NUMERICAL INVESTIGATION OF FRP-STRENGTHENED REINFORCED CONCRETE BEAMS AT HIGH TEMPERATURES

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ABSTRACT

Fiber reinforced polymers (FRP) strengthening systems are mainly used to retrofit existing and deficient structural members. The performance of such strengthened structures at elevated temperatures is a critical issue that threatens the safety of the structure. Published research includes experimental testing of reinforced concrete (R.C) beams strengthened using FRP and subjected to fire tests. However, there is a need for numerical tools that simulate the performance of these FRP-strengthened elements in case of fire. This research work presents numerical modelling and nonlinear analysis conducted to assess the performance of reinforced concrete beams strengthened with externally bonded carbon FRP sheets when subjected to standard fire conditions. Finite element model using the general purpose software ANSYS 12.1 is developed and validated with experimental results published in the literature by other researchers.

The developed finite element model achieved good correlation with the experimental results. Further, application of the validated finite element model is extended into a parametric study to explore the influence of different variables on the performance of the FRP system when subjected to fire. Different aggregate types, moisture contents, concrete cover thickness, insulation material types and insulation material thickness are included in the study. The developed finite element model is thus regarded a valid and economical alternative to experiments for prediction of the performance of FRP strengthened and insulated R.C beams under fire conditions. Additionally, it can be used for estimation of the fire rating of such structures as well as for design of adequate fire protection layers.

KEYWORDS

Fire performance, Thermal insulation, Numerical modeling, Fiber reinforced polymers (FRP), Reinforced concrete beams; Flexural strengthening

INTRODUCTION

Fiber reinforced polymers (FRP) strengthening systems are mainly used to retrofit existing and deficient structural elements. Fire performance is pointed out as a critical factor that requires more research before FRP can be used with confidence in strengthening applications. Specifications and design guidelines limit the use, increase the load factor or limit the desired strength enhancement in order to meet fire hazard [1, 2]. There are still no design guidelines available for FRP-reinforced or strengthened concrete structures under fire conditions; which is one of the major threats to buildings and other structures. Experimental studies were carried out for FPR-strengthened reinforced concrete (R.C) members under elevated temperatures or fire by several researchers [3-10]. To provide protection of CFRP from direct fire exposure, a coating layer of a thermal insulating material, typically gypsum products, was placed around the beam cross-section.

Few studies in the published literature addressed numerical modelling to predict the performance of FRP-strengthened R.C members subjected to fire [11-17] and the heat transfer through the different insulation layers during fire exposure [18]. Therefore, more research work is needed to model efficiently the performance of FRP-strengthened structures under elevated temperatures, in order to enable the analyst and designers to accurately predict the fire endurance and design efficiently the thermal insulation layers for such structures.

OBJECTIVE

The present paper aims at investigating numerically the behaviour of R.C beams strengthened by externally bonded FRP and thermally protected under standard fire test loading. Therefore, the paper provides an economical alternative to experiments for prediction of the performance of FRP strengthened and insulated RC beams under fire conditions. Additionally, it can be used for estimation of the fire rating of such structures as well as for design of adequate fire protection layers.

To achieve this aim, nonlinear finite element modelling is conducted and verified using the previously published experimental and numerical results [18, 23].

FINITE ELEMENT MODELLING

Nonlinear time analysis is performed using commercial software ANSYS 12.1 [19]. Finite element modelling is made for an R.C beam that has been subjected to fire test in the published literature [23]. The T-beam with span 3900 mm has the cross-section and reinforcement shown in Figure 1. The T-beam reinforcement details were as follows; the main steel reinforcement was two 20 mm diameter bars. Shear stirrups were 10 mm diameter bars spaced at 150 mm center to center. Concrete cover to the web stirrups was 40 mm and concrete cover for flange reinforcement was 25 mm. A CFRP laminate 1.3 mm thick and 100 mm wide is adhered to the bottom of the beam along the span and stopped at 100 mm from the support. A layer of vermiculite-gypsum (VG) plaster having thickness 25 mm is applied on the beam soffit and web and extends for a distance of 125 mm underneath the flange along the entire length of the beam. The element types used for transient thermal and structural finite element analysis are given in Table 1. The model accounts for the variation in thermal and mechanical parameters of the different materials with temperature.

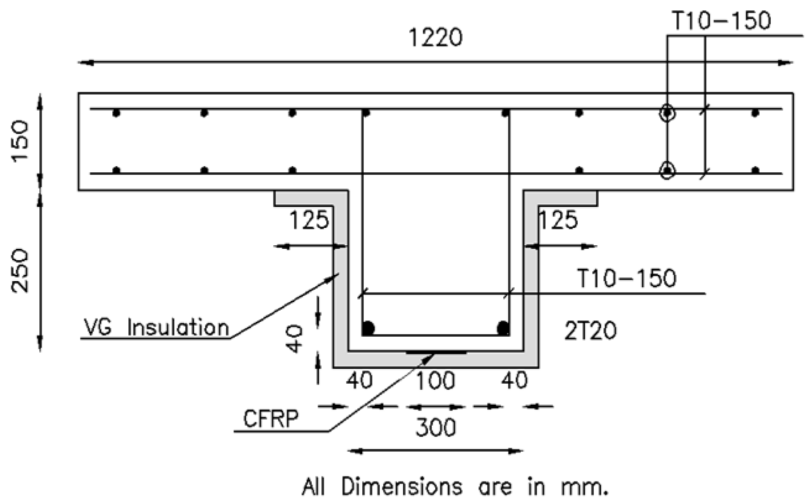

Fig. 1- Cross-section of experimentally tested T-beam [23]

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Tab. 1 - Element types used for thermal and structural analyses

Material	Thermal analysis	Structural analysis
Concrete	SOLID70	SOLID65
Steel bars	LINK33	LINK8
CFRP layer	SHELL 57	SHELL 41
VG insulation	SOLID70	SOLID45

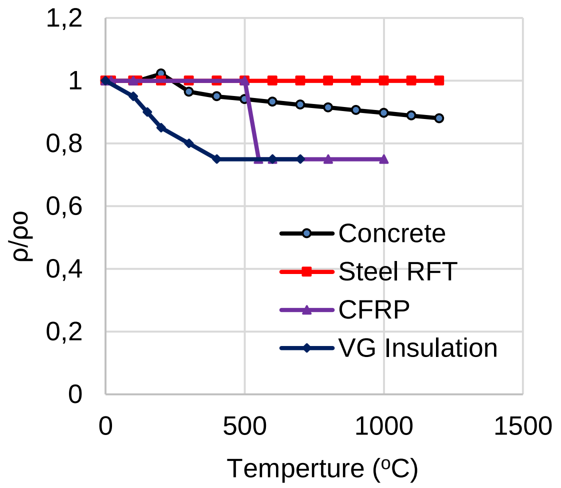
MATERIALS MECHANICAL AND THERMAL PROPERTIES

The concrete characteristic compressive strength is 41 MPa. The main steel reinforcement has yield and ultimate strengths of 500 and 650MPa, respectively. The 10mm diameter reinforcement bars have yield and ultimate strengths of 429 and 611MPa, respectively. The 1.3 mm-thick CFRP laminate possesses a design tensile strength of 460 MPa in the direction of the fibers and ultimate elongation of 2.2% at failure [23]. Table 2 gives the values for the materials mechanical and thermal properties at room temperature found in the literature [18, 20].

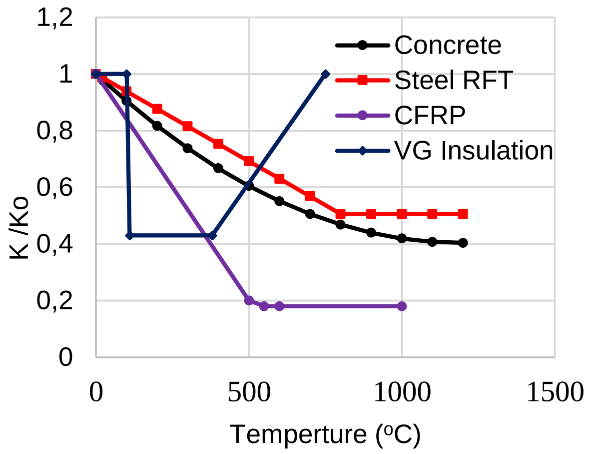
Tab. 2- Mechanical and thermal material properties at room temperature [18, 20]

Material	E_o MPa	K_o W/mm.K	C_o J/kg.K	μ	α	ρ_o Kg/m^3
Concrete	30200	2.7×10^{-3}	722.8	0.20	6.08×10^{-6}	2400
Steel bars	210000	5.2×10^{-2}	452.2	0.30	6.00×10^{-6}	7860
CFRP	228000	1.3×10^{-3}	1310	0.28	-0.90×10^{-6}	1600
VG Insulation	2100	2.5×10^{-4}	1654	0.30	1.70×10^{-5}	269

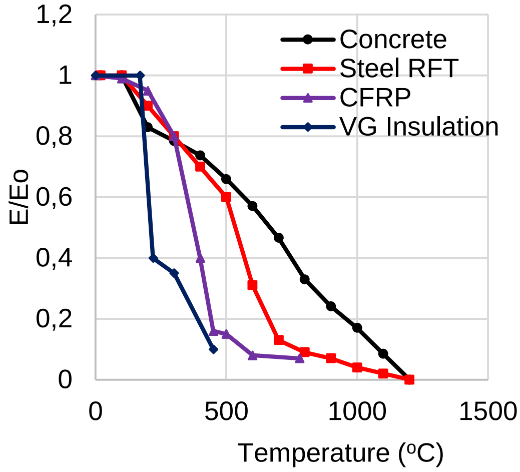
The thermal and mechanical properties at elevated temperature for concrete and steel are available in the literature [20-22, 27]. The variation of normalized density, modulus of elasticity, thermal conductivity, and specific heat with temperature for the constituent materials are shown in Figure 2.



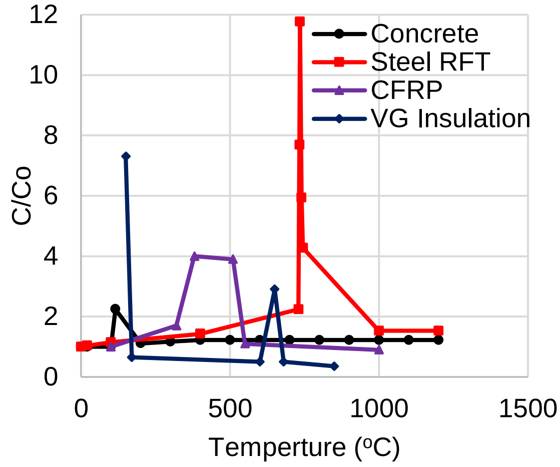
(a) *Normalized density*



(b) *Normalized thermal conductivity*



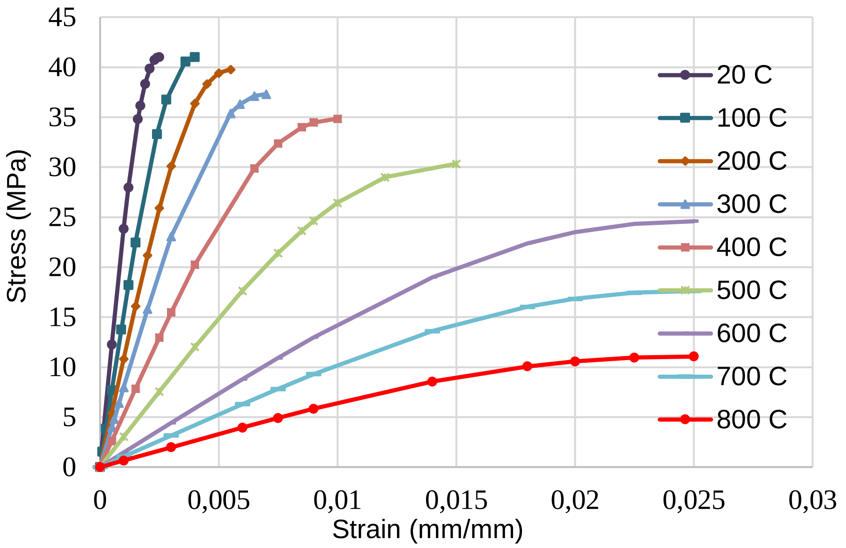
(c) Normalized stiffness



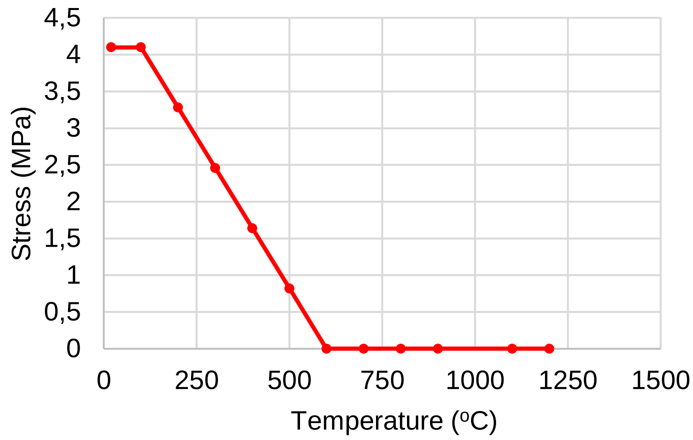
(d) Normalized specific heat

Fig. 2 - Variation of mechanical and thermal properties of materials with temperature

The stress strain-curves for concrete in compression under elevated temperature adopted in the present study are shown in Figure 3(a), and the variation of concrete tensile strength with temperature is shown in Figure 2 (b) [18, 22]. The variation of the mechanical and the thermal properties of FRP and the materials used for thermal insulation is addressed in researches and not quite established. In this study, the thermal and mechanical properties of CFRP and VG insulation and their variation with temperature are based on the findings of other researchers [21, 24 - 25].



(a) Stress-strain curves in compression under elevated temperature



(b) Variation of concrete tensile strength with temperature

Fig. 3: Concrete mechanical behavior under elevated temperature [22]

ANALYTICAL PARAMETERS, LOADING TECHNIQUE AND BOUNDARY CONDITIONS

Concrete is modelled using the standard nonlinear constitutive concrete material model implemented within ANSYS [19]. The stress-strain temperature curves for concrete in compression and tension shown in Figure 3 are utilized. When a crack occurs, elastic modulus of the concrete element is set to zero in the direction parallel to the principal tensile stress direction. Crushing occurs when all principal stresses are compressive and are outside the failure surface; then the elastic modulus is set to zero in all directions and the element local stiffness becomes zero causing large displacement and divergence in the solution.

The analysis is carried out as two consecutive load cases. First, in the transient thermal analysis load case, standard temperature-time conditions described by ASTM E119 [26] and shown in Figure 4 are applied as nodal temperature-versus-time to the bottom surface of the T-beam. Equation 1 gives the ASTM E119 time temperature loading applied to the studied beam.

$$T = 20 + 750\left(1 - e^{-0.49\sqrt{t}}\right) + 22\sqrt{t} \qquad (1)$$

The thermal gradient distribution in the T-beam from the thermal analysis is next applied to the beam as nodal temperatures at several time load steps and sub-steps and structural stress analysis is performed. The beam has simply supported end conditions, and the experimentally applied sustained uniformly distributed load of 34 KN/m [23] is simulated by applying a pressure of 0.0278 MPa to the top surface of the T-beam flange.

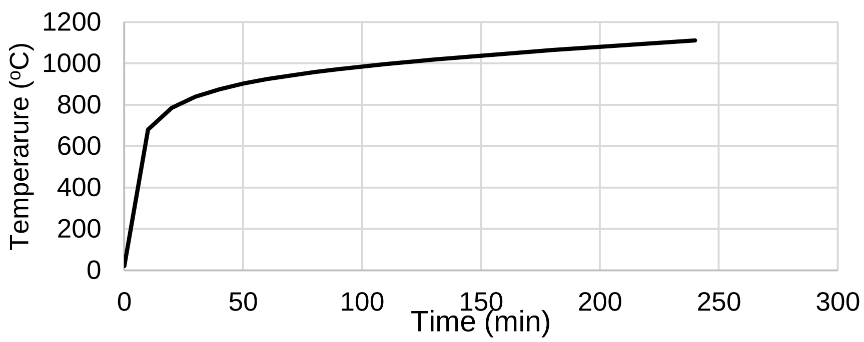


Fig. 4- Applied temperature conforming to Standard Fire Test Curve of ASTM E119

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VERIFICATION OF RESULTS

In order to validate the accuracy of the developed model, the obtained finite elements results are compared to the available experimental and numerical results. The thermal analyses results are evaluated by checking the temperatures at key locations with temperature gradients between the key locations of the beam model. The nodal temperature distribution within the T-beam cross section after four hours of fire exposure is shown in Figure 5. The variation with time of the numerically calculated temperatures in VG, CFRP, and concrete at the same points that were measured in the experiment work [23] are plotted in Figure 6. It can be concluded from these figures that there is good agreement between the presented numerically predicted temperatures and the published experimental and numerical results [18, 23].

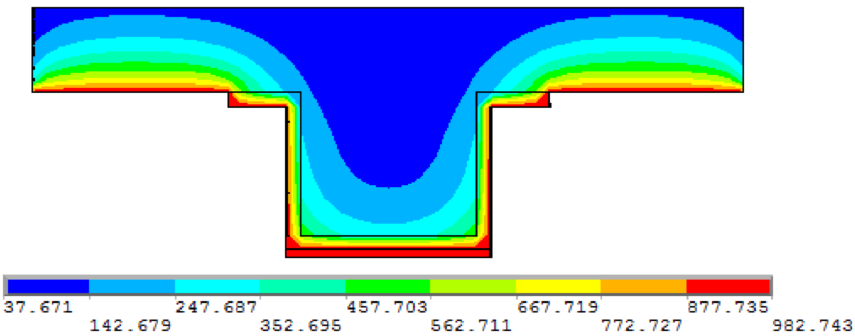


Fig.5 - Numerical predicted temperature distribution in beam cross-section (^{o}C) after four hours

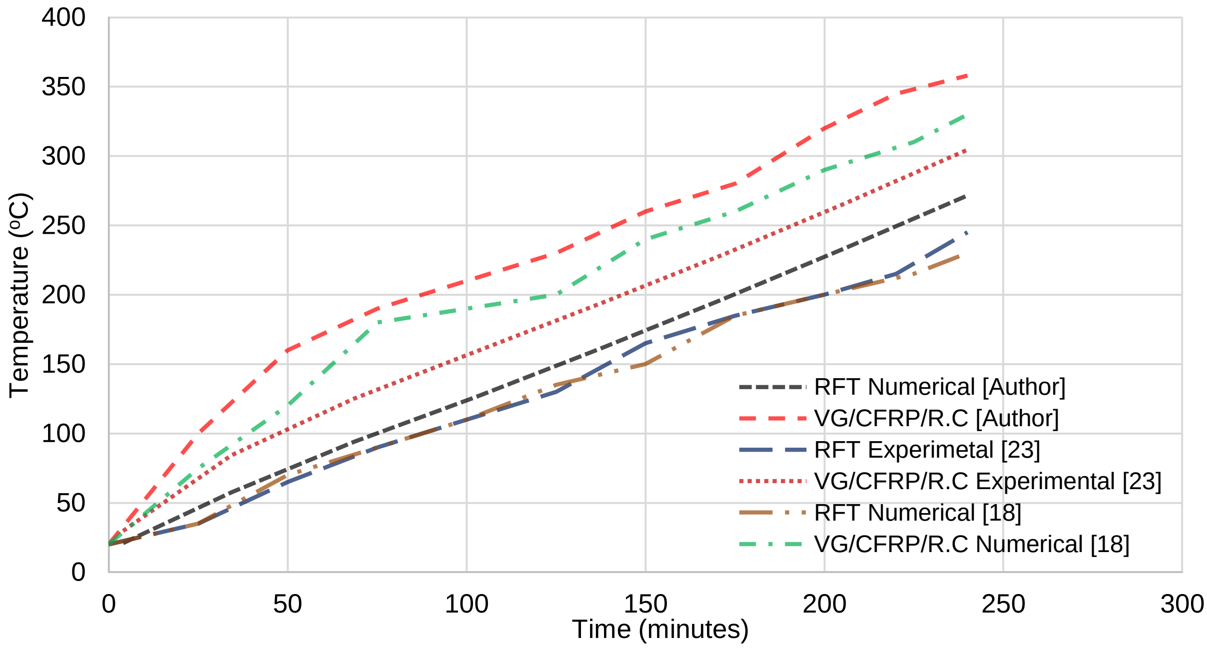


Fig. 6 - Numerical results of temperature versus time compared to experimental results

Figure 7 shows the numerically predicted and the experimentally measured mid-span deflection at the centerline of the cross section under the applied sustained uniformly distributed load as a function of fire exposure time. It can be concluded that the predicted mid-span deflection matches very closely the measured experimental one [23]. Furthermore, the adopted model is demonstrated to provide a more enhanced description of the experimental results than the published numerical results [18]. The accuracy of the adopted model herein can be attributed to modelling the FRP system using shell elements rather than the solid elements used in the published model, in addition to proper description of the constituent materials properties and the finer meshing used in the present model.

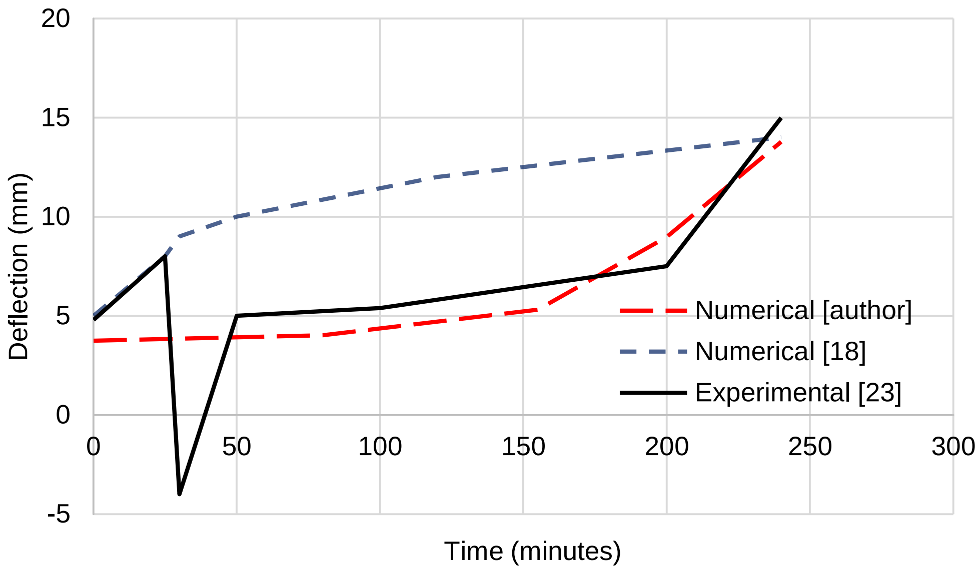


Fig. 7 - Variation of mid-span deflection with exposure time

PARAMETRIC STUDY

As the adopted finite element model achieved good correlation with the experimental program, a parametric study is designed to further investigate several different parameters on the performance of CFRP strengthened and insulated R.C beams, e.g. different aggregate types, moisture contents, concrete cover, insulation material thickness, different yield strength and concrete compressive strength. The following subsections show the results of studied parameters.

Concrete Aggregate Types

This section studies the effect of carbonate and siliceous aggregates on the behaviour of the CFRP strengthened R.C beams. The numerical results plotted in Figure 8 show that mid-span deflection of the R.C beam with carbonate aggregate in the concrete mix is 12 % less than that of a beam with siliceous aggregate, after 4 hours of exposure to standard fire conditions.

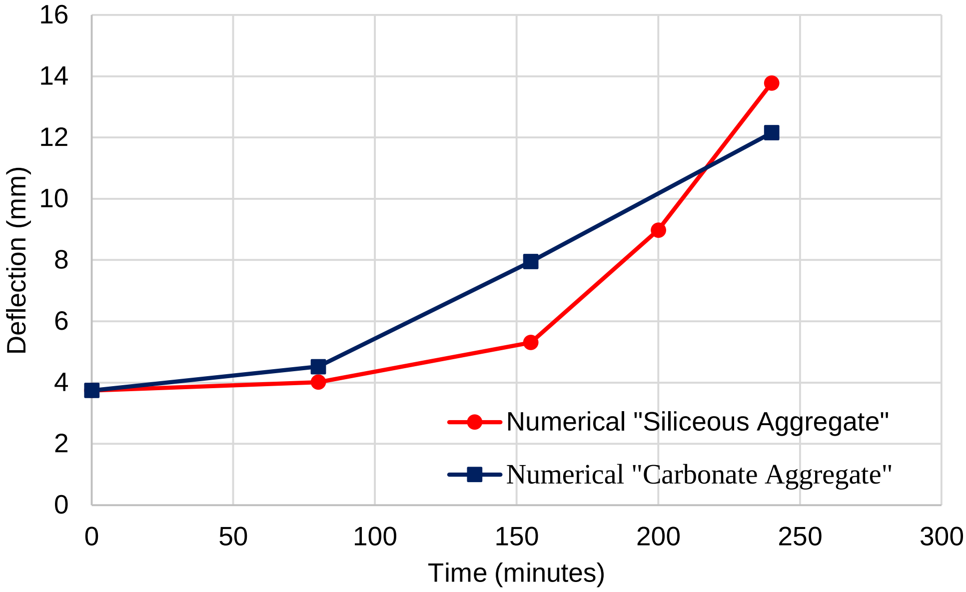
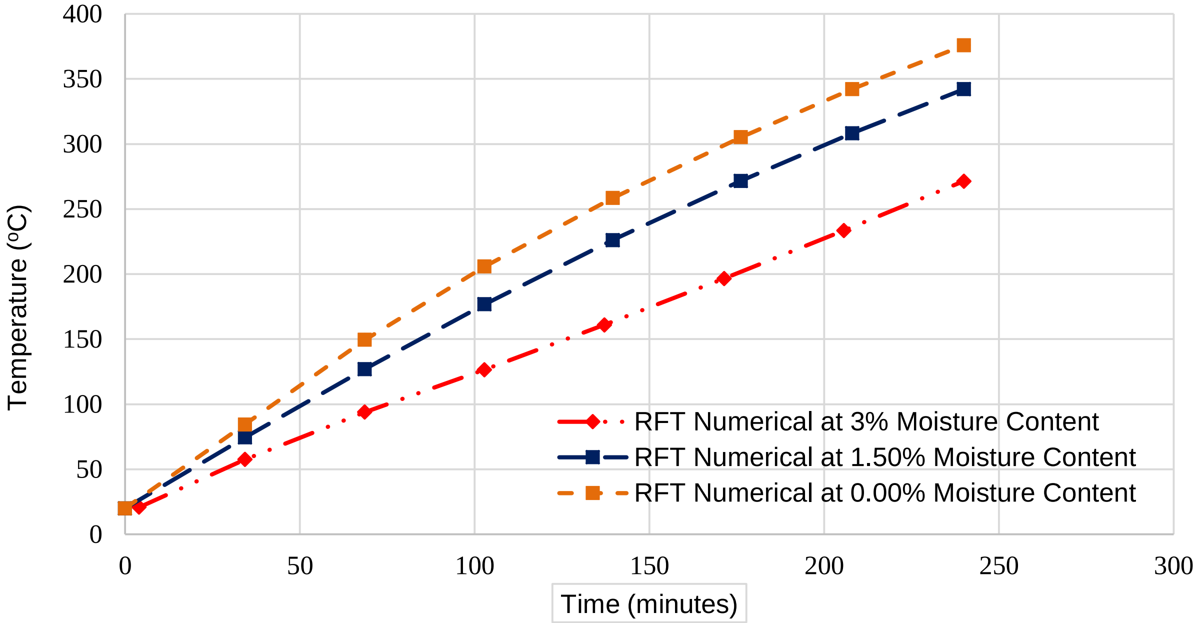


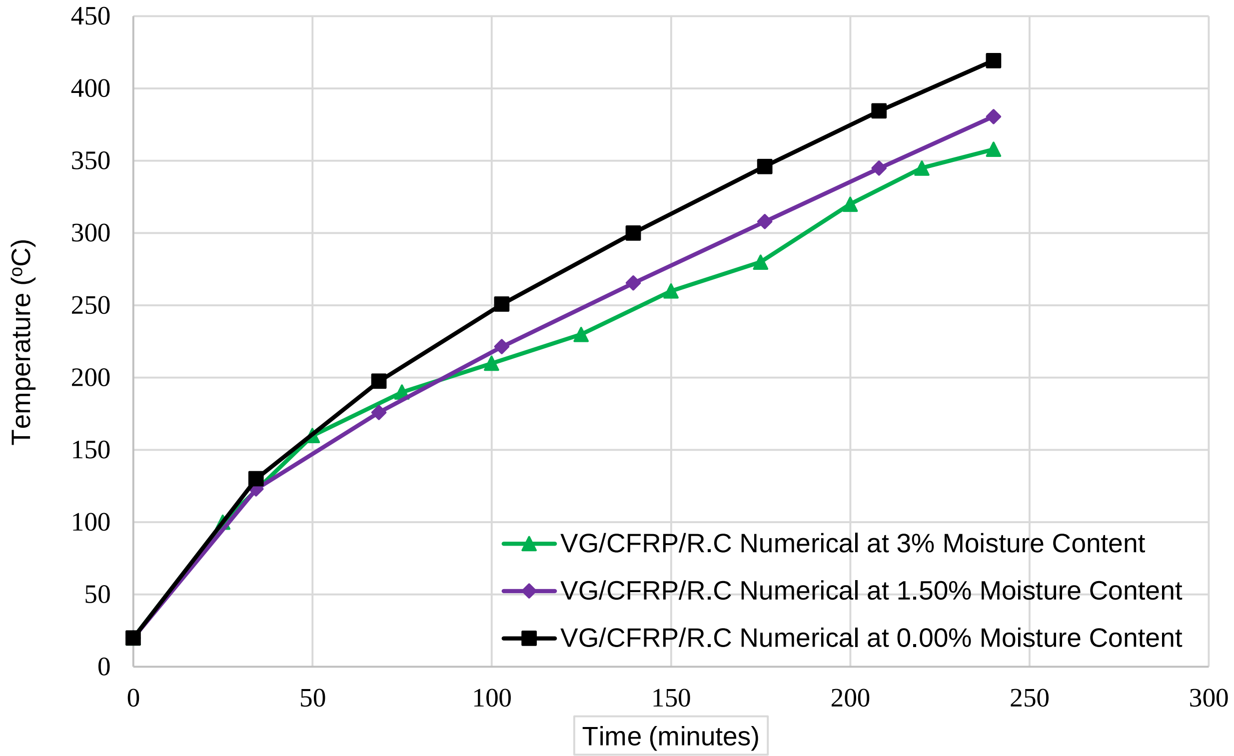
Fig. 8 - Mid-span deflection for different concrete aggregate types

Concrete Mix Moisture Content

As shown in Figures 9 (a) and (b), the temperature at steel reinforcement and VG/CFRP/R.C interface level increase with the decrease of moisture content in the concrete mix. This may be attributed to the absence of any water enough to absorb some of the thermal effects which leads to the increase in both steel reinforcement and VG/CFRP/R.C substrate temperature directly. Figure 10 shows also that at 0% moisture, the R.C beam deflection increases by 73% over the R.C beam deflection at 3% moisture. This emphasizes the importance of suitable moisture content in the concrete mixes.



(a) Effect of moisture content on the thermal response of steel reinforcement



(b) Effect of moisture content on the thermal response of VG/CFRP/R.C interface

Fig. 9- Effect of moisture content on the thermal response of the beam

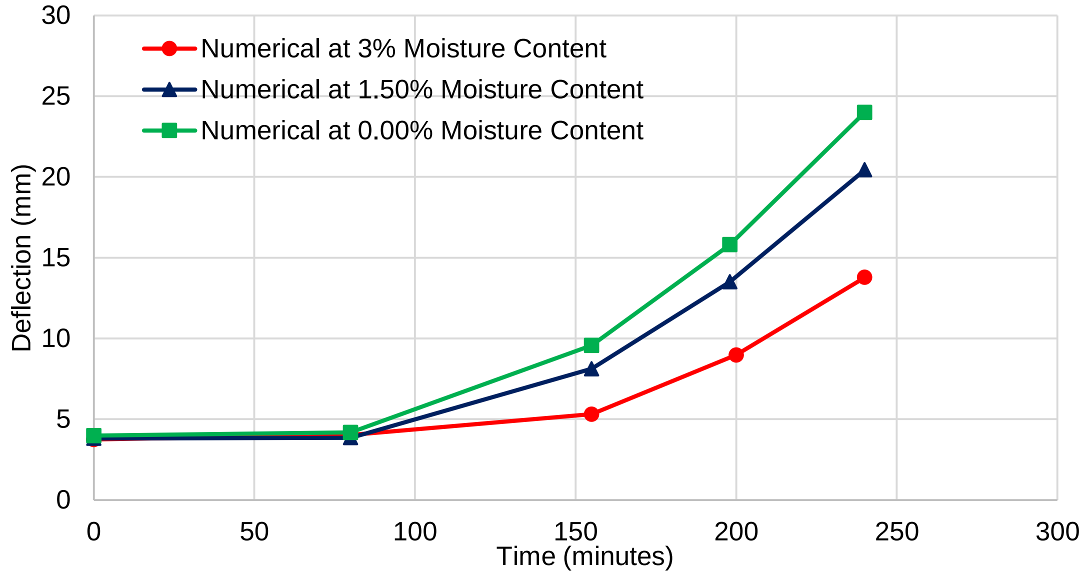


Fig. 10- Effect of moisture content on the structural response of the beam

Insulation Material Type and Thickness

Figure 11 presents the effect of increasing the VG insulation material thickness which decreases the temperature at both the steel reinforcement level and the CFRP/concrete level. Additionally, the mid-span deflection decreased with using a thicker VG material as plotted in Figure 12. This is due to the fact that a thicker insulation material with proper insulation properties is expected to decrease the thermal effect on the beam which in turn decreases the thermal strains and hence leads to a reduced mid-span deflection value.

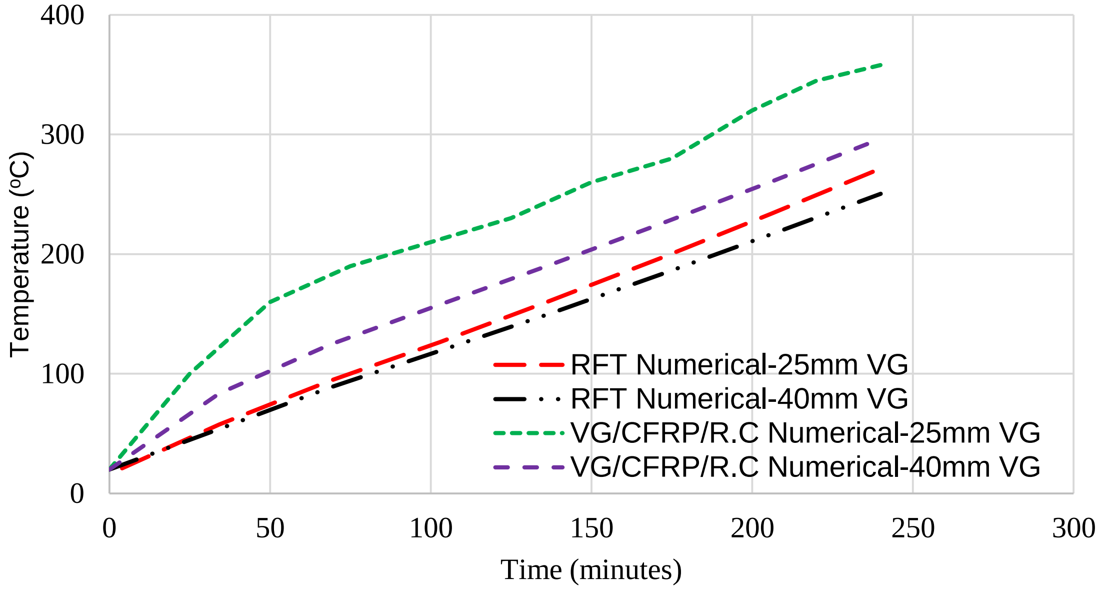


Fig. 11- Effect of changing VG thickness on thermal response of beam

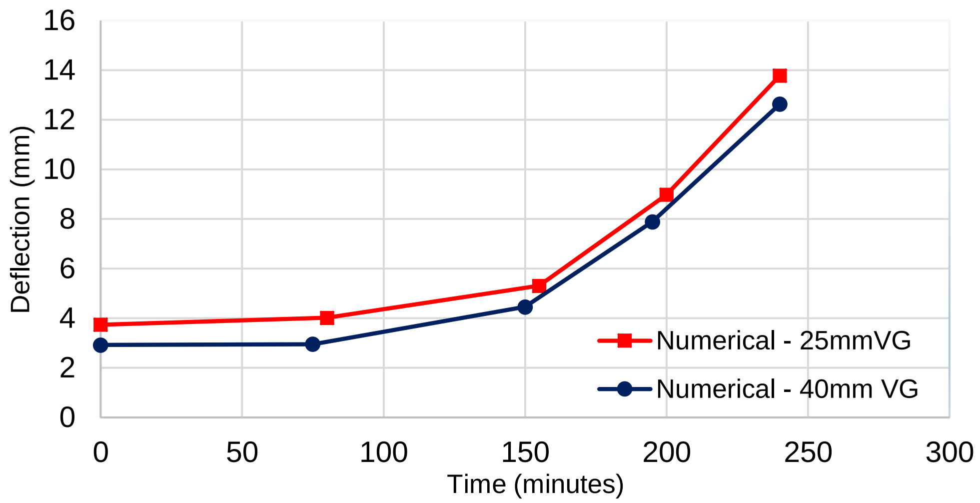


Fig. 12 - Effect of changing VG thickness on the structural response of beam

Concrete Cover

Concrete cover is an important parameter for fire rating and maintaining the durability of the R.C structural element. The increase of concrete cover thickness decreases the temperature at the steel reinforcement level as shown in Figure 13. Figure 14 presents the mid-span deflection of the beam after four hours under the standard fire test. The increase of concrete cover thickness limits and reduces the thermal strains on the beam which is reflected on the tension cracks of the beam and hence reduces the mid-span deflection. According to ACI 318-14 [28], the beam with 20 mm thick cover is regarded as unsafe in deflection despite being safe in thermal response.

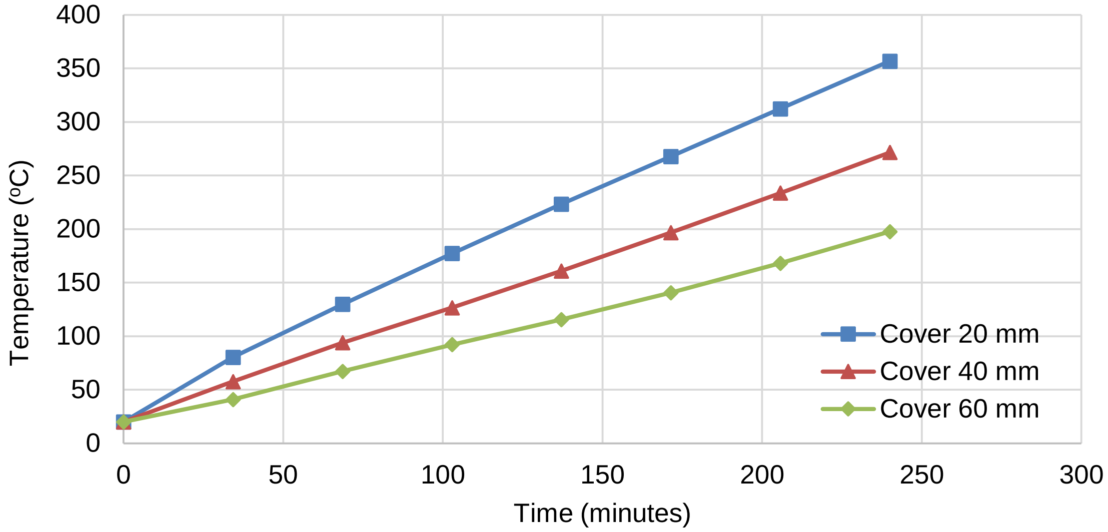


Fig. 13- Effect of changing the concrete cover thickness on thermal response of beam

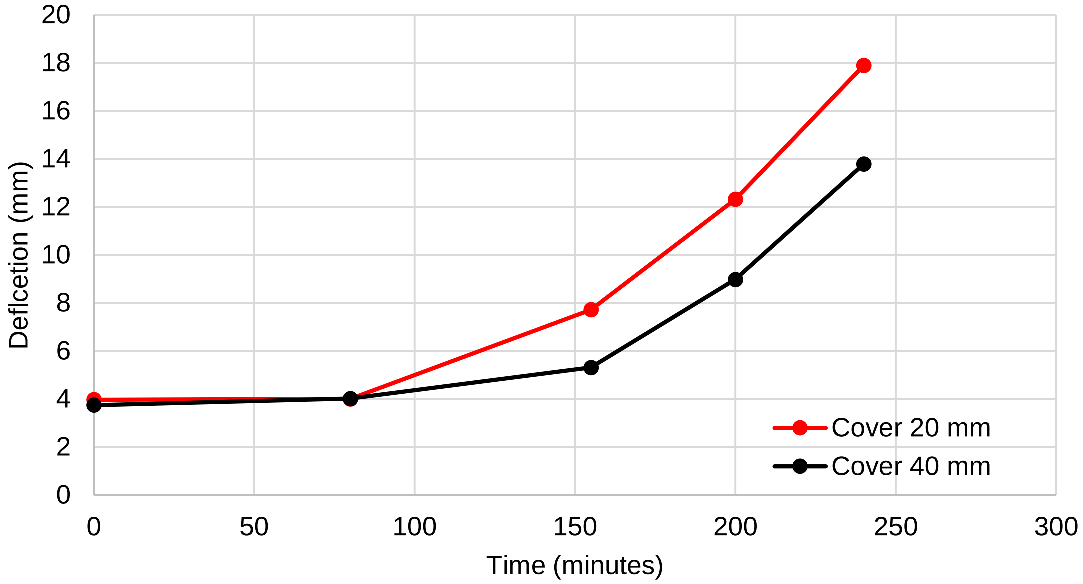


Fig. 14- Effect of changing the concrete cover thickness on structural response of beam

Steel Reinforcement Yield Strength

Despite being an important parameter in design of R.C beams, the steel reinforcement yielding strength has no vital effect on the mid-span beam deflection as shown in Figure 15.

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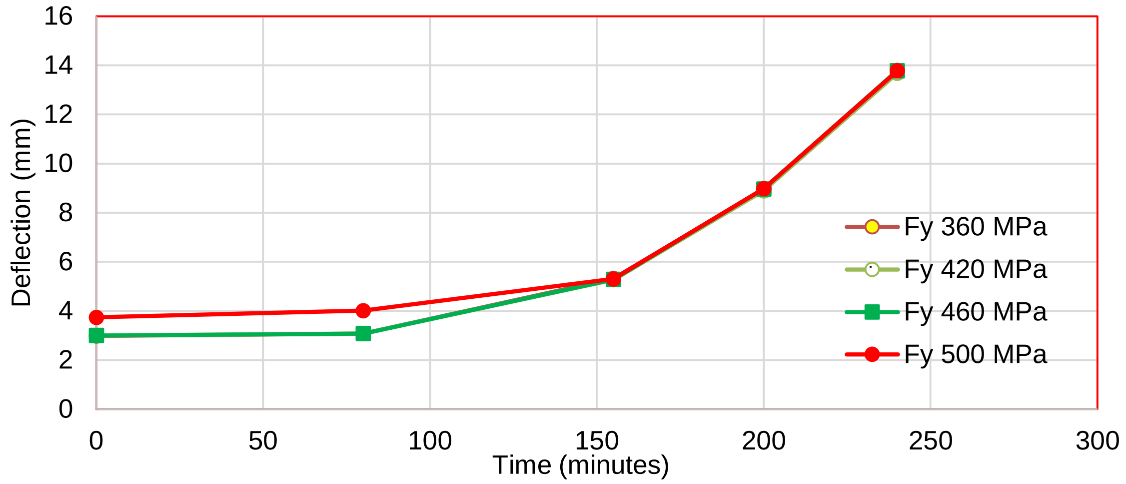

Fig. 15- Effect of changing reinforcement yield strength on structural response of beam

Concrete Compressive Strength

Concrete compressive strength has an important role in design of the R.C beam. Figure 16 shows the mid-span deflection of the R.C beam for different concrete compressive strength. The increase in compressive strength reduces the mid-span deflection as shown for concrete having C40 and C50.

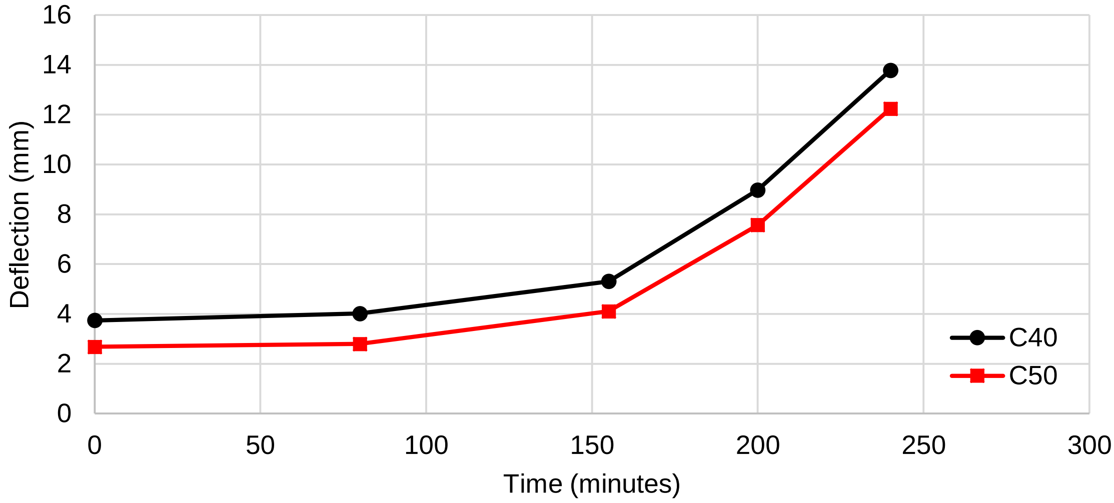

Fig. 16- Effect of changing concrete compressive strength on the structural response of beam

CONCLUSION

The paper presented numerical modelling procedure using finite elements that accurately simulates the behaviour of thermally insulated R.C beam strengthened in flexure with CFRP laminate when exposed to standard fire test. Numerical modelling and nonlinear analysis are performed using ANSYS 12.1 [19]. A parametric study is conducted for investigation of several parameters on the beam thermal behaviour. Based on the obtained numerical results the following conclusions can be drawn:

1. The numerical results of the proposed model are in good agreement with the published experimental ones regarding mid-span deflection and temperature distribution within the

cross-section throughout the elevated temperature time history.

2. The proposed model gives more accurate representation for mid-span deflection compared with published numerical results due to using shell elements for FRP, proper representation of the constituent materials used and the refined meshing used in the present model.
3. The developed models can be considered as an alternative solution for the time consuming and expensive fire testing.
4. Increasing insulation material thickness enhances the beam thermal response.
5. Mid-span deflection usually decreases with the increase of insulation thickness.
6. The concrete cover is a vital key element to protect the steel reinforcement from thermal effect and increase beams durability.
7. The steel yield strength has no important role in fire resistance of the structural element.
8. The carbonate aggregate is better than the siliceous aggregate in fire resistance of the R.C element.
9. Increasing the moisture content within the R.C structural element will enhance the thermal performance of the beam but care should be given so as not to affect the structural performance of the beam.
10. The concrete compressive strength is an important parameter that influences the thermal and structural performance of R.C beams.

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