Study of Structural Behaviour of RC Beams Strengthened With FRP in Fire Conditions

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Abstract

Recently, fiber reinforced polymers (FRP) have been widely used in repairing and strengthening of reinforced concrete (RC) structures. In order to increase the acceptance and application of FRP for strengthening requirements, their performance of in case of fire needs more investigation research works. Experimental investigations are required to be carried out for such elements to predict the fire behavior of such insulated FRP-strengthened members and their efficiency under realistic fire loads, however these experimental studies require time and cost.

The present paper gives numerical nonlinear finite element modeling of RC beams strengthened with FRP and insulated by a thermal resisting coating under elevated temperature specified by standard fire tests. The model take into consideration the variation in thermal and mechanical parameters of the concrete, steel rebar, FRP and insulation material. The nonlinear finite element analysis is performed using ANSYS 12.1. Finite element modeling of insulated RC T-beam strengthened with FRP which has been experimentally tested in the published literature is presented herein. The obtained analytical results are in good agreement with the experimental ones regarding the temperature distribution and mid-span deflection. The presented modeling gives an economical and efficient tool to investigate the performance of fire insulation layers under high temperatures. The model can be used to design thermal protection layers for FRP strengthening systems that satisfy fire resistance requirements specified in building codes and standards.

Keywords: Nonlinear finite element, flexural strengthening, fiber reinforced polymers, fire, thermal insulation.

1. Introduction

Externally bonded FRP has been used to enhance the flexural and shear capacity of RC beams. However, there are increasing concerns about their performance in the case of fire. Polymer materials exhibit change in mechanical properties and loss of stiffness and bond strength when exposed to temperatures higher than the glass transition temperature (T_g) which is about 60–82°C for the common polymers and adhesives [1,2]. 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 [3,4]. 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.

Flexural strengthening is made by external bonding of carbon fiber reinforced (CFRP) laminates to the bottom of RC beams to increase the ultimate moment carried by the strengthened member. Experimental studies were carried out for FPR-strengthened RC members under elevated temperatures or fire by several researchers [5-9]. 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 [10, 11]. Using a layer 50 mm thick of Perlite mortar protected CFRP strengthening system against 500°C for three hours with only 4-12% loss in its capacity [10]. Different coating layers of Perlite, Vermiculite and Portland Cement mortars in addition to clay and ceramic fiber were studied and experimentally demonstrated to give protection and maintain 90% of the residual flexural capacity of FRP-strengthened beams compared to control beams after two-hour exposure to 600°C [11].

A fire test program was conducted by Blontrock et al [5] in which ten CFRP-strengthened RC beams protected with calcium silicate boards were subjected to the design service loads of Eurocode [12]. Beam-slab assemblies strengthened with FRP laminate and protected with vermiculite-gypsum (VG) cementitious layer were tested by Williams et al. [13] by exposure to standard fire load of ASTM E119 [14].

Few studies in the published literature addressed numerical modeling to predict the performance of FRP-strengthened RC members subjected to fire [15-17] and the heat transfer through the different insulation layers during fire exposure [18]. Thus, more research work is needed to model efficiently the performance of FRP-strengthened structures under elevated temperatures, in order to enable analysts 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 laminates and thermally protected under standard fire test loading. Therefore, the paper provides an economic tool for design of fire protection for FRP-strengthened RC beams.

To achieve this aim, nonlinear finite element modeling is conducted. The model represents the beam geometry and accounts for the variation in thermal and mechanical parameters of the different materials with temperature. Nonlinear time analysis is performed using ANSYS 12.1 [19]. The numerical results are presented and compared to the previously published experimental and numerical results [13,18] in order to verify the efficiency of the adopted numerical procedure.

3. Modeling and Analysis

3.1.Finite Element Model

Modeling of RC beam in the published literature that has been subjected to fire test [13] is developed. 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. It should be noted that full bond is assumed between concrete and reinforcement bars, CFRP and insulation layer.

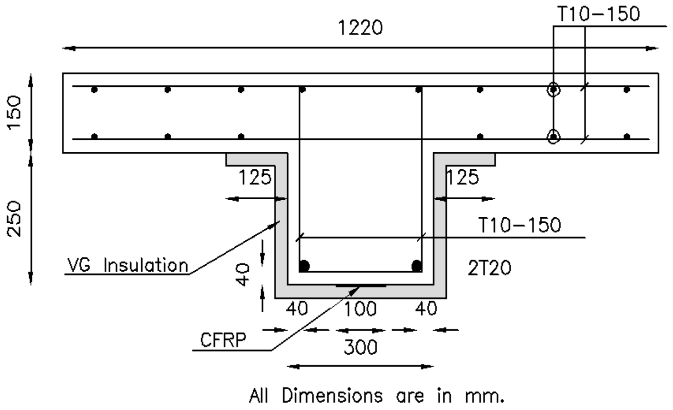


Fig. (1) Cross-section of experimentally tested T-beam [13]

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

3.2.Materials Mechanical and Thermal Properties

The concrete compressive strength is 41 MPa. The main steel reinforcement has yield and ultimate strengths of 500 and 650 MPa, respectively. The 10mm diameter reinforcement bars have yield and ultimate strengths of 429 and 611 MPa, 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 [13]. Table 2 gives the values for the materials mechanical and thermal properties at room temperature found in the literature [18,20].

The thermal and mechanical properties at elevated temperature for concrete and steel are available in the literature [12,20,21]. The variation of normalized density, modulus of elasticity, thermal conductivity, and specific heat with temperature for the constituent materials are shown in Fig. 2.

Table.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

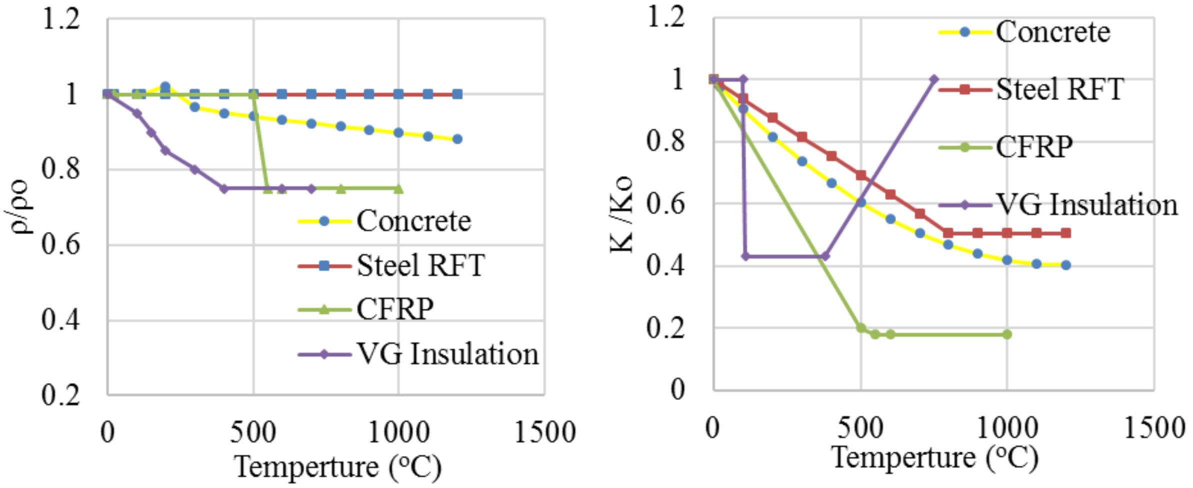


Fig. (2.a) Normalized density Fig. (2.b) Normalized thermal conductivity

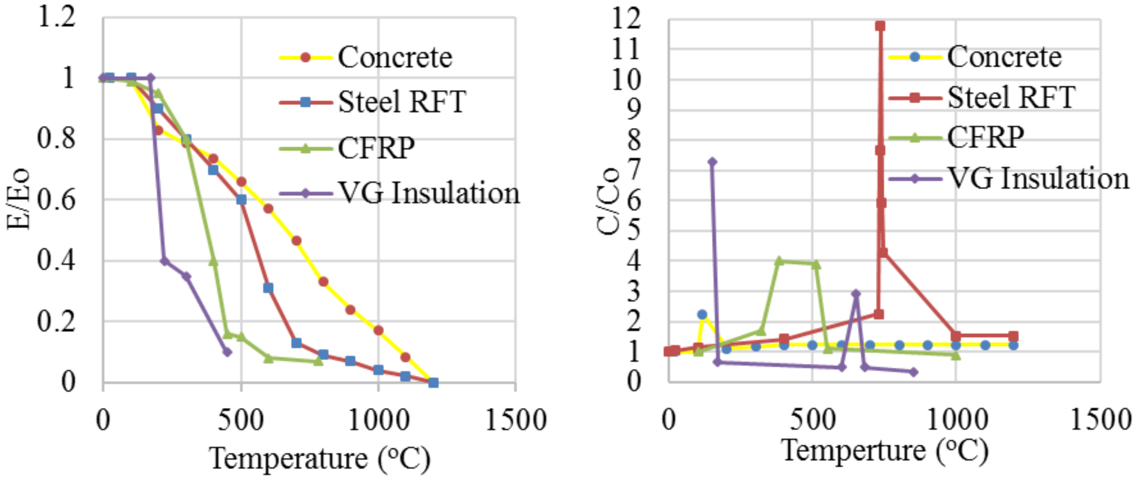
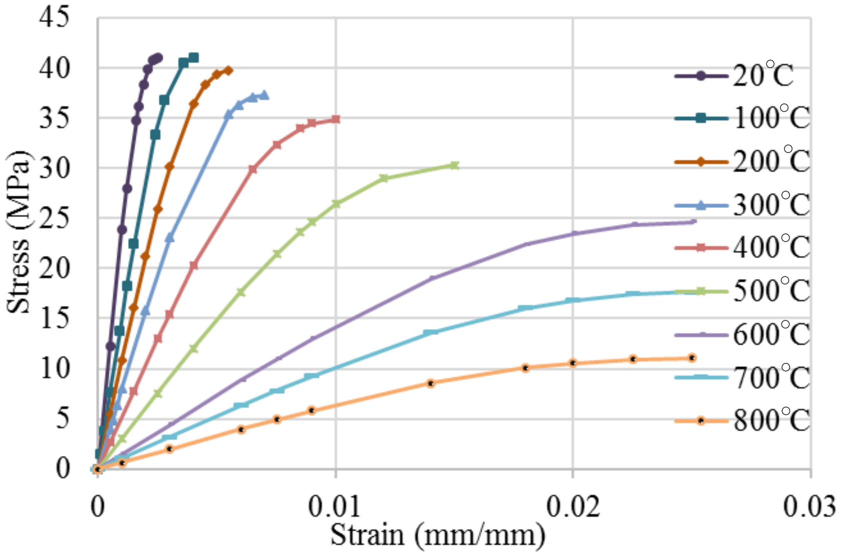


Fig. (2.c) Normalized stiffness Fig. (2.d) Normalized specific heat

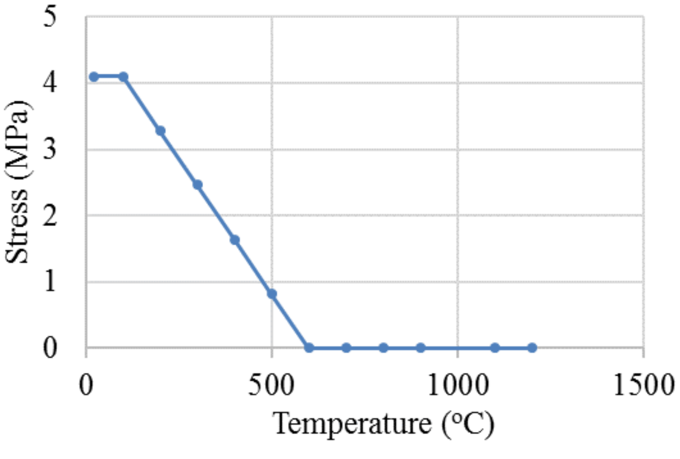
Fig. (2) Variation of mechanical and thermal properties of materials with temperature

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. (3b)

[13, 20]. The variation of the mechanical and the thermal properties of FRP and the materials used for thermal insulation is addressed in researches and is 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 [22-24].



(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

3.3.Nonlinear Analytical Parameters, Loading and Boundary Conditions

Concrete is modeled 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 Fig. (3) are based on Eurocode [12]. 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 results 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 [14] and shown in Fig. (4) are applied as nodal temperature-versus-time to the bottom surface of the T-beam. Eq. (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 [13] is simulated by applying a pressure of 0.0278 MPa to the top surface of the T-beam flange.

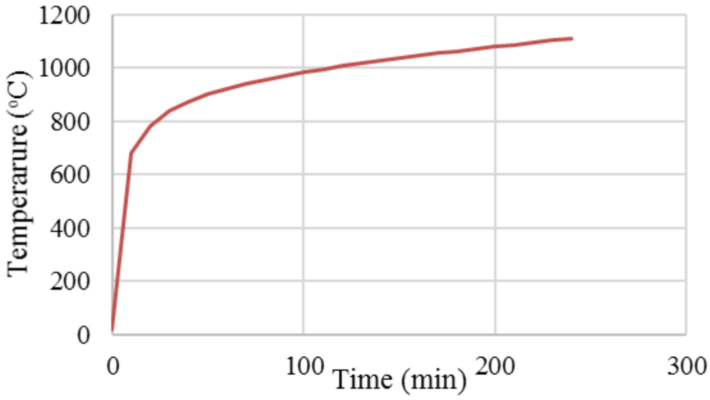


Fig. (4) Applied temperature conforming to Standard Fire Test Curve of ASTM E119

4. Results and Discussion

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 [13] are plotted in Fig. (6).

It can be concluded from Figs. (5 and 6) that there is good agreement between the presented numerically predicted temperatures and the published experimental and numerical results [13, 18]. The average temperature of the steel reinforcement is less than 270 ^{o}C after four hours of fire exposure, which is below the ASTM E119 temperature limit of 593 ^{o}C.

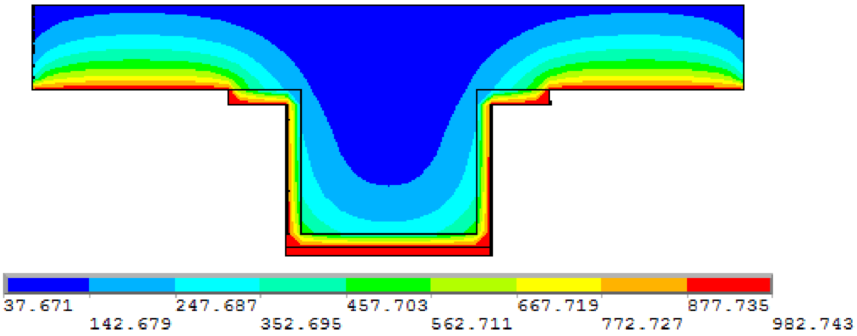


Fig.(5) Numerically predicted temperature distribution in beam cross-section (^{o}C) after four hours

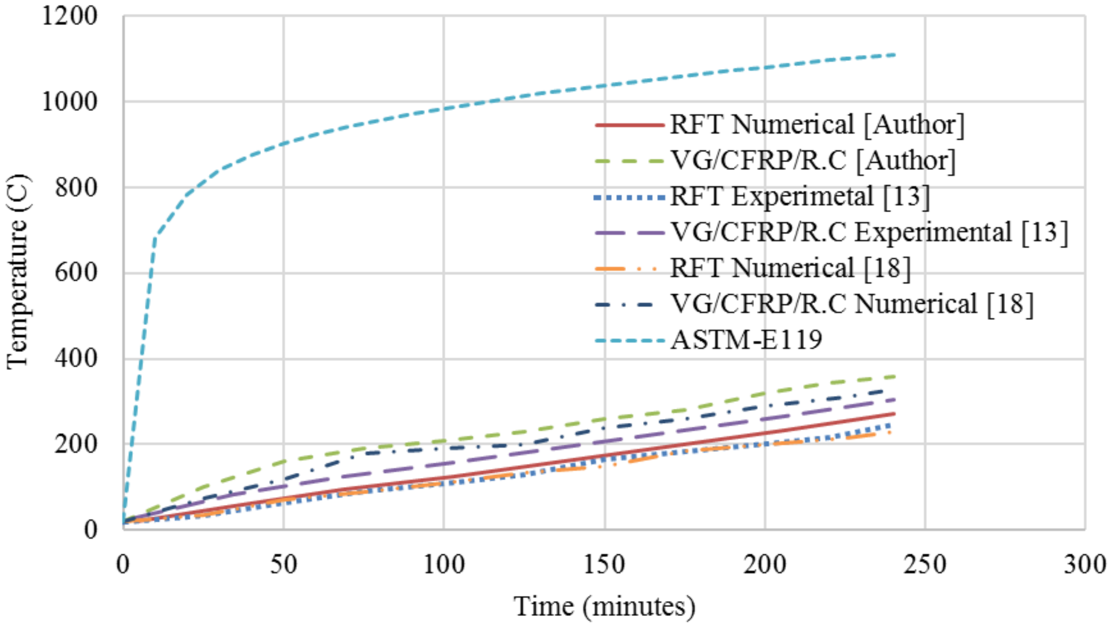


Fig. (6) Numerical results of temperature versus time compared to experimental results

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 [13]. The experimental results show a sudden drop in deflection because of an accidental loss of hydraulic pressure in the loading rig during the first 50 minutes of the fire test .The deflection continues to increase nonlinearly in the numerical model under the sustained load. It should be mentioned that structural RC members such as beams and floor assemblies typically require fire endurance ratings greater than two hours. The time until failure in both the finite element model and experiment is more than the fire endurance ratings required by North American standards in typical building applications. Also, Fig.(7) demonstrates the correlation with published numerical results [18].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.

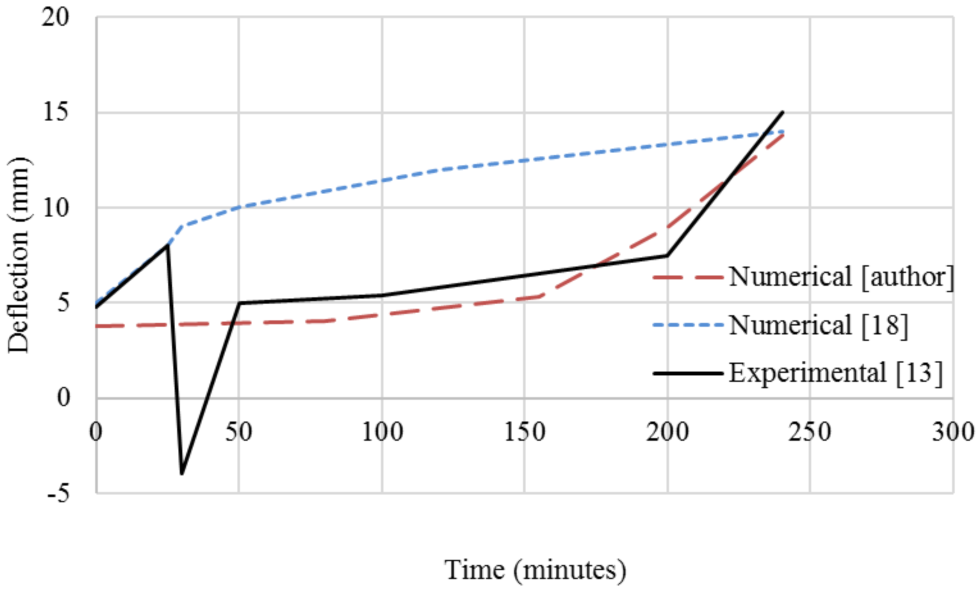


Fig. (7) Variation of mid-span deflection with exposure time

Figure (8) shows the vertical deflection of the adopted beam under elevated temperature after four hours of exposure to standard fire temperature. The mid-span deflection increases with time due to heating the bottom surface of the beam resulting in additional tensile strains which increase the mid-span deflection of the studied beam.

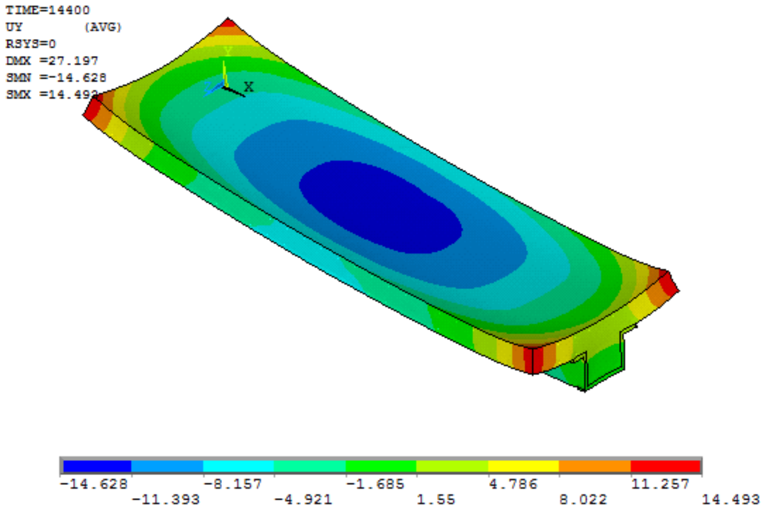


Fig. (8) Numerically predicted deflections (mm) after four hours exposure to elevated temperature

Figure (9) shows the numerically predicted cracks in the studied beam cross-section after four hours of exposure to elevated temperature. The number of cracks increases with exposure time due to the increase in the total strain in concrete resulting from both structural and thermal loading conditions.

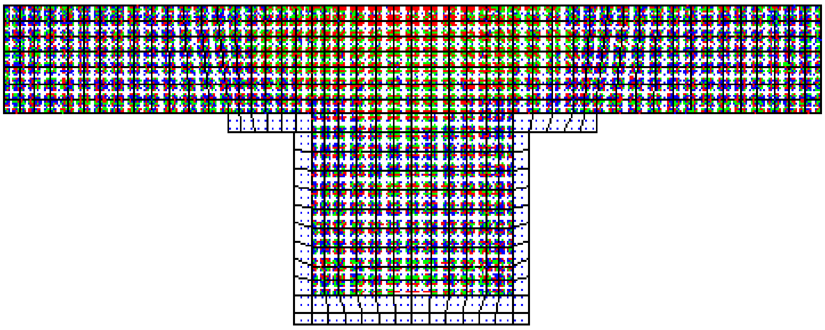


Fig. (9) Numerical predicted cracks in the beam cross-section after four hours

5. 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 [19]. The proposed procedure is verified by comparing the numerical results with experimental results in the published literature. 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 presented model can be used to accurately predict the full fields of temperatures and deflection in CFRP-strengthened insulated T-beams exposed to fire.
4. Numerical results indicate that the mid-span deflection increases nonlinearly throughout the fire exposure time. This is due to the increase in the total strain on the tension side of the beams and due to concrete cracking.
5. The developed finite element model provides reliable coupled thermal-structural results and provides useful information on the fire resistance of insulated strengthened structural member.
6. The developed numerical procedure thereby provides an economic tool to check and design fire protection layers for FRP-strengthened RC beams.

Nomenclature

C: Specific heat
C_o: Specific heat at room temperature
E: Stiffness modulus
E_o: Stiffness modulus at room temperature
K: Thermal conductivity
K_o: Thermal conductivity at room temperature
$\mathrm{T_g}$: Glass transition temperature
α: Coefficient of thermal expansion
μ: Poisson's ratios
ρ: Material density
ρ_o: Material density at room temperature
^oC: Temperature in Celsius
t: Exposure time (Minutes)

References

1. Apicella,F., Imbrogno, M., “Fire performance of CFRP composites used for repairing and strengthening concrete”, Proceedings of the 5th ASCE Materials Engineering Congress, Bank L.C., ed., ASCE, Cincinnati, Ohio, 1999, 260–266.
2. Leone, M., Matthys, S., and Aiello, M. A., “Effect of elevated service temperature on bond between FRP EBR systems and concrete”, Composites B, 40(1) (2009) 85–93.
3. 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.
4. 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.
5. 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.
6. 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.
7. 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.
8. 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) 199–205.
9. 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)157–185.
10. 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) 26–35.
11. 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) 183–190.

12. 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.
13. 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.
14. 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.
15. 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.
16. 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) 15–24.
17. 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) 3309–3106.
18. 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.
19. ANSYS. Finite Element Computer Code. Version 12.1.0. ANSYS Inc., Canonsburg, PA, 2009.
20. Harmathy, T.Z., “Fire Safety Design and Concrete, Concrete Design and Construction Series”, Longman, UK, 1993.
21. 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.
22. 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.
23. 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.
24. 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.