

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

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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.

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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. Lapisan 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

	TITLE	PAGE
	DECLARATION	iii
	DEDICATION	iv
	ACKNOWLEDGEMENT	v
	ABSTRACT	vi
	ABSTRAK	vii
	TABLE OF CONTENTS	viii
	LIST OF TABLES	xii
	LIST OF FIGURES	xiii
	LIST OF ABBREVIATIONS	xvi
	LIST OF SYMBOLS	xvii
CHAPTER 1	INTRODUCTION	1
1.1	Background of Problem	1
1.2	Problem Statement	2
1.3	Aim and Objectives	4
1.4	Scope and Limitation of Study	4
1.5	Significant of Study	6
CHAPTER 2	LITERATURE REVIEW	7
2.1	Introduction	7
2.2	Assessment on Reinforced Concrete (RC) Structural Deterioration and Rehabilitation	7
2.3	Material Properties at Elevated Temperature	8
2.4	Concrete at Elevated Temperature	9
2.4.1	Thermal Properties	9
2.4.1.1	Thermal Conductivity	9
2.4.1.2	Specific Heat	10
2.4.1.3	Thermal Diffusivity	12

	2.4.1.4	Coefficient of Thermal Expansion	13
2.4.2		Mechanical Properties	13
	2.4.2.1	Density	14
	2.4.2.2	Concrete Compressive Strength	15
	2.4.2.3	Modulus of Elasticity	17
	2.4.2.4	Compressive Stress-Strain Characteristic	18
	2.4.2.5	Creep Strain	20
	2.4.2.6	Tensile Strength	21
2.4.3		Concrete Behaviour due to Chemical and Physical Change	21
	2.4.3.1	Spalling	22
	2.4.3.2	Cracking	23
	2.4.3.3	Colour Change	24
2.5		Reinforcing Steel at Elevated Temperature	25
	2.5.1	Thermal Properties	25
	2.5.1.1	Thermal Conductivity	26
	2.5.1.2	Specific Heat	26
	2.5.1.3	Thermal Diffusivity	27
	2.5.2	Mechanical Properties	28
	2.5.2.1	Density	28
	2.5.2.2	Steel Strength and Stress-Strain Curve	28
	2.5.2.3	Modulus of Elasticity	30
	2.5.2.4	Unrestrained Thermal Expansion	31
	2.5.3	Steel Strength Reduction Factor	31
2.6		Fibre Reinforced Polymer	32
	2.6.1	Application of FRP in Structural Rehabilitation	32
	2.6.2	Characteristic of FRP	33
	2.6.2.1	General	33
	2.6.2.2	Matrix Behaviour	34

2.6.2.3	Fibre Behaviour	35
2.6.3	Thermal Properties of FRP	36
2.6.3.1	Thermal Expansion	36
2.6.3.2	Thermal Conductivity	37
2.6.3.3	Specific Heat	38
2.6.4	Mechanical Properties of FRP	39
2.6.4.1	Strength and Stiffness	39
2.6.4.2	Modulus of Elasticity	40
2.7	Insulation Layer	41
2.7.1	Type of Insulation Layer	41
2.7.1.1	Concrete	41
2.7.1.2	Sprayed Insulation	41
2.7.1.3	Board Insulation System	42
2.7.1.4	Intumescent Coating	42
2.7.2	Insulation Layer at Elevated Temperature	42
2.8	Effects of Fire on FRP Strengthening RC Beams	44
2.8.1	General	44
2.8.2	Previous Studies of Fire Test	44
2.8.3	Previous Numerical Studies	47
2.9	Numerical Modelling	49
2.9.1	Finite Element Analysis	49
2.9.2	ABAQUS Finite Element Software	50
2.9.2.1	Mesh Convergence Study	52
2.9.2.2	Heat Transfer Analysis	52
2.9.2.3	Thermo – Mechanical Analysis	54
CHAPTER 3	METHODOLOGY	55
3.1	Study Workflow	55
3.2	Stage 1 – Development of Numerical Model and Validation	56
3.2.1	Numerical Modelling	56
3.2.2	Validation of Data	58

3.3	Stage 2 – Parametric Study on Thermal-Structural Behaviour of FRP Strengthened RC Beam	61
3.4	Stage 3 – Investigation on Temperature of Steel Rebar and Steel Characteristic Strength Reduction Factor	63
CHAPTER 4	RESULT AND DISCUSSION	65
4.1	Development of Numerical Model and Validation	65
4.1.1	Mesh Convergence Study	65
4.1.2	Material Properties Used in Numerical Model	68
4.1.3	Verification of Thermal Analysis	73
4.1.4	Verification of Thermo-Mechanical Analysis	76
4.2	Parametric Study on Thermal-Structural Behaviour of CFRP Strengthened RC Beam	80
4.2.1	Effect of Concrete Grade	81
4.2.2	Effect of Fire Insulation Thickness	83
4.2.3	Deflection Analysis	87
4.2.4	Stress-Strain Curve	89
4.2.5	Summary	91
4.3	Steel Characteristic Strength Reduction Factor	92
4.3.1	Steel Reinforcement Temperature	92
4.3.2	Comparison of Coefficient of Steel Strength Reduction Factor	95
CHAPTER 5	CONCLUSION AND RECOMMENDATION	97
5.1	Conclusions	97
5.2	Recommendations	99
REFERENCES		101

LIST OF TABLES

TABLE NO.	TITLE	PAGE
Table 2.1	Value of $C_{p,peak}$	12
Table 3.1	Input Data and Material Properties Used for Validation	60
Table 4.1	Result Comparison for Mesh Convergence Study	67
Table 4.2	Material properties used in Numerical Modelling	69
Table 4.3	Relative comparison of Measured Test Results with FE prediction on steel reinforcement temperature	75
Table 4.4	Relative comparison of Measured Test Results with numerical prediction on beam mid-span deflection	79
Table 4.5	Parameters Used in Parametric Study	80
Table 4.6	Displacement Analysis CFRP Strengthened RC Beams using Different Insulation Scheme and Grade of Concrete	88
Table 4.7	Analytical Calculated and Finite Element (FE) Predicted Steel Reinforcement Temperature	94
Table 4.8	Comparison of Steel Temperature by Analytical Calculation and Finite Element (FE) Prediction	94
Table 4.9	Comparison of Steel Strength Reduction Factor, K_s by analytical calculation and numerical analysis	95

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
Figure 2.1	Variation of Concrete Specific Heat with Temperature (Source: Schneider, 1986)	11
Figure 2.2	Comparison between compressive strength of normal strength concrete at elevated temperature with experimental data (Aslani et al., 2013)	16
Figure 2.3	Comparison between compressive strength of high strength concrete (55.2-80MPa) with siliceous aggregate at elevated temperature with experimental data (Aslani et al., 2013)	17
Figure 2.4	Stress-Strain Curve for Normal Strength Concrete (30MPa) at elevated temperature (with Siliceous Aggregate) according to BS EN 1992-1-2	19
Figure 2.5	D Stress-Strain Curve for High Strength Concrete (60MPa) at elevated temperature according to BS EN 1992-1-2	19
Figure 2.6	Material Creep at Elevated Temperature	20
Figure 2.7	Comparison of spalling in NSC and HSC columns under fire conditions	23
Figure 2.8	Colour change of (a) High Strength Concrete and (b) Normal Concrete (with siliceous aggregate) heated to temperature ranging from 100°C to 1000°C (Hager, 2014)	25
Figure 2.9	Thermal conductivity of carbon steel and stainless steel with temperature	26
Figure 2.10	Specific heat of steel with temperature (BS EN 1993-1-2)	27
Figure 2.11	Stress-Strain Relationship of Reinforcing Steel Grade 500MPa at Elevated Temperature (BS EN 1992-1-2)	30
Figure 2.12	Modulus of elasticity of steel at elevated temperature	30
Figure 2.13	Thermal elongation of carbon steel and stainless steel at elevated temperature (BS EN 1993-1-2)	31
Figure 2.14	Failure of CFRP coupons at 200°C (a) just before failure and (b) just after failure	35
Figure 2.15	Thermal Conductivity and Thermal Capacity (thermal properties) of FRP as a function of temperature (Kodur et al., 2009)	38

Figure 2.16	Variation of thermal conductivity, density and specific heat with temperature for carbon / epoxy FRP (Griffis et al., 1984)	38
Figure 2.17	a) Universal Testing Machine, Thermal Chamber and Data Acquisition System. b) Thermal Chamber. c) Wedge Action Gripping System (outside the chamber)	39
Figure 2.18	Stress-strain curve of FRP at different temperatures	40
Figure 2.19	Thermal properties of Insulation as a function of temperature (Kodur et al., 2009)	43
Figure 2.20	Thermo-gravimetric Analysis (TGA) for Insulation Systems (Chowdhury et al., 2007)	44
Figure 2.21	Experimental Fire Test Furnace and Loading Setup	46
Figure 2.22	Type of Modules in ABAQUS software	51
Figure 2.23	Example of continuum element of RC beam with reinforcement	51
Figure 3.1	The Overall Study Workflow	56
Figure 3.2	Workflow for Stage 1	58
Figure 3.3	Details of beam dimension and reinforcement from Blontrock et al. (2000)	59
Figure 3.4	Insulation scheme of Beam 6 in fire test by Blontrock et al. (2000)	59
Figure 3.5	Workflow for Stage 2	62
Figure 3.6	Workflow for Stage 3	63
Figure 4.1	FEA Model with difference mesh size	66
Figure 4.2	Temperature contour at mid-span of beam cross section	73
Figure 4.3	Graph comparison of experimentally and FE predicted temperature distribution on steel reinforcement in insulated CFRP strengthened RC beam	74
Figure 4.4	Deformed shape for the numerical model using ABAQUS: (a) Before loading; (b) After loading and exposed to elevated temperature	77
Figure 4.5	Graph comparison of mid-span deflection for numerical model with the experimental results	78
Figure 4.6	Temperature Distribution at Mid-span of Beam Cross Section	81
Figure 4.7	Graph of Temperature Distribution in Steel Reinforcement	83

Figure 4.8	Graph of Temperature Distribution in Steel Reinforcement with Different Fire Insulation Layer Thickness: (a) Concrete Grade 40MPa, (b) Concrete Grade 60MPa	84
Figure 4.9	(a) Mid-span Beam Deflection Using Normal Strength Concrete (40MPa)	85
Figure 4.9	(b) Mid-span Beam Deflection Using High Strength Concrete (60MPa)	86
Figure 4.10	Comparison of Mid-span Beam Deflection with Different Insulation Scheme	87
Figure 4.11	(a) Stress-Strain Curve for beam PS1 and PS2	89
Figure 4.11	(b) Stress-Strain Curve for beam PS3 and PS4	89
Figure 4.11	(c) Stress-Strain Curve for beam PS5 and PS6	90
Figure 4.11	(d) Stress-Strain Curve for beam PS7 and PS8	90
Figure 4.12	Cross section and dimension of beam PS1	93

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
$\epsilon_{s,fi}$	-	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.

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