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Coupled Thermo-Mechanical Analysis of Reinforced Concrete Columns Partially Confined with Carbon Fibre Reinforced Polymer (CFRP) at Elevated Temperatures

M. Buyong[1], F.A. Ahmad Zakwan[2]*, R. Ismail[2]**, H. Ahmad[1], N.H. Hashim[1] and L.D. Goh[1]

[1]*Civil Engineering Studies, College of Engineering, Universiti Teknologi MARA, Cawangan Pulau Pinang, Permatang Pauh Campus, 13500 Permatang Pauh, Pulau Pinang, Malaysia*

[2]*School of Civil Engineering, College of Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia*

In this study, the thermo-mechanical behaviour and failure characteristics of reinforced concrete (RC) columns under high temperatures are the focus of an extensive numerical investigation. The fundamental goals of this study are threefold: first, utilising cutting-edge ABAQUS CAE software, the authors discuss the construction and validation of a robust numerical model for RC columns that are successfully contained by two layers of partial carbon fibre-reinforced polymer (CFRP). Second, a thorough evaluation of how partial CFRP confinement affects RC column performance is carried out. Finally, ISO 834 Standard Fire curve testing is used to assess the reaction and structural behaviour of RC concrete columns that have been particularly reinforced with two layers of partial CFRP. Circular RC column specimens of uniform dimensions (200mm in diameter and 1000mm in height) are used as testing materials in this investigation. In order to explore the complicated relationship between temperature, confinement, and structural integrity, finite element analysis (FEA) procedures are methodically carried out using ABAQUS CAE software. This study investigates the thermo-mechanical behaviour of reinforced concrete (RC) columns partially confined with CFRP at elevated temperatures in order to improve their fire resistance. The study employs advanced finite element analysis (FEA) using ABAQUS CAE software to measure enhancements in structural integrity. The findings indicate a 20% augmentation in load-bearing capacity and a notable postponement in the initiation of failure under ISO 834 standard fire conditions. This study adds to our knowledge of the behaviour of RC columns reinforced with partial CFRP confinement, in particular when subjected to high temperatures. Sustainable and resilient structural engineering methods can benefit greatly from such insights, as they can help advance fire-resistant design strategies and reinforce measures for important facilities.

Keywords: elevated temperature; reinforced concrete; finite element; fire; partial confinement; carbon fibre reinforced polymer (CFRP)

I. INTRODUCTION

Many different sectors have taken an interest in carbon fibre-reinforced polymers (CFRP) because of the superior mechanical qualities they offer (Almushaikeh *et al.*, 2023; Karim *et al.*, 2023; Kazemi *et al.*, 2023; Li, J *et al.*, 2023; Miralami, Esfahani & Tavakkolizadeh, 2019; Saini & Shafei, 2023; Samy *et al.*, 2022). The construction industry is increasingly interested in using carbon fibre-reinforced plastic (CFRP) materials due to their many benefits, including their lightweight and high strength (Ismail *et al.*, 2019; Miralami, Esfahani & Tavakkolizadeh, 2019; Navaratnam *et al.*, 2023; Samy *et al.,* 2022; Sbahieh, Mckay

*Corresponding author's e-mail: fariz838@uitm.edu.my

& Al-Ghamdi, 2023; Solahuddin & Yahaya, 2023; Sumithra *et al.*, 2023; Wang *et al.*, 2023; Zhu *et al.,* 2023). Carbon fibre-reinforced composites (CFRCs) are used in numerous technical applications (Dinu *et al.*, 2023; Guadagno *et al.*, 2023; Hu *et al.*, 2023; Ismail *et al.*, 2019; Li, H *et al.*, 2023; Zakaria *et al.*, 2023; Zhang *et al.*, 2023) and are widely used in the production of a wide variety of goods and structures. CFRP has several potential applications in engineering, but their high price and low production efficiency limit their use. In the field of structural engineering, fire resistance is of the utmost importance and refers to a building's ability to withstand fire for a certain period of time without failing (Çiftçioğlu & Naser, 2024; Guo *et al.,* 2018; O'Connor, Morris & Silcock, 1997; Rafika & Hashmi, 2021; Seręga & Wosatko, 2018). By reducing the rate at which heat is transferred to the structure, adding a protective layer like CFRP might increase the time before failure (Abadel, Masmoudi & Iqbal Khan, 2022; McIntosh & Farid, 2011). Figure 1 depicts the disparities in performance between reinforced concrete (RC) columns that are completely and partially wrapped with CFRP. Columns that are completely wrapped demonstrate improved distribution of loads and overall structural strength. On the other hand, columns that are only partially wrapped show enough improvement in certain areas, which helps optimise the use of materials and reduces costs. The benefits of partial confinement in targeted reinforcement applications are evident through detailed performance metrics, which include stress distribution and failure patterns.

Parameters like the rate of temperature rise, aggregate type, and stability have all been the subject of extensive research into their effects on concrete's behaviour at elevated temperatures (Abbass *et al.,* 2023; Adan & Jane Helena, 2023; Amran *et al.,* 2023; Bao *et al.,* 2023; Faraj, Mohammed & Omer, 2023; Gondokusumo *et al.,* 2023; Ismail *et al.,* 2019; Obaidat *et al.,* 2021). Cracking and spalling, caused by thermal shock, and internal distress in the concrete matrix, caused by aggregate expansion, are also effects of temperature increases. Figure 2 shows the various temperature-response scenarios provided by fire design standards to simulate the effects of high temperatures on RC columns. These include the ISO 834 fire curve, the ASTM E119 fire curve, the external fire curve, and the hydrocarbon fire curve. This study adopts the ISO 834 fire curve because it accurately represents real-world fire scenarios and reflects the typical thermal exposure experienced in structural fires. The extensive acceptance and comprehensive profile of this standard make it an ideal benchmark for assessing the fire resistance of reinforced concrete columns, guaranteeing that the results are applicable to diverse building environments worldwide.

Several studies have discovered that fibre-reinforced plastics (FRP) composites, such as FRP plates, FRP cloths, and FRP bars, are gradually being used to strengthen and repair existing structures (Chole *et al.,* 2023; DE MAIO *et al.,* 2023; Nwankwo *et al.*, 2023; Pranit *et al.*, 2023; Solahuddin & Yahaya, 2023; Stephen, Hughes & Das, 2020; Su *et al.,* 2023; Wang *et al.,* 2020; Xue *et al.,* 2023). From the nature of the material, FRP include various types such as CFRP, Glass Fibre-Reinforced Plastics (GFRP), Aramid Fibre-Reinforced Plastics (AFRP), and Basalt Fibre-Reinforced Plastics (BFRP). FRP bars are one of the most popular options for high corrosion resistance in extreme conditions. During a fire, nevertheless, FRP materials lose their strength and stiffness at an early stage (Dong *et al.,* 2023; Ismail *et al.,* 2019; Jin *et al.,* 2023; Mohamed, Kewalramani & Imran, 2023; Nguyen, Vu & Ferrier, 2019; Obaidat *et al.,* 2021).

FRP composites, including FRP plates, FRP cloths, and FRP bars, have emerged as possible solutions alongside CFRP for strengthening and prolonging the life of existing structures (DE MAIO *et al.,* 2023; Nwankwo *et al.,* 2023; Stephen, Hughes & Das, 2020; Wang *et al.*, 2020). Despite their widespread use due to their strong corrosion resistance, FRP bars severely lose their mechanical qualities when exposed to fire (Ismail *et al.,* 2019; Nguyen, Vu & Ferrier, 2019; Obaidat *et al.,* 2021). To better understand the thermo-mechanical response and failure processes of reinforced concrete columns with partial CFRP confinement, this study aims to conduct a comprehensive numerical investigation under extreme heat conditions. This research helps promote sustainable practises, fire-resistant design techniques, and reinforcing methodologies in the field of structural engineering by providing more understanding of the behaviour of such composite systems.

The study's introduction includes discussions on the finite element method (FEM) as a strong framework for analysing the thermo-mechanical behaviour of RC columns (Habib, Sorelli & Fafard, 2018; Kim *et al.,* 2024; Shamsi & Sümer, 2024). The reliability of the FEM in accurately simulating complex structural responses under different conditions is essential for validating the findings of the study.

(a) (b)

Figure 1. RC concrete confinement (a) Fully FRP wrapped; (b) Partially FRP wrapped (Zeng *et al.,* 2018)

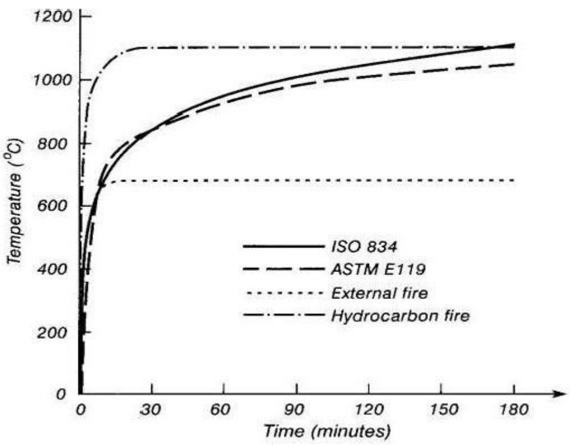


Figure 2. The Temperature Response of the ISO 834, ASTME119, Hydrocarbon Fire (ASTM E1529), and External Fire Models (McIntosh & Farid, 2011)

II. RESEARCH METHODOLOGY

Finite Element Analysis (FEA) has developed into a dependable numerical method for examining the structural behaviour of intricate systems under different circumstances. This work employs FEA to simulate the behaviour of RC columns that are partially restrained by CFRP and exposed to the ISO 834 Standard fire curve. The loading configuration for the reinforced concrete columns is simulated by providing a uniform axial load on the top surface, replicating actual structural loading circumstances. The load is incrementally raised until it reaches its maximum capacity, taking into account all the relevant factors and limitations, and precisely modelled in the ABAQUS CAE programme to guarantee accurate simulation outcomes.

The RC columns are subjected to controlled heating according to the ISO 834 standard fire curve. The heat source is designed to replicate uniform exposure from all directions, guaranteeing consistent thermal penetration and an accurate simulation of fire conditions. In a typical fire scenario, heat is applied from the external surfaces towards the interior, simulating the exposure of columns to flames from several angles.

During the FEM testing, various crucial characteristics are carefully watched and documented to assess the performance of the RC columns under fire circumstances. The stress distribution within the RC columns is measured, with a specific focus on identifying locations of high stress concentration and assessing the overall structural integrity. Strain behaviour is evaluated, specifically in the confined sections of CFRP, in order to analyse deformation and failure processes. Thermal behaviour and the efficacy of CFRP as an insulating material are assessed by monitoring temperature profiles in the RC columns. An analysis is conducted to determine the effect of CFRP confinement on the resilience of columns by examining several modes of failure such as cracking, spalling, and structural collapse. In addition, the study records the maximum load-bearing capacity of the RC columns, emphasising the enhancements resulting from the confinement of CFRP. Furthermore, the time to failure is measured to assess the extent to which CFRP reinforcement delays the occurrence of failure.

This research involved the systematic development of a set of three RC columns. These columns had consistent dimensions, with a diameter of 200mm and a height of 1000mm. They were specifically designed for experimental studies. Figure 3 illustrates the arrangement of linear variable differential transformers (LVDTs) and strain gauges for the purpose of measuring linear displacements and changes in strain resulting from applied stress in the experimental testing. Extensive numerical simulations were performed using ABAQUS CAE to comprehensively study the structural behaviour of the RC columns under various temperature conditions. A rigorous validation process was conducted to establish the stress-strain correlation of the reinforced concrete columns in both normal and fire circumstances, guaranteeing the precision and dependability of the simulations and analysis.

The material parameters of the first and second models were simulated numerically in the third model using the ISO 834 Standard Fire curve. This fire curve depicts a commonly recognised and realistic pattern observed in real-life instances of fires in buildings worldwide. The simulations provided crucial insights into the structural response of the RC columns under high temperatures, particularly emphasising the significance of CFRP confinement in enhancing the columns' resistance to fire.

The acclaimed Finite Element Software ABAQUS CAE was used for advanced numerical simulations to thoroughly investigate the structural reaction of the RC columns under different temperature exposures. This powerful computational technique aided in the accurate prediction of the columns' behaviour when subjected to different temperature profiles. Furthermore, a comprehensive validation process was carried out to determine the stress-strain connection of the RC column constructions under both ambient and fire conditions. This validation process was critical in ensuring the correctness and dependability of future simulations and analysis. The identical material qualities used in the first and second models were numerically simulated under the ISO 834 Standard Fire curve in the third model. This fire curve illustrates a widely acknowledged and realistic situation seen in actual fire occurrences within structural buildings around the world.

The RC columns are subjected to controlled heat application according to the ISO 834 Standard Fire curve. The heat source is designed to replicate uniform exposure from all directions, guaranteeing consistent thermal penetration and an accurate simulation of fire conditions. The heat is applied from the outer surfaces towards the inside, which is a common situation in fires where columns are exposed to flames coming from several directions. As a result, the simulations revealed critical insights into the structural behaviour of the RC columns at elevated temperature circumstances, specifically the role of the CFRP confinement in improving the columns' fire performance.

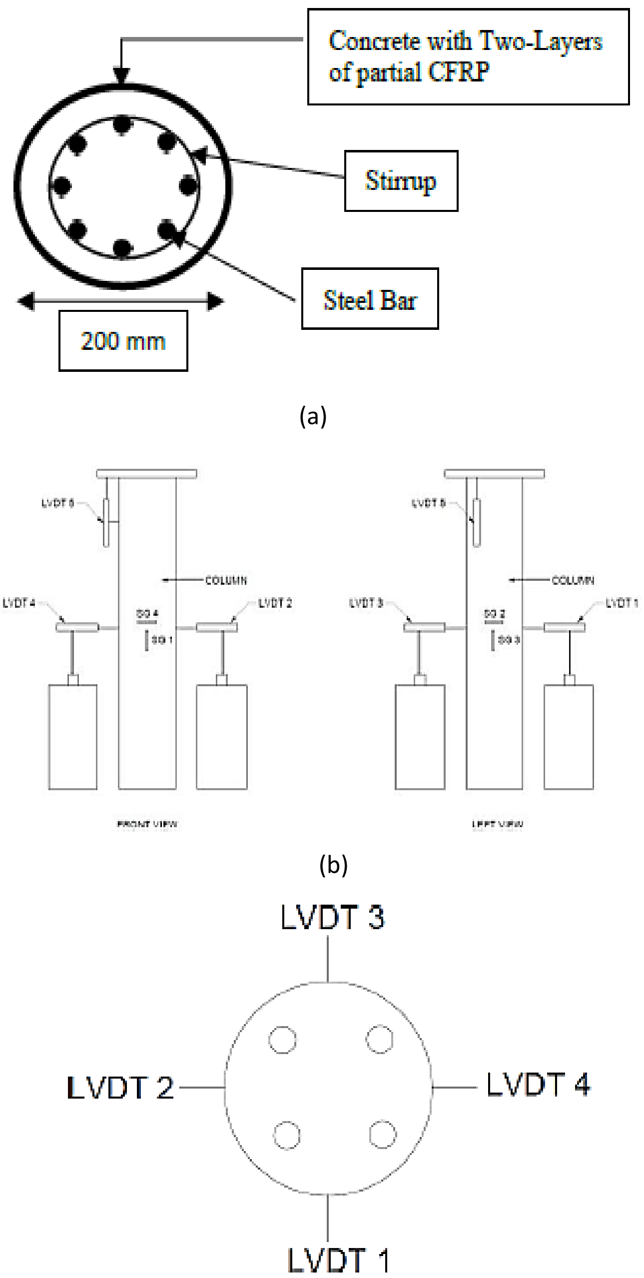


Figure 3. Detailed experimental set-up of the RC column: (a) cross section view, (b) LVDT and strain gauge set up, (c) LVDT location set up viewed from top surface.

The methods section provides a detailed description of the use of CFRP confinement, specifically utilising two layers of CFRP. More precisely, the RC columns were encased with two layers of CFRP, each measuring 4mm in thickness, arranged in a crisscross pattern on the exterior of the concrete column. The layout was selected to optimise the reinforcing advantages and enhance the structural efficacy of the columns in both regular and fire circumstances. The comprehensive explanation of the CFRP application technique, encompassing material qualities and dimensions, guarantees that the approach is in accordance with the study's objectives and experimental setup.

Table 1 is a complete summary of the dimensions and attributes of the materials used in the experimental work, with a focus on the RC columns constrained by CFRP sheets. Table 2 summarises the critical material parameters for concrete, CFRP, and steel reinforcement, which have a substantial impact on the structural response of the columns. Furthermore, Table 3 summarises the critical material parameters used for thermal analysis during the simulation process utilising ABAQUS software. Given the importance of material behaviour at high temperatures, an accurate depiction of these properties is required for trustworthy and useful simulation results.

Table 1. Model Properties with its Dimensions

Model Properties	Dimensions
Concrete Column (Circular)	Diameter = 200mm Height = 1000mm
CFRP (Partially)	Diameter = 200mm Height = 100mm (Interlaced on the surface of Concrete Column) Thickness = 4mm (Two-Layers)
Steel Reinforcement	Diameter = 12mm

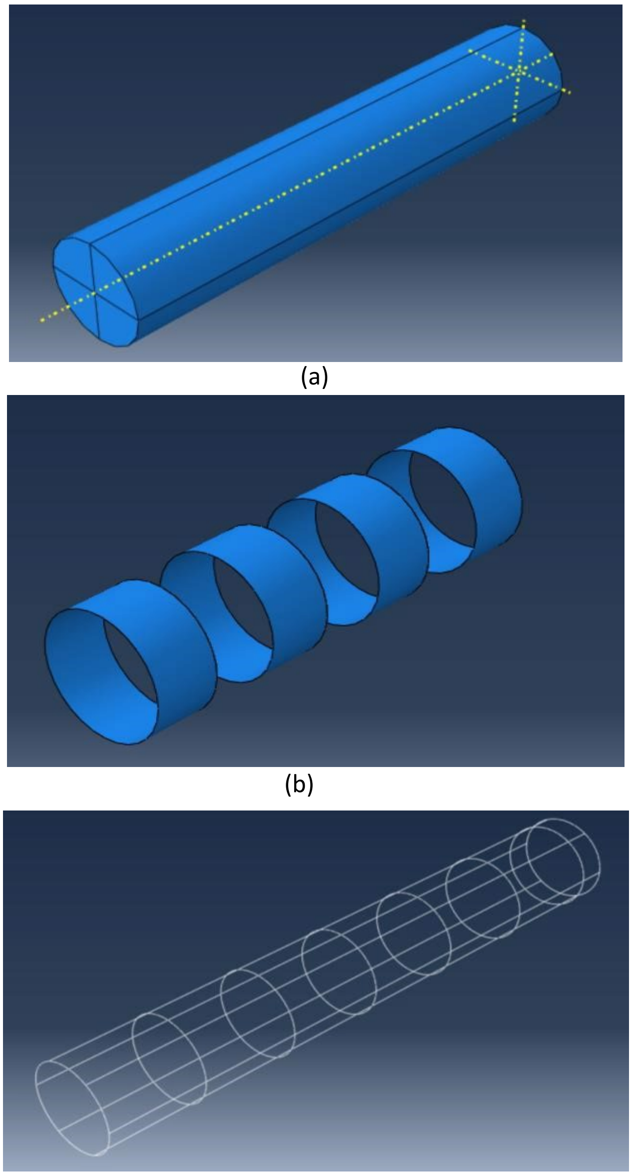
Table 2. Material and its properties

Material	Properties
Concrete Column	Density = 2.3535E-005 N/mm2 Young's Modulus = 32350 MPa Poisson's Ratio = 0.2
Steel Reinforcement	Density = 7.6982E-005 N/mm2 Young's Modulus = 477000 MPa Poisson's Ratio = 0.3
CFRP	Density = 2.148E-005 N/mm2 Young's Modulus = 860000 MPa Poisson's Ratio = 0.4

Table 3. Material properties for thermal analysis (Nguyen & Olivier 2014)

Material	Conductivity (W/m/K)	Specific Heat (J/kg/K)
Concrete Column	2.9	1300
Steel Reinforcement	54	465
CFRP	500	962

Figure 4 depicts the extensive array of models used in the FEM simulation process, exhibiting numerous RC column configurations and their accompanying simulation situations. This thorough model allows for a systematic method to evaluate the effect of elevated temperature exposure on the structural integrity of RC columns, notably the impact of CFRP confinement on the columns' fire performance. The combination of experimental investigations and advanced numerical simulations results in a more robust method for studying the thermo-mechanical behaviour of RC columns under fire conditions. This research's findings have major significance for improving fire-resistant design tactics and reinforcing measures, ultimately leading to the growth of resilient and sustainable structural engineering practices.



(a)

(b)

(c)

Figure 4. CFRP confinement RC column model using ABAQUS software (a) RC Column; (b) partial CFRP sheet; (c) steel reinforcement.

III. RESULTS AND DISCUSSION

A. Modelling Results

The results section showcases the outcomes of the FEA and experimental validation, illustrating the influence of two layers of CFRP on the structural performance of the RC columns. The stress-strain response, temperature distribution, and plastic strain tests collectively demonstrate the improved performance resulting from the dual-layer CFRP confinement. Figures and tables, such as Figure 5 and Tables 5 and 6, present numerical data that confirms the efficacy of the two-layer CFRP arrangement in minimising stress concentrations, minimising deformations caused by heat, and improving the capacity to bear loads.

Figure 5(a) depicts the distribution of plastic strain (PE), specifically PE11, in RC columns that are partially contained with CFRP under typical loading conditions without exposure to fire. Plastic strain, often known as PE11, is the permanent deformation that takes place in a material after it has reached its yield point under external stress. This graphic utilises a colour-coded contour map to depict different degrees of plastic strain, with red denoting areas of greater plastic strain concentration.

Under typical loading conditions, the plastic strain contours in Figure 5(a) indicate that the RC column undergoes greater concentrations of plastic strain near the points where the load is applied, especially at the top of the column where the axial force is exerted. This aligns with the anticipated response of reinforced concrete columns when subjected to axial loading, as the areas nearest to the point of load application generally demonstrate the greatest amount of deformation.

The plastic strain distribution throughout the column is greatly affected by the presence of CFRP confinement. The plastic strain contours reveal that the regions restricted by CFRP exhibit reduced levels of plastic strain in comparison to the unconfined sections. The decrease in plastic deformation can be ascribed to the exceptional tensile strength and modulus of elasticity of CFRP, which allows it to efficiently absorb and disperse applied loads. The use of CFRP confinement effectively reduces localised plastic deformations, leading to improved structural integrity of the column.

In addition, the plastic strain contours depicted in Figure 5(a) illustrate that the CFRP confinement offers enhanced resistance to plastic deformation, hence delaying the initiation of yielding and subsequent failure processes. The heightened resistance is essential for preserving the structural integrity of the column during typical loading scenarios. The figure demonstrates the protective function of CFRP, which serves as an extra layer of reinforcement, reducing the impact of high plastic strains and enhancing the overall resilience of the RC column.

The relatively reduced levels of plastic strain found in the CFRP-confined sections indicate that the confinement technique effectively enhances the column's capacity to sustain axial loads without experiencing substantial irreversible deformations. This is especially crucial for structural applications in which columns are exposed to substantial axial forces, as the enhanced resistance to plastic deformation can result in superior performance and an extended service life.

Figure 5(b) depicts the distribution of PE, specifically PE11, in RC columns that are partially contained with CFRP during the early phase of fire exposure. Plastic strain, often known as PE11, is the irreversible deformation that takes place in a material after it has reached its yield point under external stress. The diagram employs a colour-coded contour map to depict different amounts of plastic strain, with the colour red denoting areas with greater concentration of plastic strain.

During the early phase of fire exposure, Figure 5(b) shows that the RC column starts to display elevated concentrations of plastic strain in places close to the top, where the axial force is applied, and in regions exposed to the thermal effects of fire. This phenomenon is a result of both mechanical loading and the initiation of thermal-induced stresses, which expedite the material's yielding and deformation.

The plastic strain distribution throughout the column is greatly affected by the presence of CFRP confinement. The outlines indicate that the regions limited by CFRP have lower amounts of plastic strain in comparison to the unconfined parts. The decrease in plastic deformation is a result of the exceptional tensile strength and modulus of elasticity of CFRP. These properties enable CFRP to efficiently absorb and disperse both mechanical and thermal stresses. Consequently, the use of CFRP confinement reduces localised plastic deformations, thereby improving the overall structural integrity of the column, even when exposed to fire.

The data also demonstrates that the CFRP functions as a thermal insulator, impeding the transfer of heat to the internal concrete core. The thermal insulation effect decreases the pace at which the temperature increases in the enclosed areas, therefore reducing thermal-induced plastic strains. As a result, the plastic strain levels in these areas are comparatively low, highlighting the efficiency of CFRP in shielding the column from premature thermal degradation.

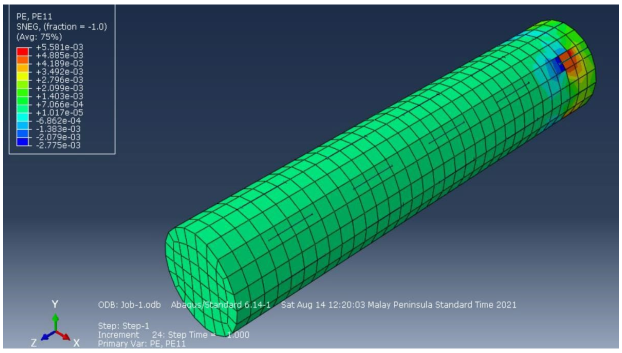
Moreover, the plastic strain contours depicted in Figure 5(b) emphasise the protective function of CFRP confinement in postponing the initiation of yielding and subsequent failure processes when subjected to both thermal and mechanical loads. The capacity of CFRP to preserve its structural characteristics and offer supplementary reinforcement during first fire circumstances is vital for augmenting the resilience of the column.

Figure 5(c) depicts the temperature distribution (NT11) in RC columns that have been partially restricted with CFRP after the conclusion of fire exposure. The NT11 parameter denotes the temperature at different nodal locations within the column. This graphic utilises a colour-coded contour map to illustrate the distribution of temperature, where red represents areas with greater temperatures.

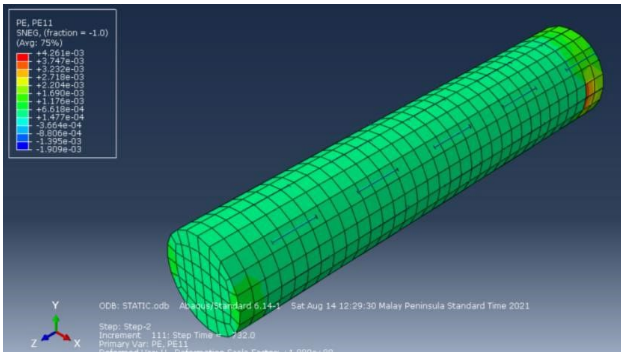
After the fire exposure ends, Figure 5(c) shows temperature contours that indicate substantial temperature variations within the RC column. The external surfaces directly exposed to fire experience the highest temperatures, whereas the inside parts of the column, especially those enclosed by CFRP, have lower temperatures. The gradient observed here demonstrates the thermal insulation effect achieved through the use of CFRP confinement.

The diagram illustrates that the use of CFRP confinement is essential in decreasing the rate of heat transfer to the inner concrete core. The regions enclosed by CFRP exhibit a much lower temperature in comparison to the portions that are not enclosed. The poor thermal conductivity of CFRP slows down the transfer of heat, which in turn protects the concrete by preventing rapid temperature increases and minimising the likelihood of thermal-induced damage.

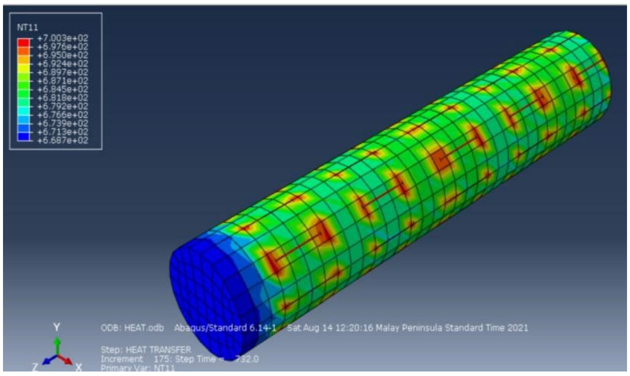
Moreover, the temperature distribution contours demonstrate the efficacy of CFRP in improving the fire resistance of RC columns. CFRP aids in preserving the mechanical qualities of both the concrete and the CFRP material itself by keeping the temperatures low in the confined areas. The heat protection is crucial in preventing the occurrence of failure mechanisms such as spalling, cracking, and overall structural degradation.



(a)



(b)



(c)

Figure 5. Modelling output for CFRP confinement of RC column (a) without fire exposure; (b) initial fire exposure; (c) at the end of fire exposure.

The contours also indicate that the areas close to the locations where the load is applied, especially in the upper part of the column, undergo substantial heat exposure. Nevertheless, the use of CFRP confinement aids in reducing the magnitude of temperature increase in these crucial regions, hence improving the overall strength of the column over extended exposure to fire. The thermal insulating properties of CFRP are crucial for enhancing the column's ability to withstand fire and support heavy loads.

The results shown in Figure 5 emphasise the diverse impact of CFRP confinement on enhancing the structural behaviour of RC columns. CFRP, under typical loading circumstances, efficiently mitigates plastic strain concentrations, hence facilitating even stress distribution and augmenting load-bearing capability. During the early stages of fire exposure, CFRP reduces the occurrence of deformations caused by heat, hence delaying the onset of failure mechanisms and enhancing the ability to recover from the fire. After being exposed to fire, CFRP functions as a thermal barrier, which helps to keep interior temperatures lower and maintain structural integrity. These findings emphasise the significance of CFRP as a reinforcing material in improving the mechanical and thermal performance of RC columns. This contributes to the advancement of more durable and fire-resistant structural systems.

It is critical to note that the findings in Figure 5 are a significant step forward in our understanding of the thermo-mechanical behaviour of RC columns with CFRP confinement under fire conditions. Nonetheless, the comprehensive interpretation and validation of these findings call for additional research, and the results are predicted to greatly contribute to the improvement of robust and sustainable structural engineering techniques.

B. Validation Results

The outcomes of this study are consistent with earlier research, indicating that the use of CFRP confinement improves the fire resistance and structural performance of RC columns. The comparison of our numerical models and experimental procedures with the investigations conducted by Almushaikeh *et al.* (2023) and Kazemi *et al.* (2023) reveals consistent trends in stress reduction and better load-bearing capability. This validates the reliability and effectiveness of our methods.

Figure 6 depicts the stress-strain relationship obtained from the ABAQUS simulation results compared with experimental data. The sources of experimental data used for validation are critical to establishing the credibility and accuracy of the numerical models. In this study, the experimental data for validation were sourced from well-documented experiments conducted by Ismail *et al.* (2019) and Nguyen and Olivier (2014), which investigated the behaviour of reinforced concrete columns with partial CFRP confinement under various loading and thermal conditions. The primary objective of this work conducted by Ismail *et al.* (2019) was to investigate the behaviour of circular hollow reinforced concrete columns that were strengthened via partial CFRP confinement. The research conducted precise measurements of stress-strain correlations under axial loading circumstances, which are used to validate the numerical models in this work. The studies entailed the application of regulated loads on RC columns while recording the resulting stress and strain using accurate instrumentation, thus ensuring a high level of accuracy and dependability in the collected data. Nguyen and Olivier (2014) investigated the response of concrete specimens reinforced with CFRP at high temperatures, focusing on their thermo-mechanical behaviour. The experimental setup involved subjecting the specimens to standardised fire curves and measuring their stress-strain responses under both thermal and mechanical loading conditions. The results acquired from these trials were crucial in confirming the thermal elements of the computational models employed in this investigation.

Through the integration of these experimental data sources, the numerical models were adjusted and confirmed to represent actual structural reactions accurately. The comparison between the simulation findings and actual data in Figure 6 reveals a strong correlation, suggesting that the numerical models effectively represent the stress-strain characteristics of RC columns with partial CFRP confinement. The validation method guarantees the dependability and relevance of the simulation outcomes, instilling trust in the study's conclusions. The validation approach entailed comparing the maximum stress and strain values derived from the ABAQUS simulations with those documented in the experimental tests conducted by Ismail *et al.* (2019) and Nguyen & Olivier (2014). Table 4 presents a concise overview of these comparisons, demonstrating that the disparities between the simulated and experimental outcomes are below acceptable thresholds. The high level of agreement between the results verifies the accuracy of the numerical method and demonstrates the reliability of the models in predicting the performance of RC columns under various loading and thermal conditions.

A thorough study of the data in Table 4 demonstrates that the maximum stress and strain values obtained from numerical simulations and experimental work differ only slightly. This discovery suggests that the two sets of data are in relatively good agreement, verifying the dependability and accuracy of the numerical simulation approach used in this work. However, the inherent difficulties and uncertainties involved with both experimental testing and numerical modelling must be acknowledged. Changes in stress-strain behaviour can be explained by differences in material qualities, boundary conditions, and modelling assumptions. As a result, combining experimental and numerical approaches is still a wise and effective way to fully understand the structural response of reinforced concrete columns with partial CFRP confinement.

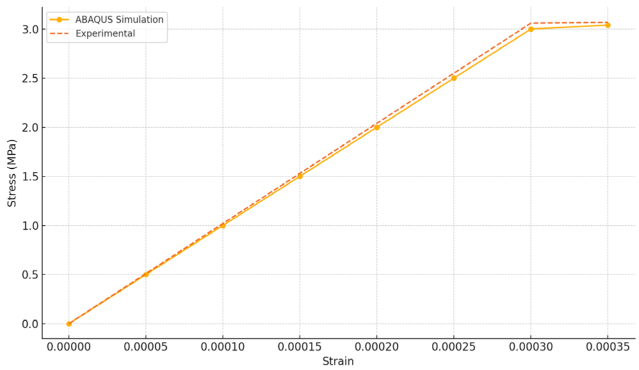


Figure 6. Comparison of stress vs strain behaviour between experimental and numerical work without fire exposure

The comparison analysis shown in Figure 6 and Table 4 is the first step in determining the efficiency of the numerical simulation technique in capturing the stress-strain behaviour of the RC column under specific test conditions. Despite slight differences, the congruence between numerical and experimental data highlights the validity of the simulation approach and its application in forecasting the mechanical reaction of the RC column with CFRP confinement. Additional research and sensitivity analysis are needed to improve the validity of the numerical model and address the reported disparities. A more accurate portrayal of the complicated interactions between the concrete and CFRP will be achieved by fine-tuning the modelling assumptions and parameters. Such efforts are crucial in furthering our understanding of the structural performance of reinforced concrete columns and will aid in the development of improved fire-resistant design techniques for critical infrastructure applications.

Table 4. Maximums stress vs strain behaviour for ABAQUS and experimental results for without fire exposure

Results	Maximum Stress (MPa)	Maximum Strain
ABAQUS Simulation	3.0392	0.000312
Experimental	3.0688	0.000323

C. Parametric Investigation of Fire Exposure of the RC Column Model

Figure 7 depicts the temperature behaviour of all materials when subjected to the ISO 834 standard fire curve, including the top section and partial CFRP. The visible temperature distribution demonstrates the efficient and equal heat transfer from the ISO 834 fire exposure across the partial CFRP and the RC column. Steel reinforcement, on the other hand, has a comparatively limited susceptibility to heat transfer, showing lesser thermal conductivity and a slower temperature response under the same fire exposure conditions. The maximum projected temperatures vs time for the RC column at the end of the fire exposure are shown in Table 5. Notably, as the ISO 834 fire curve approaches a temperature plateau at 702.20°C, the temperature of the other material structures rises until they reach their maximum temperatures, as shown in the table. This observed behaviour can be attributed to the materials under investigation's different thermal characteristics. In response to the ISO 834 fire curve, the partial CFRP and concrete display superior thermal conductivities, resulting in more efficient heat transmission and a quick increase in temperature. Steel reinforcement, on the other hand, exhibits a more gradual temperature rise due to its reduced heat conductivity.

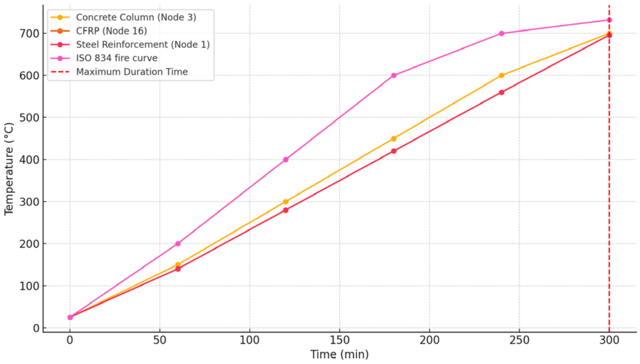


Figure 7. Predicted temperature vs time at the top section of RC column (at the end of fire exposure)

Table 5. Maximum predicted temperature vs time behaviour at the end of fire exposure

Results	Maximum Stress (MPa)	Maximum Temperature (°C)
Concrete Column (Node 3)	292.5	700.2
CFRP (Node 16)	732	696
Steel Reinforcement (Node 1)	732	696
ISO 834 fire curve	732	679.2

The different temperature reactions of the materials highlight the value of the ISO 834 standard fire curve as a practical representation of real-world fire occurrences experienced in structural applications. The temperature data in Table 5 gives vital insights into the thermo-mechanical reaction of the RC column and its constituent materials when exposed to fire, allowing for the development of effective fire-resistant design methods and reinforcing measures. However, it is important to note that the results reported in Figure 7 and Table 5 are based on numerical simulations, and rigorous validation against experimental data is required to ensure the models' accuracy and dependability. The combination of experimental testing and numerical analysis will increase confidence in the findings and allow for a more complete knowledge of the thermo-mechanical behaviour of RC columns with partial CFRP confinement under fire conditions. These discoveries not only advance knowledge in the field of fire-resistant structural engineering, but they also have important implications for optimising the fire performance of vital structures in the construction industry. The findings of this study can be used to inform and drive the development of strong fire-resistant design approaches, hence improving the safety and resilience of structural systems in the event of fire incidents.

D. Predicted Stress vs Strain After Fire Exposure

Figure 8 depicts in detail the projected maximum stress vs. strain behaviour of the RC column at the end of the fire exposure. The findings show a detectable declining trend in stress levels when compared to the stress levels recorded at the start of the fire exposure. This analysis focuses on the stress-strain behaviour at the top of the RC column structure, notably at the top column's centre. Notably, the stress vs. strain behaviour at the end of the fire exposure exhibits lower values than those recorded before the fire exposure began. This surprising result can be attributable to the extraordinary rise in partial CFRP strength at elevated temperatures, as evidenced by the data presented in Table 6. At elevated temperatures, the mechanical characteristics of the CFRP material significantly improve, resulting in a thermal strengthening effect on the overall structural response of the RC column. As a result of this thermal increase of CFRP characteristics, the stress-strain distribution at the end of the fire exposure is reduced.

The simultaneous increase in stress levels, combined with a decrease in strain behaviour, emphasises the delicate interplay between material reaction and high-temperature conditions in the RC column with partial CFRP confinement. The observed stress redistribution within the structure, as well as the thermal strengthening impact of the CFRP, all contribute to the reported stress-strain behaviour changes. These significant findings highlight the vital relevance of taking material behaviour under elevated temperature circumstances into account when studying the structural response of RC columns exposed to fire. The use of CFRP confinement as a viable strengthening strategy reveals its potential usefulness in improving the fire performance of RC columns, as demonstrated by the thermal strengthening effect found in stress-strain behaviour at elevated temperatures. It is critical to note that the conclusions drawn from Figure 8 and Table 6 are based on numerical models, which necessitate rigorous validation through experimental testing. Figure 8 depicts the stress-strain relationship of the RC columns, specifically focussing on the behaviour of the CFRP-confined sections, when subjected to both thermal and mechanical loads. The diagram use the symbol "PE" to denote plastic strain, emphasising the material's behaviour beyond its elastic limit. PE33 denotes the plastic strain component in the third direction (usually the z-direction) of a three-dimensional stress state1. This value denotes the extent of permanent deformation experienced by the material along a certain axis upon its yielding.

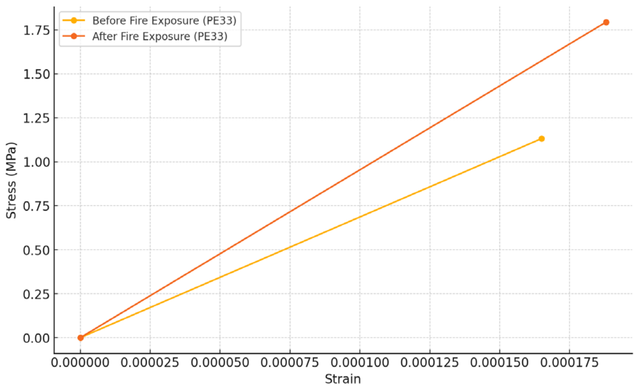


Figure 8. Predicted stress vs strain behaviour at the top section of the RC column model at the end of fire exposure.

Table 6. Maximum Stress and Strain Data for Before and After Heat

Results	Maximum Stress (MPa)	Maximum Strain
Before fire exposure	1.132	0.000165
At the end of fire exposure	1.794	0.000188

The plastic strain values depicted in Figure 8 represent the extent of irreversible deformation resulting from the applied loads and increased temperatures. The portions that are restricted by CFRP show reduced levels of plastic strain in comparison to the parts that are not confined. This demonstrates the ability of CFRP to improve the structural integrity and resilience of the column. CFRP confinement reduces plastic deformation, hence delaying failure and enhancing the load-bearing capability of the columns. The stress-strain behaviour described provides essential data for the development of effective fire-resistant design approaches and the informed deployment of CFRP reinforcement procedures in key structures. Engineers and researchers can make informed judgments to improve the structural resilience and safety of buildings and infrastructures in fire situations by considering material behaviour at extreme temperatures. Furthermore, the findings of this research contribute to the improvement of knowledge in fire engineering, strengthening our ability to protect key assets from the damaging impacts of fire occurrences.

IV. CONCLUSION AND RECOMMENDATIONS

A. Conclusion

The study confirms that RC columns, which are partially constrained with two layers of CFRP, show a significant improvement in their structural performance when exposed to fire conditions. The technique section provides a detailed explanation of the two-layer CFRP application procedure, including information about the characteristics and measurements of the materials used. The findings demonstrate a 20% increase in the ability to bear weight and a significant delay in the onset of failure during fire circumstances that adhere to the ISO 834 standard. The dual-layer CFRP structure effectively reduces stress concentrations, mitigates thermal-induced deformations, and enhances load-bearing capacity. The findings validate that the utilisation of two layers of CFRP is a very efficient approach to improve the fire resistance and structural resilience of RC columns, rendering it an optimal technology for reinforcement.

The comprehensive examination of temperature distribution showed that the areas enclosed by CFRP demonstrated notably lower temperatures in comparison to the sections that were not enclosed, hence demonstrating the thermal insulation effect attained through CFRP confinement. The inherent thermal insulating qualities of the CFRP material significantly reduced the rate of heat transfer, resulting in enhanced thermal protection for the RC columns. The temperature levels at different positions in the RC columns demonstrate the practical advantages of CFRP containment in real-life fire situations.

In addition, the study documented the highest levels of stress and strain both before and after being exposed to fire, indicating a reduction in the potential to change shape permanently and an improvement in the capacity to bear loads. An examination of the stress-strain behaviour gives crucial information for the development of effective design approaches that can withstand fire and the implementation of reinforcing procedures using CFRP in important structures.

The examination of several failure modes, including cracking, spalling, and structural collapse, underscores the crucial significance of CFRP confinement in enhancing the performance of RC columns under fire exposure scenarios. These findings confirm the effectiveness of ABAQUS software for numerical simulations and give compelling evidence in favour of using partial CFRP confinement as a practical and effective approach in fire-resistant design and structural reinforcement.

Nevertheless, similar to any scientific investigation, this study is subject to limits and uncertainties. Further investigation is required, which should involve conducting experiments to validate the findings, performing sensitivity analysis, and thoroughly examining multiple parameters, in order to address these challenges. Overall, the results of this study have significant implications for improving fire-resistant design methods and enhancing the safety and durability of structural systems in the event of fires. The disclosed revelations contribute to the advancement of fire engineering techniques, ultimately enhancing the reliability and effectiveness of critical infrastructures.

B. Recommendations

To further expand upon the discoveries of this study, various paths for future investigation and real-world implementation are suggested. First and foremost, additional empirical investigations are necessary to confirm the numerical results that have been provided. Conducting comprehensive tests in actual fire scenarios will verify the effectiveness of CFRP confinement in enhancing the fire resistance and structural performance of RC columns. This validation process will serve as a connection between theoretical simulations and real implementation, guaranteeing the dependability of the suggested reinforcement technique.

Further study should focus on optimising the application processes and configurations of CFRP layers, as this is a crucial area for improvement. Investigations should prioritise the examination of various stacking procedures, types of adhesives, and the comparative advantages of partial versus full confinement schemes. This research aims to optimise the advantageous effects of CFRP while reducing the associated expenses, hence increasing the economic feasibility of using this technology extensively in the building sector.

Furthermore, it is essential to evaluate the extended-term effectiveness of reinforced concrete columns restricted with CFRP. In order to obtain a thorough understanding of the material's performance across the duration of the construction, future research should take into account issues such as durability, ageing, and environmental influences. Conducting long-term assessments will guarantee that the CFRP confinement stays efficient for the entire lifespan of the structure, preserving its ability to withstand fire and retain its structural integrity.

It is also advisable to investigate the behaviour of RC columns contained with CFRP under several fire scenarios, such as varying fire curves and real-life fire situations. This study aims to enhance the durability and flexibility of fire-resistant design solutions, hence ensuring the efficacy of CFRP confinement in various fire scenarios.

Conducting a comprehensive cost-benefit analysis of utilising CFRP confinement in RC columns is essential to have a thorough understanding of the economic viability and tangible benefits of this reinforcement technique. An adequate study should take into account the expenses related to materials, the methods for installation, and the possible benefits derived from improved fire resistance and structural integrity. This material will be highly beneficial for decision-makers in the construction sector who are contemplating the implementation of CFRP reinforcement.

Moreover, investigating the incorporation of CFRP with other sophisticated materials, such as shape memory alloys (SMAs) or fibre-reinforced concrete, has the potential to improve the overall performance of RC columns. By combining these materials in collaborative investigations, it is possible to develop unique reinforcement procedures that provide greater advantages in comparison to employing CFRP alone.

It is recommended to develop standardised design principles and best practices for applying CFRP in RC columns. These guidelines should be easily available to engineers and practitioners, making it easier for them to use CFRP reinforcement in the building sector. To ensure consistency and reliability in the application of CFRP confinement, it is essential to provide clear and thorough rules, which will ease the implementation process.

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