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Modeling of insulated CFRP strengthened reinforced concrete T-Beam exposed to Fire

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Abstract

The use of Fiber Reinforced Polymer (FRP) has been established as the state of the art technique to strengthen concrete beams in flexure and shear. Carbon Fiber Reinforced Polymer (CFRP) has been identified as the material of choice in civil infrastructure applications. The fire performance of such CFRP-strengthened members and their resistance to heat transfer and to various environmental exposure factors needs to be investigated. In this paper, a detailed finite element model of a CFRP-strengthened reinforced concrete T-beam is developed. The model accounts for the variation in thermal and mechanical parameters of the beams' constituent materials with temperature, including CFRP and insulation materials. Time domain transient thermal-stress finite element analysis is performed using the commercial software ANSYS to study the heat transfer mechanism and deformation within the beam for fire conditions initiating at the bottom of the beam. To relate the simulation to an actual case, a reinforced concrete T-beam strengthened with CFRP and fire-tested by other investigators is modeled. The progression of temperature in the beam, CFRP, reinforcing steel, and along the CFRP-concrete interface is compared to the observed fire test data. Overall, the predicted temperature results are in a

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good agreement with the measured ones. In addition, the mid-span deflection increases steadily during the fire exposure time due to the increase in the total strain on the tension side of the beams' cross section. Successful FE modeling of this structure provides an economical, alternative solution to expensive experimental investigations.

Keywords: Finite element; Carbon fiber reinforced polymers; Fire; VG insulation; Elevated temperatures; Variable material properties

Introduction

In recent years, structural engineers started to employ Fiber Reinforced Polymer (FRP) as the state of the art technique to strengthen structural concrete members (slab, beams, and columns). FRP products are attractive materials in strengthening and rehabilitation of structural members due to their high strength to weight ratio, resistance to corrosion, lightweight, and ease of application. There are typically two types of FRP in use: Glass FRP (GFRP) and Carbon FRP (CFRP). For most civil infrastructure engineering applications, CFRP has been identified as the material of choice due its higher strength compared to GFRP. Flexural strengthening involves bonding CFRP sheets to the soffit of concrete beams to carry the extra tensile force needed for the upgraded member. These externally bonded sheets are exposed to the environment especially fire in buildings. Therefore, FRP resistance to heat transfer and to various environmental exposure factors needs to be investigated. The CFRP is typically insulated using Gypsum products to protect it from the direct fire exposure. Such insulation products act to prolong the composite action between the concrete and FRP and keep the FRP properties from degrading at the normal rate.

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Research on the performance of FRP-strengthened concrete members exposed to fire is quite lacking and needs further investigation. Few studies have been conducted on the performance of FRP-strengthened concrete beams subjected to fire exposure. Among them, Deuring [1] conducted tests on externally strengthened concrete beams subjected to ISO standard fire exposure. In this experimental program, it was observed that the unprotected FRP-strengthened beam achieved a fire endurance of 81 minutes. In contrast, an identical beam with the FRP protected with a 40 mm calcium silicate insulation board achieved a fire endurance of 146 minutes. Blontrock et al. [2] tested, in a similar fire test program, a series of 10 CFRP-strengthened reinforced concrete beams protected with calcium silicate boards. In this experimental study, the beams were subjected to the maximum service loads as calculated according to Eurocode 2. Several insulation parameters were investigated, including board thickness, length, location, and bonding method. It was observed that the best fire endurance can be achieved if U-shaped fire protection insulation is applied to both the base and sides of the beams. In addition, the loss of bond between the CFRP and concrete occurred when the temperature in the CFRP strip reached between 66 to 81°C. A maximum fire endurance of 38 minutes was achieved with this insulation scheme, which is less than the fire endurance ratings required by North American standards in typical building applications. Williams et al. [3] experimentally investigated the performance of two CFRP-strengthened reinforced concrete T-beams insulated with VG insulation under fire conditions. The specimens were exposed to ASTM E119 [4] standard fire curves in a chamber furnace. In addition, a sustained uniformly distributed service load of 34 kN/m was applied to the top surface of the flange throughout the fire exposure time. Temperature variation, member deflection, and strain in the steel reinforcement were monitored and recorded during the test. The results of this investigation indicated that a properly insulated system can

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maintain the FRP and reinforcing steel materials below a certain critical temperature value that sustains their structural integrity. It was also concluded that one layer of VG insulation can protect the beam during fire exposure and achieve fire endurance of more than 4 hours. Williams et al. [3] developed a 2-D heat transfer model which employs an explicit finite difference formulation to predict temperatures within the FRP strengthened concrete T-beam section at any time during the applied fire exposure. Overall, the model provides a reasonable estimate of temperatures at various locations and still requires further refinement.

In this paper, a detailed 3D finite element (FE) model of a CFRP-strengthened concrete T-beam is presented to evaluate its fire performance and predict and validate the experimental test results conducted by Williams et al. [3]. For the sake of the coupled thermal-mechanical analysis, material curves are digitized from the open literature to feed the analysis with temperature history of thermal conductivity, specific heat, mass loss, stiffness degradation and coefficient of thermal expansion. The effect of heat transfer on degrading the mechanical properties of the FRP and FRP-concrete interface is obtained by performing a time domain transient thermal analysis using the commercial software package ANSYS [5] for fire conditions initiating at the bottom of the beam. The accuracy of the analysis was checked by comparing the temperature results from the FE model against the measured test data of Williams et al. [3]. In addition, the analysis yields important findings on the resistance of concrete beams strengthened with CFRP exposed to under fire conditions.

Analytical Methodology

The general methodology of the model development and transient thermal-stress analysis consists of:

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1. Building a three-dimensional model of the T-beam. The model incorporates the geometry (Concrete, Reinforcement Steel, Carbon FRP Sheet, and VG Insulation), appropriate materials, and boundary conditions. There are two finite element models consisting of thermal and structural elements, respectively, to enable the thermal and structural analysis.
2. Applying the thermal loads to the bottom surface of the insulated beam resulting from the furnace transient fire (in the form of transient temperatures versus time) applied according to the ASTM E119 [4] guidelines. The top of the flange (slab) was exposed to ambient temperature.
3. Validate the finite element model by comparing the predicted and measured temperature at various points within the T-beam cross section taken at mid-span.
4. Applying a sustained uniformly distributed load at the top face of the T-beam to simulate the dead and live gravity service loads during fire. In addition, apply the thermal loads (nodal temperature) at several time points (load steps and sub-steps) including the first (static) and last time points from Step 2 on the structural finite element model and obtaining the deflection and strain (thermal and mechanical) results. The deformation field in the model at the first load step (due to the applied gravity load) is used to verify the correct behavior of the model and correct modeling of boundary and loading conditions.
5. Evaluate the thermal, mechanical, and total strain for different points within the mid-span beam cross section at all the applied time loads of the structural analysis run.

Finite Element Model

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The studied finite element model has the same geometry, configuration and dimensions as the test specimens [3]. The modeled insulated T-beam is 3900 mm in length and 400 mm in depth. The width of the flange and web is 1220 mm and 300mm respectively. Two 20 mm diameter steel rebars are used to model the internal steel reinforcement and the soffit of the beam was strengthened with a 100 mm wide CFRP layer. The exterior face of FRP along with the three sides of the T-beam web were insulated with a 25 mm layer of VG insulation. The VG insulation was extended to a distance of 125 mm into the bottom underside surfaces of the flange, along the entire beam length, Fig. 1.

The finite element analysis in this study is performed using ANSYS 11.0 [5]. The model was developed in ANSYSWORKBENCH Version 11.0 [6]. Both the cross section of the T-beam and the FE model are shown in Fig. 1.

Due to the symmetry of the loading, boundary conditions, and materials, a quarter model was built and analyzed using the commercial finite element code ANSYS [5-6]. The advantage of building a quarter models for this structure is the reduction in the total number of elements which will result in saving a lot of computational time.

The element types [5-6] chosen for the transient thermal analysis are the thermal element SOLID70 (3-D 8-Node Thermal Solid) used to model the entire structure and LINK33 (3D Uniaxial 2-Node Conduction Bar) used to model the reinforcing steel bars. The total number of elements is 50125. These thermal elements were converted to structural elements [5] to model the different materials for the structural stress analysis as follows:

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- For the concrete material, the thermal SOLID70 element is converted to structural element SOLID65 (3-D 8-Node Reinforced Concrete Solid).
- For the Carbon FRP material, the thermal SOLID70 element is converted to structural element SOLID46 (3-D 8-Node Layered Structural Solid).
- For the VG Insulation material, the thermal SOLID70 element is converted to structural element SOLID45 (3-D 8-Node Structural Solid).
- For the steel reinforcement material, the thermal LINK33 element is converted to structural element LINK8 (3-D 2-Node Structural bar).

Material Properties at Room and Elevated Temperature

In order to obtain an accurate prediction of the heat transfer within the T-beam cross section, the thermal and mechanical properties of the component materials with increasing temperature are required for the thermal and stress analysis. Table 1 provides a listing of the mechanical and thermal properties for the concrete, steel, CFRP, and insulation materials at room temperature. The normalized variation of the modulus of elasticity (stiffness), thermal conductivity, and specific heat with temperature for the constituent materials are displayed in Fig. 2.

It should be noted that the thermal and mechanical properties at elevated temperature for concrete and steel were studied comprehensively in the literature [7-9]. On the other hand, research on the thermal and mechanical properties at elevated temperature of CFRP and VG insulation materials used in building and infrastructure applications have not been extensively studied and to some extent lacking. In this study, the thermal and mechanical properties of CFRP and VG insulation have been assumed to

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vary based on the suggestions of several other researchers [10-14]. Griffis et al. [14] performed tests on a carbon/epoxy FRP used in -aerospace applications. Cramera et al. [13] studied and reported the thermal and mechanical properties of gypsum board (insulator) at elevated temperature. In this study, the resulting assumed variation in the thermal and mechanical properties of FRP and VG insulation along with the concrete and reinforcing steel materials are shown in Fig. 2.

Loads & Boundary Conditions

For the transient thermal analysis load case, a nodal temperature versus time curve shown in Fig. 3 was applied to the bottom surface of the T-beam web. The results of the thermal analyses are evaluated by examining the temperatures at key locations and temperature gradients between the key locations of the model. In the second load case, structural stress analysis was performed where the thermal gradient distribution in the T-beam from the thermal analysis was applied to the beam as nodal temperatures at several time loads and substeps. The beam was structurally analyzed with simply supported end conditions. In addition, a sustained uniformly distributed load of 34 kN/m was applied to the top face of the T-beam flange during the experimental fire test. This loading condition was simulated in the FE model by applying a pressure of 0.0557 MPa (calculated by dividing the distributed load by half the flange width of 610 mm) to the top face of the T-beam flange in addition to the beam self weight.

Results

In order to examine the validity and predictability of the model, the FE and experimental results were compared. Fig. 4 shows the nodal temperature variation in the T-beam cross section after 4 hours

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of fire exposure. The measured (test data) and predicted (from thermal analysis) temperatures in the VG, FRP, and concrete are shown in Fig. 5. In addition, Fig. 6 provides, a comparison of the temperature measured in the steel against temperature predicted by the thermal analysis. Overall, it is clear from Figs. 5 and 6 that there is a good agreement between the experimental and finite element predicted temperatures results. Although, the model slightly under-predict the temperatures at the VG-FRP interface after 1 hour of fire exposure, it provides a satisfactory agreement with the measured steel temperature at all stages of fire exposure as shown in Fig. 6. The average steel temperature was less than 250°C after 4 hours of fire exposure which is less than the ASTM temperature limit of 593°C.

Viewing of the full fields of vertical deflection, thermal and mechanical stresses/strains are possible in the FE model. This provides a great advantage over experimental testing in evaluating the fire performance of the T-beam. Fig. 7 shows the mid-span FE predicted vertical deflection at the centerline of the cross section and at the center of the flange as a function of fire exposure time, under the applied sustained uniformly distributed load of 34 kN/m. In addition, Figs. 8 and 9 show the mechanical and total strain at several locations within the cross section at the beam mid-span as a function of fire exposure time. The total strain ε_{total} is equal to the addition of the mechanical strain ε_{m} to the thermal strain ε_{th}.

It is clear that the mid-span deflection increases steadily during the fire exposure time. Heating the bottom surface of the beam resulted in additional downward deflection. It should also be noted that the increase in deflection is associated with an increase in the total strain ε_{total} on the tension side of the beam. This behavior occurred as a result of heating the FRP and reinforcing steel on the tension side of

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the beam, thus reducing their stiffness. This reduction of stiffness on the tension side of the beam will cause the neutral axis to shift upward, resulting in further beam deflection.

Summary & Conclusions

An FE model was developed to accurately predict the behavior and performance of an insulated reinforced concrete T-beam strengthened in flexure with CFRP sheets when exposed to the ASTM E119 [4] standard fire. The model has been validated and verified against data from experimental tests performed by other investigators [3]. The following conclusions can be made based on the results of the finite element and experimental investigations:

The model agrees reasonably well with experimental results. As a result the model is capable of predicting full fields of temperatures, deflections, strains, and stresses in CFRP-strengthened and insulated T-beams exposed to underside fire.

With respect to the fire performance of CRFP-strengthened insulated T-beams exposed to bottom fire, the VG insulation system used can protect the CFRP strengthened concrete T-beam from excessive heat penetration, by maintaining low temperature in the cross section of the beam. As a result, the CFRP strengthened T-beam did not fail under the applied service load during fire exposure.

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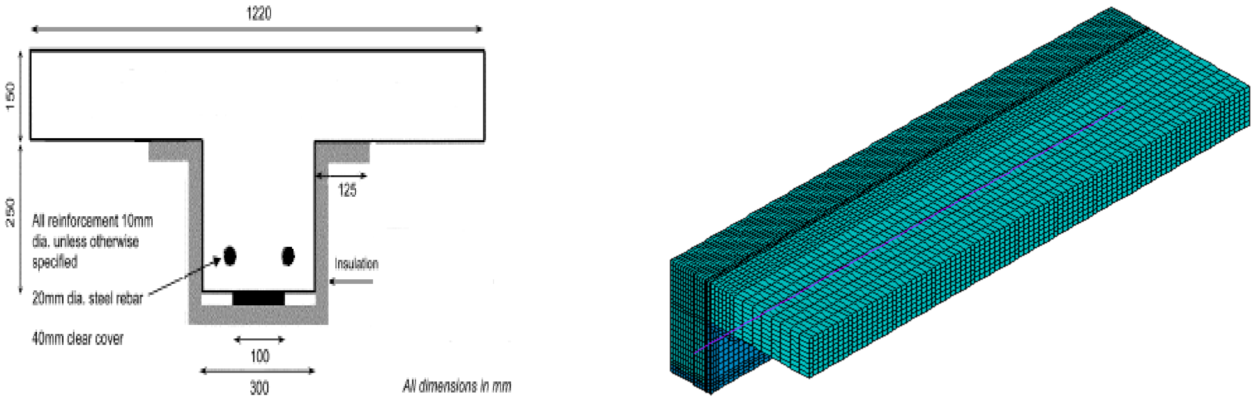

a) Insulated T-beam cross section [3]

b) Isometric view of the quarter FE Model and Mesh

Fig. 1. Finite Element Model and Dimension of the Test Specimen

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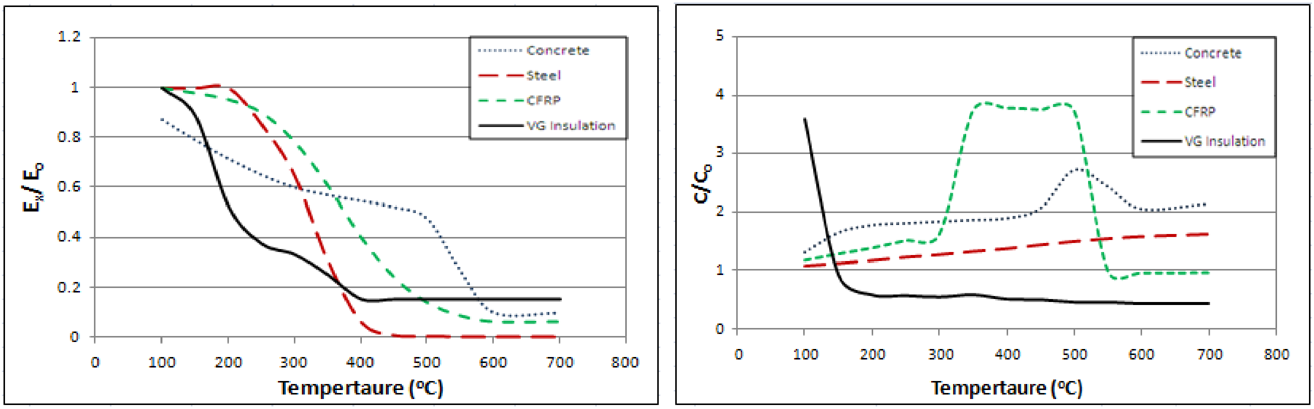
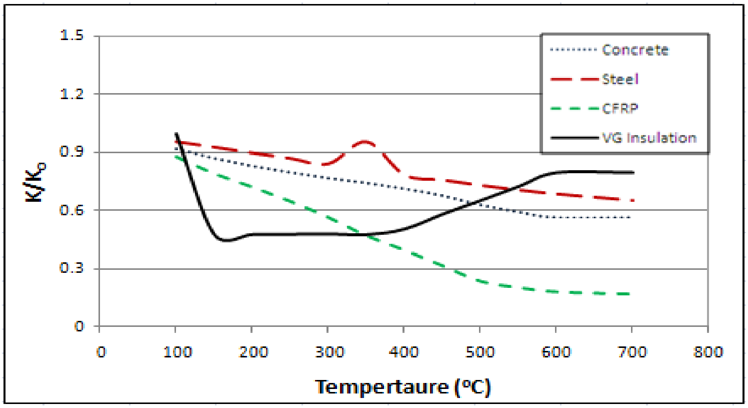


(a) Normalized Stiffness with Temperature (b) Normalized Specific Heat with Temperature



(c) Normalized Thermal Conductivity with Temperature

Fig. 2. Normalized properties of materials with elevated temperature (a) Stiffness (b) Specific Heat (c) Thermal Conductivity [7-8, 10-14]

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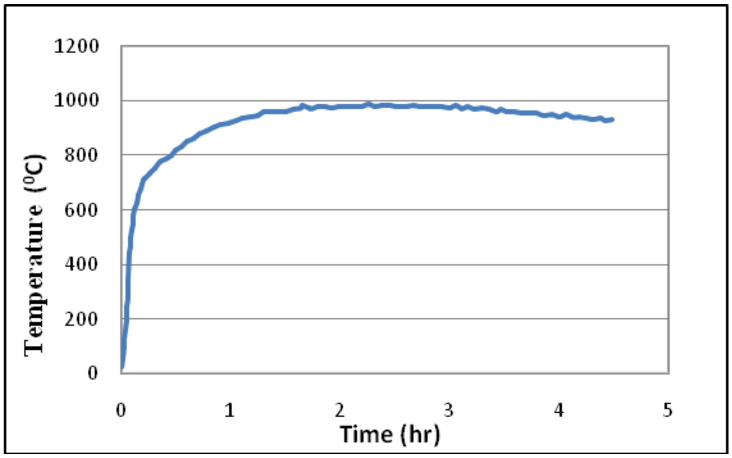

Fig. 3. Applied Furnace Temperature as function of time

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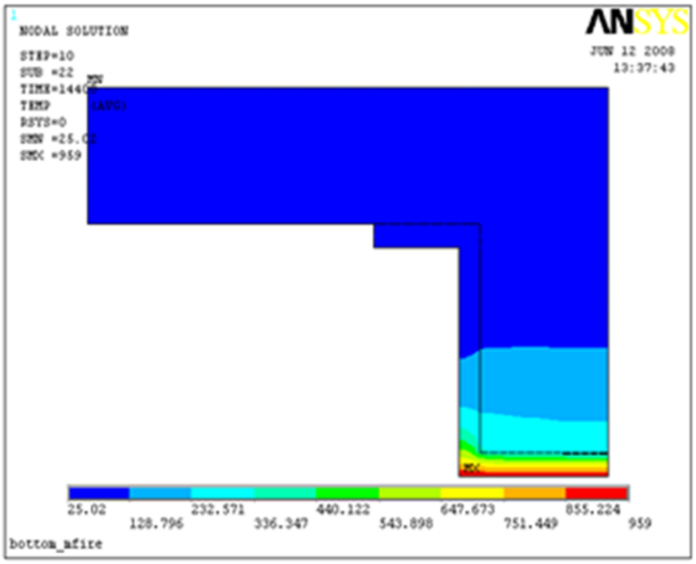

Fig. 4. Cross section temperature distribution

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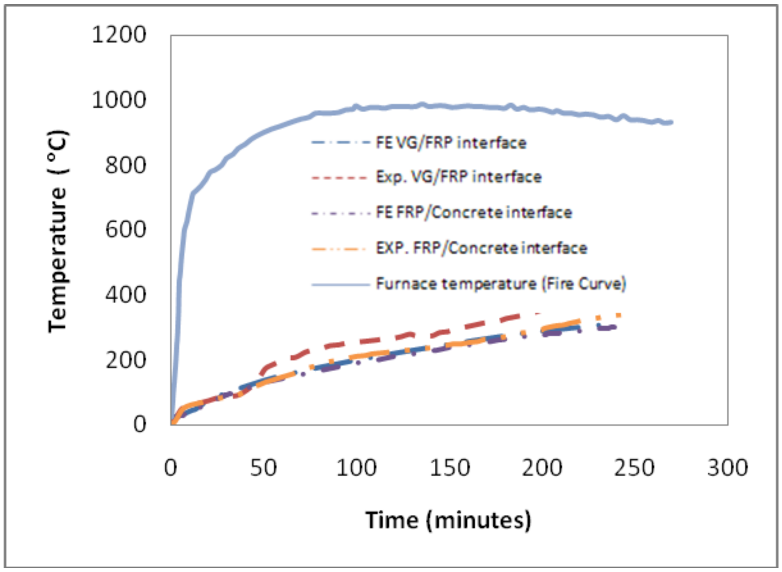

Fig. 5. FE and measured temperature as a function of time

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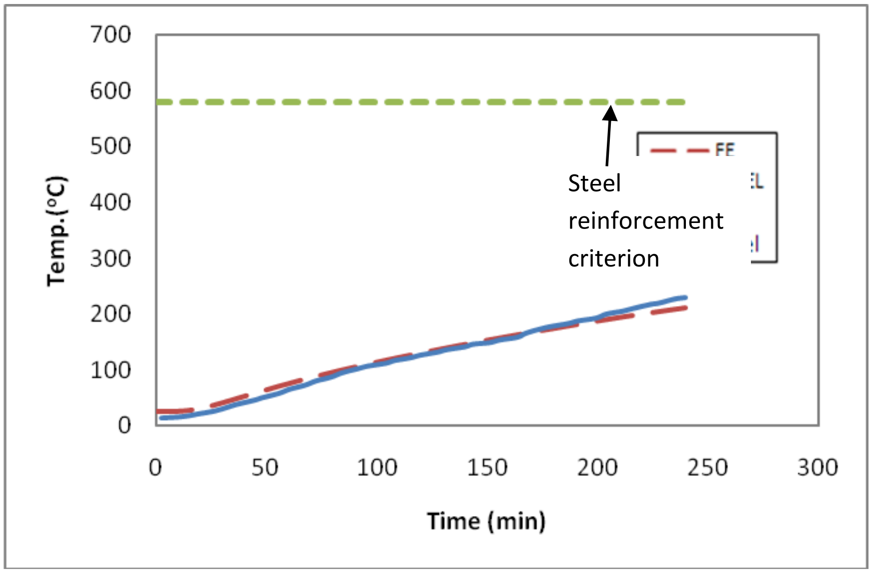

Fig. 6. Predicted and measured steel temperature as a function of exposure time

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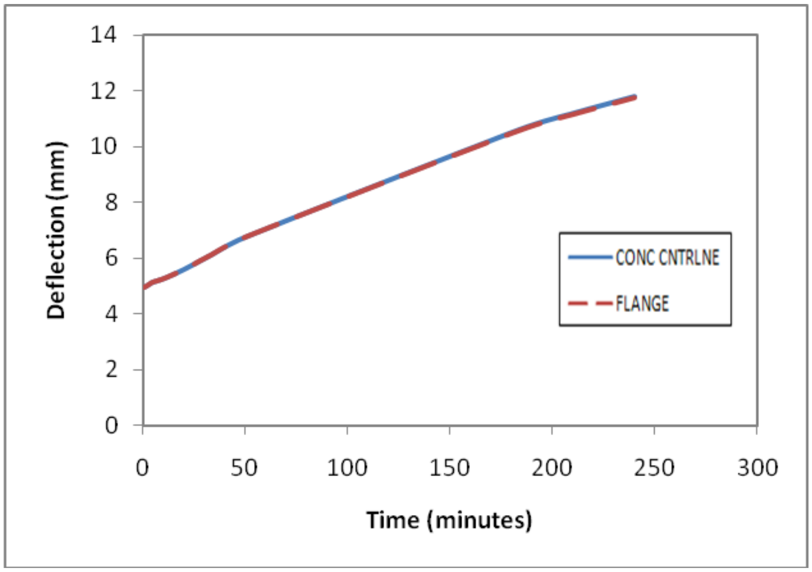

Fig. 7. FE Midspan vertical deflection

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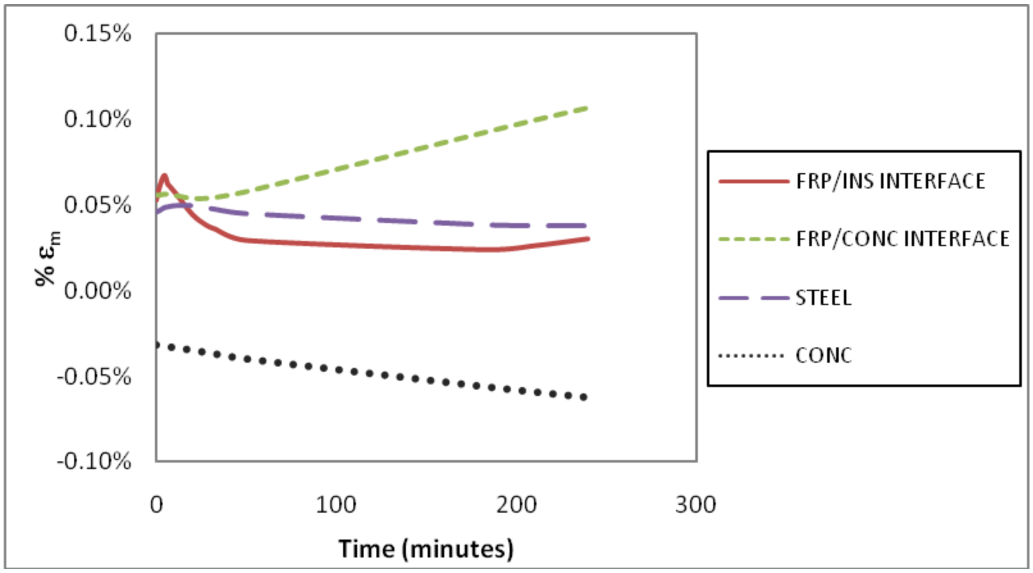

Fig. 8. FE predicted mechanical strain as a function of time

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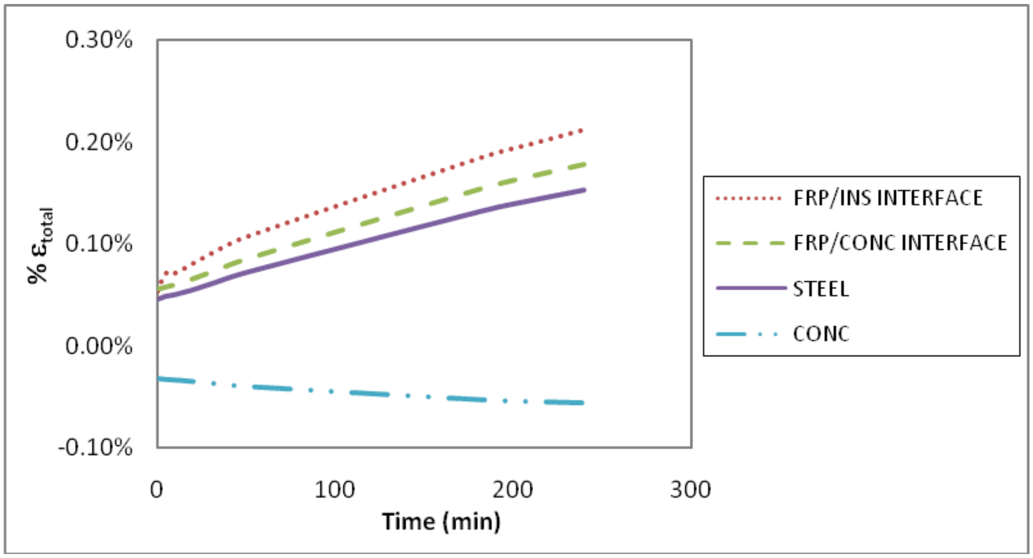

Fig. 9. FE predicted total (mechanical + thermal) strain as a function of time

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List of tables:

Table 1 Mechanical and Thermal Material Properties at room temperature

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Table 1

Mechanical and Thermal Material Properties at room temperature

Property Material	**E_x MPa**	**E_y MPa**	**E_z MPa**	**K W/mm.K**	**C J/kg.K**	**μ_x —**	**μ_y —**	**α —**	**ρ Kg/mm3**
Concrete	30200	___	___	2.7×10^{-3}	722.8	0.2	___	6.08×10^{-6}	2.40×10^{-6}
Reinforcement Steel	210000	___	___	5.2×10^{-2}	452.2	0.3	___	6.00×10^{-6}	7.86×10^{-6}
CFRP	228000	10000	10000	1.3×10^{-3}	1310	0.28	0.0122	-0.9×10^{-6}	1.60×10^{-6}
VG Insulation	2100	___	___	2.5×10^{-4}	1654	0.3	___	1.70×10^{-5}	2.69×10^{-7}