Performance of reinforced beam strengthened with carbon fiber reinforced polymer sheet at elevated temperatures

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ABSTRACT

The behaviour of reinforced concrete beam strengthened with carbon fiber reinforced polymer sheet at elevated temperature is investigated. To understand Fire performance of reinforced beam strengthened with carbon fiber reinforced polymer finite element method is adopted. Nine models with different concrete cover thickness, 20, 30 and 40 mm and strengthened with 1.2 and 2.4 mm thick CFRP sheet was developed by using commercially available software ‘ANSYS’. The models were exposed to elevated temperature ranging from 100°C to 800°C at an increment of 100°C with 30 minutes of retention period. The unstrengthened beams are compared with the strengthened beams with 1.2, 2.4 mm thick CFRP sheet. Temperature variation along the depth of beam, maximum deflection, stress and strain were obtained from the analysis. The analysis shows that, for un-strengthened beam with 20 mm concrete cover the tension reinforcement get exposed to temperature at faster rate than 30 and 40 mm concrete cover beam, which makes beam member, fail early. Results illustrate that, concrete cover and CFRP sheet are important parameters to increase the fire endurance of beam.

Key words: Finite element model; reinforced concrete beam; concrete cover; CFRP sheet; temperature distribution, deflection, stress and strain.

1. Introduction

The Reinforced Structure (RC) may subject to accidental events such as fire sabotage or post earthquake fire loads in their life span. The structures which may not designed for fire loads needs to be modified. Improvement in fire performance of structure is very much essential to upgrade fire endurance. Possible solution to improve fire resistance of structure is strengthening, retrofitting, and rehabilitation, use alternative materials like Carbon Fiber Reinforced Polymer (CFRP) in structures. The new design standard also required to be developed to think about these loads.

Due to higher cost of materials, labour charges, and impact on environment as well as nuisance of disruption of structure, total structural replacement not feasible. In recent years the use of CFRP sheets in strengthening and protection of RC structures is used often. The use of CFRP sheets is convenient over steel sheet due to number of reason such as its high strength to weight ratio, ease of installation, high thermally insulated, corrosion resistance and good in mechanical strength. The fire safety provision in structural members is specified as fire resistance rating. It is very much essential to know the behaviour of CFRP strengthened RC structure under fire, in terms of its temperature distribution in composites, variation in deflection, stress, strain and fire resistance or fire endurance.
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1.1 Performance of CFRP at elevated temperature

The numerous studies have been conducted to trace the response of CFRP strengthened RC beam at ambient and elevated temperature. These studies address the structural response of CFRP strengthened members under elevated temperatures: El-Hawary., 1996, 1997., Effect of fire on flexural and shear behaviour of RC beams; David et al., 2003. Flexural behaviour of externally bonded CFRP plate and effect of fire on structural element retrofitted; Kumar and Kumar, 2004. Fire or high temperature effect and residual strength of RCC beam; Reddy., et al., 2006. Residual exposure fire protection system and glass transition temperature; Gao., et al., 2008. Bond slip behaviour, steel to concrete interfaces and performance based design guide lines; Kodur and Dwaikat, 2008.

Fire resistance and spalling criteria on RCC beam; Rogerio et al., 2003, Behaviour of CFRP composite at high temperature, Gamge et al., 2005. Epoxy adhesive bond and bond strength variation at elevated temperature; Firno et al., 2012. Fire protection system with different thickness (calcium silicate board, and vermiculate/ perlite cement paste) and debonding effect; Hawileh et al., 2009. Insulated CFRP strengthened RC beam exposed to fire, i.e. VG insulation and varying material properties; Kodur., et al., 2009. Studied the macroscopic FE model for tracing the fire response of reinforced concrete structures; Liu. et al., 2009. Failure mode in RC beam strengthened with CFRP sheet such as flexural, shear capacity, shear crack considering as span to height ratio, confinement ratio, rich degree of shear capacity, thickness of concrete cover and thickness of fire insulation; Kodur, and Dwaikat., 2008. Numerical model for predicting the fire resistance of reinforced concrete beams. The above research papers commented on the susceptibility of CFRP material to elevated temperature.

The understanding CFRP strengthened beam at elevated temperature is very much essential to make the structure fire resistant. In the present investigation an analytical study is carried out to investigate the behaviour of CFRP strengthened beam subjected to elevated temperature.

2. Analytical modelling

2.1 Analysis and design of reinforced concrete beam

Simply supported Reinforced Concrete (RC) beam of size 3230 mm in length and cross section of 230 x 300 mm is considered. The M30 grade of concrete and Fe 415 steel grade of steel is used in the beam design. The beam is analysed for a uniformly distributed load of 30 kN/m and designed as per IS 456:2000. The details of designed reinforcement are presented in Fig.1.

![Figure 1: Details of designed beam reinforcement](image)
2.2 Models preparation

In this study, nine different 3D finite element beam models are developed by using commercially available software ‘ANSYS’ version 14.5. Three different types of RC beams are consist of, un-strengthened, 1.2 mm thick CFRP sheet strengthened and 2.4mm thick CFRP sheet strengthened beam. In addition to these to study the effect of concrete cover on fire behaviour RC (un-strengthened) and strengthened CFRP beam, three different concrete covers are also considered in this investigation. The details of the models considered in the present investigation are given in Table 1. The CFRP sheet is glued to bottom width of beam covering the entire effective span up to the support. In the finite element model, both the CFRP sheet and reinforcing bars are modelled as fully bonded to the concrete.

<table>
<thead>
<tr>
<th>Description</th>
<th>Concrete cover in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Un-strengthened</td>
<td>B₁</td>
</tr>
<tr>
<td>CFRP of 1.2mm thick</td>
<td>BS₁</td>
</tr>
<tr>
<td>CFRP of 2.4mm thick</td>
<td>BD₁</td>
</tr>
</tbody>
</table>

2.3 Element types

The selection of element type for a composite beam modelling ANSYS help menu, and Hawileh., 2009 is used. Each beam modelled with 3496 elements. For concrete material, A structural ‘SOLID65’ (3D 8-node solid) is used. For thermal analysis ‘SOLID65’ element is converted to thermal ‘SOLID70’ (3D 8-node thermal solid) element. For Steel reinforcement material, the structural element ‘LINK8’ (3D 2- node structural bar) were used to model steel reinforcement. For thermal analysis ‘LINK8’ element is converted to thermal element ‘LINK33’ (3D-2 Node Structural bar) element. For CFRP sheet material, the structural element ‘SOLID45’ (3D 8-node layered structural solid) were used to model the CFRP sheet laminate. For thermal analysis‘SOLID45’ is converted to thermal ‘SOLID70’ (3D 8-node thermal solid) element.

2.4 Materials properties

The mechanical and thermal properties of concrete, steel reinforcement and CFRP sheet used in this investigation are given in Table 2.

<table>
<thead>
<tr>
<th>Materials</th>
<th>E</th>
<th>K</th>
<th>C</th>
<th>µ</th>
<th>α</th>
<th>ρ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPa</td>
<td>W/mm °C</td>
<td>J/N °C</td>
<td>0.20</td>
<td>6.08 x 10⁻⁵</td>
<td>2.40 x 10⁻⁵</td>
</tr>
<tr>
<td>Concrete</td>
<td>30200</td>
<td>2.4 x 10⁻⁵</td>
<td>722.8</td>
<td>0.20</td>
<td>6.08 x 10⁻⁵</td>
<td>2.40 x 10⁻⁵</td>
</tr>
<tr>
<td>Steel reinforcement</td>
<td>210000</td>
<td>5.2 x 10⁻⁴</td>
<td>452.2</td>
<td>0.30</td>
<td>6.00 x 10⁻⁹</td>
<td>7.85 x 10⁻⁵</td>
</tr>
<tr>
<td>CFRP sheet</td>
<td>228000</td>
<td>1.3 x 10⁻⁵</td>
<td>1310</td>
<td>0.28</td>
<td>-0.9 x 10⁻⁶</td>
<td>1.60 x 10⁻⁵</td>
</tr>
</tbody>
</table>
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Where, \( K \) = Thermal conductivity; \( C \) = Specific heat; \( \mu \) = Poisson’s ratio; \( \alpha \) = Co-efficient of thermal expansion; \( \rho \) = Density of materials.

2.5 Procedure of analysis

The reinforced beam and strengthened CFRP beam was analysed for the maximum deflection, stress and strain subjected to different exposure temperatures. The detailed steps associated with analysis of beam are presented in the form of flow chart, which is shown in Figure 2.

3. Results and discussion

3.1 Temperature distribution

3.1.1 Effect of concrete cover thickness on RC beam

The various beam models are exposed to different exposure temperatures ranging from 100°C to 800°C with a retention period of 30 min. Figure 3 shows typical temperature distribution in the RC beam for an 800°C exposure temperature for different concrete cover thickness such as 20 mm (B₁), 30 mm (B₂) and 40mm (B₃) respectively. From Figure it is observed that, temperature reaches to the tension reinforcement is around 200°C, 100°C and 60°C for B₁, B₂ and B₃ beam respectively. This is due to concrete cover thickness which acts as thermal hurdle. From this it is observed that in case of 800°C exposure temperature and 30 min retention period, the minimum concrete cover should be more than 30 mm. The use of concrete cover is important to prolong the time of failure. The variation in temperature observed in the concrete cover is in the range of 200°C to 800°C, this may leads to spalling of concrete as per the study carried out by Kalifa et al., 2000.

3.1.2 Effect CFRP sheet on RC beam
The RC (un-strengthened) and CFRP strengthened RC beam with different thickness of CFRP for a 20 mm concrete cover are exposed to different exposure temperatures ranging from 100°C to 800°C with a retention period of 30 min. Figure 4 shows typical temperature distribution in the RC (B₁) and CFRP strengthened beam with 1.2 mm (Bₛ₁) and 2.4 mm (B₅₁) thickness for an 800°C exposure temperature.

From Figure 4 it is clearly observed that, around 200°C temperature reaches to the tension reinforcement in the B₁ beam, whereas in the Bₛ₁ and B₅₁ variation in temperature not initiated. The CFRP sheets do not allow to heat penetrate in the bottom concrete of beam, because of its high thermal conductivity of CFRP. A strengthened beam with CFRP shows fire endurance than RC beam, because the reinforcement will not get exposed to elevated temperature. Carbon fiber reinforced polymer sheet protect concrete cover against spalling when it is exposed to elevated temperature.

4. Structural Behaviour

4.1 Deflection behavior

The results of deflection behaviour in un-strengthened and CFRP strengthened beams exposed to various temperatures ranging from 100°C to 800°C with a retention period of 30 min for different concrete cover thickness is shown in Figure5 (a-c). Figure 5 (d) shows typical variation in deflection along the span of beam. From Figure5 (a-c) it is observed that, the deflection is more in un-strengthened beam as compared to CFRP strengthened beam. This is due to CFRP sheet gives additional rigidity under elevated temperature Figure 5 (a-b) shows little decrease in deflection for 100°C exposure for un-strengthened beam, due to its redistribution of moment. No significant effect is observed in strengthened beam (Bₛ₁ and B₅₁). As temperatures increases from 100°C to 800°C, deflection in un-strengthened beam
(B₁) increases. Whereas in case CFRP strengthened beams (Bₛ₁ and Bₛ₃) deflection is constant, this is due to more thermal conductivity of CFRP material. Carbon fiber reinforced polymer is more susceptible at elevated temperature. Similar kind of observation is reported by Rafi, and Nadjai, 2008. The rate of deflection rapidly increases in case of un-strengthened beam compared to CFRP strengthened beam. Deflection in beams is due to flexural steel reinforcement, if it gets exposed to temperature, deflection will be at faster rate. The concrete cover and CFRP sheets provide effective protection, which reduce heat of penetration and protect reinforcement from temperature, which controls the deflection.

4.2 Stress behaviour

The results of stress behaviour of un-strengthened (B₁, B₂ and B₃) and CFRP strengthened (Bₛ₁, Bₛ₂, Bₛ₃, Bₐ₁, Bₐ₂ and Bₐ₃) beams exposed to various temperatures ranging from 100°C to 800°C with a retention period of 30 min for different concrete cover thickness are plotted as shown in Figure 6 (a-c). The typical photograph view of stress distribution in un-strengthened beam subjected 800°C is shown in Figure 6 (d).

From Figure 6(a-c) it is observed that, for un-strengthened beam at 20 mm concrete cover thickness except 100°C exposure the stress increases as the temperature increases. In case of un-strengthened beams with 30 mm and 40 mm concrete cover, stress increases with increase in temperature. The rate of increase in stress with temperature is steep for 20mm concrete cover as compared to 30 mm and 40 mm concrete cover. This may be due to tension reinforcement getting exposed to elevated temperature. The decrease in stress is observed in un-strengthened beam for 100°C exposure temperature is because redistribution of moment.

From Figure 6(a-c) it is observed that, strengthened beam with CFRP sheet shows lesser stress as compared to un-strengthened beam. The strengthened beams subjected to elevated temperatures shows decrease in stress as temperature increases; the decrease in stress is due to the increase in stiffness of beam and stress redistribution with temperature. Carbon fiber
reinforced polymer sheet also keep hold of temperature to certain extend of time. For all strengthened beams up to 100°C exposure little decrease in stress is observed, thereafter 100°C to 800°C exposure temperature stress is constant. This is due to CFRP sheets which act as an insulating material. The 2.4 mm thick CFPR laminated strengthened beam show better performance as compared with 1.2mm thick CFRP laminated strengthened beam.

4.3 Strain behaviour

Results of strain obtained from the analysis are plotted in Figure 7(a-b). Figure 7 (a-c) shows beams with 20 mm concrete cover has little higher strain as compared with 30 and 40 mm concrete cover beams for un-strengthened and strengthened beams. As the temperature increases no much variation in strain is observed for all beams. The results show that the strain in concrete has little effect on the fire resistance of beams under bending. Similar kind of results reported in previous literature Bratina et al., 2007 and Kodur., and Dwaikat.,2007.

5. Conclusions

The FE model is developed to know accurate behaviour in the un-strengthened and strengthened beam while exposed to elevated temperature. The FE analysis results illustrate some important points governing performance of un-strengthened and strengthened beam at elevated temperature.

1. For un-strengthened beam, the concrete cover can prolong the temperature time increment and it gives initial fire protection to the beam. The concrete cover plays important role in fire resistance of RC beam. For 800°C exposure temperature and 30 min of retention period, cover should be more then 20mm to control the deflection.

2. The CFRP sheet increase the fire endurance of RC beam due to delay in temperature retention time.
3. The rate of deflection of CFRP strengthened beam at elevated temperature is less compared to un-strengthened beam.

4. The deflection of CFRP strengthened beam is constant for 100°C to 800°C exposure temperature and for 30 min retention time. For higher retention period deflection may not be constant, hence investigation is needed.

5. Carbon fiber reinforced polymer sheet with 2.4 mm thickness give a better performance at elevated temperature.

6. Carbon fiber reinforced polymer sheet strengthened beam reduces the probability of spalling of concrete.

Figure 7: Variation in strain vs. temperature

a) Un-strengthened

b) Strengthened with 1.2 mm thick CFRP sheet

c) Strengthened with 2.4 mm thick CFRP sheet

d) Photographic view of typical beam strain

6. References


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