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Experimental Investigation on FRC Beams Strengthened with GFRP Laminates

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ABSTRACT: The external bonding of fibre reinforced polymer (FRP) to reinforced concrete (RC) members has become a popular method of retrofitting/strengthening concrete structures in recent years. Extensive research has been conducted pertaining to RC beams strengthened with FRP laminates. However, the experimental studies on fibre reinforced concrete (FRC) beams strengthened using externally bonded FRP system are limited. The purpose of this research is to investigate the behaviour of steel fibre reinforced concrete (SFRC) beams strengthened with glass fibre reinforced polymer (GFRP) laminates. The beam specimens were incorporated with 1.0% volume fraction of short-steel fibres randomly distributed throughout the section. The beam cross-section was 150 mm wide and 250 mm deep and to a length of 3000 mm. All the beams were tested until failure. The study parameters of this investigation included service load, ultimate load, ductility, crack width and failure modes. Beams tested for this investigation consisted of reference (RC) beam, GFRP laminated RC beam, SFRC beam, and GFRP laminated SFRC beam. The test results showed that the SFRC beams strengthened with GFRP laminates exhibited better performance.

KEYWORDS: Glass fibre reinforced polymer, steel fibre, strength, ductility, debonding.

1 INTRODUTION

Need for strengthening reinforced concrete (RC) and prestressed concrete (PC) structures is becoming more apparent, particularly when there is an increase in load requirements, a change in use, a degradation problem, or some design/construction defects (Marco & Antonio, 1997). Of the potential solutions to the above, use of fibre reinforced polymer plastic (FRP) sheets as externally bonded reinforcement has been proven to be an effective technique for strengthening and repairing the above type of structures (Wang & Li, 2006; Denise et at., 2013; Maghsoudi & Akbarzadeh, 2011). Many of the several authors have reported that RC beams strengthened with externally bonded FRP laminates/sheets considerably reduced its ductility due to increase in stiffness that lend to unexpected failure without any prior notice (Grace et al., 1999; Khair et al., 2012; Xiong et al., 2004). Moreover, application of FRP strengthened beams in a seismic zone is less wide by known due to the complexity and not so well established resisting mechanisms.

Short discrete fibres that are randomly oriented in a concrete matrix increase its structural integrity. Addition of such fibers not only enhances the requisite properties of RC but also changes the characteristics of the material from brittle to ductile (Mohammad & Mohammad, 2013; Eswari, 2015; ACI 544.1R-96, 2002). Steel fibres are usually used in concrete for the benefits such as: improved structural strength; reduction in steel reinforcement required; improved ductility; reduced crack widths and control of crack widths thus improving durability; improved impact and abrasion resistance; improved freeze-thaw resistance (Eethar & Mahyuddin, 2011).

Many researchers have concentrated only on the flexural and shear behavior of the FRP strengthened RC beams. However, studies on FRP strengthened FRC beams are rather rare. Hence, an attempt has been made to study the GFRP strengthened RC beams incorporating short-steel fibres and to evaluate the overall performance of the beams.

In the following two sections, the details of the experimental set-up including casting and testing specimens, discussion on the experimental results have been presented. In the last section, salient conclusions drawn from the discussion of experimental programme, are presented.

2 EXPERIMENTAL PROGRAMME

2.1 *Materials used*

M20 grade concrete proportioned according to IS 10262:2009 was used for casting beams. The main flexural reinforcement for the beams consisted of two 12 mm deformed bars and two 10 mm deformed bars, as hanger bars. 8 mm diameter deformed bar spaced at 120 mm c/c formed the shear reinforcement for the beams. Hooked end short-steel fibres were used as internal fibre reinforcement and unidirectional GFRP sheets (5 mm thick) were used at beam soffit. The properties of both the fibres as provided by the manufacturers are given in Table 1.

Table 1. Properties of fibres.

Sl. No	Fibre properties	Steel fibre	GFRP cloth
1	Length (mm)	30	3000
2	Shape/Type	Hooked ends	UDC
3	Diameter/Thickness (mm)	0.5	0.8
4	Aspect Ratio	60	-
5	Density (kg/m^3)	7850	1500
6	Young's modulus (GPa)	210	72
7	Tensile Strength (MPa)	532	1720

2.2 *Details of test specimens*

A total of four beams were cast and tested in this study. The overall geometry for all the beams were maintained the same that is 150 mm (wide) and 250 mm (deep). Overall length of the beam was 3000 mm, with a span of 2800 mm between the supports at the time of testing. The length of the constant moment region or the distance between the two applied loads was 933.33 mm. Beams marked S1 L0 and S0 L0 (reference beam) were of un-strengthened RC beams, with and without short-steel fibres, respectively, and beams marked S1 L5 and S0 L5 were of GFRP strengthened RC beams with and without short-steel fibres, respectively. After the beams had been cured for about 4 weeks the strengthening process was carried out using 'wet lay-up system' on the tension face of the concrete beams using a commercially available epoxy resin. The strengthening of beam was done before applying the initial load. Various details of the test specimens are summarized in Table 2.

Table 2. Summary of Tested Beams.

Sl. No	Beam ID	Overall size of beam	Total volume of steel fibre, V_f	GFRP laminate thickness
		mm	%	mm
1	S0 L0	150* 250** 3000$^+$	0	-
2	S0 L5		0	5.0
3	S1 L0		1.0	-
4	S1 L5		1.0	5.0

* Breadth; ** Depth; $^+$ Length.

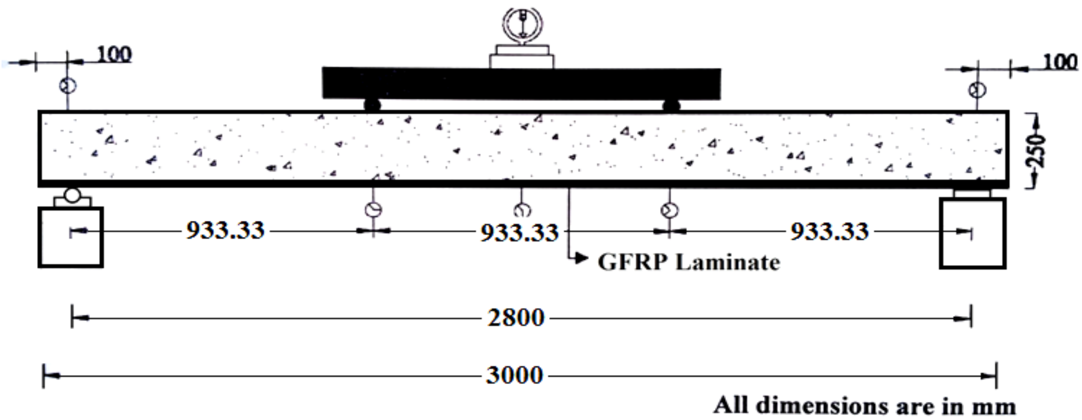

Figure 1. Schematic diagram of the experimental set-up.

2.3 *Testing procedure*

All the beams were tested under the four-point bending in a loading frame of 500 kN capacity. Loads were applied in increments of 2.5 kN and deflections were measured at mid-span and at load points using mechanical dial gauges, having an accuracy of 0.01 mm. The crack widths were measured using a crack detection microscope, with a least count of 0.02 mm. Crack development and propagation were monitored during the process of testing. All the above measurements were made at different load levels, until failure. Further, 'mode of failure' was also observed. Figure 1 shows the schematic diagram of the experimental set-up used for the study and Figure 2 shows a photographic view of the set-up showing the instrumentation used.

Based on the experimental data, load-deflection curves for all the beams were developed and the energy ductility and energy ductility ratio were calculated, and used to evaluate the ductility of the various beams and their relative performance.

Energy ductility is defined by $\mu_e = (1+ E_{tot}/E_{elastic})/2$, where, E_{tot} and $E_{elastic}$ are the total energy up to ultimate load (that is area under the load-deflection curve) and elastic energy, respectively (Naaman & Jeong, 1995).

Energy ductility ratio is defined as the ratio of the energy ductility of any individual beam to that of the energy ductility of the reference beam (S0 L0).

Figure 2. Photographic view showing instrumentation used.

3 RESULTS AND DISCUSSION

Principle test results of various beams are given in Table 3 and comparison of loads of tested beams are shown in Figure 3. It can be inferred from the results given in Table 3 that the GFRP laminated SFRC beam has improved load carrying capacity when compared to all other beams, at the ultimate stage. The increase in ultimate load for GFRP laminated SFRC beam was found to be 130%, 27.8% and 91.9%, when compared to the reference beam, GFRP laminated RC beam and SFRC beam, respectively.

Table 3. Principal test results of beams.

Sl. No.	Beam ID	Service load	Service load deflection	Ultimate load	Ultimate deflection	Energy Ductility, μ_e	Energy ductility ratio
		kN	mm	kN	mm		
1	S0 L0	32.70	7.14	49.05	30.25	4.28	1.00
2	S0 L5	58.86	9.42	88.29	21.22	2.04	0.47
3	S1 L0	39.20	11.03	58.80	48.16	6.38	1.49
4	S1 L5	75.21	16.41	112.82	34.92	2.91	0.68

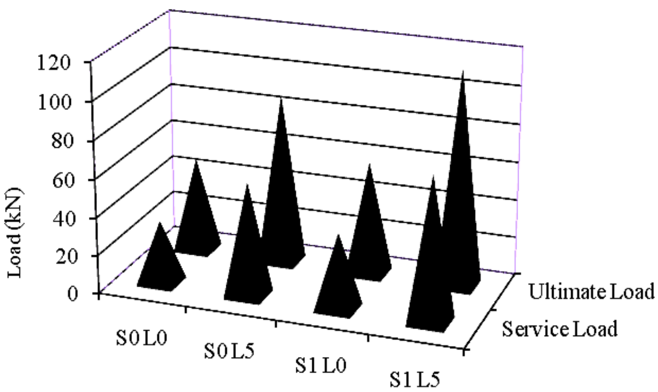

Figure 3. Load comparison of tested beams.

The maximum increase in deflection at ultimate state for GFRP laminated SFRC beam was found to be 15.4% and 64.6%, when compared to the reference beam, GFRP laminated RC beam, and 27.5% decrease when compared with SFRC beam. Decrease in energy ductility for GFRP laminated SFRC beam was upto 32% when compared to that of reference beam and 42.64% increase when compared to GFRP laminated RC beam.

The load-deflection response of the reference beam (S0 L0), GFRP strengthened RC beam (S0 L5), SFRC beam (S1 L0) and GFRP strengthened SFRC beam (S1 L5) are presented in Figure 4. It can be seen from the above Figure that the role of steel fibres has been exhibited very clearly due to the increase in the ductility of SFRC beam (S1 L0) than the reference beam (S0 L0). A similar behaviour is exhibited by GFRP strengthened SFRC beam (S1 L5), when compared to that of GFRP strengthened RC beam (S0 L5). However, there is a very marginal reduction in the energy ductility of S1 L5, which is due to the stiffening of the beam induced by the lamination of the beam.

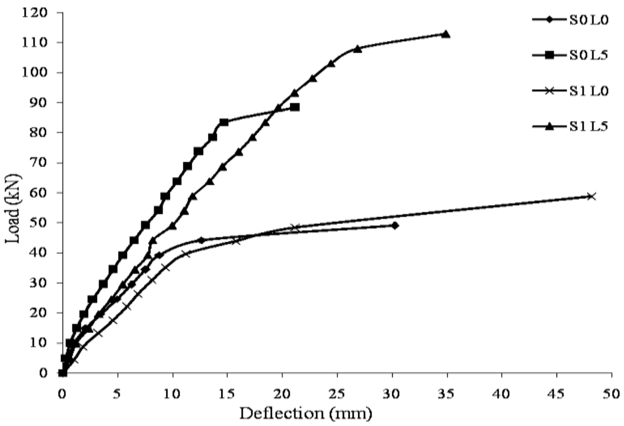

Figure 4. Load-deflection response of tested beams.

The failure patterns of tested beams are shown in Figures 5-8 and their salient details at failure is given in Table 4. It can be seen that the beam S0 L0 has failed by local concrete crushing (Figure 5), whereas wider spacing of cracks are observed due to the ductility of fibres in S1 L0 (Figure 7). There is a marked increase in the number of cracks in the beam S1 L5 (Figure 8), when compared to that of the beam S0 L5 (Figure 6), which is due to stiffening effect induced by the lamination of the beam S1 L5. Therefore, GFRP laminated SFRC beam has exhibited lesser crack spacing when compared to GFRP laminated RC beam. GFRP laminated RC and SFRC beams have failed by ‘debonding’ induced by widening of flexural cracks.


Figure 5. Failure pattern of reference beam (S0 L0).


Figure 6. Failure pattern of GFRP laminated RC beam (S0 L5).

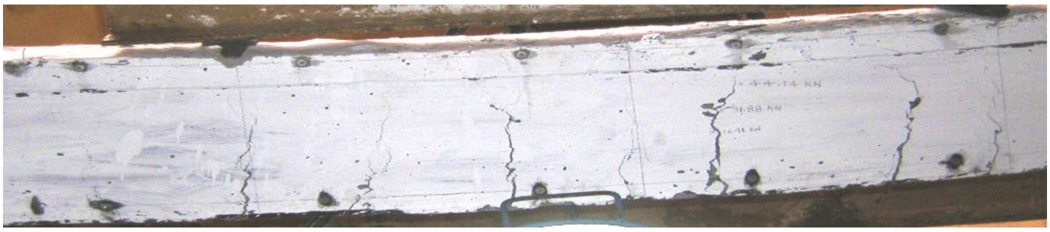
Figure 7. Failure pattern of SFRC beam (S1 L0).

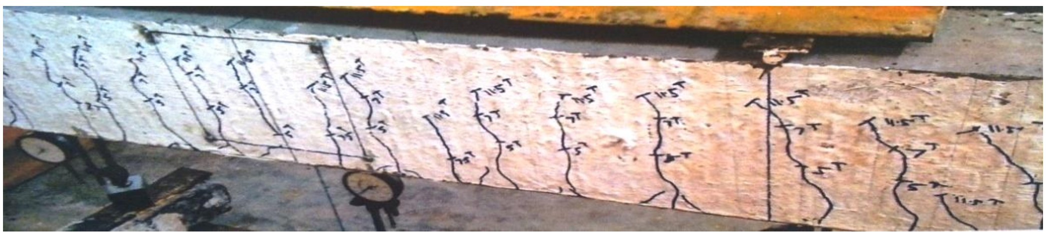
Figure 8. Failure pattern of GFRP laminated SFRC beam (S1 L5).

Table 4. Failure details of tested beams.

Sl. No.	Beam ID	Average crack spacing	Mode of failure
		mm	
1	S0 L0	156.2	Concrete crushing
2	S0 L5	81.0	Debonding
3	S1 L0	105.8	Flexural
4	S1 L5	72.4	Debonding

4 CONCLUSIONS

Based on the experimental investigations, following salient conclusions are drawn:

On overall evaluation, GFRP laminated SFRC beam exhibit the highest load carrying capacity, amongst all beams tested. The maximum increase in ultimate load the above beam is found to be 130%, when compared to that of the reference beam, and 91.9% when compared to SFRC beam (unlaminated).

However, the maximum increase in energy ductility is exhibited only by SFRC beam (unlaminated). The maximum increase in energy ductility is found to be 49% when compared to that of reference beam. Incidentally, all laminated beams exhibit lower energy ductility (amongst the beams tested). This phenomenon is on expected lines, as lamination reduces the deflection and hence exhibit lower energy ductility.

Laminated beams exhibit failure due to debonding, which again is attributed to propagation of flexural cracks. However, none of the above beams exhibited ‘delamination’.

Laminated SFRC beam exhibit lesser crack spacing when compared to that of the laminated RC beam.

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