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Nonlinear Finite Element Analysis of RC Beam Exposed To Fire With and Without CFRP Strengthening

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Abstract. The Nonlinear finite element (FE) model can accurately predict the behaviour of reinforced concrete (RC) with the RC beam's safety with and without CFRP that is designed for resistance against high temperatures. Transient thermal finite element analysis is performed using the ANSYS software. The beam was subjected to a short-duration, high-intensity (SDHI) fire at the bottom and side surfaces, in the form of transient temperatures versus time, whereas maintaining constant transversal loading on the highest body. The validation of the finite element model without CFRP is confirmed by comparing the results with experimental testing results that are carried out at similar model conditions within the same geometry, reinforced, and boundary conditions. After that, added the carbon fiber reinforced polymer sheet (CFRP) at the bottom and side surfaces of the RC beam during fire exposure as a parametric study to investigate the effect of CFRP on the strength and stiffness of the RC beam at high temperatures. The results showed that CFRP strengthening would have a significant impact on RC beam stiffness.

1. Introduction

One of the world's most important structural systems is reinforced concrete (RC). It is composed of concrete and steel. Concrete as a structural material has several advantages: high compressive strength, durability, and low thermal conductivity. Concrete protects reinforcing steel bars from high temperatures due to its high thermal conductivity. Although RC structures have many benefits, including fire resistance, its mechanical properties may degrade at high temperatures.

1.1. Fire basics

There are many reasons why fire originates, and three elements depend on it: oxygen, the fuel material, and the heat source, which can be represented by the triangle of fire shown in Fig 1. Increased fire exposure when one of these elements is increased(1)



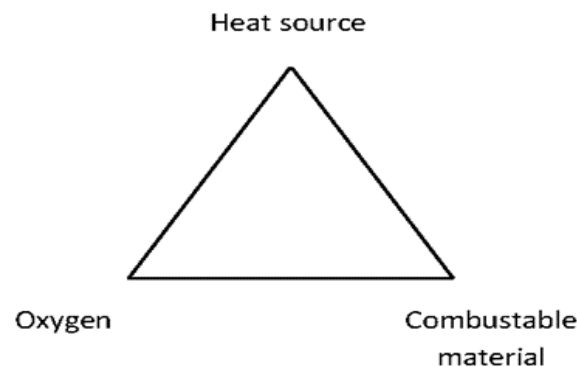


Figure 1. The fire triangle.

1.2. Fire resistance

By applying certain minimum concrete cover conditions, minimum section dimensions, the fire resistance requirement is usually indirectly used in a structural design. Although RC components are non-combustible materials, due to exposure fire, their strength and rigidity properties deteriorate. Such effects lead to a decrease in the load-bearing capacity of the structural elements affected (2). So, fire safety is now one of the most important considerations in construction applications.

1.3. Carbon fibre reinforced polymer (CFRP)

Due to their high flexural performance, lightness and corrosion resistance (3), carbon fibre reinforced polymer (CFRP) laminates are used to strengthen RC elements, particularly on columns and beams. It can be easily used by bonding epoxy resins to the concrete member to provide additional flexural strength. This research presents an investigation into the bending behavior of fired RC beams with and without CFRP laminate reinforcement.

1.4. Previous studies

The effect of fire on the RC beam has been studied in many references, whether relevant to FE applications or experimental tests. The literature (4) examined the flexural and shear behaviour of the RC continuous beam in 1991. Four RC beams were exposed to the ASTM E119 standard fire, and two to a short-duration high-intensity (SDHI) fire. Shear cracks produced near the continuous support for six beams rather early in the fire but eventually failed from the flexural crack. Another study has studied RC beams' shear behaviour subjected to fire in the shear zone for a different period (5). The results showed that fire on the compressive strain is greater than its impact on the tensile strain, and as the exposure time to fire increases, the compressive strength decreases. According to Eurocode 2 [6], high temperatures affect the mechanical properties of concrete and steel.

Concrete compressive strength decreases from 9 % to 15 % relative to ambient temperature, mainly above 300 to 400°C. On the other hand, code showed that the tensile strength of concrete decreases from 40 % to 60 % relative to ambient temperature at the same temperature, respectively. The previous studies that will increase the shear crack with high temperatures support this decrease in concrete's tensile strength. For steel, Eurocode 2 (6) showed that the modulus of elasticity and steel strength would also decrease at temperatures above 400°C. Steel behaviour under high temperatures has been studied in the literature (7). The results showed that the mechanical properties of steel significantly influence temperatures above 400 °C to 500 °C. Research (8) has also studied the temperature-dependent relationships of concrete properties at different temperatures simultaneously. The research shows that as the heating rate increases, the concrete stress-strain relationship elongates in strain and shortens in stress. Literature (9) has studied the effect of fire on the behaviour and load-carrying capacity of rectangular RC rigid beams. Test results indicate a significant decrease in load capacity and an increase in the maximum crack width with increasing fire temperature. Literature[3] presented the results of an experimental study on the flexural behaviour of (RC) beams reinforced with

CFRP laminates in fire attacks about CFRP-reinforced RC beams' behaviour under fire. The results showed that all beams with fire protection materials for long fire exposure periods provided their resistance integrity.

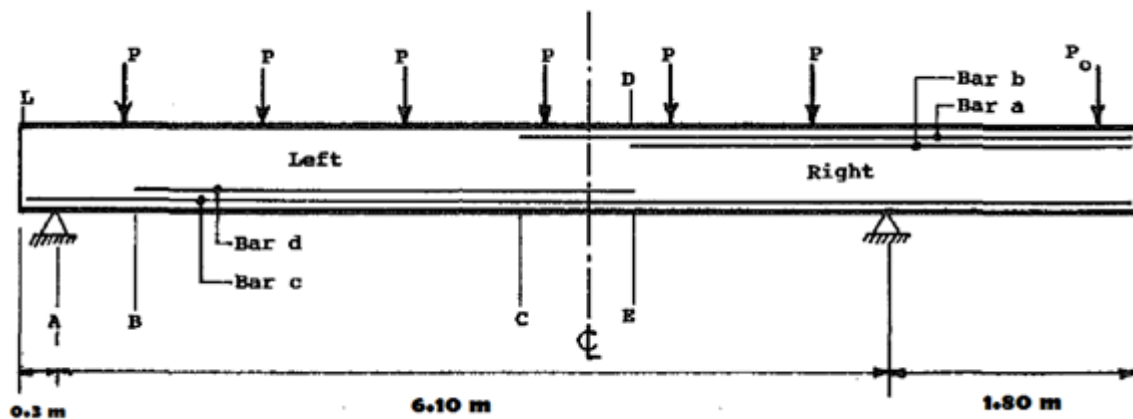


Figure 2. Detailing of the RC beam.

This paper aims to develop a three-dimensional nonlinear finite element (FE) model that is capable of accurately predicting the flexural behavior of RC that designed for resistance against high temperatures. Transient thermal-stress FE analysis is performed using the ANSYS 16 software (10).

2. Finite element model

2.1. Geometry

The RC beam's FE model has the same conditions, geometry, and dimension as beam number 5 tested by research (4) as shown in Fig.2. The RC beam section is rectangular, 225 mm width and 525 mm depth, and has a 6.1 m span and 1.8 m cantilever. There are two layers of bottom reinforcement and two layers of top reinforcement. The Bottom bars diameter is 22 mm, while the top reinforcement diameter is 25 mm. Bars lengths, diameters and spacing are given in Table.1 and Table.2. The Stirrups diameter is 10 mm. the rebar cover is 40 mm. The values of P , P_o are 44.48kN and 115.6kN, respectively.

Table 1. Details of reinforcement.

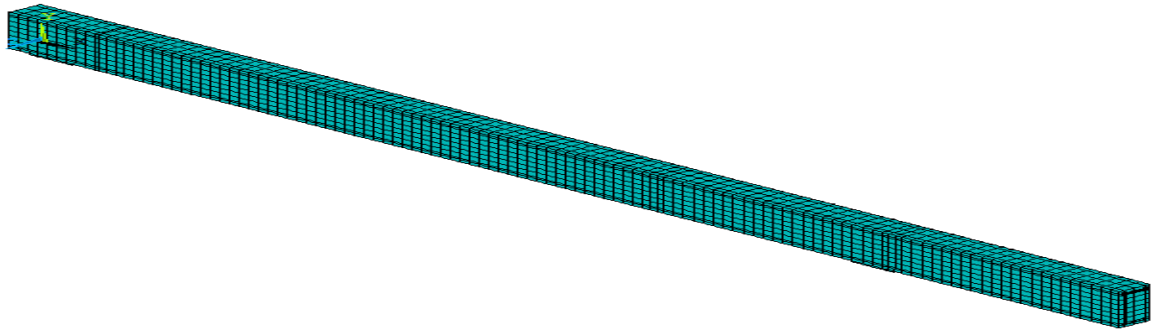
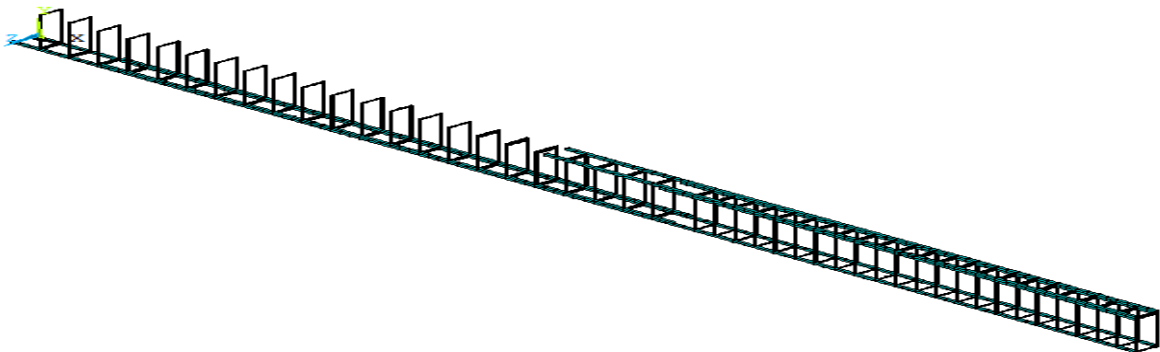
Spacing Stirrups (mm)		Bar Size (mm)			
Left	Right	a	b	c	d
215	145	25	25	22	22

Table 2. Bars Locations.

Bar End Location from L (mm)				
A	B	C	D	E
30	66	390	475	485

2.2. ANSYS finite element model

ANSYS 16 (10) was used to build the FE model. Solid65 element is used for concrete, while link180 is used for steel bars to solve structural analysis. In contrast, solid70, link33 and shell131 elements are used for concrete, steel, and CFRP, respectively, to simulate heat conduction in thermal analysis. Solid185 is used for steel plates as linear isotropic material, while shell181 is used for the CFRP sheet as an orthotropic material. Fig.3 and Fig.4 show the isometric view of the FE model of RC beam and steel reinforcement, respectively

**Figure 3.** Isometric view of the FE model of RC beam.**Figure 4.** Isometric view of Steel Reinforcement of RC beam.

The distributions of thermal were calculated first; then, performed the structural analysis by switching solid70 and link33 thermal elements to solid65 and link180 structural elements. The concrete material behaviour was based on a constitutive model for concrete's triaxial behaviour after Williams and Warnke model (10). It is a non-metal plasticity model with isotropic hardening. The failure criterion of concrete due to multi-axial stress is expressed in the form (10):

$$\frac{F}{f_c} - S \geq 0 \quad (1)$$

Where:

F: a function of principal stress state

S: failure surface

F_c: uniaxial concrete strength.

If equation 1 is satisfied, the material will crack or crush (10). The thermal analysis basis, assuming no internal heat generation, is a heat balance equation obtained from the principle of conservation of Energy (2).

$$k \frac{\partial^2 T}{\partial x^2} + k \frac{\partial^2 T}{\partial y^2} + \rho \cdot c \cdot \frac{\partial T}{\partial t} \quad (2)$$

Where:

C: specific heat coefficient.

K: thermal conductivity coefficient.

t: time.

T: temperature

2.3. Material Properties

Table.3 illustrates the material properties of concrete, steel reinforcement (2) and CFRP laminate (11) at ambient temperature. The thickness of the CFRP sheet is 0.166 mm.

Table 3. Material Properties of Concrete and Steel Reinforcement at Ambient Temperature(4,11)

Material	Concrete	Steel Bars	CFRP
Density (kg/m ³)	2400	7800	1510
Modulus of Elasticity (GPa)	26.7	200	170.9
Compressive Strength (MPa)	35	-	-
Tensile Strength (MPa)	3.66	412	2742
Poisson's Ratio	0.2	0.3	0.3
Thermal Conductivity (W/m ² °C)	1.2	60	1.38
Specific Heat (J/kg°K)	1000	500	1200

Used Euro code 2 (4) for temperature-dependent Material properties of concrete and steel.

Table.4. illustrated the degradation of concrete strength as the concrete temperature increases. The tensile strength reduction factor of concrete as temperature increases is illustrated in Fig.5.

Table.5. presented the temperature-dependent strength and modulus of elasticity of steel reinforcement as the temperature increases.

Table 4. Temperature-Dependent Relationship of Concrete compressive strength (4).

Concrete °C		Calcareous aggregates	
temp. θ	$f_{c\theta}/f_{ck}$	$\varepsilon_{c1-\theta}$	$\varepsilon_{cu1-\theta}$
1.00	5.00	6.00	7.00
20.0	1.00	0.0025	0.02
100	1.00	0.004	0.0225
200	0.97	0.0055	0.025
300	0.91	0.007	0.0275
400	0.85	0.01	0.03
500	0.74	0.015	0.0325
600	0.60	0.025	0.035
700	0.43	0.025	0.0375
800	0.27	0.025	0.04
900	0.15	0.025	0.0425
1000	0.06	0.025	0.045
1100	0.02	0.025	0.0475
1200	0.00	-	-

Table 5. Temperature-Dependent Relationship of Steel Reinforcement (4).

Steel Temperature		
$\theta(^{\circ}\text{C})$	$f_{sy\theta}/f_{yk}$ hot rolled	$E_{s\theta}/E_s$ hot rolled
1.00	2.00	6.00
20.0	1.00	1.00
100	1.00	1.00
200	1.00	0.90
300	1.00	0.80
400	1.00	0.70
500	0.78	0.60
600	0.47	0.31
700	0.23	0.13
800	0.11	0.09
900	0.06	0.07
1000	0.04	0.04
1100	0.02	0.02
1200	0.00	0.00

2.4. Boundary conditions

The FE model is roller supported at the right plate and pin supported at the left plate. The load is applied, as shown in Fig.2. The thermal load is applied at the bottom, and side surfaces of the beam are by convection with a film coefficient of 50 W/m²/c (2) according to SDHI fire exposure (4) as shown in Fig.6. The top surface is exposed to ambient temperature.

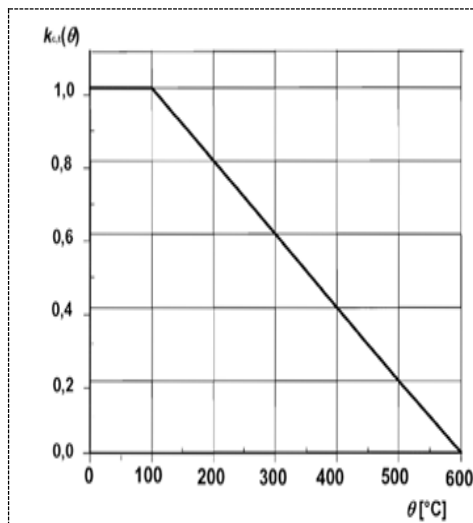


Figure 5. Concrete tensile strength reduction factor as temperature increases (4).

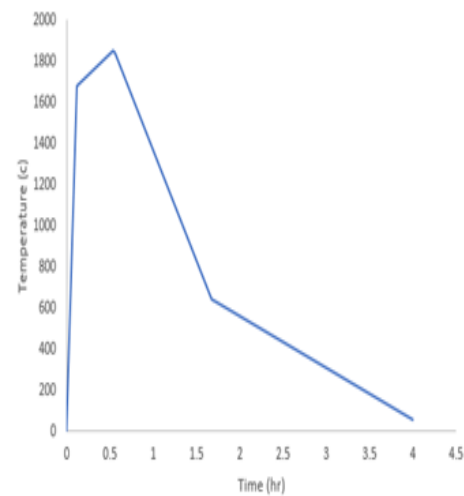


Figure 6. SDHI fire exposure curve (4).

CFRP laminate is bonded by epoxy at the RC beam's bottom and side surfaces after fire exposure, with maintaining constant transverse loading. The temperature-dependent material properties of CFRP are used according to Nasser M. (11) as shown in Fig.7.

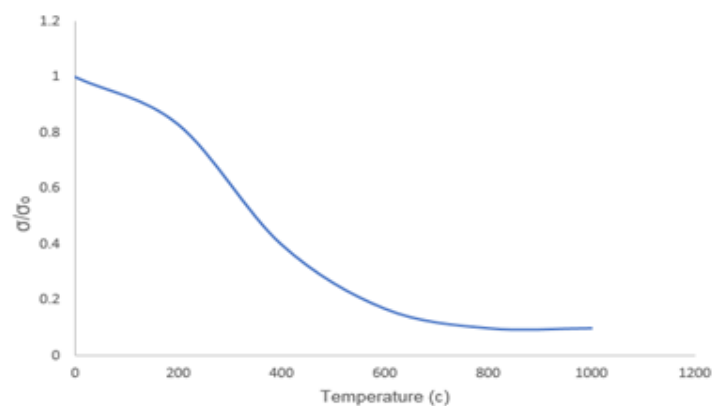


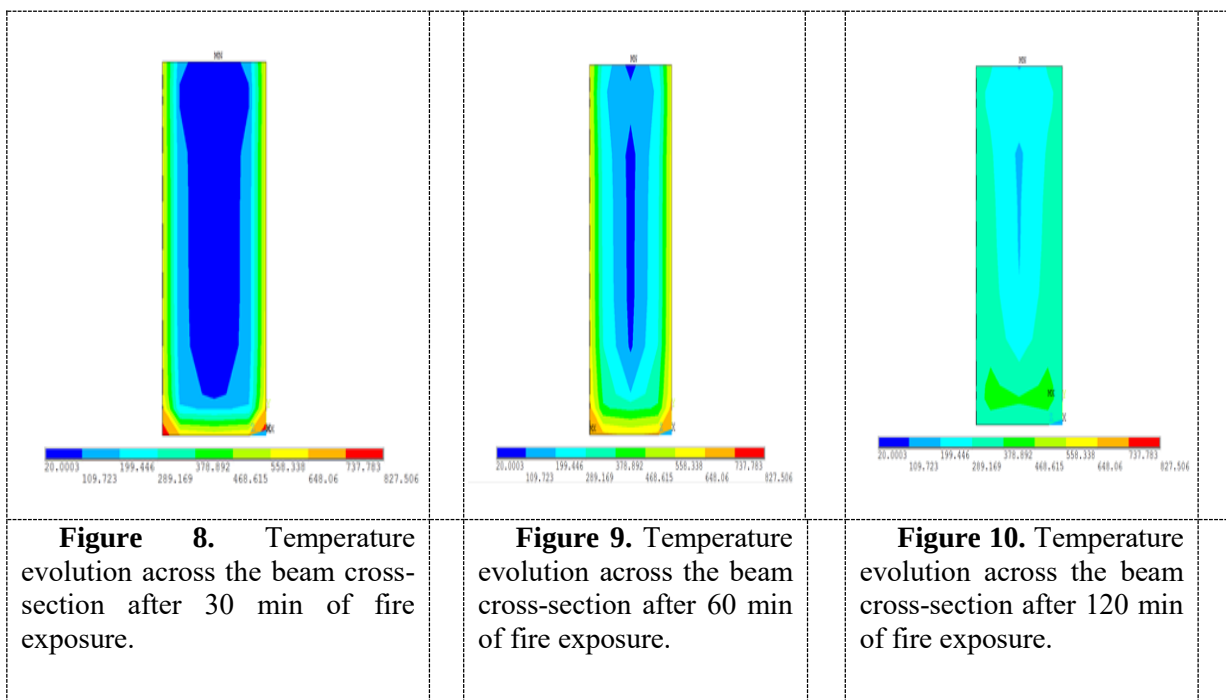
Figure 7. Comparison of strength degradation of CFRP (11).

3. Results and discussion

3.1. FE Model without CFRP

Validated The FE model without CFRP by comparing the model solution with beam five from the literature's experimental results (4). The FE model results were obtained after applied transient temperatures versus time, SDHI fire exposure, at the bottom and side surfaces of the beam while maintaining constant transverse loading on the top surface.

Fig.8, Fig.9, and Fig.10 illustrate the temperature evolution along the RC beam's cross-section after 30, 60 and 120 min of fire exposure time, respectively. The Figures show that the temperature distribution increases toward of cross-sectional center with increases in fire exposure time.



Comparing the FE model without CFRP with beam five from experimental results of literature (4) is illustrated in Fig.11. The deflection at mid-span during fire results is compared until 2 hours of fire exposure; the deflection is in the highest value. Fig.12. shows the deflection shape for FE model at the maximum deflection.

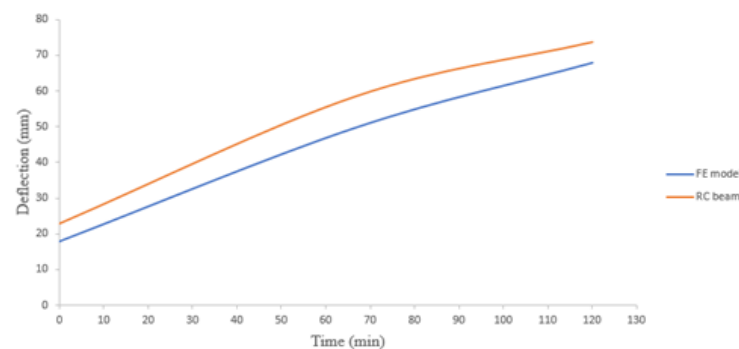


Figure11. Maximum deflection for FE model without CFRP And specimen during the fire exposure time.

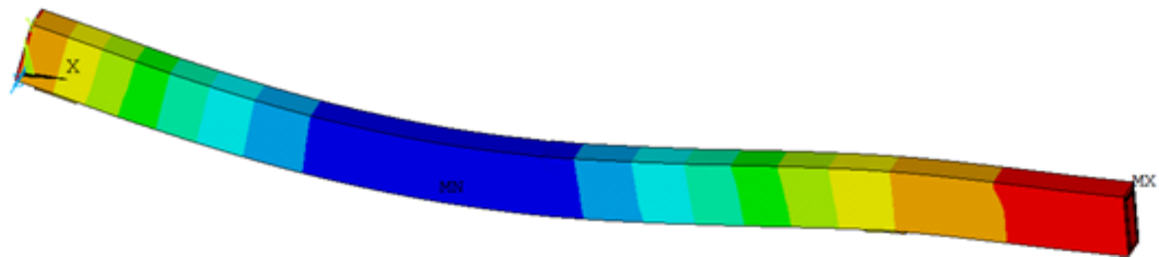


Figure 12. The Deflection Shape for FE Model.

The value of deflection for the FE model is less than that of the specimen. This is because the FE model does not include the degradation of the bond between concrete and steel due to crack propagation at elevated temperatures.

The crack formation of the FE model without CFRP at failure that resulted from the nonlinear thermal and mechanical load after 2 hr of fire exposure is shown in Fig.13. The figure shows that the diagonal shear crack is formed near supports, and it was very excessive.

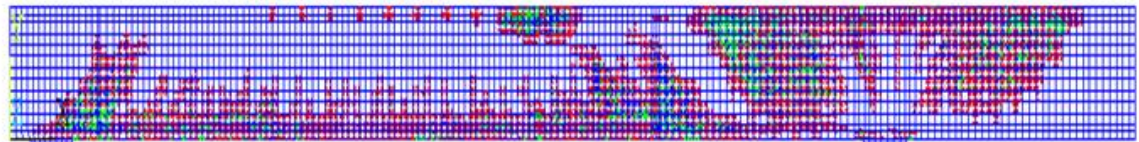


Figure 13. Cracks of the FE model without CFRP at Failure.

3.2. FE Model with CFRP

The carbon fibre reinforced polymer sheet (CFRP) is added at the RC beam's bottom and side surfaces during fire exposure as a parametric study. Fig.14, Fig.15 and Fig.16 illustrate the temperature evolution along the RC beam's cross-section with CFRP after 30, 60 and 120 min of fire exposure time, respectively.

Figure 14. Temperature evolution across the beam cross-section with CFRP after 30 min of fire exposure.	Figure 15. Temperature evolution across the beam cross-section with CFRP after 60 min of fire exposure.	Figure 16. Temperature evolution across the beam cross-section with CFRP after 120 min of fire exposure.

Fig.17 shows the comparison of deflection at mid-span for the FE model with CFRP during fire results with the specimen tested without CFRP. The crack formation of the FE model with CFRP at failure that resulted from the nonlinear thermal and mechanical load is shown in Fig.18.

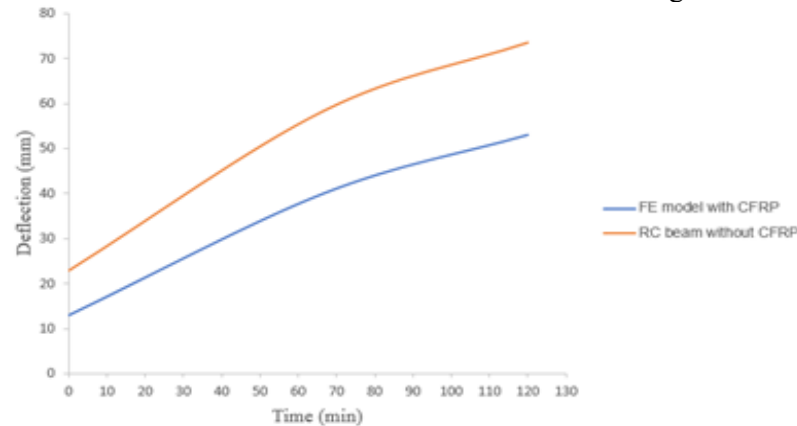


Figure. 17. Maximum deflection for FE model with CFRP And specimen during the fire exposure time.

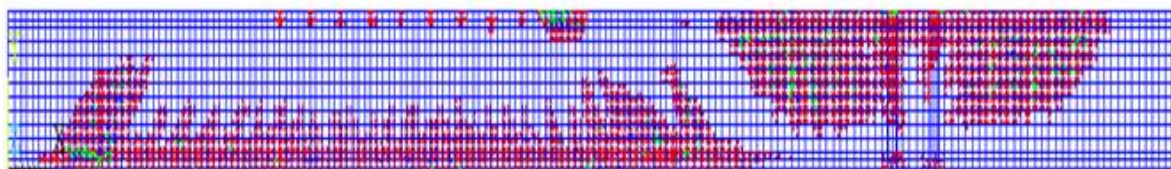


Figure 18. Cracks of the FE model with CFRP at Failure.

4. Conclusions

A finite element model was used to study the RC beam's behaviour with and without CFRP subjected to SDHI fire and service loading. Found the following conclusions were after analyzing the results:

- The FE model succeeded in describing the RC beam's behaviour without CFRP during fire attack and validated the results with the same specimen from experimental results.
- Steel reinforcement and tensile strength of concrete are more sensitive to elevated temperatures that developed during the fire, than concrete compressive strength.
- The sensitivity of concrete stiffness is less than of steel reinforcement.
- The maximum deflection at mid-span increased during a fire; this was referred to as the stiffness loss as temperature increased.
- The maximum deflection for the FE model with CFRP at elevated temperatures decreased by 22% compared with the FE model without CFRP; this referred to that CFRP sheet added more stiffness.
- The diagonal shear crack that formed near of supports at elevated temperatures was very excessive; this is attributed to the high reduction of concrete tensile strength with high temperature.
- The RC beam is designed to fail in flexure at ambient conditions, but the failure changed during fire attack; this is attributed to the high reduction of the shear reinforcement and the concrete tensile with elevated temperature.
- Added CFRP sheet to the RC beam will decrease the cracks; this shows clearly by comparing the crack formation of the FE model with CFRP and the FE model without CFRP.

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