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Study on Flexural Behavior of Reinforced Concrete Beams: Response to Fire and Sudden Cooling

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ABSTRACT

The objective of the present study was to retrofit RC beams under realistic fire followed by sudden cooling. Three reinforced concrete beams (100 mm x 150 mm x 1500 mm) were cast using M30 grade concrete. After the curing period, they were exposed to ISO: 834 standard fire curve. Three temperatures (300ºC, 500ºC and 900ºC) were applied and maintained for a specific duration. Then, the beams were cooled immediately. The beams were repaired for cracks and spalled concrete using a polymer mortar and then cured. The beams were wrapped using glass fiber sheets and PP fiber-based ECC binders. Cured beams were subjected to two-point loading for flexure. Results showed that strengthening improved the ductility and toughness values for rise in temperature. The ultimate load for the beams increased up to 500ºC and the stiffness value decreased for temperatures higher than 300ºC. For all strengthened beams, the composites were intact even at failure load.

KEYWORDS: Reinforced concrete beams, ISO:834, Sudden cooling, Retrofitting, GFPPECC, Parametric analysis.

INTRODUCTION

Fire safety is a major considerations in building design. Resistance of reinforced concrete structures and their components to thermal load is usually put up in structural design. Concrete, a load bearing material, has good fire resistance properties, but it is at high risk, since the entire structure would collapse upon its material failure. Therefore, repair and retrofit of fire-damaged structures are preferred rather than rebuilding them. The idea behind this is to save the amount of money and time required for rebuilding (Yahub and Bailey, 2007). Strengthening of deteriorated structures being subjected to elevated temperatures is necessary. Deterioration may vary according to the intensity and duration of fire loading.

High thermal load would bring down maximum load and modulus of elasticity of concrete and steel rebars. Earlier studies concentrated on deterioration of concrete and its varying properties due to the intensity of fire load (Arioz, 2009; Chang et al., 2006; Chen et al., 2009; Husem 2006). Strengthening of fire-damaged beams helps restore the ultimate load and serviceability of damaged beams. Fiber-reinforced polymer wrapping was proved to be effective compared to jacketing techniques (Amoury and Ghobarah, 2002; Antonopoulos and Triantafillou, 2003; Haddad et al., 2013; Ilki et al., 2011; Sadan et al., 2014; Yasmeen et al., 2011).

The latest procedure for retrofitting of structural members is through fiber sheets along with cementitious binders. Drawbacks of organic epoxy binder were concentrated on in earlier studies and advantages of

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inorganic binders were elaborately analyzed. Moreover, inorganic cement-based binders were effectively applied for retrofitting damaged structural members (Alina and Jonas, 2003; Bhuvaneshwari and Saravana Raja Mohan, 2015; Bjorn Taljsten and Thomas Blansksvard, 2007; Bournas and Triantafillou, 2008; Francisco et al., 2012; Stephen Kurtz and Balaguru, 2001; Thomas Blansksvard et al., 2009; Toutanji and Deng, 2007; Wu et al., 2010).

Research Significance

Strengthening of fire-damaged beams was carried out in earlier studies, where fire-affected specimens were cooled gradually. Since in practical conditions fire in buildings would be put off suddenly, alteration in material properties would occur. Different intensities of fire loading on beams based on Iso:834 fire curve were applied, followed by sudden cooling of heated beams to stimulate realistic conditions. Strengthening of damaged beam members was carried out using GFPPECC. Flexural test on strengthened beam members was carried out and parametric analysis was conducted.

EXPERIMENTAL PROCEDURE

Materials

OPC 43 grade cement conforming with IS4031-1988 and having a specific gravity of 3.12 was used in preparing the M30 concrete mix. For fine aggregate, river sand procured locally passing 4.75 mm sieve and conforming to zone III was used. For coarse aggregate, crushed granite- type aggregate of nominal size of 20 mm was used. Both aggregates conformed with IS 383-1970. Testing of the aggregates was carried out as per IS 2386-1963. Specific gravity and fineness modulus for fine aggregate were 2.6 and 3.2, respectively. The corresponding values for coarse aggregate were 2.65 and 6.8, respectively. The proportions for concrete mix were designed as per IS 10262-1959, as shown in Table 1. The properties of the rebars tested under axial tension are given in Table 2. In order to strengthen the beam members subjected to fire loading, medium-density woven bidirectional glass fiber sheets of 0.6 mm thickness were used for surface wrapping. The material properties for the fiber sheets mentioned by the supplier are detailed in Table 3.

Method

Four groups of beams (CB, SB-300˚C, SB-500˚C and SB-900˚C) with dimensions of (100 mm x 150 mm x 1200 mm) were concreted as under-reinforced sections. The reinforcement details of the cast specimens were as shown in Fig. 1.

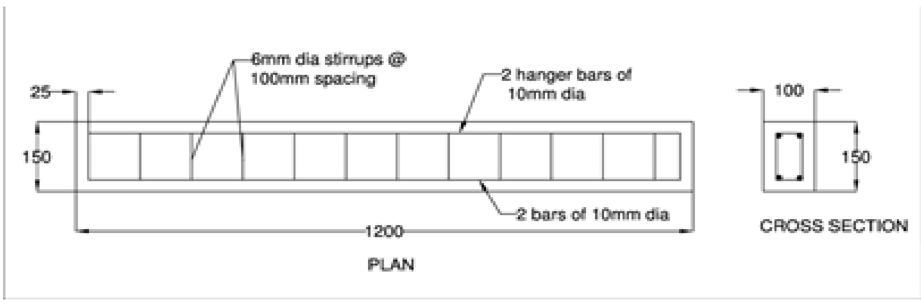

Figure (1): Rebar details of the beams

Table 1. Design mix for concrete in kg/m^3

Water	Cement	Fine aggregate	Coarse aggregate
190.5	402	782	983

Table 2. Properties of rebars loaded axially

Rebar	Yield stress (N/mm^2)	Ultimate stress (N/mm^2)	% Elongation
HYSD – 12mm	582	696	26
Mild steel – 8mm	354	502	16

Table 3. Orthotropic material properties for bidirectional glass sheets

Young's modulus	Values (N/mm^2)	Poisson's ratio	Values	Rigidity modulus	Values (N/mm^2)
E-x	72000	μ-xy	0.26	G-xy	1520
E-y	7000	μ-yz	0.26	G-yz	1820
E-z	7000	μ-zx	0.3	G-zx	2650

Group CB was used as control beams. The remaining six beams were subjected to ISO: 834 fire loading. The intensity for the remaining groups was fixed as low (300˚C), medium (500˚C) and high (900˚C). The loading sequences for the specimens are as displayed in Table 4. The duration of exposure resembled 2.25 hours (1/9 of actual fire duration) of prototype exposure (Mohamed et al., 2014). Fire load was achieved in an oil burnt furnace with a capacity of 250 kg with a temperature range of 30˚C-1000˚C. The unloaded beams (Fig.2 (a)) were cooled suddenly as shown in Fig.2 (b). Spalling of concrete in specimens was as shown in Fig. 2 (c).

(a)Unloading of beams

(b) Sudden cooling of beams

(c) Spalling in beams

Figure (2): Beams subjected to fire loading

Table 4. Fire loading on RC beams

S. No.	Temperature (°C)	Time (min)
1.	300	Achieved in 2 min and maintained for 10 min
2.	500	Achieved in 4 min and maintained for 10 min
3.	900	Achieved in 10 min and maintained for 10 min

The cracked and spalled beams were repaired using polymer mortar and then moisture-cured. Cured beams were rubbed on the surface and loose particles were removed. The PPECC binder in proportions as per Rui Zhang et al. (2014) is given in Table 5 and was prepared and applied as a coat on three faces of the beams (Fig. 3).

Table 5. Mix ratio for PPECC binder

Cement (kg)	Rheomix (ml)	Water (l)	Fiber (g)
1	12.5	0.25	18.95

Figure (3): Repaired beams

Glass fiber sheet was wrapped and pressed with a roller and one more layer was applied and pressed (ACI 440R, 1996). Strengthened beams were moisture-cured for a period of 28 days. Flexure test on cured beams was conducted in a loading frame of 1000 kN capacity as shown in Fig. 4. LVDTs were used to pick up the deflection.

(a) Loading of beams **(b) Failure of beam without debonding**

Figure (4): Flexure test on beams

RESULTS AND DISCUSSION

Material Properties

The characteristic strength obtained from cube compressive test was calculated as 35.5 MPa. Modulus of elasticity from slope of stress-strain plot of cylinder specimens was obtained as 2.5 x 10^4 MPa.

Response to Thermal Load

Medium intensity of fire load changed the colour of beams in group SB-300ºC and group SB-500ºC to grey and high intensity of thermal load changed the colour of beams in group CB to pale red as shown in Fig. 2 (c). Change in colour of the specimens due to increased intensity of fire loading was similar to that discussed earlier (Khaled Mohammed Nassar, 2011).

Load-Deflection Behavior

Flexure for the four groups of beams was compared and is shown in Fig.5. The various parameters like ultimate load, ultimate deflection, stiffness, toughness modulus and ductility ratio were compared.

Ultimate Load

Ultimate load values for the specimens are compared in Fig. 6. The ultimate load for SB-300ºC increased by 81.16% compared to CB. For SB-500ºC and SB-900ºC, the corresponding percentage increase was 65.78% and 50.66%, respectively. Even for strengthened beams, the ultimate load decreased with the increase in temperature.

Ultimate Displacement

Ultimate displacement values for the specimens are compared in Fig. 7. The displacement values for wrapped beams were higher than that of the reference beam. Percentage enhancement for SB-300ºC, SB-500ºC and SB-900ºC beams was 34.22%, 92.37% and 121.40%, respectively. The increase in temperature increased the displacement values of the strengthened beams.

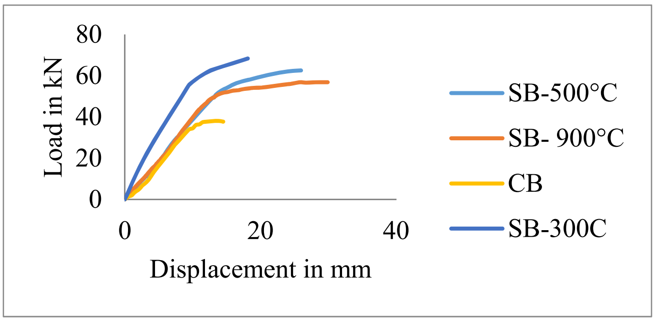

Figure (5): Comparison of load-deflection behavior

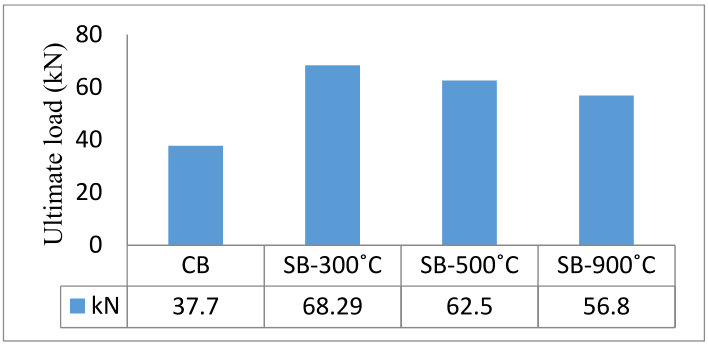

Figure (6): Comparison of ultimate load for beams

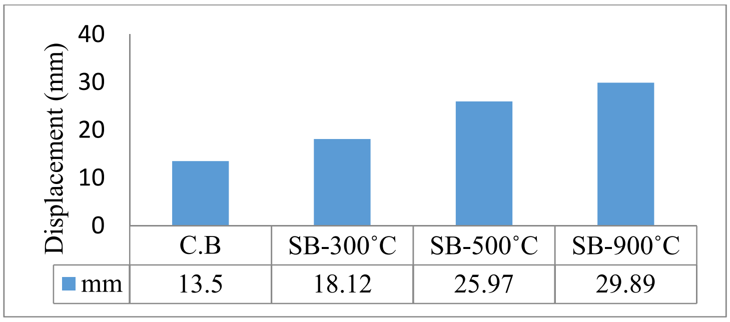

Figure (7): Comparison of displacement for beams

Stiffness

Stiffness is quantified through the slope of load-deflection curve of the specimens. Comparison of stiffness for the specimens is shown in Fig.8. The stiffness value for SB-300ºC beams increased by 27% compared to the control beam. Stiffness of the specimens improved due to prefabricated cement-based composites (Idris Bedirhanoglu, 2015). For SB-500ºC beams, stiffness decreased relatively by a smaller amount of 1.33% and for SB-900ºC beams, it decreased by a relatively larger amount of 14.8 %. The stiffness value decreased when the beam was subjected to a temperature higher than 300ºC. Applying four layers of fabric-reinforced cementitious matrix enhanced the stiffness of the shear walls (Saman Babaridarabad, 2014).

Ductility

Ratio of ultimate displacement to yield dispacement gives the displacement ductility ratio. Displacement ductility ratios for the specimens are compared in Fig.9.The ductility values of the wrapped beams were higher than that of the reference beam. Textile-based fiber-reinforced polymer showed better ductility for undamaged specimens (Hashemi and Al-Mahaidi, 2012). Ductility was enhanced showing less violent global failure (Hwai Chung et al., 2012). Compared to the control beam, the percentage increase for SB-300ºC, SB-500ºC and SB-900ºC beams was 8.55%, 11.2% and 13.82%, respectively. The increase in temperature caused an increase in ductility of strengthened specimens.

Toughness

Total energy stored in the strained specimens was quantified through toughness modulus. Toughness modulus values for the specimens are compared in Fig.10. The toughness values of strengthened beams increased for all three cases compared to the control beam. Enhancement for SB-300ºC, SB-500ºC and SB-900ºC beams was 117.40%, 183.89% and 244.80%, respectively. It was shown that the toughness value increased as the temperature increased. Retrofitting increased the toughness modulus of partially damaged beams (Haddad et al., 2013).

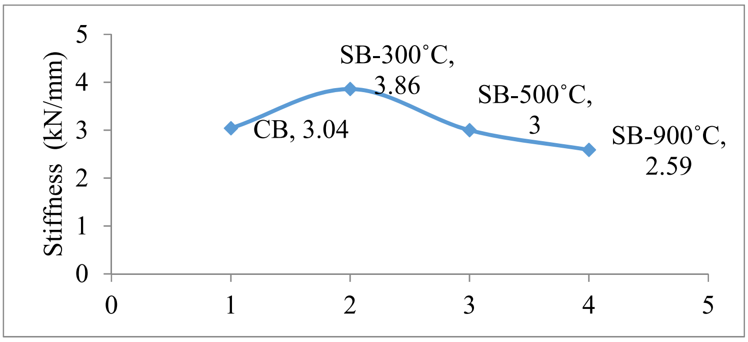

Figure (8): Comparison of stiffness for beams

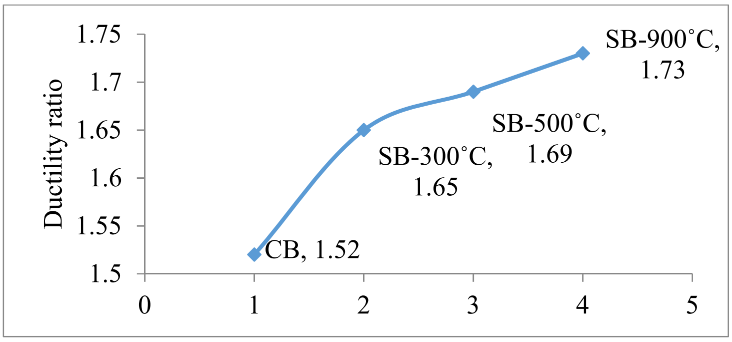

Figure (9): Comparison of ductility for beams

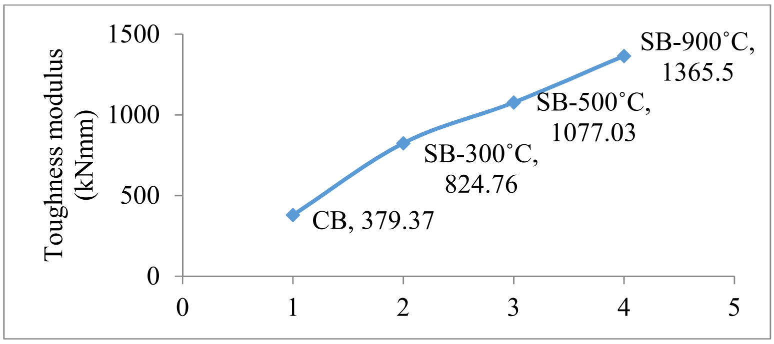

Figure (10): Comparison of toughness for beams

CONCLUSIONS

Strengthening of fire-loaded beams after sudden cooling was carried out. The conclusions drawn are summarized as follows:

- The beams subjected to 300ºC and 500ºC turned into grey colour, whereas the beams subjected to 900ºC turned pale red due to chemical reaction and spalling was higher for beams subjected to higher temperatures.
- Compared to CB beams, strengthening has improved the ultimate load by 81.16%, 65.78% and 50.66%, respectively for SB-300˚C, SB-500˚C and SB-900˚C.
- Corresponding enhancement in ultimate deflection was 34.22%, 92.37% and 121.40%, respectively.
- Wrapping has increased the stiffness of SB-300˚C beams by 27%, compared to CB beams. Improvement was not significant for beams damaged due to high fire intensity.
- Ductility and total energy absorbed were highly enhanced for strengthened beams fired under different intensities.
- Irrespective of intensity of fire load, the strengthened beams did not show any debonding even at ultimate load.

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