

BEHAVIOUR OF FOAMED CONCRETE-FILLED STEEL HOLLOW COLUMN
UNDER FIRE

BISHIR KADO

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Civil Engineering)

School of Civil Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

MARCH 2019

ACKNOWLEDGEMENT

All praise be to Almighty Allah the Beneficent the Merciful. His favour, guidance, and blessing enabled me to successfully complete this research.

My profound gratitude goes to my main Supervisor, Prof. Dr. Shahrin Mohammad for his guidance, suggestions, and encouragement toward improving the quality of this research work. Your patience, support, and kindness are really worthy of appreciation. You have been a wonderful and exceptional mentor. Similarly, I would like to express my appreciation to my co-supervisors, Dr. Mariyana Aida Ab Kadir and Dr. Shek Poi Ngian for their valuable contributions and constructive advice during this study. I would also want to extend my appreciation to the Ministry of Higher Education, Malaysia by providing research grant through the Fundamental Research Grant Scheme FRGS (No. 4F763) to support this research. I am also very grateful to all technical staff of structures and materials and Fire laboratory, School of Civil Engineering, Faculty of Engineering, UTM.

I am sincerely grateful to my Mother for her consistent prayers, care, sacrifice and moral support throughout my life. I also acknowledge and appreciate my brothers and sisters; Sani Kado, Haruna Kado, Zaliha Kado, Mansir Kado, Maryam Kado, Yusuf Kado, Abbas Kado and Suleiman Kado. My appreciation goes to my Wife and Children for their support and patience during this study. The same goes to my friends for their prayers during the research period.

Finally, my special thanks to my employer Bayero University, Kano Nigeria for the assistance rendered during the study period.

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 1500 kg/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 berbuisa boleh menjadi bahan alternatif yang bermanfaat dan inovatif. Oleh itu, kajian ini mengkaji potensi penggunaan konkrit berbuisa dalam tiang keluli bulat berongga terbentuk-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 berbuisa (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 berbuisa 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/m³ dan 1500 kg/m³ kepadatan konkrit berbuisa, masing-masing pada tahap beban 15%. Perbandingan antara beban lengkokan paksi antara ujikaji dan penggunaan Eurocode 4 mendapati bahawa tiang yang dipenuhi dengan kepadatan konkrit berbuisa 1500 kg/m³ 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 terganggu 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 berbuisa berupaya meningkatkan rintangan kebakaran bagi ruang kosong keluli. Tiang FCFHS boleh digunakan untuk struktur yang memerlukan masa rintangan api sederhana.

TABLE OF CONTENTS

| | TITLE | PAGE |
|------------------|---|--------------|
| | DECLARATION | i |
| | DEDICATION | ii |
| | ACKNOWLEDGEMENT | iii |
| | ABSTRACT | iv |
| | ABSTRAK | v |
| | TABLE OF CONTENTS | vi |
| | LIST OF TABLES | x |
| | LIST OF FIGURES | xii |
| | LIST OF ABBREVIATIONS | xviii |
| | LIST OF SYMBOLS | xix |
| | LIST OF APPENDICES | xxi |
| CHAPTER 1 | INTRODUCTION | 1 |
| 1.1 | Background | 1 |
| 1.1.1 | Advantages of CFST Columns | 3 |
| 1.1.2 | Practical Applications of CFST Columns | 4 |
| 1.2 | Statement of the Problem | 9 |
| 1.3 | Objectives | 10 |
| 1.4 | Scope of the Study | 10 |
| 1.5 | Significance of the Study | 11 |
| 1.6 | Thesis Content | 12 |
| CHAPTER 2 | LITERATURE REVIEW | 15 |
| 2.1 | General | 15 |
| 2.2 | Material Properties at Ambient Temperature | 16 |
| 2.2.1 | Steel | 16 |
| 2.2.2 | Foamed Concrete | 17 |
| 2.3 | Material Properties at Elevated Temperature | 21 |

| | | |
|------------------|---|-----------|
| 2.3.1 | Steel | 21 |
| 2.3.1.1 | Thermal Properties | 21 |
| 2.3.1.2 | Mechanical Properties | 22 |
| 2.3.2 | Foamed Concrete | 24 |
| 2.3.2.1 | Thermal Properties | 24 |
| 2.3.2.2 | Mechanical Properties | 26 |
| 2.4 | Experimental Works on Foamed Concrete and Light-weight Aggregate Concrete-filled Steel Tube Column at Ambient Temperature | 28 |
| 2.5 | Experimental Works on Concrete-filled Steel Tube Column at an Elevated Temperature | 32 |
| 2.6 | Numerical Studies on Concrete-filled Steel Tube Column at an Elevated Temperature | 39 |
| 2.7 | Existing Design Guides for Fire Resistance of Concrete-filled Steel Tube Column | 42 |
| 2.7.1 | Kodur's Model | 42 |
| 2.7.2 | Eurocode 4 Model | 44 |
| 2.7.2.1 | Axially Loaded CFST Columns | 46 |
| 2.7.2.2 | Eccentrically Loaded Columns | 49 |
| 2.8 | Behaviour of CFST Columns in Fire | 50 |
| 2.9 | Conclusion | 53 |
| CHAPTER 3 | METHODOLOGY | 55 |
| 3.1 | General | 55 |
| 3.2 | Experimental Program | 56 |
| 3.2.1 | Material Properties Test at Ambient Temperature | 57 |
| 3.2.1.1 | Steel | 57 |
| 3.2.1.2 | Foamed Concrete | 58 |
| 3.2.2 | Specimens Preparation | 61 |
| 3.2.3 | Experimental Setup and Procedures | 66 |
| 3.3 | Numerical Analysis Program | 72 |
| 3.3.1 | Geometry and Finite Element Mesh of the Model | 72 |

| | | |
|------------------|---|-----------|
| 3.3.2 | Material Properties at Elevated Temperatures | 76 |
| 3.3.2.1 | Thermal Properties | 76 |
| 3.3.2.2 | Mechanical Properties | 81 |
| 3.3.3 | Analysis Procedure | 87 |
| 3.3.3.1 | Buckling Analysis | 89 |
| 3.3.3.2 | Thermal Analysis | 92 |
| 3.3.3.3 | Structural Analysis | 96 |
| 3.4 | Conclusion | 98 |
| CHAPTER 4 | EXPERIMENTAL RESULTS AND DISCUSSION | 99 |
| 4.1 | General | 99 |
| 4.2 | Material Properties Test Results at Ambient Temperature | 99 |
| 4.2.1 | Steel | 100 |
| 4.2.2 | Foamed Concrete Properties | 101 |
| 4.3 | Temperature Development Based on Experimental Results | 101 |
| 4.3.1 | Steel Hollow Columns | 102 |
| 4.3.2 | FCFHS Columns Filled with 1800 kg/m ³ of Foamed Concrete | 104 |
| 4.3.3 | FCFHS Columns Filled with 1500 kg/m ³ of Foamed Concrete | 106 |
| 4.3.4 | Critical Temperature | 109 |
| 4.4 | Axial Deformations Results | 113 |
| 4.4.1 | Axial Deformation of Hollow Steel Columns | 113 |
| 4.4.2 | Axial Deformation of FCFHS Columns | 116 |
| 4.5 | Failure Modes | 120 |
| 4.6 | Discussion of Results | 125 |
| 4.6.1 | Effect of Load Level | 125 |
| 4.6.2 | Effect of Foamed Concrete Filling | 128 |
| 4.6.3 | Fire Concrete Contribution Ratio (FCCR) | 131 |
| 4.7 | Comparison with Existing Design Models | 133 |
| 4.8 | Concluding Remarks | 136 |

| | | |
|-----------------------------|--|------------|
| CHAPTER 5 | NUMERICAL ANALYSIS RESULTS AND | |
| DISCUSSION | 137 | |
| 5.1 | General | 137 |
| 5.2 | Sensitivity Analysis | 137 |
| 5.2.1 | Gap Thermal Conductance at Steel-concrete Interface | 138 |
| 5.2.2 | Friction contact at Steel-concrete interface | 140 |
| 5.2.3 | Initial Geometric Imperfection | 142 |
| 5.2.4 | Findings from Sensitivity Analysis | 144 |
| 5.3 | Numerical Model Validation | 145 |
| 5.3.1 | Thermal Analysis | 145 |
| 5.3.2 | Structural Analysis | 152 |
| 5.4 | Parametric Studies | 160 |
| 5.4.1 | Effect of Column Diameter | 161 |
| 5.4.2 | Effect of Steel Tube Thickness | 165 |
| 5.4.3 | Effect of Load Level | 172 |
| 5.4.4 | Effect of Column Length | 176 |
| 5.5 | Proposed Fire Resistance Design Guide for FCFHS column | 183 |
| 5.6 | Concluding Remarks | 185 |
| CHAPTER 6 | CONCLUSION AND RECOMMENDATIONS | 187 |
| 6.1 | General | 187 |
| 6.2 | Conclusions | 188 |
| 6.2.1 | Material Properties | 189 |
| 6.2.2 | Fire Resistance Test | 189 |
| 6.2.3 | Numerical Modeling | 190 |
| 6.2.4 | Parametric Studies | 190 |
| 6.3 | Recommendations for Future Work | 191 |
| REFERENCES | | 192 |
| LIST OF PUBLICATIONS | | 221 |

LIST OF TABLES

| TABLE NO. | TITLE | PAGE |
|-----------|---|------|
| Table 1.1 | High rise buildings built with CFST columns | 5 |
| Table 2.1 | Classification of light-weight concrete based on concrete properties | 18 |
| Table 2.2 | Foamed concrete applications based on its density | 20 |
| Table 2.3 | Details of Specimens tested at National Research Council, Canada (NRCC) (Rush <i>et al.</i> , 2011) | 34 |
| Table 2.4 | Limitations of Kodur's Equation model (Kodur, 1999) | 44 |
| Table 2.5 | Details of specimens used for evaluation of Eurocode 4 Model | 45 |
| Table 2.6 | Limitations of Eurocode 4 Model | 46 |
| Table 3.1 | Foamed concrete mix details | 59 |
| Table 3.2 | Specimen details | 66 |
| Table 3.3 | Boundary conditions used for the Simulation | 75 |
| Table 3.4 | Mathematical relationship for stress-strain of steel at elevated temperatures (BS EN1993-1-2,2005) | 82 |
| Table 4.1 | Average characteristics properties of steel | 101 |
| Table 4.2 | Average characteristic properties of foamed concrete | 101 |
| Table 4.3 | Steel and foamed concrete measured critical temperatures | 110 |
| Table 4.4 | Comparison of steel critical temperatures between design calculations and test results | 111 |
| Table 4.5 | Fire concrete contribution ratio (FCCR) | 132 |
| Table 4.6 | Axial buckling load comparison | 135 |
| Table 5.1 | Comparison between test and numerical critical temperatures | 151 |
| Table 5.2 | Measured and predicted Fire resistance ratings and maximum axial displacements | 156 |
| Table 5.3 | Applied loads used in the parametric analysis | 161 |
| Table 5.4 | Summary of findings from parametric analysis carried out | 182 |

| | | |
|-----------|--|-----|
| Table 5.5 | Comparison between test, finite element analysis and proposed equation results for fire resistance time. | 184 |
| Table 5.6 | Limitation for the application of proposed Equation 5.1 | 185 |

LIST OF FIGURES

| FIGURE NO. | TITLE | PAGE |
|-------------------|---|-------------|
| Figure 1.1 | Failure modes of hollow steel tube, concrete and CFST stub columns (Han et al., 2014) | 3 |
| Figure 1.2 | Abeno Harukas (Osaka, Japan) (Mizutani et al., 2015) | 6 |
| Figure 1.3 | Fleet place House, London (Hicks and Newman, 2002) | 6 |
| Figure 1.4 | Montevetro apartment block London (Hicks and Newman, 2002) | 7 |
| Figure 1.5 | Peckham Library London (Usach, 2015) | 8 |
| Figure 1.6 | Wangcang East river bridge China | 8 |
| Figure 2.1 | Elevated temperature stress-strain for structural steel at 20°C and 600 °C (Kodur et al., 2010) | 23 |
| Figure 2.2 | Thermal conductivity of lightweight concrete against temperature | 25 |
| Figure 2.3 | Comparison between average experimental stress-strain relationships and the predicted results for 1000 kg/m ³ foamed concrete (Mydin and Wang, 2012a). | 27 |
| Figure 2.4 | Comparison between average experimental stress-strain relationships and the predicted results for 1400 kg/m ³ foamed concrete (Mydin and Wang, 2012a). | 28 |
| Figure 2.5 | Comparison for axial displacement with time for hollow structural steel column filled with three types of concrete (Kodur, 1997) | 35 |
| Figure 2.6 | buckling curves (BS EN1993-1-1, 2005) | 48 |
| Figure 2.7 | Axial displacements against time for CFST columns (Espinosa et al., 2010) | 51 |
| Figure 2.8 | Axial displacements against time for CFST columns filled with plain concrete (Romero <i>et al.</i> , 2011). | 52 |
| Figure 2.9 | Axial displacements against time for CFSST columns filled with plain concrete (Ghannam et al, 2015a). | 52 |
| Figure 3.1 | Tensile coupon samples | 58 |
| Figure 3.2 | Elastic modulus test set-up for foamed concrete cylinders | 59 |
| Figure 3.3 | Splitting tensile test setup and sample teste | 60 |

| | | |
|-------------|---|----|
| Figure 3.4 | Drilling of ventilation holes on steel tube | 61 |
| Figure 3.5 | Foamed concrete casting inside steel tube | 62 |
| Figure 3.6 | Specimen filled with foamed concrete and the thermocouples for concrete attached | 63 |
| Figure 3.7 | Specimens welded with top and bottom plates | 64 |
| Figure 3.8 | Details dimension of the FCFHS column | 65 |
| Figure 3.9 | Test set-up | 67 |
| Figure 3.10 | Column specimens on base inside the furnace | 68 |
| Figure 3.11 | Data logger for thermocouples | 69 |
| Figure 3.12 | Furnace view from the software | 70 |
| Figure 3.13 | Graphical views from the software | 70 |
| Figure 3.14 | Side view of Column furnace with specimen (All dimension in mm) | 71 |
| Figure 3.15 | Components of the Model | 73 |
| Figure 3.16 | Finite Elements types used in the model (ABAQUS 2014) | 74 |
| Figure 3.17 | Finite element meshes of the model components | 75 |
| Figure 3.18 | Thermal conductivity of Structural Steel at elevated temperature (BS EN1994-1-2, 2005) | 78 |
| Figure 3.19 | Specific heat of Structural steel at elevated temperatures (BS EN1994-1-2, 2005) | 78 |
| Figure 3.20 | Thermal conductivities for 1800 and 1500 kg/m ³ foamed concrete at elevated temperatures | 80 |
| Figure 3.21 | Specific heat for 1800 and 1500 kg/m ³ foamed concrete at elevated temperature | 81 |
| Figure 3.22 | Stress-strain curves for S355 steel at elevated temperature (BS EN1993-1-2, 2005) | 83 |
| Figure 3.23 | Stress-strain curves for 1500 kg/m ³ foamed concrete density at elevated temperature | 86 |
| Figure 3.24 | Stress-strain curves for 1800 kg/m ³ foamed concrete density at elevated temperature | 86 |
| Figure 3.25 | Scheme of the analysis procedure used in this study | 88 |
| Figure 3.26 | Shape of initial imperfection of the column | 90 |
| Figure 3.27 | Schematic diagram for (initial imperfection) buckling analysis | 91 |

| | | |
|-------------|---|-----|
| Figure 3.28 | ISO-834 Standard temperature-time curve (ISO-834, 1980) | 92 |
| Figure 3.29 | Temperature distribution for FCFHS1800-15 column | 94 |
| Figure 3.30 | Schematic diagram for thermal analysis | 95 |
| Figure 3.31 | Schematic diagram for Structural analysis | 97 |
| Figure 4.1 | Temperature-time curves for steel hollow columns | 103 |
| Figure 4.2 | Temperature-time curves for 1800 kg/m ³ FCFHS column at 15% load level | 105 |
| Figure 4.3 | Temperature-time curves for 1800 kg/m ³ FCFHS column at 20% load level | 105 |
| Figure 4.4 | Temperature-time curves for 1800 kg/m ³ FCFHS column at 25% load level | 106 |
| Figure 4.5 | Temperature-time curves for 1500 kg/m ³ FCFHS column at 15% load level | 107 |
| Figure 4.6 | Temperature-time curves for 1500 kg/m ³ FCFHS column at 20% load level | 107 |
| Figure 4.7 | Temperature-time curves for 1500 kg/m ³ FCFHS column at 25% load level | 108 |
| Figure 4.8 | Critical steel temperature-load level comparisons | 113 |
| Figure 4.9 | Axial displacements with time for CHS15 Column | 114 |
| Figure 4.10 | Axial displacements with time for CHS20 Column | 115 |
| Figure 4.11 | Axial displacements with time for CHS25 Column | 115 |
| Figure 4.12 | Axial displacements with time for FCFHS1800-15 Column | 117 |
| Figure 4.13 | Axial displacements with time for FCFHS1800-20 Column | 117 |
| Figure 4.14 | Axial displacements with time for FCFHS1800-25 Column | 118 |
| Figure 4.15 | Axial displacements with time for FCFHS1500-15 Column | 118 |
| Figure 4.16 | Axial displacements with time for FCFHS1500-20 Column | 119 |
| Figure 4.17 | Axial displacements with time for FCFHS1500-25 Column | 119 |
| Figure 4.18 | Failed Steel hollow columns showing bucklings | 121 |

| | | |
|-------------|--|-----|
| Figure 4.19 | Failed steel hollow columns | 122 |
| Figure 4.20 | Failed FCFHS column showing outward local buckling | 123 |
| Figure 4.21 | Failed FCFHS columns | 124 |
| Figure 4.22 | Axial deformations with time for steel hollow columns (CHS) | 127 |
| Figure 4.23 | Axial deformations with time for FCFHS1800 columns | 127 |
| Figure 4.24 | Axial deformations with time for FCFHS1500 columns | 128 |
| Figure 4.25 | Axial deformation with time for columns subjected to 15% load level | 129 |
| Figure 4.26 | Axial deformation with time for columns subjected to 20% load level | 130 |
| Figure 4.27 | Axial deformation with time for columns subjected to 25% load level | 130 |
| Figure 4.28 | Comparison between Test and EC4 calculated axial buckling load | 136 |
| Figure 5.1 | Locations of temperature measurement points on column sections | 138 |
| Figure 5.2 | Measured and numerically predicted temperature development comparison at different gap thermal conductance for FCFHS1800-15 Column | 139 |
| Figure 5.3 | Measured and numerically predicted temperature development comparison at different gap thermal conductance for FCFHS1500-15 Column | 140 |
| Figure 5.4 | Measured and numerically predicted axial displacement comparison at different friction contact for FCFHS1800-15 Column | 141 |
| Figure 5.5 | Measured and numerically predicted axial displacement comparison at different friction contact for FCFHS1500-15 Column | 142 |
| Figure 5.6 | Measured and numerically predicted axial displacement comparison at different geometric imperfection for FCFHS1800-15 Column | 143 |
| Figure 5.7 | Measured and numerically predicted axial displacement comparison at different geometric imperfection for FCFHS1500-15 Column | 144 |
| Figure 5.8 | Cross-section showing temperature development on FCFHS columns | 146 |

| | | |
|-------------|---|-----|
| Figure 5.9 | Comparison between measured and predicted temperature developments for FCFHS1800-15 | 148 |
| Figure 5.10 | Comparison between measured and predicted temperature developments for FCFHS1800-20 | 148 |
| Figure 5.11 | Comparison between measured and predicted temperature developments for FCFHS1800-25 | 149 |
| Figure 5.12 | Comparison between measured and predicted temperature developments for FCFHS1500-15 | 149 |
| Figure 5.13 | Comparison between measured and predicted temperature developments for FCFHS1500-20 | 150 |
| Figure 5.14 | Comparison between measured and predicted temperature developments for FCFHS1500-25 | 150 |
| Figure 5.15 | Failed FCFHS columns from numerical analysis | 152 |
| Figure 5.16 | Measured and predicted axial displacements with exposure time for FCFHS1800-15 | 153 |
| Figure 5.17 | Measured and predicted axial displacements with exposure time for FCFHS1800-20 | 154 |
| Figure 5.18 | Measured and predicted axial displacements with exposure time for FCFHS1800-25 | 154 |
| Figure 5.19 | Measured and predicted axial displacements with exposure time for FCFHS1500-15 | 155 |
| Figure 5.20 | Measured and predicted axial displacements with exposure time for FCFHS1500-20 | 155 |
| Figure 5.21 | Measured and predicted axial displacements with exposure time for FCFHS1500-25 | 156 |
| Figure 5.22 | Comparison between measured and predicted fire resistance rating results | 157 |
| Figure 5.23 | Comparison between measured and predicted Maximum axial displacements results | 158 |
| Figure 5.24 | Deformed shape of FCFHS1800-15 column after exposure to fire | 159 |
| Figure 5.25 | Effects of external diameter for FCFHS columns at 20% load level | 163 |
| Figure 5.26 | Effects of external diameter for FCFHS columns at 40% load level | 164 |
| Figure 5.27 | Effects of external diameter for FCFHS columns at 60% load level | 165 |

| | | |
|-------------|--|-----|
| Figure 5.28 | Effects of Steel tube thickness for FCFHS columns with 139.7 mm diameter at 20% load level | 167 |
| Figure 5.29 | Effects of Steel tube thickness for FCFHS columns with 139.7 mm diameter at 40% load level | 168 |
| Figure 5.30 | Effects of Steel tube thickness for FCFHS columns with 219.1 mm diameter at 20% load level | 169 |
| Figure 5.31 | Effects of Steel tube thickness for FCFHS columns with 219.1 mm diameter at 40% load level | 170 |
| Figure 5.32 | Effects of Steel tube thickness for FCFHS columns with 323.9 mm diameter at 20% load level | 171 |
| Figure 5.33 | Effects of Steel tube thickness for FCFHS columns with 323.9 mm diameter at 40% load level | 172 |
| Figure 5.34 | Effects of Load level for FCFHS columns with 139.7 mm diameter | 174 |
| Figure 5.35 | Effects of Load level for FCFHS columns with 219.1 mm diameter | 175 |
| Figure 5.36 | Effects of Load level for FCFHS columns with 323.9 mm diameter | 176 |
| Figure 5.37 | Effects of Column length for FCFHS columns at 20% load level | 179 |
| Figure 5.38 | Effects of Column length for FCFHS columns at 40% load level | 180 |
| Figure 5.39 | Effects of Column length for FCFHS columns at 60% load level | 181 |

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 ($^{\circ}\text{C}$) |
| $f_{y,\theta}$ | - | effective yield strength |
| $\varepsilon_{i,\theta}$ | - | 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_{tn}^{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

| APPENDIX | TITLE | PAGE |
|------------|---|------|
| Appendix A | Section classification | 201 |
| Appendix B | Calculation for design axial resistance20 Error! Bookmark not defined. | |
| Appendix C | Material properties Result at ambient temperature | 205 |
| Appendix D | Calculations for critical temperatures | 208 |
| Appendix E | Detail calculation for axial buckling load from EC4 | 209 |
| Appendix F | Parametric Analysis Results | 217 |
| Appendix G | List of Publications | 221 |

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).

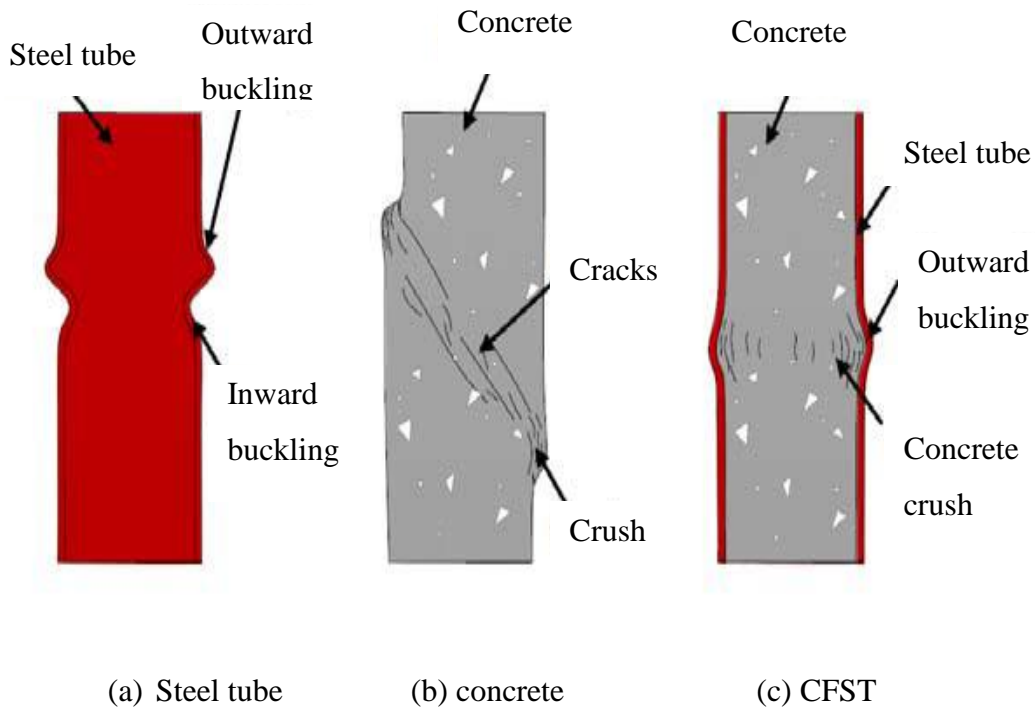


Figure 1.1 Failure modes of hollow steel tube, concrete and CFST stub columns (Han et al., 2014)

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).



Figure 1.4 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.

REFERENCES

- Aini, K., Sari, M., Rahim, A., and Sani, M. (2017) Applications of Foamed Lightweight Concrete. Pp. 1–5 in: *MATEC Web of Conferences 97*.
- Amran, Y.H.M., Farzadnia, N., and Ali, A.A.A. (2015) Properties and applications of foamed concrete; A review. *Construction and Building Materials*, **101**, 990–1005. Elsevier Ltd.
- Aribert, J.M., Renaud, C., and Zhao, B. (2008) Simplified fire design for composite hollow-section columns. *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, **161**, 325–336. ICE Publishing.
- Both, I. (2016) Benchmark studies on composite floors and composite columns subjected to elevated temperature. Pp. 1–95 in: *Support for Applications in Fire Design Universitatea Politehnica Timisoara*.
- BS EN-1994-1-2. (2005) CEN (European Committee for Standardization) Eurocode 4 - Design of composite steel and concrete structures - Part 1-2 General rules - Structural fire design. *Eurocode 4*. .
- BS EN 10002-1. (2001) Metallic materials — Tensile testing — Part 1: Method of test at ambient temperature. British Standard Institution, UK.
- BS EN 12390-13. (2013) Testing hardened concrete. Part 13: Determination of secant modulus of elasticity in compression. BRITISH STANDARDS INSTITUTION, UK.
- BS EN 12390-3. (2009) Testing hardened concrete, Part 3: Compressive strength of test specimens. British Standards Institution, UK. *British Standards Institution*. .
- BS EN 12390-6. (2009) *Testing hardened concrete part 6: Splitting tensile strength*. Brussels.
- BS EN1993-1-1. (2005) Eurocode 3: Design of steel structures- Part 1-1 General rules and rules for buildings. British Standard Institution, UK. <<http://doi.wiley.com/10.1002/9783433601099>>.
- BS EN1993-1-2. (2005) *Eurocode 3. Design of steel structures- Part 1-2: General rules - Structural fire design*. 1-84 pp.
- BS ISO 834-10. (2014) Fire resistance tests — Elements of building construction - Part 10 : Specific requirements to determine the contribution of applied fire

- protection materials to structural steel elements. BSI Standards Publication.
- Capilla, E.A. (2012) Numerical analysis of the fire resistance of circular and elliptical slender concrete filled tubular columns. Universitat Politècnica De Valencia, 402 pp.
- Chan, T., Huai, Y., and Wang, W. (2015) Experimental investigation on lightweight concrete-filled cold-formed elliptical hollow section stub columns. *Journal of Constructional Steel Research*, **115**, 434–444.
- Craveiro, H.D., Rodrigues, J.P.C., Santiago, A., and Laím, L. (2016) Review of the high temperature mechanical and thermal properties of the steels used in cold formed steel structures - The case of the S280 Gd+Z steel. *Thin-Walled Structures*. .
- Dai, X.H. and Lam, D. (2012) Shape effect on the behaviour of axially loaded concrete filled steel tubular stub columns at elevated temperature. *Journal of Constructional Steel Research*, **73**, 117–127.
- DCLG. (2015) Fire Statistics Monitor: England April 2013 to March 2014. *Fire and Rescue Statistical Release*, **14**.
- EN1994-1-1. (2004) *Eurocode 4 : Design of composite steel and concrete structures. Part 1-1 General rules and rules for buildings*.
- Espinos, A., Hospitaler, A., and Romero, M.L. (2009) Fire Resistance of Axially Loaded Slender Concrete Filled Steel Tubular Columns. *Acta polytechnica journal of Advanced engineering*, **49**, 39–43.
- 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**, 1030–46.
- Espinos, A., Gardner, L., Romero, M.L., and Hospitaler, A. (2011) Fire behaviour of concrete filled elliptical steel columns. *Thin-Walled Structures*, **49**, 239–255. Elsevier.
- Espinos, A., Romero, M.L., Hospitaler, A., Ibanez, C., Pascual, A., and Moliner, V. (2012) *Tubular Structures XIV Proceedings of the 14th International symposium on Tubular structures*,. P. in.: CRC PressTaylor and Francis Group, London UK.
- Espinos, A., Romero, M.L., Serra, E., and Hospitaler, A. (2015) Circular and square slender concrete-filled tubular columns under large eccentricities and fire. *Journal of Constructional Steel Research*, **110**, 90–100. Elsevier Ltd.

- Everard, N.J. and Issa, M.A. (2002) Short Column Design.
- Franssen, J.M. (2005) SAFIR: A thermal/structural program for modeling structures under fire. *Engineering Journal*. .
- Franssen, J.M. and Real, P.V. (2012) Fire Design of Steel Structures- European Convention for Constructional Steelwork- ECCS.
- Fu, Z.-Q., Ji, B.-H., Lei, L., and Zhou, W.-J. (2011) Behavior of lightweight aggregate concrete filled steel tubular slender columns under axial compression. *Advanced Steel Construction*, **7**, 144–156.
- Gandhi, U. (2010) Investigation of anisotropy in elastic modulus of steel. P. in: *Presentation - North American Toyota Technical Center*.
- Ghannam, M.M.A. (2015a) Behaviour of Concrete-Filled Stainless Steel Columns Under Fire. University of Western Sydney, Australia, 311 pp.
- Ghannam, S. (2015b) Buckling of Concrete-Filled Steel Tubular Slender Columns. *International Journal of Research in Civil Engineering, Architecture & Design*, **3**, 41–47.
- Ghannam, S., Orabi, A.-R., and El-khatieb, M. (2011) Experimental Study on Light Weight Concrete-Filled Steel Tubes. *Jordan Journal of Civil Engineering*, **5**, 521–529.
- Guo, H., Guo, W., and Shi, Y. (2015) Computational modeling of the mechanical response of lightweight foamed concrete over a wide range of temperatures and strain rates. *Construction and Building Materials*, **96**, 622–631.
- Guo, H., Long, X., and Yao, Y. (2017) Fire resistance of concrete filled steel tube columns subjected to non-uniform heating. *Journal of Constructional Steel Research*, **128**, 542–554. Elsevier Ltd.
- Han, L., Zhao, X., Yang, Y., and Feng, J. (2003) Experimental Study and Calculation of Fire Resistance of Concrete-Filled Hollow Steel Columns. *Journal of Structural Engineering*, **129**, 346–356.
- Han, L.H. and Yang, Y. (2003) An experimental study and calculation on the fire resistance of concrete-filled SHS and RHS columns. *Journal of Constructional Steel Research*, **59**, 427–452.
- Han, L.H., Li, W., and Bjorhovde, R. (2014) Developments and advanced applications of concrete-filled steel tubular (CFST) structures: Members. *Journal of Constructional Steel Research*, **100**, 211–228.
- Haynes, H.J.G. (2017) Fire Loss in the United States During 2016. *National Fire*

- Protection Association*, 1–47.
- Hicks, S.J. and Newman, G.M. (2002) Design guide for SHS concrete filled columns - Structural & Conveyance Business. Corus Tubes.
- Hilal, A. a., Thom, N.H., and R. Dawson, A. (2015a) The Use of Additives to Enhance Properties of Pre- Formed Foamed Concrete. *International Journal of Engineering and Technology*, **7**, 286–293.
- Hilal, A.A., Howard, N., and Robert, A. (2015b) On entrained pore size distribution of foamed concrete. *Construction and Building Materials*, **75**, 227–233. Elsevier Ltd.
- Hong, S. (2007) Fundamental behaviour and stability of CFT columns under fire loading [Dissertation]. 377.
- Hong, S. and Varma, A.H. (2009) Analytical modeling of the standard fire behavior of loaded CFT columns. *Journal of Constructional Steel Research*, **65**, 54–69. Elsevier Ltd.
- Huang, C., Yeh, Y., Liu, G., Hu, H., Tsai, K., Weng, Y., Wang, S., and Wu, M. (2002) Axial Load Behavior of Stiffened Concrete-Filled Steel Columns. *Journal of Structural Engineering*, **128**, 1222–1230.
- Hunaiti, Y.M. (1997) strength of composite sections with foamed and light weight aggregate concrete. *Journal of Materials in Civil Engineering*, **9**, 58–61.
- Hung, W.Y. and Chow, W.K. (2002) Review on the requirements on fire resisting construction. *International Journal on Engineering Performance-Based Fire Codes*, **4**, 68–83.
- ISO. (2014) ISO 834-11:2014(en), Fire resistance tests — Elements of building construction — Part 11: Specific requirements for the assessment of fire protection to structural steel elements. 2016-08-21.
- Joiya, M.I., Doger, M.A., M.Asif, Rasool, T., Ahmad, S., and Hussan, I. (2017) *Columns*. 1-47 pp.
- Kodur, V. (2007) Guidelines for Fire Resistant Design of Concrete-Filled Steel HSS Columns - State-of-the-Art and Research Needs. *steel structures*, **7**, 173–182.
- Kodur, V. and Lie, T.T. (1996a) *Factors Affecting the Fire Resistance of Square Hollow Steel Columns Filled with Bar-Reinforced Concrete - Internal Report No. 650*. 1-44 pp.
- Kodur, V. and Lie, T.T. (1996b) Fire Resistance of Circular Steel Columns Filled with Fiber-Reinforced Concrete. *Journal of Structural Engineering*, **122**, 776–

782. American Society of Civil Engineers.
- Kodur, V. and Lie, T.T. (1997) Fire Resistance of Circular Steel Columns Filled with Fiber-Reinforced Concrete. *Journal of Structural Engineering*, **122**, 776–782.
- Kodur, V., Garlock, M., and Iwankiw, N. (2007) *National Workshop on Structures in Fire : State-of-the-Art , Research and Training Needs*. 63 pp.
- Kodur, V., Dwaikat, M., and Fike, R. (2010) High temperature properties of steel for fire resistance modeling of structures. *Journal of Materials in Civil Engineering*, **22**, 423–434.
- Kodur, V.K.R. (1997) *Fire Resistance of Concrete- Filled Steel Columns*. Ottawa, 1-4 pp.
- Kodur, V.K.R. (1999) Performance-based fire resistance design of concrete-filled steel columns. *Journal of Constructional Steel Research*, **51**, 21–36.
- Kodur, V.K.R. and Lie, T.T. (1995a) *Experimental Studies on the Fire Resistance of Circular Hollow Steel Columns Filled with Steel-Fibre-Reinforced Concrete*. 39 pp.
- Kodur, V.K.R. and Lie, T.T. (1995b) Fire performance of concrete-filled hollow steel columns. *Journal of Fire Protection Engineering*, **7**, 89–97.
- Kodur, V.K.R. and Mackinnon, D.H. (2000) Design of concrete-filled hollow structural steel columns for fire endurance. *Engineering Journal-American Institute of steel construction*, **37**, 13–24.
- Kohno, M. and Okazaki, T. (2013) Performance Based Fire Engineering in Japan. *International Journal of High-Rise Buildings*, **2**, 23–30.
- Lennon, T., Moore, D.B., Wang, Y.C., and Bailey, C.G. (2007) *Designers ' Guides to the Eurocodes Designers ' Guide to EN 1991-1-2 , 1992-1-2 , 1993-1-2 and 1994-1-2 Handbook for the Fire Design of Steel , Composite and Concrete Structures to the Eurocodes*. Eurocodes Designers ' Guide Series. P. in.: Thomas Telford Publishing, Thomas Telford Ltd, 1 Heron Quay, London E14 4JD URL: www.thomastelford.com Distributors.
- 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**, 111–126.
- Lie, T.T. and Chabot, M. (1992) Experimental Studies on the Fire Resistance of Hollow Steel Columns Filled with Plain Concrete. *National Research Council Canada*, **611**.

- Lie, T.T. and Stringer, D.C. (1994) Calculation of the Fire Resistance of Steel Hollow Structural Section Columns Filled with Plain Concrete. *Canadian Journal of Civil Engineering*, **21**, 382–385.
- Liew, J.Y.R., Xiong, M.X., and Xiong, D.X. (2014) Title : Design of High Strength Concrete Filled Tubular Columns For Tall Design of High Strength Concrete Filled Tubular Columns For Tall Buildings. *International Journal of High-Rise Buildings*, **3**, 215–221.
- Lim, S.K., Tan, C.S., Zhao, X., and Ling, T.C. (2014) Strength and toughness of lightweight foamed concrete with different sand grading. *KSCE Journal of Civil Engineering*, **19**, 2191–2197.
- Liu, P., Lee, K., Ho, G.W., Lee, A., Yin, C., Liu, G., Huang, X., Ho, G., Lee, A., Yin, C., Lee, K., Liu, G., and Huang, X. (2012) The Structural Design of Tianjin Goldin Finance 117 Tower. *International Journal of High-Rise Buildings*, **1**, 271–281.
- Lowes, L.N. (1999) *Finite Element Modeling of Reinforced Concrete Beam-Column Bridge Connections*. P. in: *University of California, Berkeley*. 23-101 pp.
- Lu, H., Zhao, X.L., and Han, L.H. (2010) Testing of self-consolidating concrete-filled double skin tubular stub columns exposed to fire. *Journal of Constructional Steel Research*, **66**, 1069–1080.
- Mahendran, M. (1996) the Modulus of Elasticity of Steel. Pp. 641–648 in: *13th International Specialty Conference on Cold-Formed Steel Structures*. Missouri University of Science and Technology.
- Mizutani, K., Hirakawa, K., and Nakashima, M. (2015) Construction of a 300-Meter Vertical City: Abeno Harukas Construction of a 300-Meter Vertical City: Abeno Harukas. *International Journal of High-Rise Buildings*, **4**, 199–207.
- Moliner, V., Espinos, A., Romero, M.L., Hospitaler, A., and C., I. (2013) Fire behavior of eccentrically loaded slender high strength concrete-filled tubular columns. *Journal of Constructional Steel Research*, **83**, 137–146. Elsevier Ltd.
- Morino, S. and Tsuda, K. (2003) Design and Construction of Concrete-Filled Steel Tube Column System in Japan. *Earthquake Engineering and Engineering Seismology*, **4**, 51–73.
- Mydin, A.O. (2011a) Effective thermal conductivity of foamcrete of different densities. *Concrete Research Letters*, **2**, 181–189.
- Mydin, A.O., Awang, H., and Roslan, A.F. (2012) Determination of lightweight

- foamed concrete thermal properties integrating various additives. **48**, 9286–9291.
- Mydin, M.A.O. (2011b) Potential of Using Lightweight Foamed Concrete in Composite Load-Bearing Wall Panels In Low-Rise Construction. *Concrete Research Letters*, **2**, 213–227.
- Mydin, M.A.O. and Wang, Y.C. (2012a) Mechanical properties of foamed concrete exposed to high temperatures. *Construction and Building Materials*, **26**, 638–654. Elsevier Ltd.
- Mydin, M.A.O. and Wang, Y.C. (2012b) Thermal and mechanical properties of lightweight foamed concrete at elevated temperatures. *Magazine of Concrete Research*, **64**, 213–224.
- Newman, J., Choo, B.S., and Owens, P. (2003) *Advanced concrete technology*. P. in: *Advanced Concrete Technology*. First. Butterworth-Heinemann, Great Britain, 1-1433 pp.
- NIST. (2005) *Final Report on the Collapse of the World Trade Center Towers*. 1-233 pp.
- Oliveira, T.A. de C.P. de. (2013) Fire resistance of composite columns made of concrete filled circular hollow sections and with restrained thermal elongation. 1-222 pp.
- Online, R., Chen, J., Young, B., Uy, B., Chen, J., Young, B., Asce, M., and Uy, B. (2006) Behavior of high strength structural steel at elevated temperatures. *Journal of Structural Engineering*, **132**, 1948–1954.
- Othuman, M.A. and Wang, Y.C. (2011) Elevated-temperature thermal properties of lightweight foamed concrete. *Construction and Building Materials*, **25**, 705–716. Elsevier Ltd.
- Outinen, J. (2006) Mechanical properties of structural steels at elevated temperatures and after cooling down. *Fire and materials conference, San Francisco, USA*.
- Parhizkar, T., Najimi, M., and Pourkhorshidi, A.R. (2012) Application of pumice aggregate in structural lightweight concrete. *Asian Journal of Civil Engineering*, **13**, 43–54.
- Poh, K.W. (2001) Stress-strain-temperature relationship for structural steel. *Journal of Materials in Civil Engineering*, **13**, 371–379.
- Poon, D.C.K., Shaw-song, S., M., J.L., and Chang, C. (2002) *the Sky ' s the Limit*. Modern steel construction.

- Purkiss, J.A. and Li, L. (2014) *Fire Safety Engineering-Design of structures*. P. in.: Third. CRC PressTaylor and Francis Group, Boca Raton, 1-412 pp.
- Rahim, M.S.N.A. (2015) The current trends and challenging situations of fire incident statistics. *Malaysian Journal of Forensic Sciences*, **6**, 63–78.
- Rizalman, A.N., Md Tahir, M., Mohammad, S., and Sulaiman, A. (2015) Numerical Simulation for Predicting Fire Behavior of Axially Loaded Circular Concrete Filled Steel Tubular Columns. *Applied Mechanics and Materials*, **752–753**, 507–512.
- Romero, M.L., Moliner, V., Espinos, A., Hospitaler, A., Ibanez, C., Romero, M.L., Hospitaler, A., C., I., Moliner, V., Espinos, A., Hospitaler, A., and Ibanez, C. (2011) Fire behavior of axially loaded slender high strength concrete-filled tubular columns. *Journal of Constructional Steel Research*, **83**, 1953–1965. Elsevier Ltd.
- Rush, D. (2013) Fire performance of unprotected and protected concrete filled steel hollow structural sections. The University of Edinburgh UK, 380 pp.
- Rush, D., BISBY, L., MELANDINOS, A., and LANE, and B. (2011) Fire Resistance Design of Unprotected Concrete Filled Steel Hollow Sections: Meta-Analysis of Available Furnace Test Data. *Fire Safety Science*, **10**, 459–470.
- Sayadi, A.A., Vilches, T.J., Neitzert, T.R., and Clifton, G.C. (2016) Effectiveness of foamed concrete density and locking patterns on bond strength of galvanized strip. *Construction and Building Materials*, **115**, 221–229. Elsevier Ltd.
- Schneider, U., Diederichs, U., and Ehm, C. (1982) Effect of temperature on steel and concrete for PCRV's. *Nuclear Engineering and Design*, **67**, 245–258.
- Shehdeh, G., Hamid, R.A., and Orabi, A. (2010) Comparative Study of Load Carrying Capacity of Steel Tube Columns Filled with Lightweight Concrete and Normal Concrete. *Jordan Journal of Civil Engineering*, **4**, 164–169.
- Thakrele, M.H. (2014) Experimental study on foam concrete. *International Journal of Civil, Structural, Environmental and Infrastructure Engineering Research and Development*, **4**, 145–158.
- Tondini, N., Hoang, V.L., Démonceau, J.-F., and Franssen, J.-M. (2013) Experimental and numerical investigation of high-strength steel circular columns subjected to fire. *Journal of Constructional Steel Research*, **80**, 57–81. Elsevier Ltd.
- Twilt, L., Hass, R., Klingsch, W., Edwards, M., and Dutta, D. (1994) *Design Guide*

- For structural hollow section columns exposed to fire.* P. in.: CIDECT Verlag TUV Rheinland, Germany, 5-15 pp.
- Ukanwa, K.U., Sharma, U., Hicks, S.J., Abu, A., Lim, J.B.P., and Clifton, G.C. (2017) Behaviour of continuous concrete filled steel tubular columns loaded concentrically in fire. *Journal of Constructional Steel Research*, **136**, 101–109. Elsevier.
- Usach, C.I. (2015) Fire response analysis of circular concrete filled tubular columns and the effects of axial and rotational restraints. UNIVERSITAT POLITÈCNICA DE VALÈNCIA.
- Varghese, S., Ashok, A.M., Joseph, A.K., Emmanuel, S., and Swathylekshmi, O. V. (2017) A study on properties of foamed concrete with natural and synthetic foaming agent. 2009–2011.
- Wan, C.-Y., Zha, X.-X., and Dassekpo, J.-B.M. (2017) Analysis of axially loaded concrete filled circular hollow double steel tubular columns exposed to fire. *Fire Safety Journal*, **88**, 1–12. Elsevier.
- Wang, K. and Young, B. (2013) Fire resistance of concrete-filled high strength steel tubular columns. *Thin-Walled Structures*, **71**, 46–56.
- 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. Elsevier B.V.
- Xu, L. and Sun, J. (2012) Temperature Field Calculation and Analysis within Steel Tube Reinforced Columns. *The open Civil Engineering Journal*, **6**, 15–20.
- Yao, Y., Li, H., Guo, H., and Tan, K. (2016) Fire resistance of eccentrically loaded slender concrete-filled steel tubular columns. *Thin-Walled Structures*, **106**, 102–112. Elsevier.
- Yu, X., Tao, Z., and Song, T.-Y. (2016) Effect of different types of aggregates on the performance of concrete-filled steel tubular stub columns. *Materials and Structures*, **49**, 3591–3605. Springer Netherlands.
- Zahari, N.M., Rahman, I.A., and A Mujahid A Zaidi. (2009) Foamed Concrete: Potential Application in Thermal Insulation. Pp. 47–52 in: *Muceet*.