BEHAVIOUR OF 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 cold-formed hollow steel columns for improving fire resistance. The hollow steel is of grade S355, section diameter of 139.7 mm, and 6 mm thickness. An experimental and numerical programs were carried out in this study. Nine columns were tested in fire testing furnace: three were hollow steel columns and six were hollow steel columns filled with foamed concrete (FCFHS). An ISO-834 standard temperature-time curve was used for the fire resistance test. All the columns were tested without any external fire protection, and were subjected to concentrically applied load under fixed-fixed end conditions. Fire resistance time, temperature development, and axial displacements on the column were the parameters recorded from the fire test. The experimental result showed that filling hollow steel column with foamed concrete improves its fire resistance time. Maximum fire resistance periods of 36 minutes and 43 minutes were achieved for hollow steel column filled with 1800 kg/m^3 and 1500 kg/m^3 foamed concrete density, respectively, at 15% load level. Comparison between experimental and Eurocode 4 design axial buckling load revealed that the columns filled with 1500kg/m^3 foamed concrete density can be predicted accurately using Eurocode 4 general design method. Failure mode observed in hollow steel columns was global and local buckling (inward and outward). However, only global and outward local buckling were observed on FCFHS columns, as concrete filling prevents the inward local buckling. A three-dimensional non-linear numerical simulation was performed on FCFHS columns using ABAQUS software. Sequentially coupled thermal stress analysis was used for the thermo-mechanical analysis of the columns. The model developed was validated by comparing the predicted numerical fire resistance time and maximum axial displacements with the experimental results. Parametric studies reveal the influence of column diameter, length, load level, steel tube thickness, and concrete strength on the FCFHS columns. A simplified design equation was proposed using multi linear regression analysis for calculating the fire resistance of FCFHS columns under fire. The proposed equation can accurately estimate the fire resistance time of FCFHS columns without using standard codes or performing fire resistance test. Finally, foamed concrete enhances the fire resistance of steel hollow columns. FCFHS columns can be used for structures that require moderate fire resistance time.

ABSTRAK

Pengurangan berat-diri struktur dan pencapaian rintangan api yang mencukupi adalah beberapa pertimbangan penting dalam reka bentuk struktur tinggi. Penggunaan tiang tiub keluli diisi konkrit ringan (CFST) merupakan kaedah alternatif yang boleh memenuhi tujuan ini. Kajian terkini mengenai tiang tiub CFST pada suhu ambien menunjukkan bahawa konkrit berbusa boleh menjadi bahan alternatif yang bermanfaat dan inovatif. Oleh itu, kajian ini mengkaji potensi penggunaan konkrit berbusa dalam tiang keluli bulat berongga terbentak-sejuk bertujuan untuk meningkatkan rintangan api. Keluli berongga tersebut bergred S355, dengan garis pusat 139.7 mm dan 6 mm tebal. Kaedah ujikaji dan berangka telah dijalankan dalam kajian ini. Sembilan tiang telah diuji dalam relau pengujian kebakaran, tiga adalah tiang keluli berongga dan baki enam adalah tiang berongga diisi dengan konkrit berbusa (FCFHS). Lengkokan suhu ISO-834 digunakan untuk ujian ini. Semua tiang telah diuji tanpa sebarang perlindungan kebakaran luaran, dan tertakluk kepada beban yang digunakan secara sepusat dengan kedua hujungnya terikat. Masa rintangan kebakaran, pembangunan suhu, dan anjakan paksi pada tiang adalah parameter yang direkodkan semasa ujian kebakaran. Keputusan ujikaji menunjukkan bahawa dengan mengisi keluli berongga dengan konkrit berbusa boleh meningkatkan masa rintangan api. Masa rintangan kebakaran maksimum selama 36 minit dan 43 minit telah dicapai untuk tiang keluli berongga yang diisi dengan 1800 kg/m^3 dan 1500 kg/m^3 kepadatan konkrit berbusa, masing-masing pada tahap beban 15%. Perbandingan antara beban lengkokan paksi antara ujikaji dan pengunaan Eurocode 4 mendapati bahawa tiang yang dipenuhi dengan kepadatan konkrit berbusa 1500 kg/m^3 boleh diramalkan dengan tepat menggunakan kaedah reka bentuk umum Eurocode 4. Mod kegagalan yang diperhatikan dalam tiang keluli berongga adalah lengkokan global dan tempatan (ke dalam dan ke luar). Walau bagaimanapun, hanya lengkokan tempatan global dan ke arah luar diperhatikan pada tiang FCFHS, kerana pengisian konkrit menghalang lengkokan tempatan ke arah dalam berlaku. Simulasi berangka tidak linear tiga dimensi dilakukan pada tiang FCFHS menggunakan perisian ABAQUS. Analisis tegasan haba terganding bersiri dijalankan untuk tiang mekanik-haba. Model yang dibangunkan telah disahkan dengan membandingkan jangkaan numerik masa rintangan api dan anjakan paksi maksimum tersebut dengan hasil data dari ujikaji. Kajian parametrik menjelaskan pengaruh diameter tiang, panjang, tahap beban, ketebalan tiub keluli, dan kekuatan konkrit ke atas tiang FCFHS. Satu rumusan reka bentuk yang dipermudahkan telah dicadangkan berdasarkan analisis regresi multi linear untuk mengira rintangan api tiang FCFHS akibat kebakaran. Rumusan yang dicadangkan dapat menganggarkan masa rintangan kebakaran FCFHS secara tepat tanpa menggunakan kod piawai atau melakukan ujian rintangan kebakaran. Akhir sekali, konkrit berbusa berupaya meningkatkan rintangan kebakaran bagi ruang kosong keluli. Tiang FCFHS boleh digunakan untuk struktur yang memerlukan masa rintangan api sederhana.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ASCE	-	American Society of Civil Engineers
ASTME	-	American Society for Testing Materials
BS	-	British Standard
CFSST	-	Concrete filled stainless steel tube
CFST	-	Concrete filled steel tube
CFT	-	Concrete filled tube
CHS	-	Circular Hollow Steel
CHS15	-	Circular Hollow Steel with 15% load level
CHS20	-	Circular Hollow Steel with 20% load level
CHS25	-	Circular Hollow Steel with 25% load level
EC4	-	Eurocode 4
FCCR		Fire Concrete Contribution Ratio
FCFHS	-	Foamed Concrete Filled hollow steel
FE	-	Finite Element
FEA	-	Finite Element Analysis
FIB	-	Fiber Reinforced Concrete
FRR	-	Fire Resistance Rating
ISO	-	International Standard Organisation
LFC	-	Lightweight Foamed Concrete
NIST	-	National Institute of Standards and Technology
NRC	-	National Research Centre
UK	-	United Kingdom
USA	-	United States of America
WTC	-	World Trade Centre

LIST OF SYMBOLS

θ_a - steel temperature (^{o}C)

$f_{y,\theta}$ - effective yield strength

$\varepsilon_{t,\theta}$ - limiting strain for yield strength

$f_{p,\theta}$ - proportional limit

$E_{a,\theta}$ - slope of the linear elastic range

$\varepsilon_{p,\theta}$ - strain at the proportional limit

$\varepsilon_{u,\theta}$ - ultimate strain

$\varepsilon_{y,\theta}$ - yield strain

λ_a - thermal conductivity of steel

A_a - cross-sectional areas of steel

A_c - cross-sectional areas of concrete

A_s - cross-sectional areas of reinforcement

C_{add} - Additional heat required to get rid of water

C_{max} - maximum load during fire

$C_{p,dry}$ - Specific heat of dry foamed concrete

E_C - elastic modulus of foamed concrete at ambient temperature

F_C - foamed concrete compressive strength at ambient temperature

K_{dry} - thermal conductivity of dry foamed concrete

K_s - thermal conductivity of solid

K_w - thermal conductivity of water

V_w - volume percentage of water

d_e - pores diameter

f_c - Concrete compressive strength

f_c' - specified 28 day concrete strength in MPa

f_{ya} - Steel yield stress

f_{ys} - Reinforcement yield stress respectively at temperature θ

$\gamma_{fi,s}$ - Reduction coefficient factor for reinforcement in the fire situation

ε_{CT} - strain at temperature T

ε_{OT} - strain at peak stress at temperature T

ε_{ln}^{pl} - plastic strain

ε_{nom} - nominal strain

σ_{nom} - nominal stress

σ_{true} - true stress

μ - load level

A_s - Area of steel

R - Fire resistance in minutes

$\theta_{a,cr}$ - steel critical temperature

ρ - Density

χ - Reduction coefficient for buckling curve

ε - porosity of foamed concrete

$C_{p,dry}$ - Specific heat of dry foamed concrete

E_C - elastic modulus of foamed concrete at ambient temperature

F_C - foamed concrete compressive strength at ambient temperature

K_{dry} - thermal conductivity of dry foamed concrete

K_s - thermal conductivity of solid

K_w - thermal conductivity of water

V_w - volume percentage of water

d_e - pores diameter

f_c - Concrete compressive strength

f_c' - specified 28 day concrete strength in MPa

f_{ya} - Steel yield stress

LIST OF APPENDICES

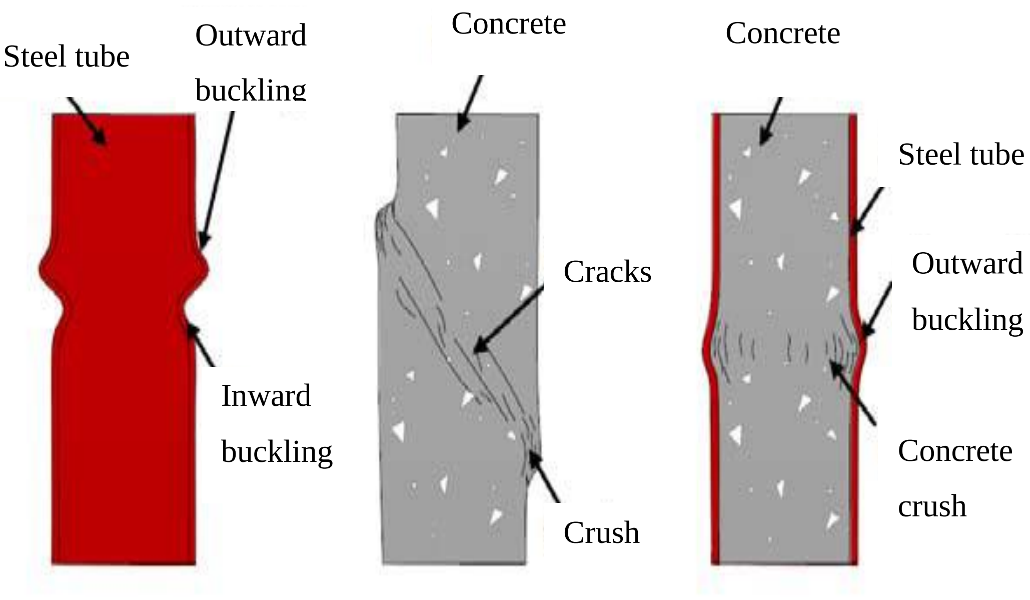
CHAPTER 1

INTRODUCTION

1.1 Background

Fire is one of the most feared hazards affecting structures in the world. The United States recorded 475,500 structure fires in 2016, which account for 74% of the total property loss estimates due to fires in that year (Haynes, 2017). There were 39,600 dwelling fire incidences and 22,200 other buildings that are not housing structure recorded fire incidences in Great Britain from 2013 to 2014 (DCLG, 2015). Structure fires in Malaysia increased by 6.8% from 5,447 in 2012 to 5,817 in 2013. Structure fire cases usually cause major loss of money and property, both directly and indirectly. In 2013, majority of structure fires recorded in Malaysia are categorized into other and unknown, with 57.4% and 11.6%, respectively (Rahim, 2015). When a structure is exposed to fire, the members are gradually weakened and will eventually cause the whole or part of the structure to fail. The collapse of World Trade Center (WTC) USA in 2001 was as a result of subsequent multi-floor fires after the aircraft impact. The aircraft impact dislodged the fire insulation on the structural steel members, causing the fires to weaken the core columns and therefore overloading the perimeter columns. NIST (2005) reported that the WTC towers would likely resist the combined effect of aircraft impact damage and the multi-floor fires had the thermal insulation not been widely or minimally dislodged by the aircraft impact.

In order to minimize loss due to a fire, buildings should be designed such that it can withstand fire for a certain period, known as fire resistance designs. Hollow steel sections are construction materials for medium to high rise structures. Unprotected structural hollow steel sections have a characteristic fire resistance of 15 to 30 minutes. Whenever a steel hollow section is required to resist a fire for a period above 30 minutes, certain measures have to be taken such as; external insulation of the steel sections, concrete filling of the steel section, and water cooling of the section (Twilt *et al.*, 1994). However, concrete has much higher compressive strength than tensile strength. Its compressive strength improved more when subjected to biaxial or triaxial restraint. On the other hand, structural steel has high tensile strength, but under compression, its shape can buckle locally. Hence, in concrete-filled steel tube columns, both the steel and concrete characteristic properties are utilized. The local buckling in the steel tube is improved due to the presence of core concrete, and the steel tube confinement increased the compressive strength of the core concrete. The failure mode of hollow steel, concrete, and concrete-filled steel tube (CFST) column are shown in Figure 1.1. From the figure, it is noticed that the inward buckling of the steel tube was prevented by the core concrete (Han *et al.*, 2014).



(a) Steel tube (b) concrete (c) CFST

Figure 1.1 Failure modes of hollow steel tube, concrete and CFST stub columns (Han et al., 2014)

Besides the good characteristic properties of concrete-filled steel tube columns at ambient temperature, its inherent high fire resistance attracts more attention in the construction industry, particularly in high rise buildings. The combined action of steel tube and concrete core delays the temperature rise in the steel tube, and the steel tube shields the concrete core from direct exposure to fire. The loss of strength and stiffness in concrete is delayed, and the degradation was slower than that of steel under fire exposure (Twilt *et al.*, 1994).

1.1.1 Advantages of CFST Columns

CFST columns have become popular among designers and structural engineers due to its great advantages. Among the advantages highlighted by (Morino and Tsuda, 2003; Rush, 2013) are:

1. Concrete filling increases the axial and flexural load-bearing capacity of the steel hollow section.

2. Steel hollow sections confine the core concrete, increasing its strength and stiffness; also the steel hollow sections shielded the concrete from direct exposure to fire.

3. The concrete core restrains the steel tube, thereby preventing the inward local buckling.

4. Formwork is not required; the steel hollow section acts as the permanent formwork, thus construction speed and efficiency are increased.

5. Labor and formwork are omitted, since the concrete casting was by pumping method, as such construction efficiency increased.

6. Filling steel hollow section with concrete improves its fire resistance; therefore steel tube columns can be designed and constructed without any external fire protection.

7. Reduction of construction cost when compared to using steel hollow section only, in which external fire protection must be provided, and thus occupy the useable floor area and requires maintenance.

1.1.2 Practical Applications of CFST Columns

The first work patented on concrete-filled steel circular hollow sections was dated 1898, but the technology attracted more attention in the middle of the 20th century after advantageous results were obtained from several kinds of research (Hicks and Newman, 2002). Concrete-filled steel tube columns were used in the construction of high rise buildings and bridges; it is commonly being used in structures like industrial buildings, subways, office blocks and electricity transmission poles (Han *et al.*, 2014). CFST columns are gaining popularity in the construction of high rise buildings due to the desire to decrease member size and self-weight of the structure. By combining the action of steel and concrete in CFST columns, higher load-bearing capacity can be achieved with small cross-section size (Liew *et al.*, 2014). Some examples of high rise buildings in which CFST columns technology is employed are presented in Table 1.1. As an example, the Taipei 101 building in Taiwan is a tower constructed with structural steel of 508 meters tall. It consists of steel box-core columns and super-columns filled with concrete up to the 62nd floor, and the rest of the columns are filled with concrete up to the 26th floor in order to add stiffness (Poon *et al.*, 2002; Liu *et al.*, 2012).

Table 1.1 High rise buildings built with CFST columns

Building Name	**Country**	**Year completed**
Taipei 101	Taiwan	2004
Wuhan International securities building	China	2008
Abeno Harukas	Japan	2014
Otemachi tower	Japan	2014
Wilshire Grand tower	USA	2017
Goldin 117 tower	China	2018 (expected completion)
Greenland’s Suzhou center	China	2019 (expected completion)

Abeno Harukas is the tallest building in Japan, the building height is 300 m with 60 stories above ground as shown in Figure 1.2. The building is made with CFT columns using high strength steel materials (Mizutani *et al.*, 2015). Fleet Place House London, UK is an office building that was made with CFST columns. The building is eight stories made of 323.9 mm diameter circular CFST columns as shown in Figure 1.3 (Hicks and Newman, 2002).

Figure 1.2 Abeno Harukas (Osaka, Japan) (Mizutani et al., 2015)

Figure 1.3 Fleet place House, London (Hicks and Newman, 2002)

Montevetro apartment block London shown in Figure 1.4 is a residential building made with CFST columns. Other residential buildings made with CFST columns include student residence in Toulouse France, and Montevideo residential tower constructed on Wilhelmina Pier in Rotterdam, Netherlands (Hicks and Newman, 2002; Usach, 2015).

Museum of flight at King County Airport in Seattle USA, St Thomas Elementary School Ontario Canada, and Peckham Library London, UK are some examples of public buildings made with CFST columns. Figure 1.5 shows Peckham Library London, which was made with circular CFST columns to support its front (Kodur and Mackinnon, 2000; Hicks and Newman, 2002).

Figure1.4 Montevetro apartment block London (Hicks and Newman, 2002)

Figure 1.5 Peckham Library London (Usach, 2015)

CFST column members have also been used in different types of bridges, which include arch bridges, suspension bridges, cable-stayed bridges and truss bridges. Figure 1.6 shows a Wangcang East river bridge in China, one of the earliest CFST arch bridge built in 1992 (Han *et al.*, 2014).

Figure 1.6 Wangcang East river bridge China

1.2 Statement of the Problem

The current standards and codes provision for fire resistance design are purely prescriptive, highly restrictive, and very simplistic in nature and cannot be used under performance-based codes (Kodur, 2007).

In many cases, exposed steel structures are required for aesthetic purposes, such as at the airports, schools, and atriums. The dimensions of the columns in such structures are beyond those allowed in the current design Equations. As such, designers cannot take advantage of high fire resistance ratings, high load bearing and aesthetic appearance that can be achieved using CFST columns.

As a result of the above limitations of the current design standard and codes, many opportunities for using the CFST columns are being lost. In some cases where CFST columns are used, external fire protection is still provided, without taking advantage of inherent fire resistance present in the composite hollow structural steel and concrete system.

Reduction in member size and structural self-weight makes the combination of ultra-high strength concrete and high tensile steel as CFST member more attractive for high rise structures (Liew *et al.*, 2014). However, normal and high strength concrete have a high density (i.e more weight) compared to light-weight foamed concrete.

High strength to weight ratio and low density are some of the characteristic properties of foamed concrete. Reducing self-weight of structures and cost of labor in construction are some of the advantages of using foamed concrete compared to normal concrete (Amran *et al.*, 2015). An investigation by (Varghese *et al.*, 2017) showed that the low density of foamed concrete makes it produce about 25% reduction in weight on the structure. Foamed concrete is an innovative and an alternative material to conventional normal weight concrete or high strength concrete because foamed concrete has much lower thermal conductivity than normal weight or high strength concrete. Another advantage of foamed concrete is its low density, which will cause the reduction of self-weight of a structure when compared to normal weight concrete.

As such replacing normal or high strength concrete with foamed concrete may result in achieving required member capacity, fire resistance, and reduction in self-weight of the structure.

1.3 Objectives

The aim of this research is to investigate the behavior of lightweight foamed concrete-filled steel circular column under fire. To achieve it, the following objectives were set out:.

1. To investigate the foamed concrete-filled steel hollow column behavior under standard fire.

2. To develop a finite element model for predicting the fire response of foamed concrete-filled steel hollow column.

3. To determine the effect of various parameters of foamed concrete-filled steel hollow column at an elevated temperature.

1.4 Scope of the Study

The scope of this research is limited to experimental and numerical study on unprotected cold formed circular hollow column and cold formed circular hollow column filled with lightweight foamed concrete of 1500 kg/m^3 and 1800 kg/m^3 density. The steel tube used is Circular cold-formed steel hollow section of grade S355JOH manufactured according to BS EN10219 by Mig-Melewar Company

Malaysia. Foamed concrete used is made of 0.5 water-cement ratio and the cement-sand ratio of 2:1. The length of the columns was 2400 mm, steel tube outer diameter of 139.7 mm and 6 mm steel tube thickness.

The applied axial concentric load is at a Load ratio of 15%, 20%, and 25% of the design resistance of circular hollow steel and circular hollow steel filled with foamed concrete calculated according to BS EN1993-1-1 and BS EN1994-1-1, respectively. Moreover, this work focused on axially loaded columns exposed to ISO 834 (ISO, 2014) standard temperature-time curve for the control of fire tests. ABAQUS Finite element (FE) is adopted in the simulation. Elevated temperature material properties for steel tube and foam concrete available from relevant codes and literature are adopted.

1.5 Significance of the Study

Design trends are now changing from prescriptive based approach towards performance-based approach. A Performance-based approach is gaining popularity in fire safety design because it is economical and it provides sound fire safety solutions (Kodur, 2007).

At present, there is very little research on CFST columns using light-weight foamed concrete at ambient temperature. A comprehensive research program is required to explore the benefit of substituting normal or high strength concrete in CFST columns at elevated temperature.

An investigation by Mydin found that low thermal conductivity of foamed concrete, which is as a result of its porous nature, makes it an appropriate material for insulation or fire resistance in a building. Foamed concrete can be used as load bearing material because a reliable compressive resistance foamed concrete can be produced (Mydin, 2011a).

Since Lightweight foamed concrete (LFC) is new material in CFST column, a new formulation for the contribution of the LFC in the composite system is necessary.

The results of this research may effectively eliminate the use of fire protection for steel hollow columns filled with foamed concrete, and thus provide a large potential for creating innovative designs using exposed steel.

By carrying out the experimental and numerical studies on Foamed concrete-filled hollow section (FCFHS) columns under fire, sets of data are provided for future use. This research will also introduce another use of foamed concrete.

1.6 Thesis Content

The contents of this thesis are divided into 6 chapters. Chapter 1 is an introduction part, which highlighted the background of the research, problem statement, objectives and significance of the research. In Chapter 2 an extensive literature review of material properties, experimental and numerical investigations are presented. The available existing design guides for CFST columns is also discussed. The detailed research methodology employed in this research is discussed in Chapter 3. It includes material properties test at ambient temperature, preparation, and testing of samples in a furnace. Then the development of the numerical model using ABAQUS for simulating the tested column behavior under fire is elaborated. The result of experimental investigations is presented in Chapter 4. It includes the results on material properties at ambient temperature and fire resistance test. The fire resistance results were classified into temperature development results and axial deformation results. Chapter 5 presents the results of numerical investigations; sensitivity study and validation of the model was carried out in this chapter. After that a parametric study was carried out to determine the influence of parameters on the behavior of FCFHS columns under fire. A summary, conclusion of the entire work, and the recommendations for future study are presented in Chapter 6.

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