Transient Thermal-Stress Finite Element Analysis of CFRP Strengthened RC beams Exposed to different Fire Scenarios

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Abstract

A detailed 3D thermal-stress finite element analysis is performed to study the heat transfer mechanism within a CFRP strengthened concrete beam. The effect of heat transfer on degrading the mechanical properties of the FRP in time domain transient thermal analysis using the software package ANSYS is studied for fire conditions initiating at the top of the beam. This loading scenario has not been investigated earlier neither experimentally nor analytically. Accordingly a reinforced concrete T-beam strengthened with CFRP and fire-tested by other investigators is modeled here to compare the fire rating of top and bottom exposure. The progression of temperature and total strain (thermal + mechanical) in the beam and CFRP is studied, and a fire rating is established. The finite element results correlated very well with the experimental measured results for the bottom fire exposure. In addition, the investigation of the top fire exposure yielded important findings on the resistance of concrete beams when subjected to such fire conditions. It is concluded that heating the top surface (slab) of reinforced concrete beams seems to be beneficial in minimizing mid-span deflection.

Keywords *CFRP Strengthening; Concrete Beams; Finite Elements; Fire Loading.*

Introduction

Fiber Reinforced Polymer (FRP) has been excessively used as the technique of choice to strengthen concrete beams in both flexure and shear. While there are many types of FRP, Carbon Fiber Reinforced Polymer (CFRP) has been selected for civil infrastructure applications, e.g. bridges and buildings, due to its many superior characteristics like the very high strength to weight ratio as well as corrosion and fatigue resistance. 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 surrounding environment especially fire exposure in buildings. Thus, their resistance to heat transfer and to various environmental factors needs to be investigated. The CFRP is typically insulated using Gypsum products to protect it from the direct fire exposure.

Few researchers investigated the response and behavior of CFRP strengthened reinforced concrete T-Beams when subjected to several fire loading scenarios. **Deuring [1]** conducted tests on concrete beams strengthened with externally bonded FRP sheets subjected to ISO standard fire exposure. Deuring carried out two fire scenarios. In his first scenario, 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 using a 40 mm calcium silicate insulation board achieved a fire endurance of 146 minutes.

Blontrock et al. [2] tested in a similar fire test experiment a series of 10 reinforced concrete beams strengthened with CFRP and protected with calcium silicate insulations. 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.

Zhou and Vecchio [3] developed a 2D finite element model to predict the response and study the behavior of reinforced concrete structures when subjected to transient thermal loads using the nonlinear finite element software VecTor2. The predictions of the FE analysis were compared with experimental results and it was concluded that the suggested nonlinear finite element analysis procedure is capable of modeling the complete response of a concrete structure to thermal and mechanical loads.

Williams et al. [4] experimentally investigated the performance of two CFRP-strengthened reinforced concrete T-beams insulated with VG insulation under fire conditions initiated at the soffit of the beam. The VG insulation is a fire resistant, lightweight cementitious plaster that can be sprayed or trowelled (manually applied) onto structural members to thermally protect them from fire. The specimens were exposed to **ASTM E119 [5]** standard fire curves in a furnace chamber. 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. The results of this investigation indicated that a properly insulated system can 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.

Other investigators developed finite element models to predict the response of reinforced concrete members when strengthened with CFRP without thermal load exposure. Among them, **Kim and Aboutaha [6]** created 3D finite element models to simulate the behavior of reinforced concrete beams strengthened with CFRP to improve the flexural capacity as well as ductility of the beams. Two models were developed using smeared and contact bond elements respectively. The predictions from the two FE models showed good agreement with experimental data on full-scale reinforced concrete members.

Park and Aboutaha [7] investigated different finite element modeling methodologies for strengthened reinforced concrete members with externally bonded FRP sheets using ANSYS. A total of 22 experimental deep beams with or without FRP flexural and/or shear strengthening systems were analyzed. For each test specimen, a total of 16 cases of modeling factor combinations were developed and analyzed to find the optimal FEA methodology. In addition, SHELL63 and SOLID46 ANSYS element types were investigated and compared to find the best element that predicts the response of FRP strengthened beams. It was concluded in this study that the nonlinear finite element analysis of concrete structures are sensitive to the shear transfer coefficient (STC) for an open crack and force convergence tolerance value (CONVTOL) with an optimal combination of 0.25 for STC and 0.2 for CONVTOL, respectively. In addition, SOLID46 element which represented the FRP strengthening system yielded better results than that of SHELL63.

The scenario of fire exposure initiated at the top surface of CFRP-strengthened concrete beams has not been investigated experimentally or analytically. Since there is no experimental investigation on insulated concrete beams strengthened with CFRP when exposed to fire initiated at the top flange surface (slab), a reinforced concrete T-beam strengthened with CFRP and fire-tested by **Williams et al. [4]** with fire exposure initiating at the soffit of the beam is chosen in this study. **Hawileh et al. [8]** validated the experimental results by developing a 3D finite element model. They performed time domain transient thermal-stress analysis to simulate the temperature distribution within the beam. They also generated the structural response due to the fire exposure given by ASTM E119 [5] at the bottom surface of the CFRP-strengthened concrete

T-beam. The developed model predicted the experimental results of Williams et al. [4] and the results will be summarized in a subsequent section.

In this paper, a detailed 3D thermal-stress finite element analysis is performed to study the heat transfer mechanism within the beam. The effect of heat transfer on degrading the mechanical properties of the FRP and FRP-Concrete interface in time domain transient thermal analysis using the software package **ANSYS (2008)[9]**?? is studied for fire conditions initiating at the soffit and top surface of the beam. The progression of temperature, deflection, and strains in the beam, CFRP and along the CFRP-Concrete interface are studied with a fire rating established. The model takes into account the variation of thermal and mechanical material properties with temperature. The model uses the temperature curves of thermal conductivity, specific heat, mass loss, stiffness degradation and the variation of the coefficient of thermal expansion. The analysis yields interesting and important findings on the resistance of concrete beams to such fire conditions.

Analytical Methodology

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

1) Building a 3-D finite element model of the T-beam. The model incorporates the geometry (Concrete, Reinforcement steel, Carbon FRP sheet, and VG Insulation), appropriate materials, fine meshing, and boundary conditions. Thermal elements are used for the thermal analyses that were converted to structural elements in the structural stress analysis load step.

2) Applying the standard ASTM E119 (2002) fire exposure to the bottom (soffit) or top (slab) surface of the T-beam in the form of transient temperatures versus time. The rest of the surfaces of the T-beam were exposed to ambient temperature. Perform transient thermal analysis to obtain the temperature distribution in the T-beam.

3) Investigating the temperature variation within the cross section. From the results of the thermal analysis, obtain the predicted temperature with time at various locations within the T-beam cross section at midspan.

4) Performing structural stress analysis to obtain deflection, and strain results. The temperature distribution along the beam from the thermal analysis (Step 2) run is applied as nodal temperature at several selected time points. In addition, a sustained uniformly distributed load (dead + live) of 34 KN/m is applied along the beam's span top face with simply supported ends.

5) Evaluating the deflection, thermal strain, mechanical strain, and total strain for different points within the mid-span beam cross section at all the applied time loads.

Finite Element Model

The FE model of the T-beam has the same geometry configuration and dimensions as the test specimens [4]. The simply supported 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. The flange thickness is 150 mm. 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 (cementitious plaster). The VG insulation was spray-applied and was extended to a distance of 125 mm into the bottom underside surfaces of the flange, along the entire beam length. Due to the symmetry of the loading, boundary conditions, and materials, it was decided to build a quarter beam-model to reduce the total number of elements resulting in tremendous saving of computational time.

The FE model was built in ANSYSWORKBENCH [10]. The FE analysis is performed using ANSYS [9]. The dimensions of the T-beam's cross section and the FE model are shown in Figure 1. Two types of elements from ANSYS [9] are chosen for the transient thermal analysis. These elements are: SOLID70 (3-D 8-Node Thermal Solid) used to model the entire structure and LINK33 (3-D Uniaxial 2-Node Conduction Bar) used to model the reinforcement steel bars. The total number of elements is 50125. For the structural analysis run, the thermal elements were converted to equivalent structural elements as follows: SOLID 65 element (3-D 8-Node Reinforced Concrete Solid) for the concrete material, SOLID45 element (3-D 8-Node Structural Solid) for both the CFRP and insulation materials, and LINK8 (3-D 2-Node Structural Spar) for the reinforcement steel material.

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 and Tables 2 through 5 provide a listing of the normalized properties with temperature. It should be noted that the thermal and mechanical properties at elevated temperature for concrete and steel were studied comprehensively in the literature [11-13]. On the other hand, research on the thermal and mechanical properties at elevated temperature of FRP 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 FRP and VG insulation have been assumed to vary based on the suggestions of Kodur, **Bisby et al.** and Cramera et al. [14-16]. Bisby **et al. [15]** performed tests on a carbon/epoxy FRP used in aerospace applications. It should be noted from Table 4 that the CFRP will lose about 40% of its original stiffness and strength at a temperature of 350 °C. **Cramera et al. [16]** studied and reported the thermal and mechanical properties of gypsum board (insulator) at elevated temperature. The resulting assumed variation in thermal and mechanical properties of FRP and VG insulation are listed in Tables 4 and 5, respectively.

Loads & Boundary Conditions

For the transient thermal analysis load case, a nodal temperature versus time curve shown in Figure 2 was applied to the bottom face (soffit) and the top surface of the T-beam flange (slab). 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 were 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 sub-steps. The beam was structurally analyzed with simply supported end conditions. In

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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 for Bottom Fire Loading (Model Validation)

The model can be validated by comparing the FE results with the experimental results of Williams et al. [4] when the T-Beam is exposed to fire loading initiated at the soffit of the beam. The results of the thermal analysis were compared with the experimental thermocouple measurements at different locations within the beam’s cross section at mid-span. The experimental and predicted temperatures in the VG, FRP, and concrete are shown in Fig. 3. It is clear from Fig. 3 that there is a good agreement between the experimental and finite element predicted temperatures results. Although, the model slightly under-predicts the temperatures at the VG-FRP interface after 1 hour of fire exposure, it provides a satisfactory agreement with the measured temperature at the CFRP-concrete interface and steel at all stages of fire exposure as shown in Fig. 3. The average steel temperature was on average less than 250°C after 4 hours of fire exposure which is less than the ASTM temperature limit of 593°C.

It can be concluded that the FE model agrees reasonably well with experimental results. As a result the model is capable of predicting full fields of temperatures in CFRP-strengthened and insulated T-beams exposed to fire at the top surface of the T-beam (slab).

Results for Top Fire Loading

After having a viable and reliable FE model, the behavior and performance of the beam is investigated when subjected to ASTM E119 fire curve (Fig. 2) applied at the top surface of the T-beam's flange (slab). Fig. 4 shows the nodal temperature variation in the T-beam cross section after 4 hours of fire exposure. The predicted temperature variation with temperature in the VG, FRP, concrete, and reinforcement steel are shown in Fig. 5. The average steel temperature was on average less than 80 °C after 4 hours of fire exposure which is way less than the ASTM temperature limit of 593 °C. In addition, the CFRP temperature was less than 50 °C and as a result its structural integrity was maintained.

A viewing of the full fields of vertical deflection, thermal and mechanical stresses and strains is possible in the FE model. This provides a great advantage over experimental testing in evaluating the fire performance of the T-beam. Fig. 6 shows the predicted mid-span 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. 7 and 8 display the mechanical ε_m and total (mechanical + thermal) strain ε_t at several locations within the cross section at the beam's mid-span as a function of fire exposure time.

It is clear that the mid-span deflection decreases steadily during the fire exposure time. Heating the top surface of the beam resulted in a reduction of the downward deflection. This behavior has occurred as a result of heating the concrete on the compression face of the beam, thus reducing its stiffness and strength. This reduction of concrete strength on the compression side of the beam will cause the neutral axis to shift downward, resulting in a reduction of beam deflection. In addition, this reduction of the downward deflection occurred due to a decrease in the tensile strain at the bottom fiber (camber effect) of the beam's cross section as a result of applying the fire loading on the compression side of the beam.

Summary & Conclusions

An FE model was developed to evaluate the performance of an insulated reinforced concrete T-beam strengthened in flexure with CFRP sheets when exposed to top fire loading which was not investigated in the literature. The model was validated by comparing the results with an experimental study conducted by Williams et al. [4] with the fire exposure at the soffit of the beam. The results of the FE model were in a good agreement with the experimental measured data. Accordingly, the investigation for top fire loading will yield reasonable behavior of the beam when subjected to such fire scenario. The following additional conclusions can be made based on the results of the finite element investigation:

1. With respect to the fire performance of CFRP-strengthened insulated T-beams exposed to top fire, the temperature in the FRP was relatively low during the fire exposure and therefore its structural integrity was maintained.

2. As a result of heating the top surface of the beam, the downward deflection was decreased. On the other hand, an increase in the downward deflection will occur if the beam is heated from the soffit of the beam. Heating the top surface of the beam seems to be beneficial in minimizing the midspan deflection with a behavior similar to beam prestressing.

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List of tables:

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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}

Table 2 Normalized Properties of Concrete with Temperature [World Trade Center, 2002]

Property / Temp.(°C)	E_x/ E_o	K/ K_o	C/C_o	ρ/ρ_o
100	0.870	0.919	1.304	0.867
150	0.788	0.872	1.642	0.863
200	0.713	0.832	1.769	0.858
250	0.649	0.799	1.799	0.850
300	0.598	0.769	1.828	0.850
350	0.569	0.744	1.855	0.846
400	0.546	0.714	1.884	0.842
450	0.522	0.678	2.052	0.838
500	0.476	0.630	2.711	0.829
550	0.265	0.593	2.424	0.821
600	0.098	0.564	2.040	0.808
700	0.098	0.564	2.129	0.742

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Table 3 Normalized Properties of Reinforcement Steel with Temperature [Kodur, 2004]

Property / Temp.(∘C)	E_x/E_o	K/K_o	C/C_o
100	1.000	0.958	1.067
150	1.000	0.930	1.110
200	1.000	0.900	1.162
250	0.853	0.873	1.218
300	0.645	0.845	1.260
350	0.305	0.958	1.315
400	0.059	0.787	1.362
450	0.006	0.760	1.426
500	0.003	0.732	1.485
550	$1.35*10^{-4}$	0.708	1.532
600	$1.18*10^{-7}$	0.687	1.568
700	$1.18*10^{-7}$	0.653	1.609

Table 4 Normalized Properties of CFRP with Temperature [Kodur, 2004, 2002]

Property / Temp.(˚C)	E_x/ E_o	E_y/ E_o	E_z/ E_o	K/ K_o	C/C_o	ρ/ρ_o
100	1.000	1.000	1.000	0.880	1.171	1.000
150	0.980	0.980	0.980	0.792	1.280	1.000
200	0.954	0.954	0.954	0.723	1.380	1.000
250	0.901	0.901	0.901	0.648	1.508	1.000
300	0.783	0.783	0.783	0.564	1.613	1.000
350	0.607	0.607	0.607	0.468	3.731	1.000
400	0.404	0.404	0.404	0.394	3.772	1.000
450	0.241	0.241	0.241	0.314	3.744	1.000
500	0.140	0.140	0.140	0.233	3.717	1.000
550	0.088	0.088	0.088	0.200	0.985	0.781
600	0.064	0.064	0.064	0.178	0.957	0.775
700	0.064	0.064	0.064	0.166	0.957	0.775

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Table 5 Normalized Properties of VG Insulation with Temperature [Cramera, 2003]

Temp.(˚C)	E_x/E_o	K/K_o	C/C_o	ρ/ρ_o	α/α_o
100	1.000	0.997	3.581	0.970	0.959
150	0.888	0.479	0.918	0.907	0.935
200	0.528	0.479	0.577	0.844	0.906
250	0.380	0.480	0.566	0.829	0.882
300	0.336	0.482	0.541	0.814	0.859
350	0.253	0.478	0.580	0.796	0.829
400	0.156	0.507	0.506	0.777	0.806
450	0.156	0.584	0.496	0.777	0.776
500	0.156	0.655	0.452	0.777	0.753
550	0.156	0.727	0.453	0.777	0.724
600	0.156	0.799	0.430	0.777	0.700
700	0.156	0.799	0.430	0.777	0.647

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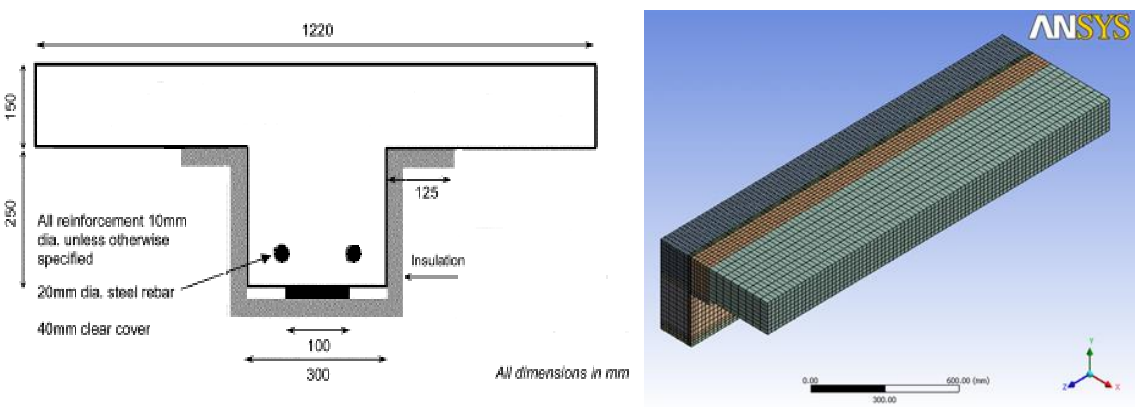

a) Insulated T-beam cross section [4]   b) Isometric view of the quarter FE Model and Mesh

Fig. 1 T-beam Cross Section and Finite Element Model

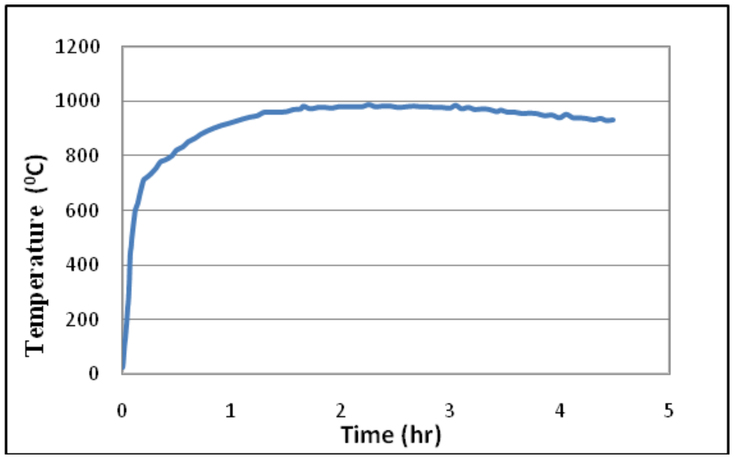

Fig. 2 Applied Transient Temperature as function of time

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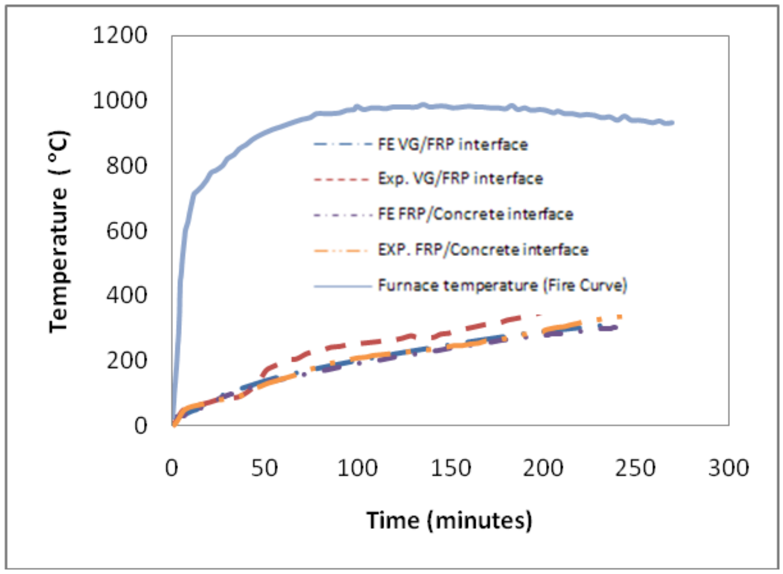

Fig. 3 FE and measured temperature as a function of time (bottom fire)

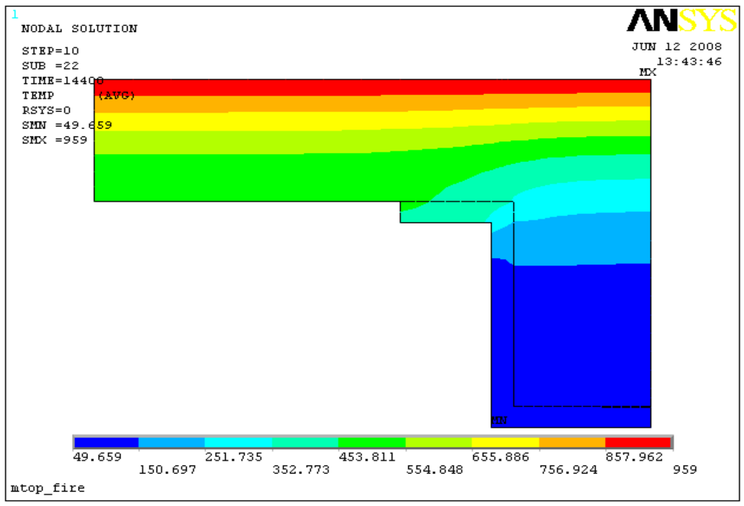

Fig. 4 Cross section temperature distribution

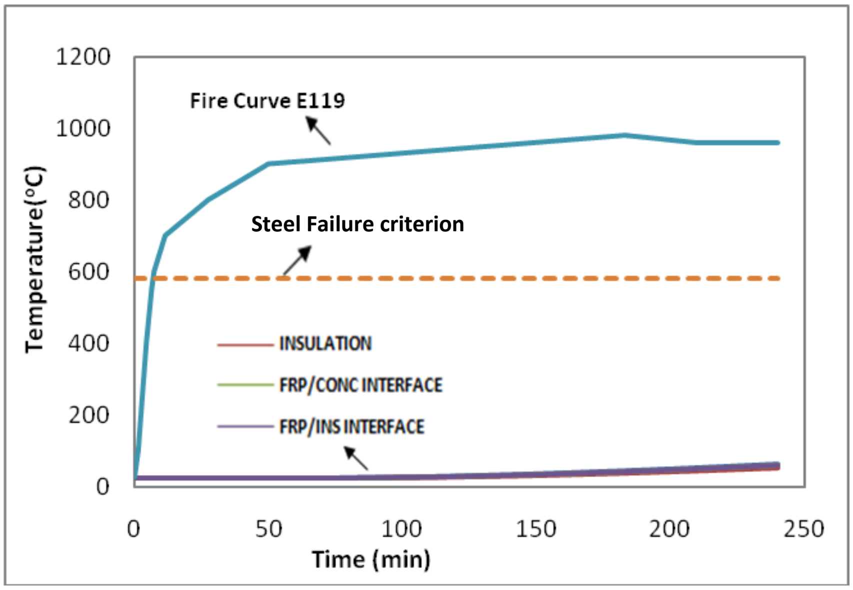

Fig. 5 FE predicted temperature versus time

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http://www.tandfonline.com/doi/abs/10.1080/15376494.2010.499019

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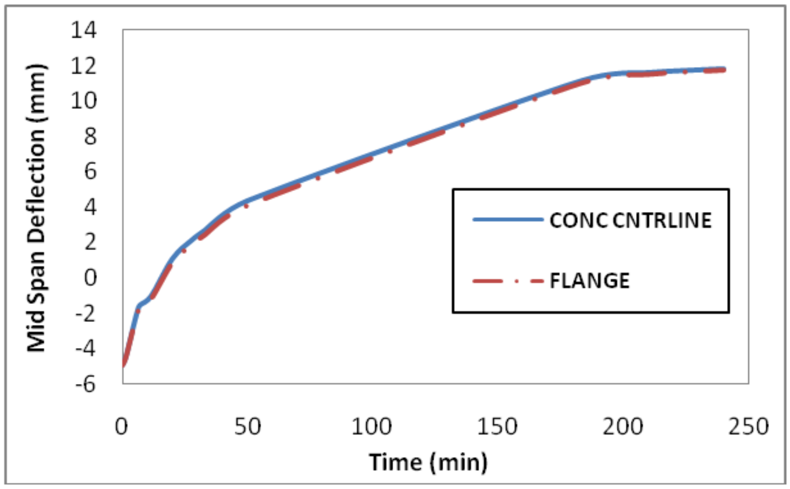

Fig. 6 Midspan vertical deflection

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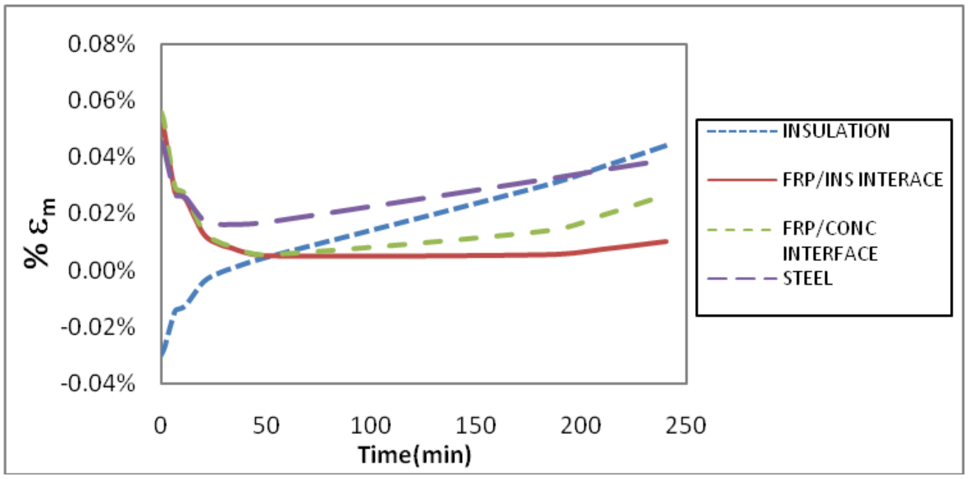

Fig. 7 FE predicted mechanical strain versus time

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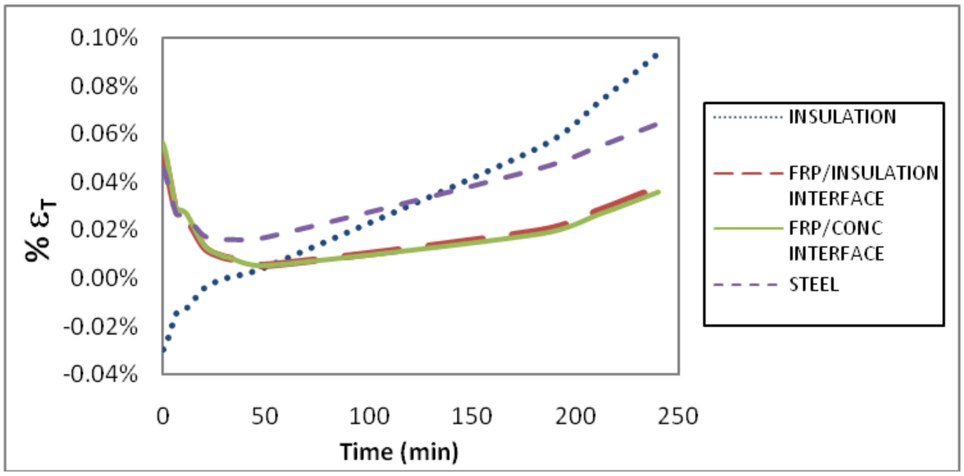

Fig. 8 Total (mechanical + thermal) strain versus time