Structural Engineering and Mechanics, *Vol. 66*, *No. 5 (2018) 631-636*
DOI: https://doi.org/10.12989/sem.2018.66.5.631

Behaviour of hybrid fibre reinforced concrete beams strengthened with GFRP laminates

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(Received May 31, 2016, Revised March 26, 2018, Accepted March 27, 2018)

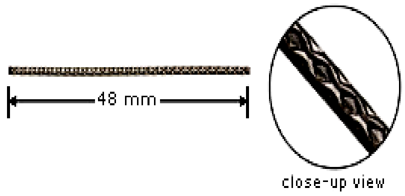
Abstract. This study aims to investigate the flexural behaviour of glass fibre reinforced polymer (GFRP) laminated hybrid fibre reinforced concrete (HFRC) beams. The flexural and ductility performance of GFRP laminated HFRC beams having different proportions of polyolefin and steel fibres with 1.0% of total volume fraction were investigated. The parameters of this investigation included: load and deflection at first crack, yield, and ultimate stages, ductility and crack width. A total of seven beams of 150×250 mm in cross-section were tested in the laboratory over an effective span of 2800 mm. One reinforced concrete (RC) beam without any internal or external GFRP was taken as the reference beam. Of the remaining six beams, one beam was strengthened with GFRP, one beam with 100% steel fibres was strengthened with GFRP and four beams, each with different volume proportions of polyolefin and steel fibres (20:80, 30:70, 40:60, 50:50) were strengthened with GFRP. All the above beams were tested until failure. The experimental results show that a fibre volume proportion of 40:60 (polyolefin-steel) has significantly improved the overall performance of the tested beams.

Keywords: GFRP; polyolefin fibre; steel fibre; HFRC; strength; ductility

1. Introduction

Role of fibre reinforced polymers (FRP) or continuous fibre sheets have become more popular in civil engineering applications worldwide, especially, as an external reinforcement, since their introduction in the mid-1980s, due to various advantages offered by them such as: lightweight, noncorrosive, high tensile strength, etc., compared to conventional steel plate bonding technique (Hashemi *et al*. 2009, Lenwari and Thepchatri 2009, Sen and Jagannatha 2013, Almusallam *et al.* 2015). However, a major problem frequently encountered in respect of FRP strengthened reinforced concrete (RC) beams is debonding of laminates/sheets/wraps from the concrete surface and the sources of debonding as investigated by several researchers have already been highlighted (Kim and Harries 2013). This phenomenon also significantly limits the strengthening performance of FRP sheets (Rosenboom and Rizkalla 2008, Alfano *et al*. 2012).

To overcome the above issue, a simple and effective technique is to incorporate small amounts of short fibres into concrete. This can greatly improve concrete toughness or ability to resist crack growth which could be measured by means of the equivalent fracture energy of RC (CNR-DT204/2006 2007, Singh and Singhal 2011, Barros *et al*. 2013, Zhan and Meschke 2014). Experimental studies on FRP strengthened beams with steel fibres have shown that mixing of short steel fibres has greatly affected the cracking behavior in concrete, from localized crack to distributed crack. Further, the failure mode also changed from peeling-induced debonding to the rupture of FRP sheets (Yin and Wu 2003, Maalej and Leong 2005, Li *et al*. 2008, Ferrari and Hanai 2012). It has been shown recently that hybrid fibre reinforced concrete (HFRC) composites can offer more attractive engineering properties due to the presence of more than one type of fibre in the matrix and thus enable efficient utilization of the potential properties of various fibres both in pre and post-cracking zone (Eswari *et al.* 2008, Surinder 2011, Qureshia *et al*. 2013, Alberti *et al.* 2014).



(a) Polyolefin fibre

(b) Hooked end steel fibre

(c) Glass fibre cloth

Fig. 1 Pictorial view of fibres

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http://www.techno-press.com/journals/sem&subpage=7
ISSN: 1225-4568 (Print), 1598-6217 (Online)

Table 1 Properties of fibres

Sl. No.	Fibre properties	Type of short-fibre	
		Polyolefin	Steel
1	Length (mm)	48	30
2	Shape / Type	Straight	Hooked ends
3	Size (mm)	1.22 × 0.732	0.5 Ø
4	Aspect Ratio	39.34	60
5	Density (kg/m^3)	920	7850
6	Tensile strength (MPa)	550	532
7	Young’s modulus (GPa)	6	210

Table 2 Properties of steel rebar and GFRP laminate

Sl. No.	Properties	Tensile steel ratio (%)	No. of layer	Yield / failure stress* (MPa)	Elasticity modulus (MPa)	Poisson’s ratio
1	Main steel rebar	0.60	-	415.00	200000	0.30
2	GFRP laminate	-	3	503.52	1603.50	0.38

*Yield for steel rebar and failure for GFRP laminate

Inherent advantages of FRP composites and FRC/HFRC composites can be coupled in seismic strengthening, where not only strength, but also, ductility is important. Earlier attempts taken up in this direction to study the structural performance of glass fibre reinforced polymer (GFRP) laminated steel fibre reinforced concrete beams have shown appreciably improved strength and ductility performance (Ibrahim *et al*. 2015, Ibrahim *et al*. 2016). However, further extensive and systematic studies are required to understand the role of hybrid fibres in GFRP laminated RC beams.

Hence, an effort has been made to study an effective method of strengthening RC beams by incorporating short polyolefin-steel hybrid fibres throughout the section and bonding of 5 mm thick GFRP laminates to the tension face of the beams. The present research investigation is intended to address three major concerns. The first is to explore the possibility of using hybrid fibres system for improved performance of GFRP laminated RC beams; the second is to examine the enhancement in flexural capacity of GFRP laminated HFRC beams and the third is to evaluate the ductility of GFRP laminated HFRC beams.

2. Experimental programme

2.1 Material properties and specimen characteristic

Mix proportion was designed to produce workable concrete with target strength of 26.6 MPa for the control mix. The longitudinal reinforcement consisted of 2 numbers of 12 mm diameter HYSD bars in the tension zone and 2 numbers of 10 mm diameter HYSD bars in the compression zone. The transverse reinforcement for all the beams consisted of 8 mm diameter HYSD stirrups equally spaced at 120 mm and the concrete clear cover provided was 25 mm. Pictorial view of steel fibre, polyolefin fibre, and glass fibre cloth used in the experimental programme are shown in Figs. 1(a)-(c). The properties of the fibres, as provided by

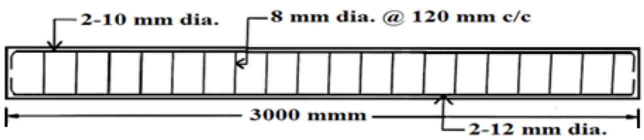

Fig. 2 Steel reinforcement details of beam

Table 3 Details of tested beams

Sl. No.	Beam ID	Beam size B × D × L (mm)	Total volume of fibre (%)	Fibre proportion		GFRP laminate thickness (mm)
				Polyolefin	Steel	
1	RB$^+$		0	--	--	--
2	RB1^{++}		0	--	--	5
3	HB1		1.0	0	100	5
4	HB2	150 × 250 × 3000	1.0	20	80	5
5	HB3		1.0	30	70	5
6	HB4		1.0	40	60	5
7	HB5		1.0	50	50	5

$^+$RB: Control (RC) beam; $^{++}$RB1: GFRP strengthened RC beam

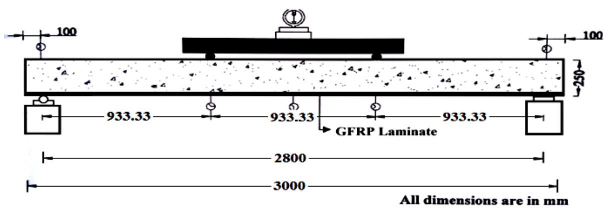

Fig. 3 Test set-up and instrumentation

Fig. 4 Surface grinding in progress

the manufacturers are given in Table 1. Properties of steel rebar and GFRP laminate are presented in Table 2.

The fibre volume content was assumed as 1% and maintained constant throughout the study (the above fibre volume content corresponds to ‘medium level’, as reported in literature). As two types of fibres are used, it is necessary to determine their strength properties/optimum content. For the above purpose, HFRC cylindrical specimens of size 200 mm dia.×300 mm height for evaluating the compressive strength and 100 mm dia.×200 mm height for evaluating the split-tensile (or indirect tensile) strength of the above specimens were cast, in accordance with the respective

Fig. 5 GFRP lamination in progress

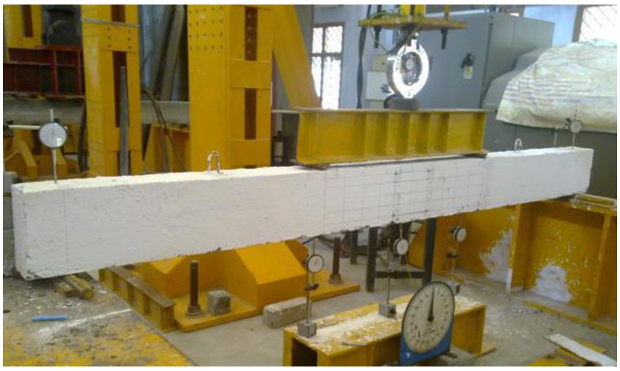

Fig. 6 Photographic view of test set-up

Indian standard codes (IS: 516-1959 and IS: 5816-1999). One plain concrete (R-P0S0) without fibres to serve as a 'control' specimen, and six HFRC specimens reinforced with different volume proportions of polyolefin and steel fibres (0:100, 20:80, 30:70, 40:60, 50:50, 100:0) were cast. Three cylindrical specimens of each types of concrete were cast and tested for obtaining the (average) compressive strength and split-tensile strength.

2.2 Casting and strengthening of beams

A total of seven beams were cast and tested in this study. All the beams were of same cross-section 150 mm×250 mm (breadth×depth) and had a clear span of 3000 mm. One RC beam (RB) was left without any internal fibres or external GFRP and one RC beam was strengthened with GFRP (RB1) to act as control beams. Five beams with different volume proportions of polyolefin and steel fibres (0:100, 20:80, 30:70, 40:60, 50:50) were strengthened with GFRP. The total fibre volume fraction was maintained at 1%. Fig. 2 shows the typical steel reinforcement details of the beams. The strengthened beams consisted of 5 mm thick GFRP laminates bonded to the tension face of the beams. The designation and details of tested beams are given in Table 3. The details of instrumentation, GFRP length, support and loading conditions are shown in Fig. 3.

After casting and curing the beams for 28 days, the beams were strengthened by external bonding of unidirectional glass fiber sheets using epoxy resin as the adhesive at the bottom of the beams (i.e., on the tension

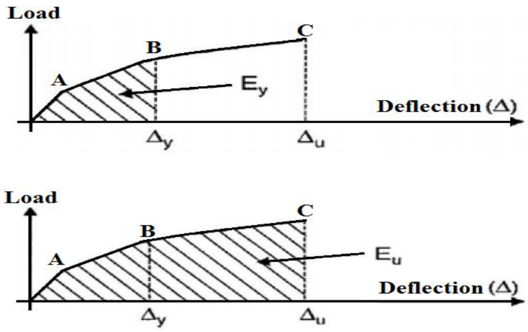

Fig. 7 Deflection ductility and energy ductility definitions

face). In order to ensure proper bonding between concrete and laminate, the beam surface was prepared using mechanical grinding as shown in Fig. 4 and then the surface was cleaned with the help of air blower to remove all fine particles from the prepared surface. By this way, surface preparation was completed on the designated specimens prior to bonding of the sheets. Wet layup system was used for strengthening the beam specimens and complying with ACI Committee 440 recommendations (ACI 440-2R 2008). Fig. 5 shows the simultaneous process of the application of resin and removal of air bubbles by using a roller. The laminated beams were left free for curing at room temperature before testing.

2.3 Instrumentation and test procedure

All the beams were tested in a loading frame having a capacity of 500 kN under static monotonic loading. The loading configuration had an effective span of 2800 mm and a constant moment region of 933.33 mm. The loads were applied in increments of 2.5 kN under four-point bending. The deflections were measured at mid-span and at load points using mechanical dial gauges having 0.01 mm accuracy. The crack widths were measured using a crack detection microscope with a least count of 0.02 mm. Crack development and propagation was monitored during the entire process of testing. All the above measurements were taken at different load levels until failure. The details of actual test set-up are shown in Fig. 6. Based on the incremental load given and the corresponding deflection, the load-deflection curves of tested beams were developed. The load at initial crack, yield and ultimate strengths, and the corresponding deflections, were noted for computing the deflection and energy ductilities of tested beams.

The first-crack load of a beam is defined as 'the point at which the load-deflection response deviates from linearity' and the 'corresponding deflection' is known as 'first-crack load deflection'. The yield load of a beam is defined as the stage at which main 'steel reinforcement begins to deform plastically' and the 'corresponding deflection' is known as 'yield load deflection'. The ultimate load of a beam is defined as the 'maximum load a beam can sustain before its failure due to flexure or failure of a component', and the 'corresponding deflection' is known as 'ultimate load deflection'. The maximum crack width was measured at the level of tensile steel reinforcement, between constant moment region, after failure of the beam.

Table 4 Strength properties of HFRC specimens

Sl. No.	Specimen ID	Compressive strength (MPa)	Tensile strength (MPa)
1	R-P0S0	26.70	3.78
2	H1-P0S100	27.80	4.12
3	H2-P20S80	28.25	4.20
4	H3-P30S70	28.50	4.29
5	H4-P40S60	30.28	4.58
6	H5-P50S50	28.67	4.34
7	H7-P100S0	27.12	4.10

Table 5 Principal test results of HFRC beams

Sl. No.	Beam ID	First crack Load (kN)	First-crack load deflection (mm)	Yield Load (kN)	Yield load Deflection (mm)	Ultimate Load (kN)	Ultimate load deflection (mm)	Maximum crack-width (mm)
1	RB	19.62	3.48	39.24	8.83	49.05	30.25	0.58
2	RB1	29.43	3.70	73.58	12.45	88.29	21.22	0.52
3	HB1	39.24	7.75	78.48	17.25	112.82	34.92	0.38
4	HB2	41.69	7.04	83.39	15.61	115.27	35.40	0.36
5	HB3	44.14	6.33	88.29	15.11	117.72	37.55	0.34
6	HB4*	46.59	6.19	90.74	14.78	120.17	38.62	0.32
7	HB5	44.14	6.98	85.83	15.36	115.27	36.75	0.34

*HB4: Optimum performance level of GFRP strengthened HFRC beam

'Ductility' of a structural element is its 'ability to undergo inelastic deformation' and with no substantial reduction in strength. Ductility of a specimen was found based on the deflection and energy absorbed. The deflection ductility (μ_Δ) is the ratio of the ultimate deflection (Δ_u) to that at the first yielding of steel reinforcement (Δ_y) (Fig. 7). Energy ductility index (μ_E) is defined as the 'ratio between the energy of the system at failure (E_u)' and the 'energy of the system at yielding load of tensile steel (E_y)' (Fig. 7) (Vijayakumar and Babu 2012).

3. Results and discussion

Table 4 shows the results of HFRC specimens. It can be seen that the compressive strength of HFRC specimens are slightly higher than that of the 'control specimen'. This is in line with the observation/(s) of a few investigators (Ferrari and Hanai 2012, Qureshi *et al*. 2013). Addition of fibres has increased the split-tensile strength (that is indirect tensile strength) in all concretes. The best performance was obtained with the polyolefin-steel hybrid fibres when compared to SFRC, which may be attributed to the positive interaction between the fibres and the resulting hybrid performance, thus exceeding the sum of individual fibre performances (i.e., both synergies and an improvement of the orientation and distribution of the fibres on the fracture surface). Moreover, addition of polyolefin fibre (40:60, polyolefin:steel fibres) has also increased the tensile strength, which is 21.20% and 11.17% higher than that of control concrete and SFRC, respectively. Thus, the desirable fibre content is 40:60 (polyolefin:steel) for use in

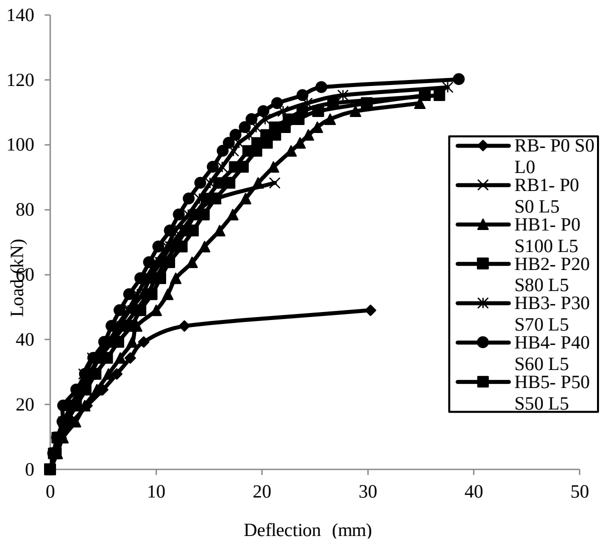

Fig. 8 Load-deflection response of tested beams

HFRC specimens.

The principal test results of beams are presented in Table 5. The load carried by all the test beams at first crack stage, yield stage, and ultimate stage, were obtained experimentally. It can be inferred from the above Table that the GFRP laminated beams with a hybrid fibre volume proportion of 40:60 (polyolefin: steel) has significantly improved the overall performance of the tested beams. The increase in yield load and ultimate load for GFRP laminated HFRC beams (HB4**)** was found to be 131.2%, and 145% respectively, when compared to the control beam (RB) and 23.3% and 36.1% respectively, when compared to GFRP laminated RC beam (RB1). Whereas, polyolefin fibres have a low modulus and high elongation, having the capacity to absorb large amount of energy, thereby impart toughness to the composite, steel fibres have high modulus and high elongation, thereby impart strength and stiffness to the composites, including dynamic properties to varying degrees (Mahadik *et al*. 2014).

Two types of flexural strength for the beams were observed. The first one is: first-crack flexural strength, which shows a linear behaviour. The second one is the ultimate flexural strength, which is related to maximum load achieved, and therefore is more important for design considerations. Flexural strength can be increased by increasing fibre volume fraction and aspect ratio (Malhotra and Chand 2017). Whereas, addition of steel fibres is expected to improve the first-crack and ultimate strengths, polyolefin fibres added is expected to improve the strain capacity and toughness, especially, in the post-cracking stage of laminated beams.

SFRC beam (HB1) is found to have increased load-carrying capacity at various stages (first crack, yield and ultimate) due to the contribution of steel fibres in the post-cracking stage, that is, the bridging effect on macro-cracks, which have started after or during the formation of first-crack. On the other hand, in HFRC beams, crack arresting mechanism is due to the pre and post-cracking behaviour of polyolefin-steel hybrid fibres, i.e., the bridging effect on both micro and macro-cracks, which start even before the

Table 6 Ductility and failure details of tested beams

Sl. No.	Beam ID	Deflection ductility	Energy ductility	Failure mode
1	RB	3.43	4.28	Concrete compression failure
2	RB1	1.70	2.04	Debonding of laminate
3	HB1	2.02	2.91	Debonding of laminate
4	HB2	2.26	3.13	Debonding of laminate
5	HB3	2.48	3.31	Debonding of laminate
6	HB4*	2.61	3.46	Debonding of laminate
7	HB5	2.39	3.21	Debonding of laminate

*HB4: Optimum ductility response level of GFRP strengthened

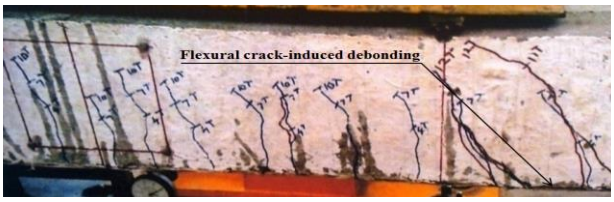

Fig. 9 Failure mode of GFRP laminated HFRC beam (HB4)

formation of first-crack. Due to the above reason, HFRC beams are found to exhibit better performance at various stages (first-crack, yield, and ultimate) when compared to SFRC beams. Further, may be due to the 'synergy effect' of the different fibres, the beam HB4 with 40% polyolefin fibres and 60% steel fibres, exhibits higher first-crack load, yield load, and ultimate load, than the rest of the beams. The above phenomenon explains the behaviour of HB1 and HB4 beams.

The load-deflection response of tested beams is shown in Fig. 8. The increase in ultimate deflection for GFRP laminated HFRC beam (HB4) was found to be 27.6%, when compared to the control beam (RB), and 82% when compared to conventional strengthened beam (RB1). The reduction in crack-width for GFRP laminated HFRC beam (HB4) was up to 44.8% when compared to the control beam (RB), and 38.4% when compared to GFRP laminated RC beam (RB1).

The ductility and failure details of tested beams are given in Table 6. GFRP laminated HFRC beams (HB4) also exhibit enhanced ductility than that of GFRP laminated RC beam (RB1). The increase in deflection ductility and energy ductility were found to be 53.5% and 69.6% when compared to that of GFRP laminated RC beam (RB1). Several investigators have reported that the ductility of RC beams strengthened with FRP laminates/sheets is considerably reduced due to increase in their stiffness, thus, leading to unexpected failure without any prior notice (Xiong *et al*. 2004, Bsisu *et al*. 2012). It can be seen from Table 6 that the deflection ductility and energy ductility of the beams RB1, HB1, HB2, HB3, HB4 and HB5 is considerably reduced, than that of the control beam, due to the increase in the (bending) stiffness of GFRP laminates. The ductility of HFRC beams (HB2, HB3, HB4, and HB5) is shown to be increased than that of SFRC beam (HB1), due to the toughening effect induced by addition of polyolefin fibre. Further, widening of flexural crack-induced debonding failure of GFRP laminated HFRC beam (HB4) is shown in Fig. 9.

4. Conclusions

Based on the experimental investigations carried out in this study following conclusions are drawn:

- GFRP laminated beam with a hybrid fibre volume proportion of 40:60 (polyolefin-steel) (that is HB4), has significantly improved overall performance amongst the tested beams.
- An overall evaluation of the flexural test results and load-deflection behaviour indicate that the above GFRP laminated HFRC beam exhibit higher load-carrying capacity, and deformation capacity.
- The increase in ultimate load and ultimate deflection (of HB4) were found to be 145% and 27.6% respectively, when compared to the control beam, and 36.1% and 82% respectively, when compared to GFRP laminated RC beam.
- The maximum reduction in crack-width (of HB4) was found to be 44.8%, when compared to the control beam, and 38.4% when compared to GFRP laminated RC beam.
- The increase in deflection ductility and energy ductility (of HB4) were found to be 53.5% and 69.6% when compared to that of GFRP laminated RC beam.
- All the (tested) beams failed in 'flexure mode' only.

Acknowledgments

This forms part of an ongoing research work of the first author, under the guidance of the senior author/(s). The facilities extended and the cooperation extended for carrying out this research work, by the Civil Engineering Department, and by the college (Pondicherry Engineering College) are great fully acknowledged.

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