ASSESSMENT OF EXTERNALLY BOUNDED FIBRE REINFORCED POLYMER STRENGTHENING REINFORCED CONCRETE BEAMS AT ELEVATED TEMPERATURE USING FINITE ELEMENT MODELLING

NG CHEE KEONG

A project report submitted in partial fulfilment of the
requirements for the award of the degree of
Master of Forensic Engineering

School of Civil Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

JANUARY 2020

DEDICATION

Specially dedicated to my beloved mom, dad and wife who offered me unconditional love, endless support and encouragement throughout the course of this master project report.

ACKNOWLEDGEMENT

First and foremost, I would like to express my sincere gratitude and appreciation to my supervisor, Ts. Dr. Mariyana Aida Ab. Kadir for her guidance and invaluable advice throughout the project. Her insights into the finite element modelling using ABAQUS was of immense help to complete this project. Her continuous inspiration, kind consideration, encouragement and support has been of great value for me.

I would also like to thank my fellow colleague, Siti Jalilah binti Ahmad who have always been supportive and helpful throughout this project. I am thankful for her insights and sharing her opinions. My sincere appreciation also extends to my family, friends and JKR colleagues who give undivided support to make this project a success.

Apart from that, I would like to thank Public Service Department Malaysia for providing me with the scholarship to complete this Master Degree study.

Lastly, I would like to convey my sincere gratitude to everyone who has directly or indirectly help and contributed to the successful completion of this project.

ABSTRACT

Over the years, fibre reinforced polymer (FRP) had been found as one of the structural rehabilitation methods that widely used in infrastructures and buildings to strengthen and retrofit the reinforced concrete (RC) structural elements such as RC beams. However, the mechanical properties of FRP such as strength and stiffness as well as the bonding interface between FRP and concrete will be badly deteriorated when exposed to high temperature. This study is to assess the thermal-structural behaviour of insulated FRP strengthened RC beam exposed to elevated temperature using numerical modelling ABAQUS. The proposed numerical model of 200mm x 300mm RC beam subjected to 2 hours standard fire time-dependent curve (ISO 834) had been validated with the experimental test data carried out by previous study. The validated numerical model then is used in parametric study to investigate the behaviour of fire damaged normal strength concrete (40MPa) and high strength concrete (60MPa)of reinforced concrete beam strengthened with FRP using various fire insulation thickness of 0mm, 12.5mm, 25mm and 40mm respectively. The result of steel characteristic strength reduction factor is compared with analytical using 500°C Isotherm methods. The parametric studies indicated that the fire insulation layer is essential to provide fire protection to the CFRP strengthened RC beams when exposed to elevated temperature. The insulation layer thickness of 25mm had been found to be the optimum thickness to be used as it is able to meet the criteria in term of temperature distribution, displacement requirement and retention of beam mechanical properties regardless the use of normal or high strength concrete. In conclusion, the numerical model developed using the FE software (ABAQUS) in this study is able to carry out assessment on the thermal-structural behaviour of the insulated CFRP-strengthened RC beams at elevated temperature.

ABSTRAK

Sejak kebelakang ini, penggunaan Polimer Bertetulang Gentian (FRP) sebagai salah satu kaedah pemulihan struktur telah didapati digunakan secara meluas di dalam instruktur dan bangunan untuk mengukuh dan memulihkan elemen struktur konkrit bertetulang (RC) seperti rasuk konkrit bertetulang. Akan tetapi, sifat mekanikal FRP seperti kekuatan dan kekakuan serta ikatan antara permukaan FRP dengan konkrit akan terjejas dengan teruk sekiranya terdedah kepada suhu yang tinggi. Kajian ini dijalankan dengan menggunakan perisian ABAQUS untuk menilai tingkah laku struktur rasuk konkrit bertetulang yang telah diperkukuhkan dengan FRP dan terdedah kepada suhu tinggi. Model berangka yang berdimensi 200mm x 300mm dan terdedah kepada standard suhu haba ISO 834 telah divalidasi dengan menggunakan keputusan ujian eksperimen yang dijalankan oleh penyelidik-penyelidik terdahulu. Model berangka yang telah divalidasi kemudian digunakan dalam analisis parametrik untuk menyiasat kelakuan rasuk konkrit bertetulang diperkukuhkan dengan FRP yang mempunyai konkrit berkekuatan normal (40MPa) and konkrit berkekuatan tinggi (60MPa) dengan lapisan penebat api yang bertebalan 0mm, 12.5mm, 25mm dan 40mm. Keputusan pengiraan pekali pengurangan kekuatan ciri keluli juga dibandingkan dengan pengiraan analitik yang menggunakan kaedah 500°C Isotherm. Analisis parametrik menunjukkan bahawa lapisan penebat api adalah diperlukan untuk melindungi rasuk konkrit bertetulang yang diperkukuhkan dengan CFRP apabila terdedah kepada suhu tinggi. Lapiran penebat api dengan ketebalan 25mm didapati adalah ketebalan optimum yang boleh digunakan kerana ianya dapat memenuhi kriteria dari segi pengedaran suhu, keperluan pesongan rasuk dan pengekalan sifat mekanikal rasuk samada menggunakan konkrit berkekuatan normal atau berkekuatan tinggi. Sebagai kesimpulan, satu model berangka telah berjaya dibangunkan dengan menggunakan perisian ABAQUS dalam kajian ini di mana ianya dapat digunakan untuk menilai kelakuan struktur rasuk konkrit bertetulang yang dilindungi dengan lapisan penebat api apabila terdedah kepada suhu yang tinggi.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AFRP	-	Aramid Fibre Reinforced Polymer
ASTM	-	American Society for Testing and Materials
CAE	-	Complete ABAQUS Environment
CFRP	-	Carbon Fibre Reinforced Polymer
CTE	-	Coefficient of Thermal Expansion
EC	-	Eurocode
FE	-	Finite Element
FEA	-	Finite Element Analysis
FRP	-	Fibre Reinforced Polymer
GFRP	-	Glass Fibre Reinforced Polymer
ISO	-	International Organisation of Standardisation
NSM	-	Near Surface Mounted
RC	-	Reinforced Concrete
TGA	-	Thermo-gravimetric Analysis
UBBL	-	Uniform Building By-Law
VG	-	Vermiculite-gypsum

LIST OF SYMBOLS

T_g	-	Glass Transition Temperature
k_s	-	Coefficient of Steel Characteristic Strength Reduction Factor
$c_{p,peak}$	-	Peak Specific Heat Value for Concrete
c_p	-	Specific Heat of Concrete
c_a	-	Specific Heat of Steel
a_c	-	Thermal Diffusivity of Concrete
a_a	-	Thermal Diffusivity of Steel
$\varepsilon_{s,fi}$	-	Reinforcing Steel Strain at elevated temperature
ε_s	-	Thermal Strain of Steel
λ_c	-	Thermal Conductivity of Concrete
θ_c	-	Temperature of Concrete
ε_c	-	Free Thermal Strain of Concrete
ρ_c	-	Density of Concrete
α_c	-	Coefficient of Thermal Expansion for Concrete
λ_a	-	Thermal Conductivity of Steel
θ_a	-	Temperature of Steel
ρ_a	-	Density of Steel

CHAPTER 1

INTRODUCTION

Reinforced concrete (RC) structures will experienced in deterioration over the years of service due to excessive loading, changes of usages, incidents such as fire etc. Therefore, forensic structural assessment generally will be carried out to evaluate the residual strength and durability of the RC structures before any rehabilitation works or strengthening works can be carried out. Over the years, fibre reinforced polymer (FRP) had been found as one of the structural rehabilitation methods that widely used in infrastructures and buildings to strengthen and retrofit the RC structural elements such as RC beams. However, the mechanical properties of FRP such as strength and stiffness will be severely degraded when expose to high temperature. In particular, if the temperature raise above the glass transition temperature of FRP adhesive, the bonding interface between FRP and concrete will be badly deteriorated. All this had drawn great concern on its functionality and effectiveness to strengthen the RC beams. In addition, the application of FRP in the building structures also needs to comply with fire resistance requirements in the building codes and standards such Uniform Building By-Law, UBBL (Ahmed et al., 2011a) which sometimes fire insulation layers may be provided to satisfy the fire resistance requirements on FRP strengthened RC structural elements. Thus, the performance of FRP strengthened RC beams subjected to fire had attracted great attention among the researchers and structural engineers.

1.1 Background of Problem

Fibre reinforced polymer (FRP) had been used to strengthen the RC beams due to its great material properties such as high strength to weight ratio (compare to steel plate bonding method), excellent corrosion resistance and light weight. The external bonded FRP sheets also able to increase the flexural strength and shear capacity of RC beams.

However, the usage of FRP had drawn doubts among the structural engineers as they concerned about FRP performance and thermal properties at elevated temperature which may jeopardise its function to strengthen the RC beams. FRP consists of two (2) main components, namely fibre and polymer matrix or bonding adhesive which have a very low glass transition temperature (T_g). Generally, the glass transition temperature for common polymers and adhesives is between 60°C and 82°C. When exposed to the temperature that beyond the glass transition temperature of FRP, the polymer matrix from the FRP will undergo changes in mechanical properties and also severe its stiffness and bond strength (Yu et al., 2014). For instant, the bonding between external bonded FRP sheets and concrete surface will be damaged if the temperature reached above its glass transition temperature.

Therefore, in order to protect FRP sheets used in the strengthening of RC beams, an external coating layer of thermal resisting material will be provided as an insulation layer for fire protection to the FRP strengthening RC beams (El-Mahdy et al., 2018). Nevertheless, further studies are required to assess the thermal-structural behaviour of FRP strengthened RC beams (with insulation layer) subjected to fire before the structural engineers can adopt this rehabilitation method with confident.

Besides that, the use of FRP for the strengthening of RC beams might exhibit different thermal-structural behaviour if different strength of concrete being used, such as the normal strength concrete and high strength concrete. This was due to the different changes in mechanical and chemical properties when these two types of concrete being used in RC elements at elevated temperature.

1.2 Problem Statement

In general, RC structure either using normal strength concrete or high strength concrete performed well when exposed to elevated temperature due to its behaviour as fire resisting element. However, the behaviour of high strength reinforced concrete elements under fire condition are complicated which they might experience explosive spalling due to high temperature if no appropriate fibre such as polypropylene fibre added to control the spalling effects. Furthermore, due to low glass transition temperature, FRP will experience drastic change of its properties and strengths when expose to the temperature above its low glass transition temperature. Thus, when FRP is used to strengthen the deteriorated RC beams, the study on thermal-structural behaviour of the combination of both materials when subjected to high temperature need to be conducted in order to assess whether the FRP strengthened RC beams able to perform and withstand its intended loading when exposed to fire.

Based on previous studies and literature reviews, the more accurate and comprehensive method to investigate the thermal-structural behaviour of the FRP strengthening RC beams when expose to fire is through the full scale fire test as it may able to observe the real structure behaviour and material properties changes during the fire test. Such fire test (experimental test) had been carried out by other researchers such as William et al. (2008) and Ahmed et at. (2011b) in their countries and seldom found to be carries out in Malaysia. In addition, these experimental tests were also very costly, time consuming and prone to human errors.

Therefore, one of the alternative approach is through numerical approach by using finite element modelling to assess and evaluate the thermal-structural behaviour of FRP strengthening RC beams. With the advancement in finite element modelling, a model can be developed to accurately enough to predict the actual behaviour of RC beams from the experimental test. Currently, there are limited studies had used numerical modelling to evaluate the thermal – structural behaviour of FRP strengthening RC elements such as RC beams oversea which some of the studies only concerned about the determination of fire resistance rating (Dai et al., 2014). Besides that, there is still lack of studies on this field in Malaysia especially using the numerical approach which there are inadequate extensive studies had been conducted even from the local universities. This had caused the industry to lack references to refer to when needed to assess and evaluate the use of FRP in RC beams strengthening works when expose to fire. Thus, there is an urgent need to carry out this study using finite element modelling without carried out the costly experimental test.

1.3 Aim and Objectives

The aim of this study is to evaluate the thermal-structural behaviour of FRP strengthened RC beams at elevated temperature using numerical modelling. The model then is used to assess the effect of concrete grade and insulation layer thickness on the thermal-structural behaviour of FRP strengthened RC beams. To achieve this aim, the following objectives are carried out: -

a) To develop a finite element model using ABAQUS for FRP strengthened RC beams protected by insulation layer and subjected to standard fire test and validated with experimental fire test results.

b) To undertake parametric analysis to assess the fire resistance of different grade of concrete with various insulation layer thickness on the thermal-structural behaviour of FRP strengthened RC beam when subjected to elevated temperature.

c) To investigate the temperature of steel rebar and steel characteristic strength reduction factor within the FRP strengthened RC beam using analytical solution and numerical analysis.

1.4 Scope and Limitation of Study

This study is focused on the development of a Finite Element (FE) model using 3D modelling software, ABAQUS which able to predict the thermal-structural behaviour of FRP strengthened RC beams subjected to elevated temperature. The temperature-time curve that had been adopted in this study is based on the ISO 834 for 2 hours as fire loading. Fire load is assumed to be apply at the soffit of beam only with the used of fixed concrete cover which adopted from experimental fire test (Blontrock et al., 2000). Type of FRP used in this study is Carbon Fibre Reinforced Polymer (CFRP). Material parameters depending on temperature are used according to Dai et al. (2014) and BS EN 1992-1-2.

The model then is validated with the experimental test result of deformation parameter and steel reinforcement temperature carried out in Fire Test on Concrete Beam strengthened with Fibre Composite Laminates (Blontrock et al., 2000). The failure criteria used in the analysis of FRP strengthened RC beams is based on beam flexural failure mode only.

After the numerical model is developed, it then used in parametric analysis to determine the optimum insulation layer thickness in FRP strengthening RC beams in comparison to different concrete grade used. The type of insulation layer that proposed to use in this study is Promatect H (calcium silicate board) with thickness varies from 0mm, 12.5mm, 25mm to 40mm. Meanwhile, two (2) type of concrete grade that will be used in parametric study are concrete grade C40/50 and C60/75. The thermo-mechanical analysis for using high strength concrete such as C60/75 will not take into consideration of spalling effect in the model.

Besides that, the analytical calculation is carried out to compute the steel reinforcement temperature and compare with the FE model results in order to determine the coefficient of steel characteristic strength reduction factor subject to elevated temperature. The limitations of this study are: -

a) The effect of bond degradation on FRP adhesive layer is not considered in the model due to the limitation data from the fire test and experimental results on this subject. However, it is assumed that the external bonded FRP which is protected with an insulation layer is able to keep the FRP temperature below its glass transition temperature during the fire test.

b) The tie between nodes of concrete with steel reinforcement and FRP with concrete surface is assume to be perfect.

c) Spalling effect is not taken into consideration in the FE model.

1.5 Significance of Study

The finite element model provided significant contribution in term of new 3D numerical model to be used as assessment tool in predicting and simulating the thermal – structural behaviour such as flexural behaviour for the FRP strengthened RC beam when expose to fire. It is an alternative method to conduct the costly and time consuming experimental tests and also an effective method to predict the behaviour of FRP strengthened RC beams in a fast and convenient way. The model also can be used for future study in this area of study to determine effect of other design parameters such as the bonding of FRP to concrete surface or steel reinforcement to concrete on flexural strength of FRP strengthening beam and also carry out the shear strength prediction.

REFERENCES

ABAQUS Documentation (2018). SIMULA User Assistance 2018 (Build-in with ABAQUS software version 2018SE).

Adelzadeh, M. (2013). Structural and Thermal Behaviour of Insulated FRP-Strengthened Reinforced Concrete Beams and Slabs in Fire. PhD Thesis. Queen University, Kingston, Canada.

Ahmad Nurfaidhi Rizalman (2016). Numerical Simulation of Axially Loaded Concrete Filled Hollow Steel Section Columns at Elevated Temperatures. PhD Thesis. Universiti Teknologi Malaysia, Skudai.

Ahmed, A., & Kodur, V. (2011a). Effect of bond degradation on fire resistance of FRP-strengthened reinforced concrete beams. Composites Part B: Engineering, 42(2), 226-237.

Ahmed, A., & Kodur, V. (2011b). The experimental behaviour of FRP-strengthened RC beams subjected to design fire exposure. Engineering Structures, 33(7), 2201-2211.

Albrektsson, J., Flansbjer, M., Lindqvist, J.-E., & Jansson, R. (2011). Assessment of Concrete Structures after Fire. SP Technical Report, Research Institute of Sweden.

Alsayed, S. H., Al-Salloum, Y. A., & Almusallam, T. H. (2000). Fibre-reinforced polymer repair materials—some facts. In Proceedings of the Institution of Civil Engineers-Civil Engineering, Thomas Telford Ltd, 38(3), pp. 131-134.

Amirul Rasyid Zulkepli (2018). Numerical Modelling of Reinforced Concrete Columns Subjected to Fire Loading. Degree Dissertation. Universiti Teknologi Malaysia, Skudai.

Aslani, F., & Samali, B. (2013). Predicting the bond between concrete and reinforcing steel at elevated temperatures. Structural Engineering and Mechanics, 48(5), 643-660.

Bank, L. C. (1993). Properties of FRP reinforcements for concrete. In Fiber-Reinforced-Plastic (FRP) Reinforcement for Concrete Structures (pp. 59-86): Elsevier.

Bisby, L. A. (2003). Fire Behaviour of FRP Reinforced or Confined Concrete. PhD Thesis. Queen University, Kingston, Canada.

Bisby, L., Green, M., & Kodur, V. (2005). Modeling the behavior of fiber reinforced polymer-confined concrete columns exposed to fire. Journal of composites for construction, 9(1), 15-24.

Blontrock, H., Taerwe, L., & Vandevelde, P. (2000). Fire tests on concrete beams strengthened with fibre composite laminates. Proceedings of the International PhD Symposium in Civil Engineering, Vienna (Austria), 5-7 October 2000 / ed. Konrad Bergmeister. - Volume 2, 151-161.

Blontrock, H., Taerwe, L., & Vandevelde, P. (2001). Fire Testing of Concrete Slabs Strengthened with Fibre Composite Laminates. In FRPRCS-5: Fibre-reinforced plastics for reinforced concrete structures Volume 1, pp. 547-556.

British Standards Institution (2004). Eurocode 2: Design of Concrete Structures – Part 1-2: General Rules – Structural Fire Design. BS EN 1992-1-2. London, UK.

British Standards Institution (2005). Eurocode 3: Design Steel Structures – Part 1-2: General Rules – Structural Fire Design. BS EN 1993-1-2. London, UK.

British Standards Institution (2005). Eurocode 4: Design of Composite Steel and Concrete Structures – Part 1-2: General Rules – Structural Fire Design. BS EN 1994-1-2. London, UK.

Buchanan, A.H. and Abu, A.K. (2017). Structural Design for Fire Safety (2nd Edition), John Wiley & Sons Inc., United Kingdom. pp 69 – 74, pp 202.

Chowdhury, E., Bisby, L., Green, M., Bénichou, N., & Kodur, V. (2012). Heat transfer and structural response modelling of FRP confined rectangular concrete columns in fire. Construction and building materials, 32, 77-89.

Chowdhury, E., Eedson, R., Bisby, L., Green, M., & Benichou, N. (2011). Mechanical characterization of fibre reinforced polymers materials at high temperature. Fire technology, 47(4), 1063-1080.

Chowdhury, E., Green, M., Bisby, L., Bénichou, N., & Kodur, V. (2007). Thermal and mechanical characterization of fibre reinforced polymers, concrete, steel, and insulation materials for use in numerical fire endurance modelling. *Uneversi ondece documents etrouvedans: Structures under Extreme Loading, Proceedings of Protect—2007*, Whistler, BC—2007.

Chowdhury, E., Eedson, R., Bisby, L., Green, M., Benichou, N., Kodur, V., & Fyfe, E. (2008). Mechanical characterization of fibre reinforced polymers for numerical fire endurance modelling. Paper presented at the Proceedings of the 5th International Conference: Structures in Fire.

Dai, J., Gao, W., & Teng, J. (2010). Finite element modeling of insulated FRP-strengthened RC beams exposed to fire. In Advances in FRP Composites in Civil Engineering (pp. 428-432): Springer.

Dai, J.-G., Gao, W.-Y., & Teng, J. (2014). Finite Element Modeling of insulated FRP-Strengthened RC Beams exposed to Fire. Journal of Composites for Construction, 19(2), 04014046-1 to 04014046-15.

Dong, K., Hu, K., & Gao, W. (2016). Fire behavior of full-scale CFRP-strengthened RC beams protected with different insulation systems. Journal of Asian Architecture and Building Engineering, 15(3), 581-588.

El-Mahdy, O., Hamdy, G., & Abdullah, M. (2018). Numerical Investigation of the Performance of Insulated FRP-strengthened Reinforced Concrete Beams in Fire. Civil Engineering Journal-Stavebni Obzor, 4, 573-586

Gao, W., Dai, J.-G., Teng, J., & Chen, G. (2013). Finite element modeling of reinforced concrete beams exposed to fire. Engineering Structures, 52, 488-501.

Gao, W., Hu, K., & Lu, Z. (2008). Modeling the behavior of insulated FRP-strengthened reinforced concrete beams exposed to fire. Paper presented at the Concrete Repair, Rehabilitation and Retrofitting II: 2nd International Conference on Concrete Repair, Rehabilitation and Retrofitting, ICCRRR-2, 24-26 November 2008, Cape Town, South Africa.

Gosain, N. K., Drexler, R. F., & Choudhuri, D. (2008). Evaluation and repair of fire-damaged buildings. Structure Magazine (9).

Griffis, C.A., Masumura, R.A., & Chang, C.I. (1984). Thermal response of graphite epoxy composite subjected to rapid heating. Environmental Effects on Composite Materials, 2, Technomic Publishing Company, Lancaster, Pennsylvania, pp. 245-260.

Hager, I. (2014). Colour Change in Heated Concrete. Fire Technology, 50, 945-958.

Hawileh, R. A., Naser, M., Zaidan, W., & Rasheed, H. (2009). Modeling of insulated CFRP-strengthened reinforced concrete T-beam exposed to fire. Engineering Structures, 31(12), 3072-3079.

Ingham, J. P. (2009). Application of petrographic examination techniques to the assessment of fire-damaged concrete and masonry structures. Materials characterization, 60(7), 700-709.

Khoury, G. A. (2000). Effect of fire on concrete and concrete structures. Progress in Structural Engineering and Materials, 2(4), 429-447.

Kodur, V. (2014). Properties of concrete at elevated temperatures. ISRN Civil engineering, 2014.

Kodur, V. K. R. (1999). Fire performance of high-strength concrete structural members: Institute for Research in Construction, National Research Council of Canada.

Kodur, V., & Ahmed, A. (2010). Numerical model for tracing the response of FRP-strengthened RC beams exposed to fire. Journal of composites for construction, 14(6), 730-742.

Kodur, V., & Mcgrath, R. (2003). Fire endurance of high strength concrete columns. Fire technology, 39(1), 73-87.

Kodur, V., Ahmed, A., & Dwaikat, M. (2009). Modeling the Fire Performance of FRP-strengthened Reinforced Concrete Beams. COMPOSITES & POLYCON, 15-17.

Kodur, V. K. R., & Sultan, M. A. (1998). Structural behaviour of high strength concrete columns exposed to fire. International Symposium on High Performance and Reactive Powder Concrete, 217-232.

Lie, T.T. (1992). Structural Fire Protection: ASCE Manuals and Reports on Engineering Practice No.78. American Society of Civil Engineers (ASCE), New York. pp 17 – 36.

López, C., Firmo, J. P., Tiago, C., & Correia, J. R. (2012). Fire protection systems for reinforced concrete beams and slabs strengthened with CFRP laminates. Paper presented at the Proceedings of the 6th International Conference on FRP Composites in Civil Engineering (CICE), Rome.

Mariyana, A. A. K, A.S.M. Abdul Awal & Mahmood Md. Tahir (2015). Finite Element Modelling Of Compartment Fire Using ABAQUS. Jurnal Teknologi, 74(4), 33-38.

Naus, D. J. (2006). The effect of elevated temperature on concrete materials and structures-a literature review. Oak Ridge National Laboratory (United States)

Ong Kee Yen (2017). Modelling of Fibre-Reinforced Polymer Confined High Strength Concrete Columns By Nonlinear Finite Element Method. Degree Dissertation. Universiti Teknologi Malaysia, Skudai.

Osama, Abdulrazak Abdulwahab, (2013). Finite Element Simulation of Reinforced Concrete Deep Beam with Opening Strengthened with FRP Laminates. Master Thesis. Universiti Teknologi Malaysia, Skudai.

Palmieri, A., Matthys, S., & Taerwe, L. (2011). Fire testing of RC beams strengthened with NSM reinforcement. Paper presented at the 10th International Symposium Fiber-Reinforced Polymer Reinforcement for Concrete Structures.

Peng, G.F (2000). Evaluation of Fire Damage to High Performance Concrete. PhD Thesis. The Hong Kong Polytechnic University, Kowloon.

Purkiss, J.A. and Li, L.Y. (2014). Fire Safety Engineering Design of Structures (3rd Edition), CRC Press, Boca Raton, Florida. pp 75 -144.

Sayin, B. (2014). Behavior of insulated carbon-FRP-strengthened RC beams exposed to fire. Mechanics of Composite Materials, 50(4), 477-490.

Schneider, U. (1986). Properties of materials at high temperatures concrete: Gesamthochsch.-Bibl.

Short, N., Purkiss, J., & Guise, S. (2001). Assessment of fire damaged concrete using colour image analysis. Construction and building materials, 15(1), 9-15.

Tan, K. H., & Zhou, Y. (2010). Performance of FRP-strengthened Beams Subjected to Elevated Temperatures. Journal of Composites for Construction, 15(3), 304-311.

Williams, B., Kodur, V., Green, M. F., & Bisby, L. (2008). Fire endurance of fiber-reinforced polymer strengthened concrete T-beams. ACI structural Journal, 105(1), 60.

Yan, X., Li, H. and Wong, Y.L. (2007). Assessment and repair of fire-damaged high-strength concrete: strength and durability. Journal of Materials in Civil Engineering, 19(6), 462-469.

Yoon, M., Kim, G., Kim, Y., Lee, T., Choe, G., Hwang, E., & Nam, J. (2017). Creep behavior of high-strength concrete subjected to elevated temperatures. Materials, 10(7), 781.

Yu, B., & Kodur, V. (2014). Effect of temperature on strength and stiffness properties of near-surface mounted FRP reinforcement. Composites Part B: Engineering, 58, 510-517.