Jurnal
Teknologi

Full Paper

REVIEW ON COLUMN FIRE RESISTANCE DESIGN FOR CONCRETE FILLED STEEL TUBE

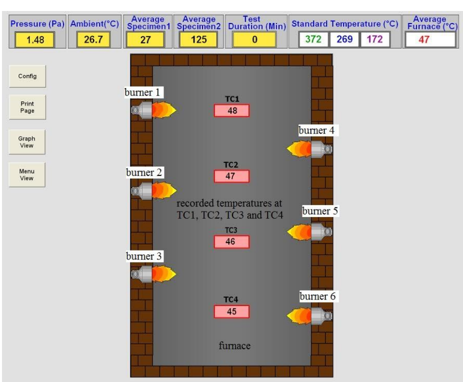
Bishir Kado[a,b], Shahrin Mohammad[a], Yeong Huei Lee[c*], Poi Ngian Shek[d], Mariyana Aida Ab. Kadir[a], Fadhluhartini Muftah[a,e]

[a]School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[b]Department of Civil Engineering, Faculty of Engineering, Bayero University Kano, Nigeria
[c]Department of Civil Engineering, School of Engineering, Faculty of Engineering, Computing and Science, Swinburne University of Technology Sarawak Campus, Jalan Simpang Tiga, 93350 Kuching, Sarawak, Malaysia
[d]Construction Research Centre (CRC), Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[e]Faculty of Civil Engineering, Universiti Teknologi Mara Pahang, Pahang, Malaysia

Article history
Received
30 May 2017
Received in revised form
23 June 2018
Accepted
15 July 2018
Published online
5 October 2018

*Corresponding author
yhlee@civil.my

Graphical abstract



Abstract

The use of concrete filled steel tube (CFST) columns offers an alternative for providing the required fire resistance and load bearing capacity, making its use in medium and high rise structures are highly popular. This paper aims to review the previous studies on CFST column under fire. The standards or codes of practice used in fire resistance designs have been highlighted. The design of the CFST column is summarised with previous investigations on experiments and numerical modelling at ambient temperature and elevated temperature. Different conclusions were drawn depending on the material's properties, considered parameters and the method used for the investigations. Outer diameter or width of the steel tube, steel tube thickness, concrete grade, column length, and eccentricity of loadings are among the parameters that affects the structural behaviour of CFST columns under fire. Several numerical analyses software were adequately used for simulating the behaviour of CFST columns at elevated temperatures, and validated using experimental results. Furthermore, the advantages of using the fire resistance design approaches on CFST columns filled with lightweight foamed concrete is highlighted. In conclusion, there is the need for more studies on standard fire tests of CFST column filled with light weight foamed concrete which is not covered in the current design guide.

Keywords: Fire resistance, concrete filled steel tube, column, foamed concrete

Abstrak

Penggunaan tiang tiub keluli yang diisikan dengan konkrit (CFST) menawarkan alternatif untuk ketahanan api di samping memberi galas beban kapasiti yang diperlukan, menjadikan penggunaannya popular dalam struktur bangunan sederhana tinggi dan tinggi. Kertas kerja ini bertujuan untuk meneliti dan menilai hasil penyelidikan lepas tentang tiang CFST pada keadaan kebakaran atau kewujudan api. Standard atau kod amalan yang digunakan dalam reka bentuk ketahanan api juga dinyatakan dalam kertas kerja ini. Hasil kerja rekabentuk tiang CFST yang lalu melalui kajian eksperimen dan model berangka pada suhu ambien dan suhu tinggi telah dirumuskan. Pelbagai kesimpulan boleh dibuat bergantung kepada sifat bahan tersebut, parameter yang dipertimbangkan dan kaedah yang digunakan. Diameter luar atau lebar tiub keluli, ketebalan tiub keluli, gred konkrit, ketinggian tiang, dan kekuatan beban adalah antara parameter yang memberi kesan kepada kelakuan struktur tiang CFST di bawah keadaan api. Beberapa perisian analisis berangka boleh digunakan untuk simulasi tingkah laku tiang CFST pada suhu tinggi, dan disahkan dengan keputusan eksperimen. Tambahan pula, kelebihan menggunakan reka bentuk ketahanan api untuk tiang CFST yang diisi dengan konkrit ringan berbusa dipromosikan. Kesimpulannya, lebih banyak ujian kebakaran perlu dijalankan untuk tiang CFST dengan konkrit ringan berbusa yang tidak diliputi dalam panduan rekabentuk semasa.

Kata kunci: Ketahanan api, tiang tiub keluli yang diisikan dengan konkrit, tiang, konkrit ringan berbusa

1.0 INTRODUCTION

Fire is one of many severe environmental conditions. When a structure is exposed to fire, the members are gradually weakened and will eventually fail, causing the whole – or part – of the structure to fail. A typical example is the collapse of the Twin towers in New York, USA as a result of terrorist attack on September 11, 2001. The chronology has been documented in a FEMA report [1], which also described the structural performance of WTC1, WTC2, WTC5 and WTC7 under fire. In a previous survey [2], it was summarised that there were 22 cases of collapses due to fires from 1970-2002 in the USA and Canada. These reported cases of compounding occupant losses were caused by the continued spreading of fire, leading to the partial or total collapse of a multi-storey building.

In order to minimise loss due to a fire, buildings should be designed in such that it is able to withstand fire for a certain period, also known as fire resistance designs. During a fire, the moisture in the concrete will gradually turn into steam at 100°C. An explosive spalling (pop-corn cracking) of the concrete will occur when the pressure builds up and these steams are unable to dissipate quickly through the microstructure of the concrete [3]. Thus, this will induce the progressive collapse of a structure. Simple minimum design requirements have been recommended for progressive collapses resulting from fires [3]. Hollow steel sections are construction materials for medium to high rise structural members. Unprotected structural hollow steel sections have 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 [4].

The fires are categorised into accidental fires, arson fires, terrorist attack fires, and natural disaster fires [5]. Fire safety provisions are specifically for accidental fires [5]. Structural fire safety is the least developed within the field of fire science [6], yet remains as an important consideration in the design and maintenance of a building [7]. Nevertheless, new construction materials such as fibre-reinforced polymers [7], foamed concrete or composite materials are being applied in building system where it has a little of references can be obtained from its fire resistance properties. This paper summarises the design specifications of fire resistance designs according to current codes of practice and reviews previous research on structural fire resistance of columns for concrete-filled steel tube columns.

2.0 DESIGN PHILOSOPHY

The engineered structural protection design was initiated with the publication of the design manual [7] and it was used as the reference for the second generation code development for Eurocode. There are two methods in structural fire safety design, namely prescriptive and performance-based. Fire resistance designs show the change from prescriptive approaches (standard fire tests or empirical approaches) to performance based designs (validated engineering practice and computer simulation predictions) [8]. The fire resistance of construction materials has been applied to the design; this allows it to retain the fire from spreading for several hours in order to let the occupants escape from the tragedy.

A prescriptive method is a structural fire safety design that is fairly precise in terms of materials, member sizing, fire protection material, etc. It is mainly based on experience with identical standard fire tests in the design recommendations. This conventional prescriptive rating is based solely on furnace testing to the standard time-temperature curve [9]. With proper assumptions made, prescriptive fire ratings performed a satisfactory historical safety record in US building codes [9]. Work in static conditions is inevitable but it inhibits innovations and development in the construction industry.

There are some limitations that come with the prescriptive method. The effects can be divided into both beneficial and detrimental when analysing the survival of the building members in a fire as a whole item. The formation of an alternative load path such as compressive and tensile membrane action, catenary action and rotational restraint from connections will increase the likelihood of building survival. Extra compressive load may add to the vertical members due to thermal expansion, resulting instability. In addition, the obtained standard curve does not represent a real fire that consists of growth, steady burning and decaying. A real fire will affect the geometry of the compartment, amount of combustible material, ventilation and compartment boundary of thermal characteristics. Furthermore, as there are many new forms of construction that have different fire ratings, they may generate inaccurate designs using test findings that have not been updated since the end of the Second World War.

The standard temperature-time curve is the furnace temperature rather than surface temperature of the test specimen [5]. As filling the lack of prescriptive method, a performance-based approach emphasises the fire model, heat transfer model and structural analysis towards the prescribed fire load. The developed fire model is affected by several factors, namely fire type, fire density, fire distribution, combustion behaviour of fire load, compartment size, compartment geometry, ventilation, and thermal properties of boundary.

The heat transfer models may also consist of conduction, convection and radiation. In standard fire tests, the total heat flux equals to the sum of convective and radiative heat flux [5]. However, for flames, considerable radiation is detected which is excluded from the standard tests [10]. A full-scaled fire test has been carried out for steel framed buildings [11] where the beneficial effects of membrane action for floor slabs are to be included in the structural design. These Cardington test results [11] can be used with any fire model. Numerical modelling is an alternative to performance-based approaches where all fire load, heat transfer and structural analysis can be simulated to achieve a real fire condition.

2.1 Standards and Codes of Practice

2.1.1 Fire Resistance Standard Tests

The buildings are required to be designed in a smaller member or to have an adequate fire resistance period for preventing the spread of smoke and flame according to the prescriptive design. The national Fire Protection Association (NFPA) was established in the year 1896; it is well-known as a code and standards organisation devoted to eliminating death, injury, property, and economic loss due to fire, electrical and/or related hazards. The 300 published codes and standards by NFPA cover a variety of fields in order to minimise the risk and effects of fire. There are several related code references for building construction, namely NFPA 251 [12], NFPA 220 [13], NFPA 5000 [14], NFPA 255 [15], and NFPA 259 [16].

According to the British Standard and Eurocode, the related references are BS476 [17-21], BS EN1363 [22, 23] and BS EN13381 [24-32]. For BS476, a majority of the parts are not updated and may refer to the Eurocode, BS EN1363 and BS EN13381 in designs to resist fire. Moreover, the International Organization of Standardization (ISO) is also involved in the code development by the committee of ISO/TC 92 Fire safety, namely ISO 834 [33-39]. The ISO 834 is developed to cover a range of thickness for the protectors, a range of steel sections with section factors, a range of design temperatures and a range of valid fire resistance classification period [39]. Other related reginal codes and standards include AS1530-4 [40], MS1073-2 [41], IS3809 [42], and UL263 [43] while the New Zealand Standard follows the BS476.

2.1.2 Performance-based Design

The United Kingdom revised the prescriptions for the functional requirements of Building Regulations in 1985 but is limited by the verification approaches and lack of performance requirements [44], whereas, New Zealand introduced these regulations in 1991 and it also faced the problem of implementation [45]. In 1994, Sweden revised its code and transferred the responsibility to the building owner [46].

Followed by Australia [47], the national performance-based code was introduced in 1996 with a closed format of New Zealand code. Canada progressively introduced its related code from 1998 to 2001 [48]. Moreover, Japan developed a framework for the transformation to a performance-based code [49]. In United State of America [50], two organisations, namely the National Fire Protection Association (NFPA) and the Society of Fire Protection Engineers (SFPE) promoted the performance-based in fire engineering [51].

Fire protection engineering has evolved from prescriptive requirements to performance-based designs (PBD). ASTM E119 [52] is applied to make sure a construction assembly or structural element achieves the fire resistance rating specified in prescriptive building codes. The lack of engineering data from standard fire resistance test methods and the analysis requires PBD to utilize the data obtained from ad hoc test methods that performed outside of the scope of standard test methodologies [53].

A serious issue has been discovered that there are some limitations to the test procedures, mostly the measurements for standard furnace testing [53]. The uniqueness of the fire test will cause significant problems in a PBD environment. Hence, relative fire models should be developed. PD7974-1 [54] provides the initiation and development of compartment fires.

There are several references can be made for standard/nominal fire models, time equivalences, parametric fire models, localised fires, external window fires, zone models, and CFD or field models. These references are summarised in Table 1. Table 2 describes the codes of practice from different regions for PBD.

3.0 CONCRETE-FILLED STEEL TUBE COLUMN

3.1 Applications of CFST Columns in Buildings

Concrete filled steel tube columns are widely used in the construction of industrial buildings, air ports, offices, high rise structures, and bridges. This is due to the fact that concrete preforms well under compression, while steel is good in tension. As such, when the two materials combine, they produce a member with a high load bearing capacity, earthquake resistance, higher fire resistance, better appearance, rapid construction methodology, smaller cross-section, and is highly economical [60, 61]. These advantages have led to its wide use in practical applications. CFST columns were applied in structures found in China, Japan, USA, England, and Canada [61-63].

The SEG Palaza in Shenzhen and Wuhan International Securities Buildings are high rise buildings made of CFST columns in China [61]. The Mitsui Soko Hokozaki building and ENICOM Computer centre are buildings in Tokyo,Japan made of CFST columns without external fire protection [64]. The application of CFST columns have been reported in the USA and Canada [65]. CFST columns were used for high fire resistance in the Museum of Flight at King Country Airport (Washington, USA) and St. Thomas Elementary School (Ontario, Canada). Other applications of CFST columns in buildings can be found in Fleet Palace and Peckham Library in London, United Kingdom [66].

3.2 Previous Research Works for CFST Columns

Previous studies of CFST columns have been carried out at ambient and elevated temperatures. For elevated temperatures, previous investigation outputs have been summarized in Table 3.

3.2.1 Behaviour at Ambient Temperatures

Many studies have been done regarding the behaviour of concrete filled steel tube columns at ambient temperature. The behaviour of the short axially loaded concrete filled steel tube columns and the effects of tube shape and steel tube thickness were investigated [67]. It was found that circular steel tubes perform better than square and rectangular sections in terms of post yield axial ductility [67]. Higher column diameter to steel tube thickness ratio up to 150 was studied [68], the result was similar to that of [67]. The reported works in [69] studied the effect of steel tube tensile strength and concrete strength on CFST columns. The effect of steel tube thickness, bond between steel tubes and concrete and also concrete confinement on the behaviour of CFST columns have been investigated [70].

A total of 32 specimens were tested for behavioural studies of concrete filled steel tubular stub columns subjected to axially local compression. The varied parameters were sectional types, local compression area ratio and the endplate thickness [71]. It has been reported in [72] that pin ended fibre reinforced concrete filled stainless steel circular tube columns have been investigated; the tubes were cold-rolled from flat shapes of austenitic stainless steel. The studies support available published literature on concrete filled stainless steel composite columns [73, 74].

Ghannam and his group [75] investigated the behaviour and load carrying capacity of CFST columns filled with normal concrete and light weight aggregate concrete using 8 full scale rectangular cross-section columns. It was concluded that sections filled with light weight aggregate concrete failed due to local as well as overall buckling and supported more than 92% of squash load. The sections filled with normal weight aggregate concrete failed due to overall buckling at mid height and supported more than 87% of the squash load. It was also reported that the weight of CFST columns filled with light weight aggregate concrete was 30% less than that of the CFST columns filled with normal concrete of the same cross-section, at the same time high load carrying capacity was achieved.

3.2.2 Prescriptive Standard Fire Test

Prescriptive approach is the design method based on standard fire resistance tests and do not provide a realistic assessment of structural performance in buildings [5]. The condition of buildings, heat transfer mechanism and the fire scenarios are rarely to be considered in the design. Lie and his group [76-81] carried out an experimental test at National Research Council of Canada (NRCC) on square and circular hollow structural steel columns using plain, bar reinforced and fibre reinforced concrete fillings. Parameters investigated under standard fire exposure, include; concrete filling type, strength of concrete, intensity and type of loading, and column size. They developed a mathematical model that was later applied to similar columns with rectangular sections and circular columns filled with fibre reinforced concrete. Nevertheless, the diameter of column, steel tube thickness, axial load ratio, percentage of steel reinforcement, concrete cover, and aggregate type are the factors affecting the fire resistance of CFST columns [80]. It was concluded that the major parameters influencing the fire resistance of CFST columns in fires include external diameter or column width, load ratio and concrete grade.

The behaviour of the axially loaded square and circular CFST columns at elevated temperatures were studied [82]. It was found that CFST columns with the same steel and concrete cross-section areas are slightly fire resistant than the square CFST columns. Moreover, fire resistance tests on 13 large sized circular CFST columns subjected ISO 834 standard fire were carried out [83]. It was indicated that the section dimension and fire protection thickness had a significant effect on fire resistance, whereas load eccentricity had only moderate influence [83].

Table 1 References for fire models

No.	Fire models	Fire type	Referred codes
1.	Standard/ nominal fire models	External, standard, hydrocarbon, smoldering fire	✓PD7974-1 [54] ✓BS EN1991-1-2 [55]
2.	Time equivalences	Relate standard fires to real fires	✓BS EN1991-1-2 [55], Annex F
3.	Parametric fire models	For post-flashover fires	✓BS EN1991-1-2 [55], Annex A
4.	Localized fires	For pre-flashover fires	✓BS EN1991-1-2 [55], Annex C
5.	External window fires	For fires through openings of fire compartment	✓BS EN1991-1-2 [55], Annex B
6.	Computational Fluid Dynamics (CFD) or field models	For general fire and smoke modelling	✓BS EN1991-1-2 [55], Annex D

Table 2 Codes of practice for PBD

No.	Region	Codes
1.	United Kingdom	PD7974-1 [54], BS EN1991-1-2 [55]
2.	Australia	Building Code of Australia [56]
3.	New Zealand	New Zealand Building Code [57]
4.	Canada	National Building Code of Canada (NBCC) [58]
5.	Japan	Building Standard Law [59]
6.	United States of America	ASTM E119 [52]

Table 3 Previous studies on CFST column at elevated temperatures

References	Specimens	Investigated parameters	Outputs
		Prescriptive Standard Fire Test	
[76-81]	Square and circular hollow steel columns with plain, bar reinforced and fibre reinforced concrete fillings	Concrete filling type, strength of concrete, intensity and type of loading, and column size	A mathematical model was developed with rectangular sections and circular columns filled with fibre reinforced concrete
[82]	Square and circular CFST columns	Steel and concrete cross-section areas	CFST columns with the same steel and concrete cross-section areas are slightly more slightly fire resistant than the square CFST columns
[83]	Large sized circular CFST columns	Section dimension and fire protection thickness	Section dimension and fire protection thickness had a significant effect on fire resistance, whereas load eccentricity had only moderate influence
[84]	Slender concrete filled circular hollow columns	Concrete grade	There is no effect on the fire resistance of normal or high strength concrete filled slender columns
[85]	Slender concrete filled circular hollow columns	Concrete strength, infilling type and axial load level	There is no effect on the fire resistance of normal or high strength concrete filled slender columns
		Numerical and Performance-based Studies	
[87]	Circular, elliptical, square, and rectangular steel hollow sections	Steel cross-section shapes	Circular concrete steel tubular column provides the best structural behaviour when on fire
[88]	Circular CFST columns	De-bonding separation	An increase in the size of the de-bonding gap leads to a decreased load carrying capacity of CFST columns
[90]	Circular and square concrete filled sections	Performance-based	fire resistance varied from about 60 minutes to more than 3 hours depending on the column size and type of concrete infill
[91-92]	Circular and square sections of CFST columns	Thermal properties	A slip between steel and concrete and tensile behaviour of concrete has no significant effect on the fire resistance time of CFST columns
[93]	CFST columns with high strength concrete	-	The results yielded discrepancies between experimental and predicted results as the developed model was not capable of taking into account local effects such as concrete cracking and local buckling of steel tube columns filled with plain concrete

The study of the fire behaviour for slender concrete filled circular hollow columns has been carried out [84] and demonstrated that there is no effect on the fire resistance of normal or high strength concrete filled slender columns. Slender circular hollow section columns filled with normal and high strength concrete were tested under fire [85]. Concrete strength, infilling type and axial load level were the parameters tested under fixed-pinned boundary conditions; the same results were obtained as that of [84].

3.2.3 Numerical Investigation and Performance-based Design

A worldwide trend for fire designs have enabled a development from a prescriptive based approach to a performance based approach, with more emphasis on validated engineering models from computer simulations of fire scenarios with structural components. For over decade, much progress has been made in the finite element software programmes such as VULCAN and SAFIR, which specify in structural fire design [86]. ANSYS and ABAQUS are for general purposes and are commercially available to be used for structural fire modelling.

A high volume of numerical studies have been carried out on concrete filled steel tube columns at ambient and elevated temperatures. Circular, elliptical, square, and rectangular hollow sections were investigated [87]. A numerical study with ABAQUS was carried out and it showed that the circular concrete steel tubular column provides the best structural behaviour when on fire [87]. The axial loading behaviour of the circular CFST columns with de-bonding separation was investigated [88]. Three dimensional nonlinear finite element models were developed and the results showed that an increase in the size of the de-bonding gap leads to a decreased load carrying capacity of CFST columns [88]. Three dimensional non-linear finite element analysis of axial compressive behaviour of circular CFST columns was conducted using ABAQUS/ standard solver [89] and it was reported that the developed numerical models using ABAQUS could be used to predict the main structural behaviour of ultra-strength CFST columns under axial compressive loads. Fire resistance of concrete filled steel columns for both circular and square shapes was investigated [90] using the performance-based approach. It was shown that fire resistance varied from about 60 minutes to more than 3 hours depending on the column size and type of concrete infill.

The ANSYS finite element code was used to simulate the behaviour of the circular and square sections of CFST columns. For the thermal analysis, the thermal properties model was adopted [91] and three dimensional structural solid elements were used for structural analysis [92]. It was concluded that a slip between steel and concrete and tensile behaviour of concrete has no significant effect on the fire resistance time of CFST columns [92]. Nonetheless, Schaumann *et al*. developed a computer program, BoFire [93] and used it to observed the behaviour of CFST columns at elevated temperatures for high strength concrete. The results yielded discrepancies between experimental and predicted results as the developed model was not capable of taking into account local effects such as concrete cracking and local buckling of steel tube columns filled with plain concrete.

A numerical model was developed using SAFIR computer code for analysis of double skin steel tube columns filled with SCC subjected to ambient and standard ISO fire conditions [94]. Slip between the steel tube and concrete was neglected in the analysis [94]. A research conducted at Tsinghua University, Beijing, China investigated the behaviour of circular and square concrete filled stub columns under various combinations of thermal and mechanical loading phases [95]. ABAQUS was used for the study and the stress- strain model was similar to [71] at ambient, heating, cooling, and post fire conditions. The column ends was modelled as fixed end conditions. Concrete was meshed as 8–node brick elements and the steel was modelled as 4–node shell elements.

A realistic three dimensional finite element model has been developed using ABAQUS for circular and elliptical CFST columns under fire [96, 97]. They adopted coupled thermal stress analysis in the models. A sequentially coupled analytical method was used to predict the behaviour of square CFST columns under standard fire loading. The analysis was divided in to three stages. Fire dynamic analysis was conducted for surface temperature time curve using Fire Dynamic Simulator (FDS) [98] at the first stage. The temperature time curve was used for the thermal load in the second stage. Finally, a three dimensional nonlinear stress analysis was carried out using ABAQUS [99, 100].

4.0 DISCUSSIONS

4.1 Fire Records in Malaysia

According to the Fire and Rescue Department Malaysia (FRDM), more than 2000 fire incidents have been recorded annually from 1990 to 2002 [101]. The involved building types can be categorised into residential units, shops, factory, store (small scale storage), squatters, office, school or institution, workshop, amusement parks (like disco or pubs), restaurant, hospital, resthouse or hotel, shopping centres, warehouse (large scale storage), and others. Residential houses were the most prone building to fires in Malaysia, according to the FRDM.

4.2 CFST Columns

From the review of the literatures, CFST columns with circular steel tube perform better than the rest of the steel tube shapes. Plain, fibre reinforced and bar reinforced concrete are the major types of available concrete infill from fire resistance tests, it showed that filling the CFST column with plain concrete offers an economical advantage and are easily placed [7]. The type of concrete infill highly affects the fire performance of CFST columns. Unprotected plain concrete filled CFST columns fail at comparatively low loads when exposed to fire, forcing the use of applied fire protection. In terms of the quantity for research works, plain concrete dominated most of the reported tests available at almost 68%, while reinforced concrete and fibre reinforced concrete have 25% and 7% reported tests, respectively [102].

Reinforced concrete filled CFST columns provide good fire resistance without the need for applied fire protection, but practical placement of internal steel reinforcements may be difficult, costly and time consuming. Fibre reinforced concrete infill provides fire resistance ratings which are comparable to those of reinforced concrete CFST columns. In addition, the types of aggregate used in concrete plays an important role during a fire. Different aggregates in concrete results in different thermal expansions of concrete, which may affect the heat transfer within the section of CFST columns and hence the deformation and ultimate failure of the columns. The recent trend in sustainable, lightweight concrete should influence the direction of research as it can reduce the frequent use of machinery and transportation. Therefore, lightweight foamed concrete will be another alternative for the infills of CFST columns.

Generally, the building codes for determining the requirements for fire resistance of structures were developed based on the response of specimens to standard fire exposure. These codes, such as ASTM E119, ISO 834 and NFPA 251, provide a satisfactory level of safety due to non-occurrence of frequent building failures due to fires. The time-temperature curves used by these standards are not closely similar to the time-temperature curve of a real compartment fire, as such, it was suggested that the testing procedure used by the standards are non-realistic. The performance based design guide through modelling the thermal and mechanical response of CFST column provide better and more realistic, necessary information.

4.3 Available Facilities for Fire Tests in Malaysia

Standard furnaces used for standard fire tests are unique. They varied in terms of size, loading capacity, heat flux applied to test element resulting from various fuel sources, furnace linings, furnace control, heated length to the total length, etc. Furnaces used in literature are of different height, width, loading capacity, and fuel sources for heat flux. SIRIM QAS International provides fire protection tests according to Malaysian and British Standards [103]. The testing facilities include horizontal, vertical and indicative fire resistance test furnace, non-combustibility test apparatus, fire propagation test apparatus, surface spread of flame test apparatus, cyclic movement endurance test apparatus, facilities for performance testing of portable fire extinguishers, and hydrostatic test apparatus.

The standard furnace in Universiti Teknologi Malaysia is 4 m high, 1.5 m width, 1000 kN maximum loading capacity with gas burners as a source of heat flux. The laboratory was launched in April 2014 [104]. Figure 1 shows the fire curve according BS 476 for the furnace and Figure 2 indicates the fire location during testing.

Figure 1 Fire curve that according to BS 476 for the furnace in Universiti Teknologi Malaysia

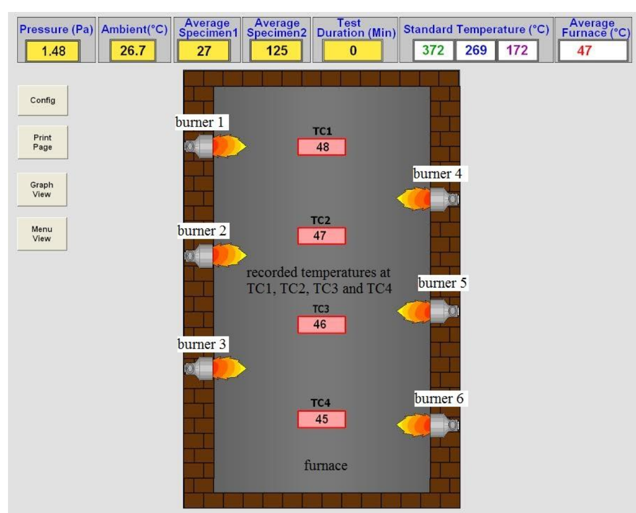


Figure 2 Location of the fire during testing

5.0 CONCLUSION

This paper presents a review on the behaviour of CFST columns when on fire. Previous studies show that unprotected steel tube columns have increased fire resistance when filled with normal or high strength concrete. There are some gaps that need to be filled up concerning the fire resistance of CFST columns using light weight foamed concrete as infill material without reinforcement, considering its advantage of low thermal conductivity and light-weight over normal, high strength concrete. The behaviour of a CFST column filled with light weight foamed concrete is not known, thus it is necessary to study its behaviour as it might provide another alternative arrangement of the CFST column design looking at safety and economic aspects.

Fire resistance design studies are required due to the several restrictions in the design guide available in the literature. Due to the uniqueness of standard fire tests, there is the need for more studies on standard fire tests of CFST column filled with light weight foamed concrete which is not covered in the current design guide (NRCC and Eurocode).

The performance-based design approach using ABAQUS software can be used for modelling thermal and mechanical responses of the CFST column to a more realistic fire exposure. As such, modelling the CFST column filled with light-weight foamed concrete using ABAQUS software can depict its behaviour when exposed to fire.

Acknowledgement

This research is supported by FRGS grant, 4F763 from Ministry of Higher Education (MOHE) and GUP grant 17H53 from Universiti Teknologi Malaysia. The supports are gratefully acknowledged.

References

[1] FEMA. 2002. World Trade Center Building Performance Study: Data Collection, Preliminary Observation, and Recommendations. Federal Emergencu Management Agency (FEMA), Federal Insurance and Mitigation Administration, Washington, DC.

[2] Beitel, J. J. & Iwankiw, N. R. 2006. Historical Survey of Multi-story Building Collapse Due to Fire. White Papers of Jensen Hughes. Retrieved on 28 April 2016 from http://www.jensenhughes.com/wp-content/uploads/2014/02/White_Paper_Historical_Survey_Building_Collapse_NIST_JBeitel-NIwankiw_OCT-2006.pdf.

[3] Scott, D., Lane, B. and Gibbons, C. Fire Induced Progressive Collapse. *Proceedings of the Workshop on Prevention of Progressive Collapse, Multihazard Mitigation Council of the National Institute of Building Sciences, Rosemont, Il, July 10-12, 2002*. Retrieved on 28 April 2014 from https://c.ymcdn.com/sites/www.nibs.org/resource/resmgr/MMC/wppc_scott_paper.pdf.

[4] L. Twilt, R. Hass, W. Klingsch, M. Edwards, and D. Dutta. 1994. *Design Guide for Structural Hollow Section Columns Exposed to Fire*. Verlag TUV Rheinland GmbH, CIDECT, Koln Germany. 16-18.

[5] Hung, W. Y. and Chow, W. K. 2002. Review on the Requirements on Fire Resisting Construction. *International Journal of Engineering Performance-based Fire Codes*. 4(3): 68-83.

[6] Barry, C. 2007. Fire Inside: Structural Design with Fire Safety in Mind. *Science News*. 172: 122-124.

[7] Petterson. O., Magnusson. S. and Thor. J. 1976. Fire Engineering of Steel Structures. Publication 50, Swedish Institute of Steel Construction, Stockholm.

[8] Kodur, V., Garlock, M. and Iwankiw, Nestor. 2007. National Workshop on Structures in Fire: State-of-the-Art, Research and Training Needs. Grant Report: CEE-RR-2007/03, Department of Civil and Environmental Engineering, Michigan State University, East Lansing, Michigan.

[9] Iwankiw, N., Beyler, C. 2016. New Standards for Engineering Design of Structural Fire Protection. SFPE Fire Protection Engineering eNewsletter, Issue 79. Retrieved on 9 May 2016 from http://www.sfpe.org/page/FPE_ET_Issue_79/New-Standards-for-Engineering-Design-of-Structural-Fire-Protection.htm.

[10] Morris, W. A., Read, R. E. H and Cooke, G. M. E. 1988. *Guidelines for the Construction of Fire-resisting Structural Elements*. Building Research Establishment, UK.

[11] Kirby, B. R. 1998. The Behavior of a Multi-storey Steel Framed Building Subjected to Fire Attack. British Steel plc, Swinden Technology Centre, UK.

[12] NFPA. 2006. Standard Methods of Tests of Fire Resistance of Building Construction and Materials. Batterymarch Park, Quincy, MA, US. NFPA 251.

[13] NFPA. 2015. Standard on Types of Building Construction. Batterymarch Park, Quincy, MA. NFPA 220.

[14] NFPA. 2015. Building Construction and Safety Code. Batterymarch Park, Quincy, MA. NFPA 5000.

[15] NFPA. 2006. Standard Method of Test of Surface Burning Characteristics of Building Materials. Batterymarch Park, Quincy, MA. NFPA 255.

[16] NFPA. 2013. Standard Test Method for Potential Heat of Building Materials. Batterymarch Park, Quincy, MA. NFPA 259.

[17] British Standard Institute. 2009. BS 476: Fire Tests on Building Materials and Structures – Part 10: Guide to the Principles, Selection, Role and Application of Fire Testing and Their Outputs. London:BSI. BS476-10.

[18] British Standard Institute. 1987. BS 476: Fire Tests on Building Materials and Structures – Part 20: Method for Determination of the Fire Resistance of Elements of Construction (General Principles). London:BSI. BS476-20.

[19] British Standard Institute. 1987. BS 476: Fire Tests on Building Materials and Structures – Part 21: Methods for Determination of the Fire Resistance of Loadbearing Elements of Construction. London:BSI. BS476-21.

[20] British Standard Institute. 1987. BS 476: Fire Tests on Building Materials and Structures – Part 22: Methods for Determination of the Fire Resistance of Non-Loadbearing Elements of Construction. London:BSI. BS476-22.

[21] British Standard Institute. 1987. BS 476: Fire Tests on Building Materials and Structures – Part 23: Methods for Determination of the Contribution of Components to the Fire Resistance of a Structure. London:BSI. BS476-23.

[22] British Standard Institute. 2012. BS EN1363 - Fire Resistance Tests: Part 1: General Requirements. London:BSI. BS EN1363-1.

[23] British Standard Institute. 1999. BS EN1363 - Fire Resistance Tests: Part 2: Alternative and Additional Procedures. London:BSI. BS EN1363-2.

[24] British Standard Institute. 2014. BS EN13381 – Test Methods for Determining the Contribution to the Fire Resistance of Structural Members – Part 1: Horizontal Protective Membranes. London:BSI. BS EN13381-1.

[25] British Standard Institute. 2014. BS EN13381 – Test Methods for Determining the Contribution to the Fire Resistance of

Structural Members – Part 2: Vertical Protective Membranes. London:BSI. BS EN13381-2.

[26] British Standard Institute. 2015. BS EN13381 – Test Methods for Determining the Contribution to the Fire Resistance of Structural Members – Part 3: Applied Protection to Concrete Members. London:BSI. BS EN13381-3.

[27] British Standard Institute. 2013. BS EN13381 – Test Methods for Determining the Contribution to the Fire Resistance of Structural Members – Part 4: Applied Passive Protection to Steel Members. London:BSI. BS EN13381-4.

[28] British Standard Institute. 2014. BS EN13381 – Test Methods for Determining the Contribution to the Fire Resistance of Structural Members – Part 5: Applied Protection to Concrete/Profiled Sheet Steel Composite Member. London:BSI. BS EN13381-5.

[29] British Standard Institute. 2012. BS EN13381 – Test Methods for Determining the Contribution to the Fire Resistance of Structural Members – Part 6: Applied Protection to Concrete Filled Hollow Steel Columns. London:BSI. BS EN13381-6.

[30] British Standard Institute. 2002. Draft for Development ENV13381 – Test Methods for Determining the Contribution to the Fire Resistance of Structural Members – Part 7: Applied Protection to Timber Members. London:BSI. DD ENV13381-7.

[31] British Standard Institute. 2013. BS EN13381 – Test Methods for Determining the Contribution to the Fire Resistance of Structural Members – Part 8: Applied Reactive Protection to Steel Members. London:BSI. BS EN13381-8.

[32] British Standard Institute. 2015. BS EN13381 – Test Methods for Determining the Contribution to the Fire Resistance of Structural Members – Part 9: Applied Fire Protection Systems to Steel Beams With Web Openings. London:BSI. BS EN13381-9.

[33] International Organization for Standardization. 1999. ISO834 – Fire Resistance Tests – Elements of Building Construction – Part 1: General Requirements. Geneva:ISO. ISO834-1.

[34] International Organization for Standardization. 2000. ISO834 – Fire Resistance Tests – Elements of Building Construction – Part 4: Specific Requirements For Loadbearing Vertical Separating Elements. Geneva:ISO. ISO834-4.

[35] International Organization for Standardization. 2000. ISO834 – Fire resistance Tests – Elements of Building Construction – Part 5: Specific Requirements for Loadbearing Horizontal Separating Elements. Geneva:ISO. ISO834-5.

[36] International Organization for Standardization. 2000. ISO834 – Fire Resistance Tests – Elements of Building Construction – Part 6: Specific Requirements for Beams. Geneva:ISO. ISO834-6.

[37] International Organization for Standardization. 2000. ISO834 – Fire Resistance Tests – Elements of Building Construction – Part 7: Specific Requirements for Columns. Geneva:ISO. ISO834-7.

[38] International Organization for Standardization. 2014. ISO834 – Fire Resistance Tests – Elements of Building Construction – Part 10: Specific Requirements to Determine the Contribution of Applied Fire Protection Materials to Structural Steel Elements. Geneva:ISO. ISO834-10.

[39] International Organization for Standardization. 2014. ISO834 – Fire Resistance Tests – Elements of Building Construction – Part 11: Specific Requirements for the Assessment of Fire Protection to Structural Steel Elements. Geneva:ISO. ISO834-11.

[40] Australia Standard Committee. 2005. AS1530 – Methods for Fire Tests on Building Materials, Components and Structures – Part 4: Fire-Resistance Test of Elements of Construction. Sydney:ASC. AS1530-4.

[41] Standard & Industrial Research Institute of Malaysia. 1996. MS1073 – Method for Determination of the Fire Resistance – Part 2: General Principle. Malaysia:SIRIM. MS1073-2.

[42] Bureau of Indian Standards. 1979, Reaffirmed in 2002. IS3809 – Fire Resistance Test of Structures. New Delhi:BIS. IS3809.

[43] American National Standards Institute. 2011. UL263 – Standard for Fire Tests of Building Construction and Materials. North America:ANSI. UL263.

[44] Rackliffe, C. A. (996. Performance-based Building Codes: The United Kingdom Experience. International Conference on Performance-based Codes and Fire Safety Design Methods, Sept. 24-26, Ottawa, Ontario, Canada, SFPE, Boston, MA.

[45] Hunt, J. H. 1996. Performance-based Codes: The New Zealand Experience. International Conference on Performance-based Codes and Fire Safety Design Methods, Sept. 24-26, Ottawa, Ontario, Canada, SFPE, Boston, MA.

[46] Johnsson, Rand Rantatalo, T. 1996. Performance-based Codes: The Swedish Experience. International Conference on Performance-based Codes and Fire Safety Design Methods, Sept. 24-26, Ottawa, Ontario, Canada, SFPE, Boston, MA.

[47] Bowen, N. 1996. The Performance Building Code of Australia. A Study of its Development. International Conference on performance-based Codes and Fire Safety Design Methods, Sept. 24-26, Ottawa, Ontario, Canada, SFPE, Boston, MA.

[48] Thomas, R and Bowen, R. 1996. Objective-based Codes: The Canadian Direction. *International Conference on Performance-based Codes and Fire Safety Design Methods, Sept. 24-26, Ottawa, Ontario, Canada, SFPE, Boston, MA*.

[49] Nakaya, I and Hirano, Y. 1996. Japan's Approach toward the Building Code and Standards. *International Conference on Performance-based Codes and Fire Safety Design Methods, Sept. 24-26, Ottawa, Ontario, Canada, SFPE, Boston, MA*.

[50] Traw, J. S. 1996. Future Prospective of the U.S. Model Building Codes. *International Conference on Performance-based Codes and Fire Safety Design Methods, Sept. 24-26, Ottawa, Ontario, Canada, SFPE, Boston, MA*.

[51] Bukowski, R. W. 1995. International Activities for Developing Performance-based Fire Codes. Fire Safety Design of Buildings and Fire Safety Engineering. *Proceedings of the Mini-Symposium June 12, Tsukuba Japan, Building Research Institute, MOC Japan*. 25-27.

[52] ASTM. 2016. E119 - Standard Test Methods for Fire Tests of Building Construction and Materials. ASTM International, West Conshohocken, PA. ASTM E119.

[53] Beyler C, Beitel J., Iwankiw N., and Lattimer B. 2007. Fire Resistance Testing for Performance-based Fire Design of Buildings. Final Report for the Fire Protection Research Foundation, USA. HAI Project # 2843-000.

[54] British Standard Institute. 2003. PD 7974 - Application of Fire Safety Engineering Principles to the Design of Buildings – Part 1: Initiation and Development of Fire within the Enclosure of Origin (Sub-system 1). London:BSI. PD7974-1.

[55] British Standard Institute. 2002. BS EN1991 Eurocode 1: Actions on Structures – Part 1.2: General Actions - Actions on the structures exposed to fire. London:BSI. BS EN1991-1-2.

[56] Australia Building Codes Board (ABCB). 2016. National Construction Code: Building Code of Australia – Class 2 to Class 0 Buildings. Canberra, Australia: ABCB.

[57] Department of Building and Housing. 2005. Building Regulations 2004. Wellington, New Zealand: DBH.

[58] National Research Council Canada. 2010. National Building Code of Canada. Canada: NRCC.

[59] The Building Center of Japan (BCJ). 2015. The Building Standard Law of Japan. Japan: BCJ.

[60] L. Twilt, R. Hass, W. Klingsch, M. Edwards and D. Dutta, 1996. Design Guide for Structural Hollow Sections Exposed to Fire, second edition. Germany:CIDECT Publications.

[61] X.L. Zhao, L.H. Han and H. Lu. 2010. *Concrete-filled Tubular Members and Connections*. Taylor & Francis.

[62] Wardenier, J. J. A. Packer, X.-L. Zhao and G.J. van der Vegte. 2010. Hollow Sections in Structural Applications. Netherlands: CIDECT.

[63] Capilla, A. E. 2012. Numerical Analysis of the Fire Resistance of Circular and Elliptical Slender Concrete Filled Tubular Columns. PhD thesis. Valencia, Spain: Universitat Politecnica de Valencia.

[64] Ikeda, K. and Y. Ohmiya. 2009. Fire Safety Engineering of Concrete-Filled Steel Tubular Column without Protection. *Fire Science and Technology*. 28 (3): 106-131.

[65] Kodur, V.K.R. and D.H. MacKinnon. 2000. Design of Concrete-Filled Hollow Structural Steel Columns for Fire Endurance. *Engineering Journal.* 37(1): 13-24.

[66] Hicks, S. J. and G. M. Newman. 2002. Design Guide for Concrete Filled Columns. Berkshire:CORUS Tubes and Steel Construction Institute.

[67] Schneider, S. P. 1998. Axially Loaded Concrete-filled Steel Tubes. *Journal of Structural Engineering.* 124(10): 1125–1138.

[68] Huang, C. S., Yeh, Y. K., Hu, H. T., Tsai, K. C., Weng, Y. T., Wang, S. H. 2002. Axial Load Behavior of Stiffened Concrete-filled Steel Columns. *Journal of Structural Engineering.* 128(9): 1222-1230.

[69] Sakino, K., Nakahara, H., Morino, S., Nishiyama, I. 2004. Behavior of Centrally Loaded Concrete-filled Steel-Tube Short Columns. *Journal of Structural Engineering.* 130(2): 180-188.

[70] Giakoumelis, G., and Lam, D. 2004. Axial Capacity of Circular Concrete-filled Tube Columns. *Journal of Constructional Steel Research.* 60(7): 1049-1068.

[71] Han, L. H, Liu, W., Yang, Y. F. 2008. Behaviour of Concrete-filled Steel Tubular Stub Columns Subjected to Axially Local Compression. *Journal of Constructional Steel Research.* 64(4): 377-387.

[72] Ellobody, E. Ghazy, M. F. 2012. Tests and Design of Stainless Steel Tubular Columns Filled with Polypropylene Fibre Reinforced Concrete. *Proceedings of the 10th International Conference on Advances in Steel Concrete Composite and Hybrid Structures, ASCCS. Singapore, 2–4 July, 2012.*

[73] Young B. and Ellobody E. 2006. Experimental Investigation of Concrete-filled Cold-formed High Strength Stainless Steel Tube Columns. *Journal of Constructional Steel Research.* 62(5): 484-492.

[74] Lam D., Gardner L. 2008. Structural Design of Stainless Steel Concrete Filled Columns. *Journal of Constructional Steel Research*. 64(11): 1275-1282.

[75] Ghannam, S.; Al-Ani, H, R.; Al-Rawi, O. 2010. Comparative Study of Load Carrying of Steel Tube Columns Filled with Light Weight Concrete and Normal Concrete. *Jordan Journal of Civil Engineering.* 4(2): 164-169.

[76] Lie, T. T., R. J. Irwin, and M. Chabot. 1991. Factors Affecting the Fire Resistance of Circular Hollow Steel Columns Filled with Plain Concrete. IRC Internal Report 612. National Research Council of Canada.

[77] Lie, T. T. and M. Chabot. 1992. Experimental Studies on the Fire Resistance of Hollow Steel Columns Filled with Plain Concrete. National Research Council Canada. 1992. Internal Report No. 611.

[78] Lie, T. T. and Chabot, M. 1990. A Method to Predict the Fire Resistance of Circular Concrete Filled Hollow Steel Columns. *Journal of Fire Protection Engineering*. 2(4): 111-126.

[79] Lie, T. T., Irwin, R. J. 1995. Fire Resistance of Rectangular Steel Columns Filled with Bar Reinforced Concrete. *Journal of Structural Engineering.* 121(5): 797-805.

[80] Kodur, V. K. R. and T. T. Lie. 1995. Experimental Studies on the Fire Resistance of Circular Hollow Steel Columns Filled with Steel-Fibre-Reinforced Concrete. National Research Council Canada. Internal Report No. 691.

[81] Kodur, V. K. R., and Lie, T. T. 1996. Fire Resistance Of Circular Steel Columns Filled With Fiber-Reinforced Concrete. *Journal of Structural Engineering, ASCE*. 776-782.

[82] Yin, J., Zha, X. X., Li L. Y. 2006. Fire Resistance of Axially Loaded Concrete Filled Steel Tube Columns. *Journal of Constructional Steel Research.* 62(7): 723-729.

[83] Han, L. H., Yang, Y.F., Xu, L. 2003. An Experimental Study and Calculation on the Fire Resistance of Concrete-filled Square Hollow and Round Hollow Columns. *Journal of Construction Steel Research.* 59(4): 427-452.

[84] Espinos, A., M. L. Romero, A. Hospitaler, C. Ibanez & A. Pascual. 2012. An Experimental Study of the Fire Behavior of Slender Concrete Filled Circular Hollow Section Columns. *Proceedings of the 14th International Symposium on tubular structures, London, UK*. 583-590.

[85] Manuel, L. Romero, V. Moliner, A. Espinos, C. Ibanez, A. Hospitaler. 2011. Fire Behavior of Axially Loaded Slender High Strength Concrete-filled Tubular Columns. *Journal of Constructional Steel Research.* 67(12): 1953-1965.

[86] Franssen, J. M. 2005. SAFIR: A Thermal/Structural Program for Modeling Structures Under Fire. *Engineering Journal-American Institute of Steel Construction.* 42(3): 143-158.

[87] Dai X. H. & D. Lam. 2012. Shape Effect on Structural Fire Behaviour of Axially Loaded Concrete Filled Tubular (CFT) Stub Columns. *Proceedings of the 14th international Symposium on Tubular Structures, London, UK, 12–14 September 2012.*

[88] Chen Shiming and Zhang Huifeng. 2012. Numerical Analysis of the Axially Loaded Concrete Filled Steel Tube Columns with De-Bonding Separation at the Steel-Concrete Interface. *Steel and Composite Structures*. 13(3): 277-293.

[89] Z. Yang, Y. Zhang, M. Chen, G. Chen. 2013. Numerical Simulation of Ultra-strength Concrete-filled Steel Columns. *Engineering Review*. 33(3): 211-217.

[90] Kodur, V. R. 1999. Performance-based Fire Resistance Design of Concrete-filled Steel Columns. *Journal of Constructional Steel Research.* 51(1): 21-36.

[91] British Standard Institute. 2005. BS EN 1994 - Design of Composite Steel and Concrete Structures - Part 1-2: General Rules - Structural Fire Design. London, BS EN 1994-1-2.

[92] Ding, J. and Y. C. Wang. 2008. Realistic Modelling of Thermal and Structural Behaviour of Unprotected Concrete Filled Tubular Columns in Fire. *Journal of Constructional Steel Research.* 64(10): 1086-1102.

[93] Schaumann, P., Kodur V. and Bahr O. 2009. Fire Behaviour of Hollow Structural Section Steel Columns Filled with High Strength Concrete. *Journal of Constructional Steel Research*. 65(8-9): 1794-1802.

[94] Chu, T. B. 2009. Hollow Steel Section Columns filled with Self-Compacting Concrete under Ordinary and Fire Conditions. Ph.D. University de Liege.

[95] Song, T.Y., Han L. H. and Yu H. X. 2010. Concrete Filled Steel Tube Stub Columns under Combined Temperature and Loading. *Journal of Constructional Steel Research.* 66(3): 369-384.

[96] Espinos, A., Romero M. L. and Hospitaler A. 2010. Advanced Model for Predicting the Fire Response of Concrete Filled Tubular Columns. *Journal of Constructional Steel Research.* 66(8-9): 1030-1046.

[97] Espinos, A., Gardner L., Romero M. L. and Hospitaler A. 2011. Fire Behaviour of Concrete Filled Elliptical Steel Columns. *Thin-Walled Structures.* 49(2): 239-255.

[98] McGranttan, K. B., Klein B., Hostikka S. and Floyd J. 2002. Fire Dynamic Simulator (Version 5) User's Guide.User's guide. 3rd ed. Washington, National Institute of Standards and Technology.

[99] Hong, S. 2007. Fundamental Behaviour and Stability of CFT Columns under Fire Loading. PhD thesis. Purdue University.

[100] Hong, S. and A. H. Varma. 2009. Analytical Modelling of the Standard Fire Behavior of Loaded CFT Columns. *Journal of Constructional Steel Research*. 65(1): 54-69.

[101] Chen, T. L. September 2006. Report on Position Paper on Safety against Fire in Buildings. In Jurutera: An Elevated

View Of The KL Tower Surroundings. *Bulletin of Institute Engineers Malaysia, IEM.* 42.

[102] David Rush. 2013. Fire Performance of Unprotected and Protected Concrete Filled Steel Hollow Structural Sections. PhD thesis University of Edinburgh. 25-27.

[103] SIRIM QAS International. Fire Testing. Retrieved on 31 August 2016, from http://www.sirim-qas.com.my/index.php/en/our-services/product-testing/fire-protection-testing.

[104] Shah M. F. Fire-testing Lab at UTM Can Test Various Kinds of Fire-Proof Materials. The Star Online News. 24 April 2014. Retrieved on 31 August 2016, from http://www.thestar.com.my/news/community/2014/04/24/boost-for-construction-firetesting-lab-at-utm-can-test-various-kinds-of-fireproof-materials/.