Performance of FRP-Strengthened Reinforced Concrete Beams in Fire

O.El-Mahdy*, **G.Hamdy**** and **M.Abdullah*****

**Professor of Structural Analysis, **Associate Professor, ***Teaching Assistant*
Civil Engineering Department, Faculty of Engineering at Shoubra, Benha University, Egypt
108 Shoubra Street, Shoubra, Cairo 11241, Egypt
os8294@hotmail.com
osama.alhenawy@feng.bu.edu.eg

Abstract

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 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 modeling 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 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.

Keywords: Fire; fire performance; thermal insulation; numerical modeling; fiber reinforced polymers (FRP); reinforced concrete beams; flexural strengthening

1. 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 RC members under elevated temperatures or fire by several researchers [3-7]. 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 [8, 9].

Some studies in the published literature addressed numerical modeling to predict the performance of FRP-strengthened RC members subjected to fire [10-12] and the heat transfer through the different insulation layers during fire exposure [13]. 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.

2. Research Objective

The present paper aims at investigating numerically the behavior of RC 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 modeling is conducted and verified using the previously published experimental and numerical results [11,13]. The model accounts for the variation in thermal and mechanical parameters of the different materials with temperature. Nonlinear time analysis is performed using ANSYS 12.1 [14].

3. Finite Element Modeling

Modeling of RC beam in the published literature that has been subjected to fire test [11]. The T-beam with span 3900 mm has the cross-section and reinforcement shown in Fig. (1). 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.

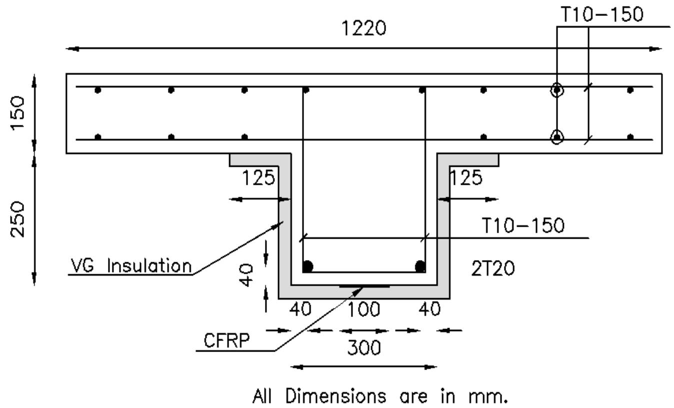


Fig. (1) Cross-section of experimentally tested T-beam [11]

Table 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

4. Materials Mechanical and Thermal Properties

The concrete 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 [11]. Table 2 gives the values for the materials mechanical and thermal properties at room temperature found in the literature [13,15].

Table.2 Mechanical and thermal material properties at room temperature [13,15]

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 [15-17]. The variation of normalized density, modulus of elasticity, thermal conductivity, and specific heat with temperature for the constituent materials are shown in Fig. 2.

The stress strain-curves for concrete in compression under elevated temperature adopted in the present study are shown in Fig. (3a), and the variation of concrete tensile strength with temperature is shown in Fig. (2b) [15, 18]. 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 [16, 17, 18].

5. Analytical Parameters, Loading Technique and Boundary Conditions

Concrete is modeled using the standard nonlinear constitutive concrete material model implemented within ANSYS [14]. The stress-strain temperature curves for concrete in compression and tension shown in Fig. (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 [21] and shown in Fig. (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 [18] is simulated by applying a pressure of 0.0278 MPa to the top surface of the T-beam flange.

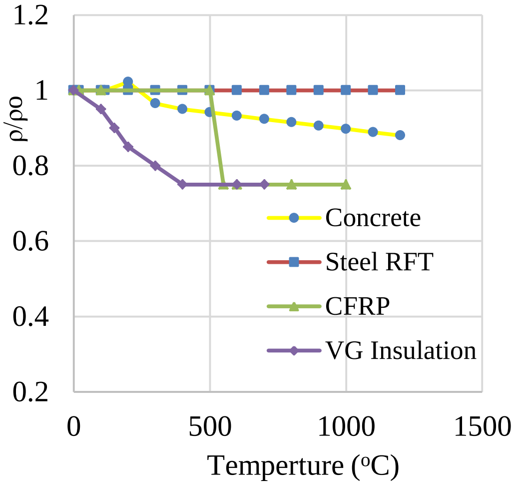


Fig. (2.a) Normalized density

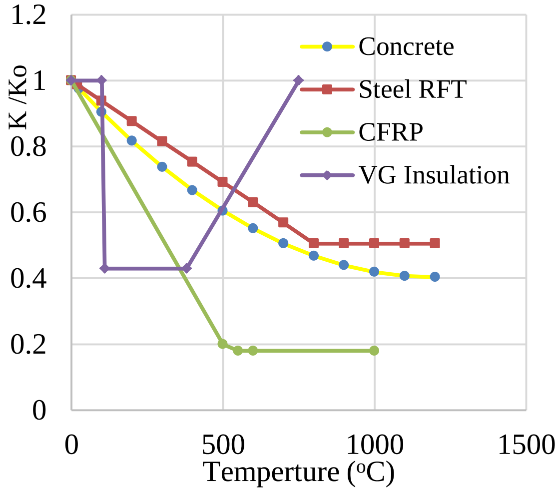


Fig. (2.b) Normalized thermal conductivity

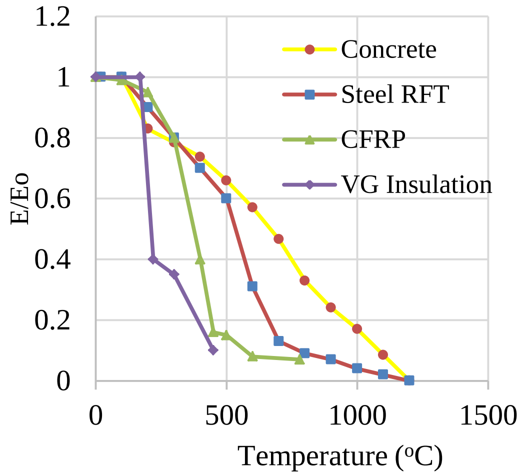


Fig. (2.c) Normalized stiffness

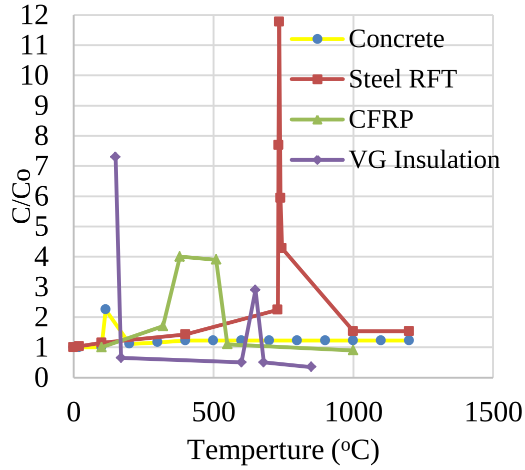
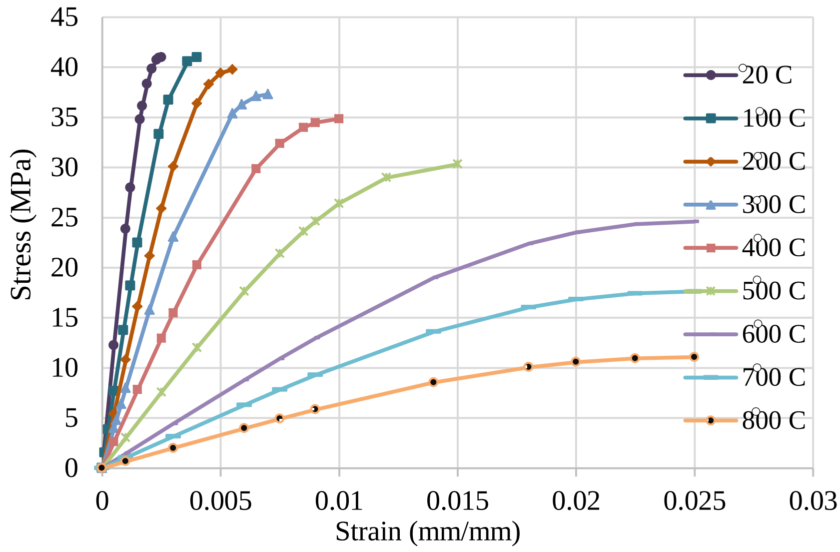
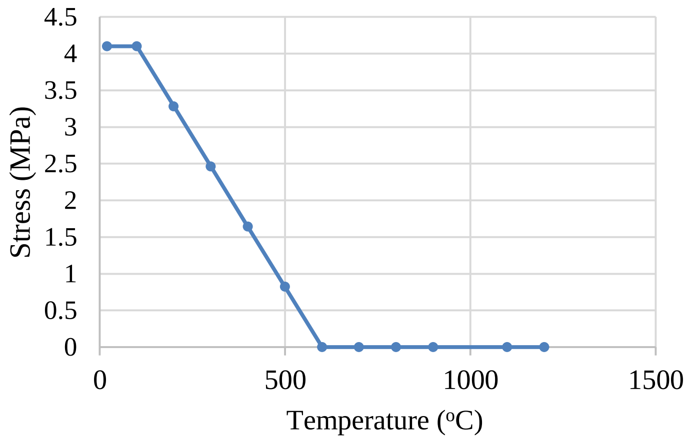


Fig. (2.d) Normalized specific heat

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



(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 [17]

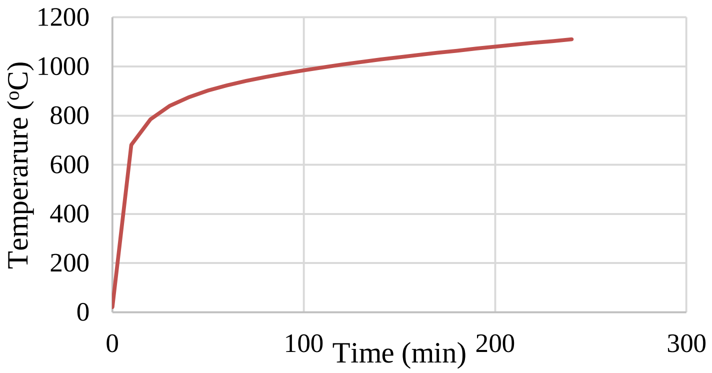


Fig. (4) Applied temperature conforming to Standard Fire Test Curve of ASTM E119

6. 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 are shown in Fig. (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 [18] are plotted in Fig. (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 [13, 18].

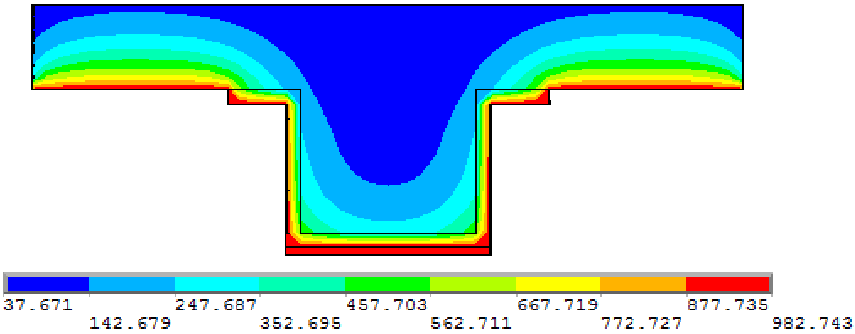


Fig.(5) Numerically predicted temperature distribution in beam cross-section (°C) after four hours

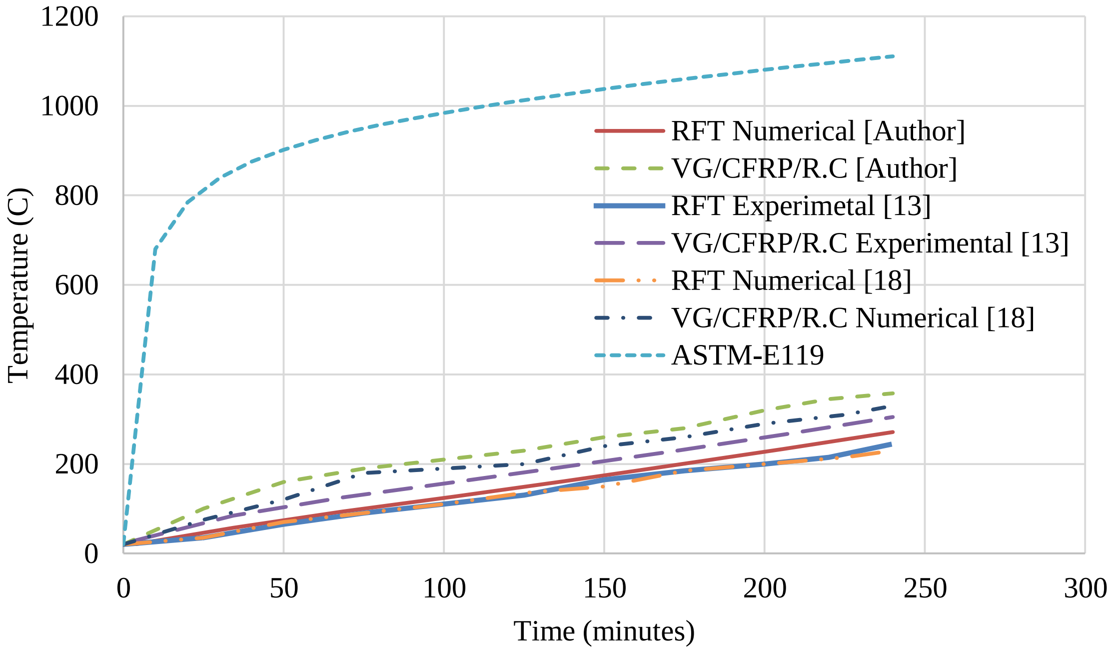


Fig. (6) Numerical results of temperature versus time compared to experimental results

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 [13]. Furthermore, Fig.(6) demonstrates the enhancement results with published numerical ones. The accuracy of the adopted model herein is due to modeling the FRP system using shell elements rather than the solid elements used in the published model [18], in addition to proper description of the constituent materials properties and the finer meshing used in the present model.

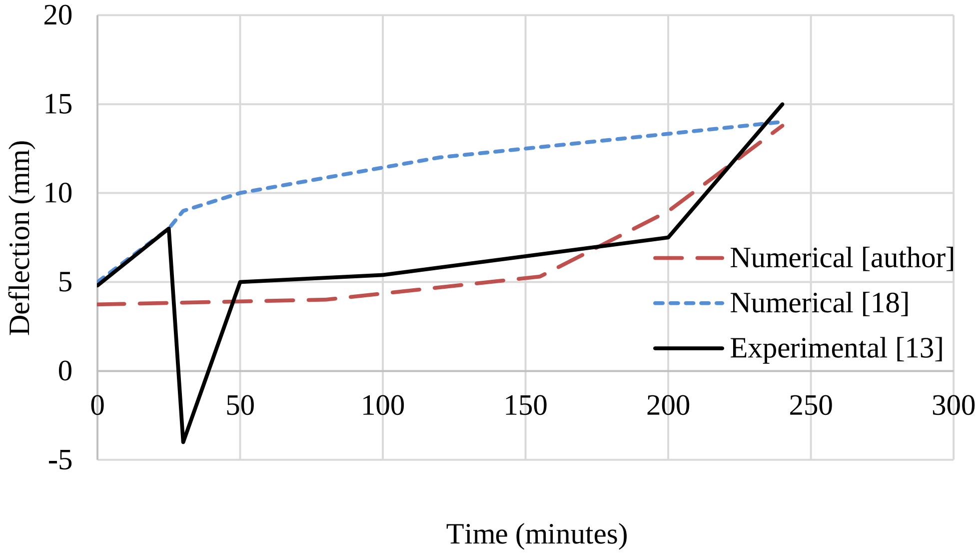


Fig. (7) Variation of mid-span deflection with exposure time

7. Parametric Study

As the finite element model achieved a 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 RC 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.

7.1. Concrete Aggregate Types

This section declares the effect of carbonate and siliceous aggregates on the behavior of the CFRP strengthened RC beams. Figure (8) shows that the RC beam mid-span deflection is enhanced on using carbonate aggregate in the concrete mix by 12 % less than the mid-span deflection of a beam with siliceous aggregate.

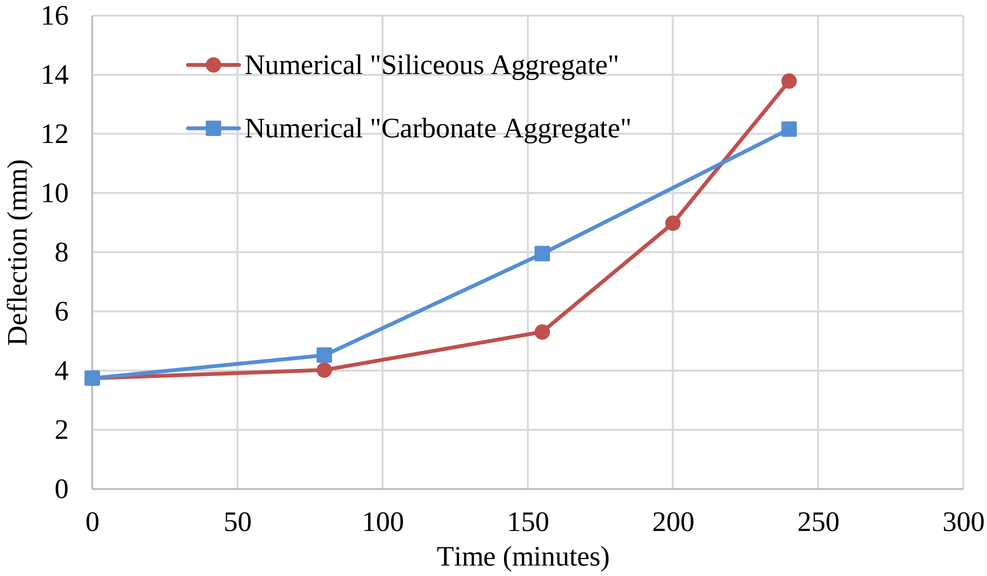


Fig. (8) Mid-span deflection for different concrete aggregate types

7.2. Concrete Mix Moisture Content

As shown in Fig. (9) the temperature at steel reinforcement and VG/CFRP/RC substrate level increases with the decrease of moisture content in the concrete mix. This mainly occur as there is no any water enough to absorb some of the thermal effects which leads to the increase in both steel reinforcement and VG/CFRP/RC substrate temperature directly. Figure (10) shows also that at 0% moisture, the RC beam deflection increases by 73% over the RC beam deflection at 3% moisture. This shows the importance of the accurate moisture content in the concrete mixes.

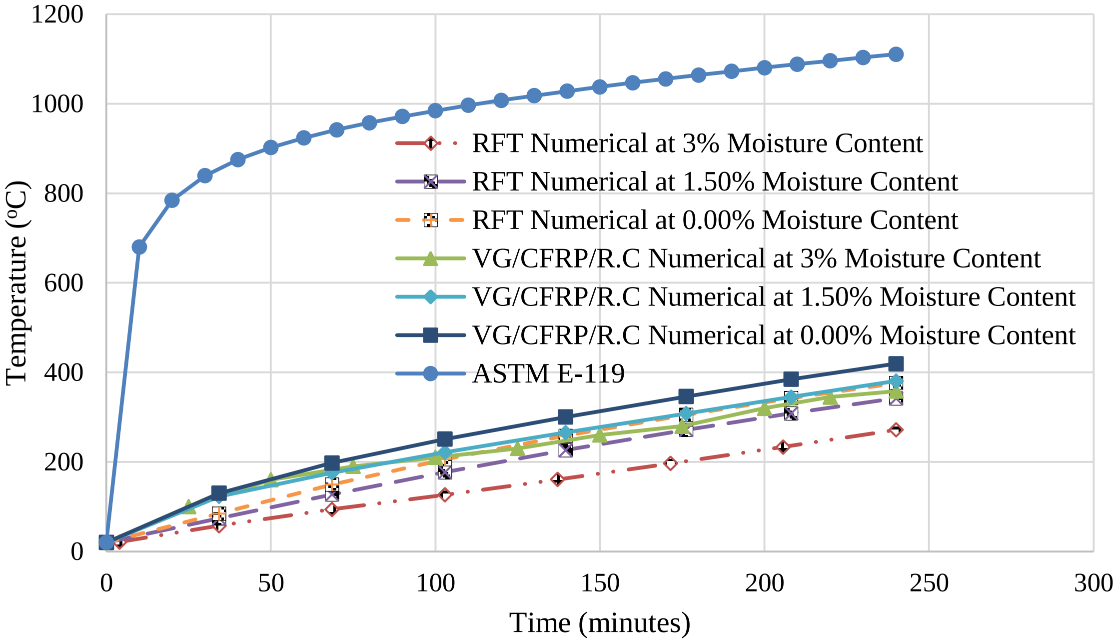


Fig. (9) Effect of moisture content on the thermal response of the beam

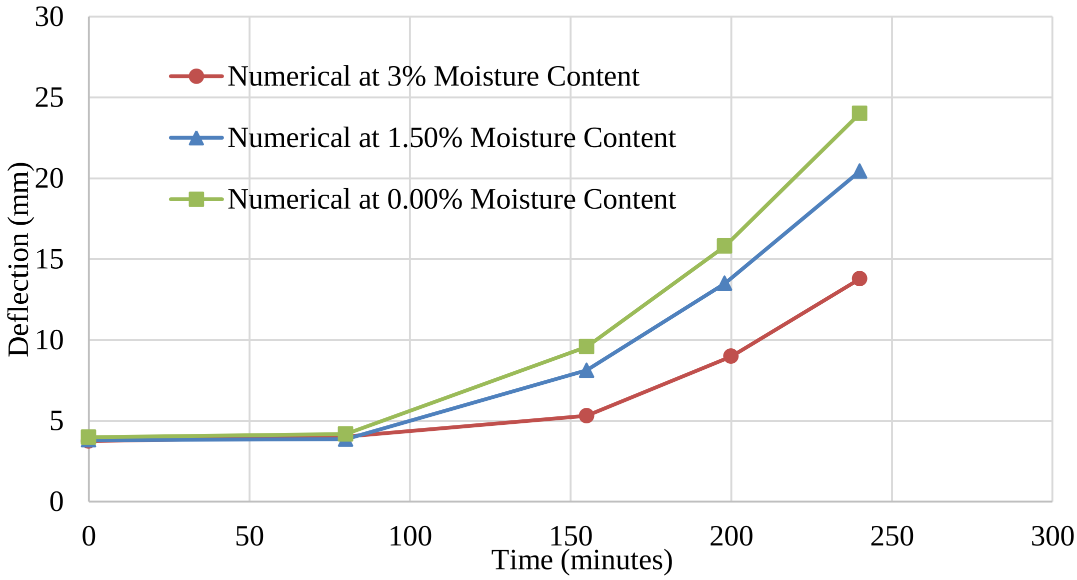


Fig. (10) Effect of moisture content on the structural response of the beam

7.3. 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. On the other hand, the mid-span deflection decreased with using a thicker VG material as shown in Fig. (12). This is due to the fact of a thicker insulation material with a proper insulation properties should decrease the thermal effect on the beam which decreases the thermal strains and hence leads to a reduced mid-span deflection value.

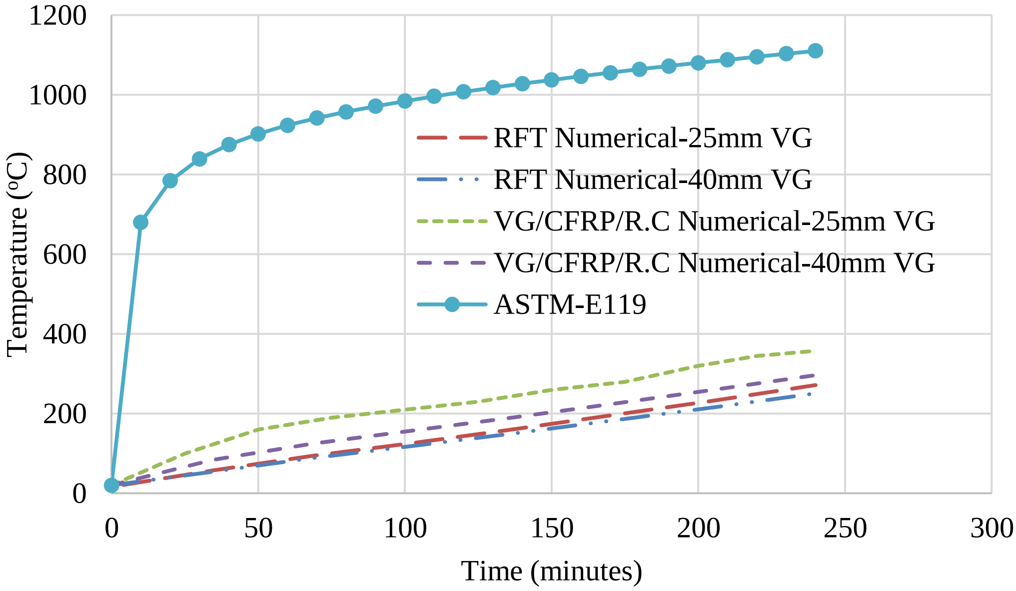


Fig. (11) Effect of changing VG thickness on thermal response of beam

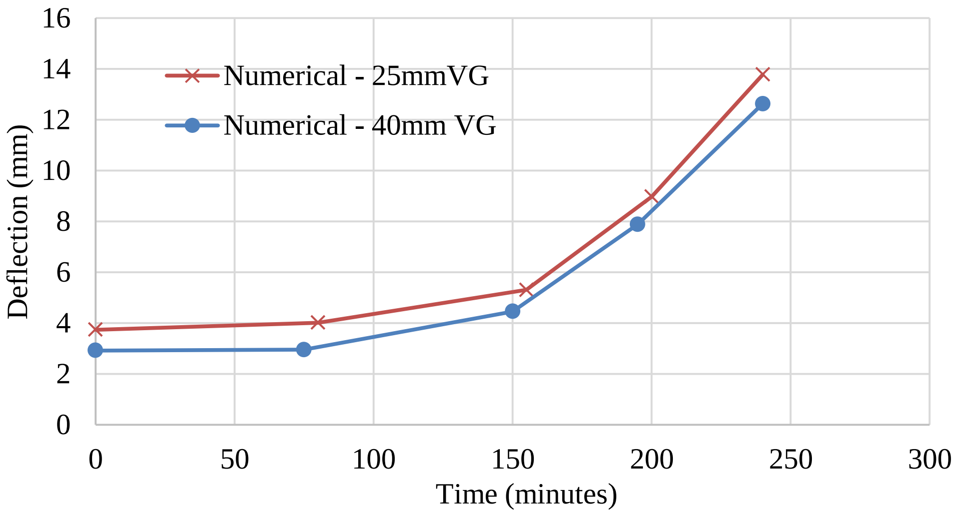


Fig. (12) Effect of changing VG thickness on structural response of beam.

7.4. Concrete Cover

Concrete cover is an important parameter for fire rating and maintaining the durability of the RC structural element. The increase of concrete cover decrease the temperature at the steel reinforcement level as shown in Fig. (13). Figure (14) presents the mid-span deflection of the beam after four hours under the standard fire test. The increase of concrete cover 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. The beam with 60 mm cover cracked early and subjected to a premature failure. According to ACI 318-14 [23] the beam with 20 mm cover is unsafe deflection despite being safe in thermal response.

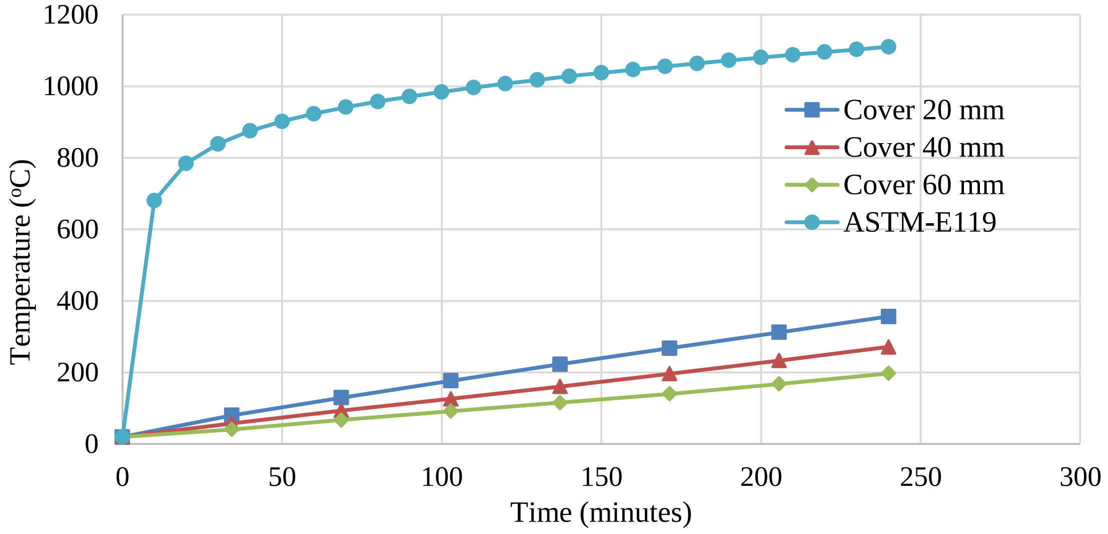


Fig. (13) Effect of changing the concrete cover thickness on thermal response of beam

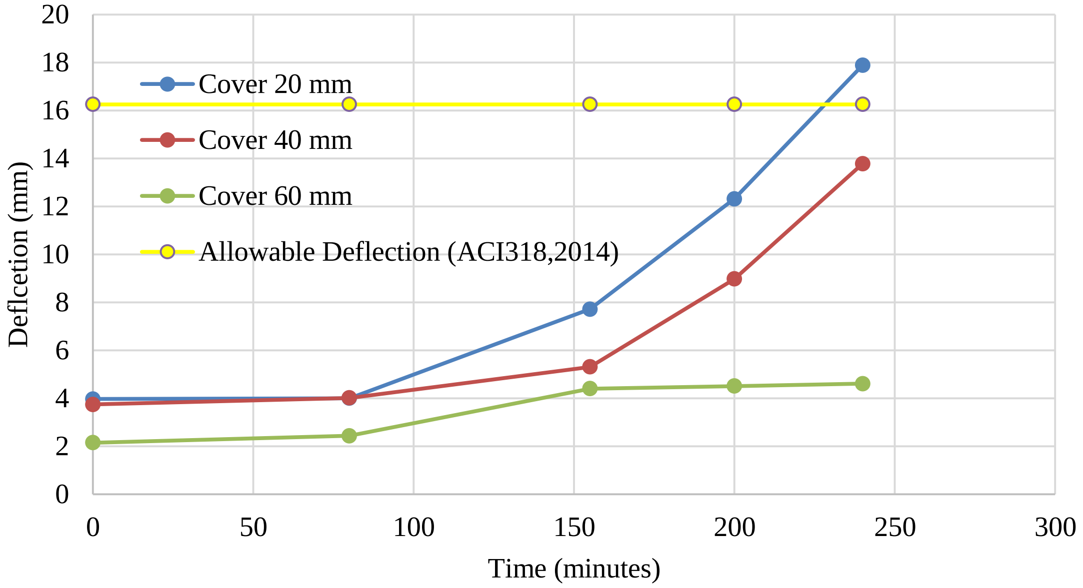


Fig. (14) Effect of changing the concrete cover thickness on structural response of beam

7.5. Steel Reinforcement Yield Strength

Despite being an important parameter in design of RC beams, the steel reinforcement yielding strength has no vital effect on the mid-span beam deflection as shown in Fig. (14).

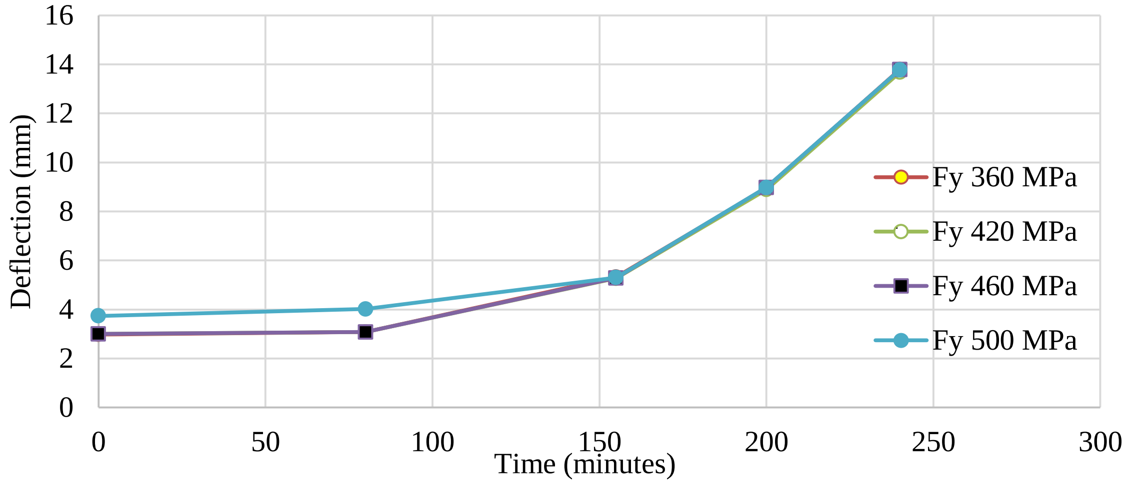


Fig. (14) Effect of changing reinforcement yield strength on structural response of beam.

7.6. Concrete Compressive Strength

Concrete compressive strength has an important role in design of the RC beam. Figure (15) shows the mid-span deflection of the RC beam for different concrete compressive strength. The increase in compressive strength reduces the mid-span deflection as shown for concrete having C40 and C50. Also a premature failure is encountered for the normal strength concrete having grades C20 and C30 due to the lower compressive strength of the beam under the proposed thermal and structural loads.

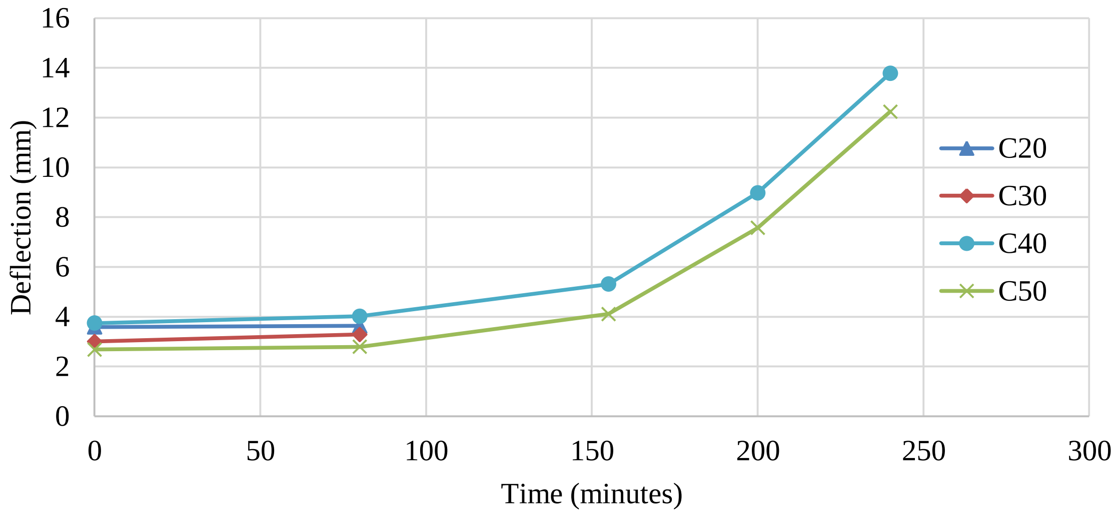


Fig. (15) Effect of changing concrete compressive strength on the structural response of beam

8. Summary and Conclusions

The paper presented numerical modeling procedure by finite elements that accurately simulates the behavior of thermally insulated RC beam strengthened in flexure with CFRP laminate when exposed to standard fire test. Numerical modeling and nonlinear analysis are performed using ANSYS 12.1 [14]. A parametric study is done for further investigations of other parameters on the beam. 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 to the time consuming and the expensive fire testing.
4. Mid-span deflection usually decreases with the increase of insulation thickness.
5. Increasing insulation material thickness enhances the beam thermal response.
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 an important role in fire resistance of the structural element.
8. The carbonate aggregate is better than the siliceous aggregate in fire resistance of the RC element.
9. Increasing the moisture content within the RC structural element will enhance the thermal performance of the beam but with caring of the structural performance of the beam.
10. The concrete compressive strength is an important parameter to ensure thermal and structural performance of the beams.

References

1. American Concrete Institute (ACI), ACI 440.2R-08, “Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures”, ACI Committee 440, Farmington Hills, MI, USA, 2008.
2. ECP Committee 208, ECP 208-05: “Egyptian code of practice for the use of fiber reinforced polymer in the construction field”, ECP Committee 208, Ministry of Housing and Urban Communities, Egypt, 2005.
3. Blontrock, H., Taerwe, L., and Vandevelde, P., “Fire tests on concrete beams strengthened with fiber composite laminate”, Third Ph.D. Symposium, Vienna, Austria, (2000), 10 pp.
4. Blontrock, H., Taerwe, L, and Vandevelde, P., “Fire testing of concrete slabs strengthened with fiber composite laminate”, 5th Annual Symposium on Fiber-Reinforced-Plastic Reinforcement for Concrete Structures (FRPRCS-5), London, U.K., 2001, pp. 547–556.
5. Williams, B., Bisby, L., Green, M., Kodur, V.K.R., and Su, J, Z., “An investigation on fire performance of FRP strengthened RC Beams”, 8th International Symposium on Fire Safety Science, Beijing, 2005, pp. 247–258.
6. Gamage, J., Al-Mahaidi, R., and Wong, M.B., “Bond characteristics of CFRP plated concrete members under elevated temperatures”, Composite Structures, 75(1-4), 2006, pp.199–205.
7. Klamer, E.L., Hordijk, D.A. and Hermes, M.C.J., “The influence of temperature on RC beams strengthened with externally bonded CFRP reinforcement”, Heron, 53(3), 2008, pp. 157–185.
8. Salama, A.E., Ghanem, G.M. Abd-Elnaby, S.F., El-Hefnawy, A.A., and Abd-Elghaffar, M., “Behavior of thermally protected RC beams strengthened with CFRP under dual effect of elevated temperature and loading”, HBRC Journal, 8(1), 2012, pp. 26–35.
9. Kamal, O.A., Hamdy, G.A., and Abou-Atteya, M.A., “Efficiency of coating layers used for thermal protection of FRP strengthened beams”, HBRC Journal, 10, 2014, pp. 183–190.
10. Bisby, L.A., “Fire Behavior of Fiber-Reinforced Polymer Reinforced or Confined Concrete”, Ph.D. thesis, Department of Civil Engineering, Queen's University, Kingston, Canada, 2003.
11. Bisby, L.A., Green, M.F., and Kodur, V.K.R., “Modeling the behavior of FRP-confined concrete columns exposed to fire”, J.Compos. Constr., 9(1), 2005, pp. 15–24.
12. Bai, Y., Keller, T, and Vallée, T., "Modeling of stiffness of FRP composites under elevated and high temperatures”, Compos. Sc. Techn., 68 (15-16), 2008, pp. 3309–3106.

13. Hawileh, R., A., Naser, M., Zaidan, W., and Rasheed, H. A., "Modeling of insulated CFRP strengthened reinforced concrete T-beam exposed to fire", Eng. Struct., 31(12), 2009, pp. 3072–3079
14. ANSYS. Finite Element Computer Code. Version 12.1.0. ANSYS Inc., Canonsburg, PA, 2009.
15. Harmathy, T.Z., "Fire Safety Design and Concrete, Concrete Design and Construction Series", Longman, UK, 1993.
16. Griffis, C. A., Masmura, R.A., and Chang, C.I., "Thermal response of graphite-epoxy composite subjected to rapid heating", Journal of Composite Materials., Vol. 15 (1981), pp. 427-442.
17. Eurocode 2. EN 1992-1-2: Design of concrete structures. Part 1-2: General rules- Structural fire design, European Committee for Standardization, Brussels, Belgium, 2004.
18. Williams, B., Kodur, V.K.R., Green, M.F., and Bisby, L. ,"Fire endurance of fiber-reinforced polymer strengthened concrete T-beams, J. ACI Struct; 105(1) (2008) 60–67.
19. Cramer, S.M., Friday, O.M., White, R.H., and Sriprutkiat, G., "Mechanical properties of gypsum board at elevated temperatures", Fire and Materials (2003) 33–42.
20. Park, S. H., Manzello, S., L., Bentz, D., P., and Mizukami, T., "Determining thermal properties of gypsum board at elevated temperatures", Fire and Materials, (2009), pp. 237-250.
21. American Society for Testing and Materials (ASTM). ASTM E119: Standard Test Methods for Fire Tests of Building Construction and Materials, West Conshohocken, PA, USA, 2007.
22. Eurocode 3. EN 1993-1-2: Design of steel structures. Part 1-2: General rules- Structural fire design, European Committee for Standardization, Brussels, Belgium, 2005.
23. American Concrete Institute (ACI), ACI 318-14, "Building code requirements for structural concrete", ACI 318, Farmington Hills, MI, USA, 2014.