For the 25% load level, still foamed concrete filling was able to make steel tube to resist combine action of loading and fire for longer period than the hollow steel column. The temperature rise in the hollow steel column at 25% load level was rapid at above 500 ºC as shown in figure 5.

Generally, foamed concrete slows the temperature development in the steel columns. For all the columns tested, the rate of temperature rise in FCFHS1800 is high than FCFHS1500, and hollow steel has the lowest fire resistance time. Low thermal conductivity and possible moisture content of the foamed concrete make the column to have high critical temperature and fire resistance time than unfilled hollow steel tube.

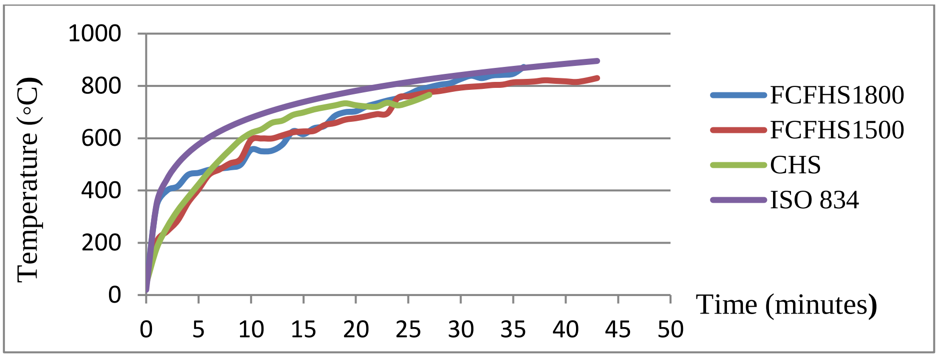

Figure 3. Steel Temperature development at 15% load level.

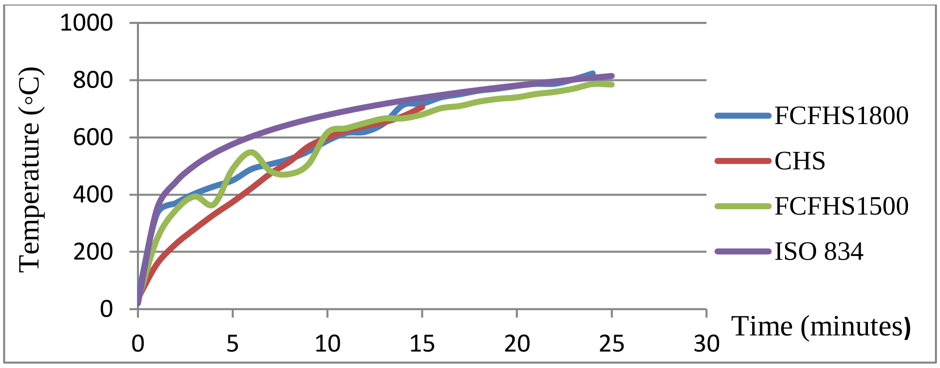

Figure 4. Steel Temperature development at 20% load level.

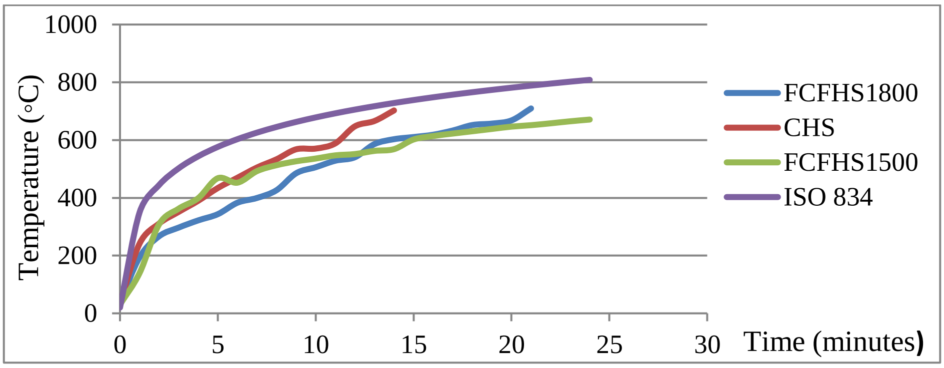

Figure 5. Steel Temperature development at 25% load level.

3.2 Effect of Load level on Steel Temperature development

Figure 6 shows the unfilled steel hollow columns temperature at different load levels. The rate of temperature development was almost the same for all the columns tested. The higher the load level, the less the critical steel temperature, there is no much difference in critical temperature when the load levels increases from 20 to 25%.

FCFHS1800 temperatures at different load levels presented in figure 7, shows that the less the load level applied on the column, the higher the critical temperature. The critical temperature difference was high between 20 to 25% load level.

From figure 8, effect of load levels on FCFHS1500 shows the same response with FCFHS1800. There was high critical temperature difference at load level above 20%. Therefore, filling steel tube column with 1500 kg/m^3 foamed concrete produce high fire resistance time for the column.

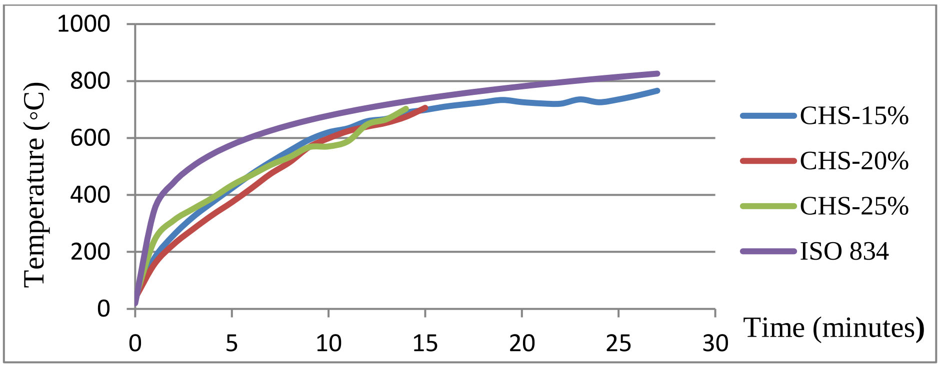

Figure 6. Hollow steel temperature development at different load levels.

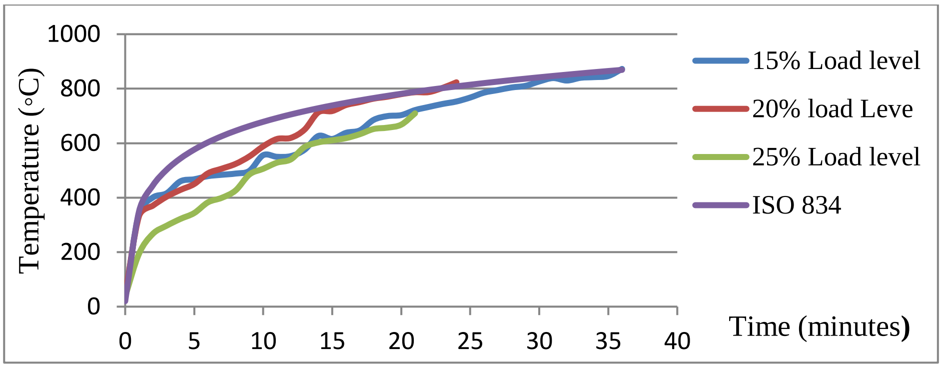

Figure 7. 1800 kg/m^3 foamed concrete filled steel column temperature development at different load levels.

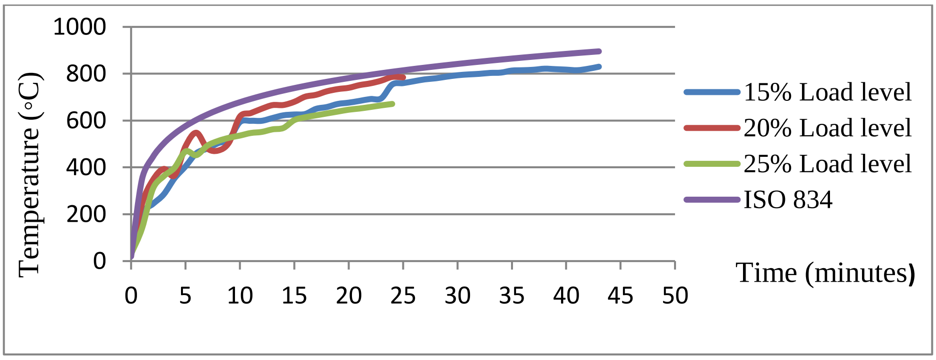

Figure 8. 1500 kg/m^3 foamed concrete filled steel column temperature development at different load levels.

3.3 Critical Temperature

Critical temperature refers to the temperature at which the column fails. The failure temperatures for the steel and in filled foamed concrete are presented in table 3. It can be seen that the foamed concrete critical temperature was very low compared to steel tube. The highest foamed concrete temperature at the center (70 mm) and 35 mm distance from the outside tube of the column cross-section was 243 ºC and 436 ºC respectively. Temperature development with time in the foamed concrete is slow and on steel tube outer surface is rapid, this supported the findings by Xu and Sun [4].

From the above result, at the same load level, fire resistance of foamed concrete filled steel tube column increases with lower foamed concrete strength. This shows that foamed concrete filled steel column behaves like normal weight concrete filled column as investigated by Wang and Young [10].

Table3. Steel and foamed concrete critical temperatures.

Specimen	Load level	FRR	Critical Temperature (◦C)			
			ISO 834	Steel	Foamed concrete	
					35 mm	70 mm
CHS15	15	27	826	766	-	-
CHS20	20	15	739	706	-	-
CHS25	25	14	728	703	-	-
FCFHS1800-15	15	36	869	873	436	243
FCFHS1800-20	20	24	809	824	197	121
FCFHS1800-25	25	21	789	710	153	118
FCFHS1500-15	15	43	896	830	224	181
FCFHS1500-20	20	25	815	785	255	147
FCFHS1500-25	25	24	809	671	233	135

CHS= Unfilled circular hollow steel,
FCFHS= Foamed concrete filled hollow steel,
1800/1500 = foamed concrete density in kg/m^3
15/20/25 = % of ultimate predicted column strength
FRR= Fire resistance rating.

4. Conclusions

From the above results, the following conclusions can be made:

1. Filling hollow steel tube with foamed concrete increases fire resistance time of the steel tube column.
2. Foamed concrete absorbs heat from the steel, making the steel tube to withstand temperature rise for longer time.
3. The higher the load level on the foamed concrete filled steel column, and the less the critical temperature on the column.
4. Fire resistance of foamed concrete filled steel tube column increases with lower foamed concrete strength (density).

Acknowledgement: This research work is supported by FRGS grant of 4F763 from Ministry of Higher Education Malaysia (MOHE). The supports from both Universiti Teknologi Malaysia (UTM) and MOHE are gratefully acknowledged.

References

[1] British Standards Institution BS EN1993-1-2. Eurocode 3. Design of steel structures- Part 1-2: General rules - Structural Fire design London: BSI; 2005.
[2] British Standards Institution. BS EN-1994-1-2 Design of Composite steel and concrete structures Part 1-2 General rules- Structural fire design . London: BSI 2005
[3] Fabio Masini Rodrigues and Armando Lopes Moreno Junior 2017 Temperature field of concrete-filled steel tubular columns in fire *International Engineering Journal* **70** 137–147.
[4] Xu L, Sun J 2012 Temperature Field Calculation and Analysis within Steel Tube Reinforced Columns *The Open Civil Engineering Journal* **6** 15–20.
[5] Dong J S, Ren Q X, Jia L G 2014 Temperature Field Analysis of Circular Concrete Filled Steel Tube Reinforced Concrete Column under Fire *Advanced Materials Research* **1015** 219-222
[6] Xiang K, Wang G H, Pan Y C 2014 Thermal Properties and Heat Transfer in Concrete Filled

Steel Tube Reinforced Concrete Columns Exposed to Fire *7th International Conference on Intelligent Computation Technology and Automation IEEE* 869–74

[7] Jacintho A E P G A, Silva V P, Requena J A V, Lintz R C C, Barbosa L A G, Pimentel L L 2012 Short steel and concrete columns under high temperatures *Rev. IBRACON Estrut. Mater* ***5(4)*** 530–547

[8] Ana Elisabete P. G. A Jacintho, Valdir P. Silva, João A. V. Requena, Rosa C. C. Lintz, Luisa A Gachet-Barbosa and Lia L. Pimentel 2014 Analysis of composite steel and concrete columns at high temperatures *Fire and Materials* **40**:305–317.

[9] Espinós Capilla, A.; Romero García, Ml. (2013). *Finite Element Modelling Of Innovative Concrete Filled Tubular Columns Under Room And Elevated Temperatures*. Editorial Universitat Politècnica De València 60

[10] Wang K, Young B 2013 Fire resistance of concrete-filled high strength steel tubular columns. *Thin-Walled Structures* **71** 46–56

[11] Romero ML, Moliner V, Espinos A, Hospitaler A, Ibanez C, Romero M L 2011 Fire behavior of axially loaded slender high strength concrete-filled tubular columns. *Journal Construction Steel Research* **83** 1953–1965

[12] Xiang K and Wang G 2014 Experimental Study on Temperature Distribution of Concrete Filled Steel Tube Reinforced Concrete Square Short Columns. *Procedia Engineering* **71** 16–21.

[13] Mydin A O 2011 Effective thermal conductivity of foamcrete of different densities. Concrete Research Letter **2(1)** 181–189.

[14] British Standards Institution. BS EN 1993-1-1:2005 Design of steel structures – Part 1-1 General rules and rules for buildings. London: BSI; 2005.