Investigation of HFRC beams retrofitted using GFRP for enhancement in flexural capacity

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Abstract: The applications of FRP have been widely used in repair and upgrading of concrete structures. Research and design guidelines accomplished that externally bonded FRP could increase the load carrying capacity of RC elements efficiently. A study was undertaken to investigate the flexural behaviour of hybrid fibre reinforced concrete (HFRC) beams, which were preloaded and retrofitted by externally bonded with glass fibre reinforced polymer (GFRP) laminate to the bottom (soffit) of the beam. The compressive, split tensile and flexural strength tests were conducted to find the optimum percentage of hybrid fibre which can be used for casting of beam specimens. Two sets each containing three numbers of beams were cast and tested in this study. Based on the test results, it is found that the HFRC beams retrofitted with GFRP show an improvement in load carrying capacity of about 45% and 23% than the same set of retrofitted control beams.

Keywords: hybrid fibre reinforced concrete; HFRC; glass fibre reinforced polymer; GFRP; laminate; steel; glass and polypropylene fibres; nonlinear finite element analysis; NLFEA; finite element analysis; FEA; ANSYS.

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1 Introduction

Generally, conventional concrete has low tensile strength and tends to brittle earlier; apart from that it has some drawbacks such as limited ductility, lesser impact and abrasion resistance and little resistance to cracking. There is a need to overcome these problems in the modern construction field. The term fibre reinforced concrete (FRC) is defined by ACI Committee 544 (2002) as a concrete made of hydraulic cements containing fine and coarse aggregates and discontinuous discrete fibres. Wafa (1990) emphasised the use of fibres to be selected based on various factors such as fibres function, density, modulus of elasticity, tensile strength and aspect ratio is incorporated into concrete to control cracking, increase the tensile strength, toughness and to improve the deformation characteristics of concrete. It has been demonstrated as of late Xu and Hannant (1992), Kakemi and Hannant (1995) and Mobasher and Li (1996) that by utilising the idea of hybridisation with two different fibres incorporated into a common cement matrix, the hybrid composite can offer more attractive engineering properties because the presence of one fibres enables the most efficient utilisation of the potential properties of the other fibres. Ganesan et al. (2014) found that the use of hybrid fibres in concrete arrests the micro cracks as well as macro cracks. Low modulus fibres arrests the micro cracks and controls the formation of macro cracks, where as high modulus fibres control macro cracks. Admitting the fact that reinforced concrete (RC) structures need a fairly consistent modification in design which improves its performance throughout the service life period, Obaidat et al. (2010) summarises that retrofitting technique has the potential to be a promising solution for the RC structures. The rehabilitation of concrete structures is one of the most critical problems in area of the civil engineering applications. The retrofitting of concrete structures is not new and several projects have been carried out around the world for the past few decades. One of the challenges in retrofitting of concrete structures is selection of a retrofitting technique that will improve the strength and serviceability of the concrete structures. External bonding of steel plates is the most commonly adopted retrofitting technique in existing RC members. Hosny et al. (2006) demonstrated that, fibre reinforced polymers (FRP) have been used increasingly in the last two decades to strengthen and retrofit the RC structural elements (Hosny et al., 2006). FRP can be more suitable as compared to steel plate for several reasons such as, these materials have higher ultimate strength and lower density, easy installation and temporary support is not required until the adhesive gains its strength due to its less in weight.

2 Related research work

Many researchers have compared the strength of various fibres incorporated in the concrete. It has been shown that, using the concept of hybridisation, incorporating different fibres in concrete gives better performance. Yao et al. (2003) examined and found that among the three types of fibres (carbon, steel and polypropylene), carbon fibres have the highest compressive strength and polypropylene fibres has the lowest compressive strength. When the fibres were used in a hybrid form, it obviously increased strength in both carbon-steel fibres and carbon-polypropylene fibres. Test results showed that the fibres, when used in a hybrid form, results in superior composite performance in mechanical properties. Qian and Stroeven (2000) examined the flexural behaviour of the hybrid steel-polypropylene hybrid using 100 mm × 100 mm × 500 mm prism with four-point loading. In this investigation, polypropylene fibres and three different sizes of steel fibres of varying aspect ratio were used. Test result shows that the large sized steel fibres with polypropylene fibres improve the toughness and load carrying capacity of concrete. Sharmila and Thirugnanam (2013) demonstrated that incorporating hybrid fibres influence the behaviour of RC beams increasing the ductility characteristics by 80% and energy absorption characteristics by more than 160%. Finally proved that, instead of adding single fibres, the mixture of different types of fibres increases the load carrying capacity, energy absorption capacity, stiffness and ductility characteristics substantially.

FRP composites have been used for strengthening or retrofitting of RC structural members. Sobuz et al. (2012) demonstrated that the externally bonded CFRP sheet has shown excellent performance to repair, restore and increase the load-carrying capacity of RC structures. The test variables included different degrees of strengthening scheme for both uncracked and cracked beams. Esfahani et al. (2007) investigates the flexural behaviour of reinforced concrete beams strengthened using carbon fibre reinforced polymers (CFRP) sheets. From the test results, it was found that the flexural strength and stiffness of the strengthened beams increased as compared to the control specimens. Adam et al. (2015) conducted an experimental, numerical and analytical study on the flexural behaviour of concrete beams reinforced with locally produced glass fibre reinforced polymers (GFRPs) bars. A nonlinear finite element analysis (NLFEA) was constructed to simulate the flexural behaviour of tested beams, in terms of crack pattern and load deflection behaviour. From the investigation, he concluded that the good agreement between the experimental and numerical results was achieved. Sallam et al. (2013) carried out the laboratory tests on RC beams strengthened with bonded CFRP laminates and showed that the similar behaviour can be captured using finite element analysis (FEA) software package ANSYS.

From the review of literature presented, it was revealed that, when fibres are used in hybrid form in concrete results in enhanced performance in hardened properties when compared to single hybrid and control concrete. Research and design guidelines concluded that, the tests on RC beams strengthened or retrofitted with externally bonded FRP increases the load carrying capacity and also found that the similar response was obtained during FEA. Separate studies have been carried out on both FRC beams and retrofitting of RC beams. However, in this study, a new attempt has been made to investigate the flexural behaviour of HFRC beams retrofitted using FRP laminates.

3 Research significance

From the experiment research until now carried out, the external bonding of FRP in RC beams for strengthening/retrofitting could not be achieved adequately, because of the formation of localised flexural and shear cracks which affects the bonding between the interface of concrete and FRP, as a result the improvement in load carrying capacity cannot be obtained effectively. Hence, adding hybrid fibres into the concrete is an effective method to control the formation of micro cracks and propagation of macro cracks and this may avoid or delay the de-bonding of FRP composites. This study presents an approach to improve the FRP strengthening performance to concrete beams by adding hybrid fibres into the RC beam. It was realised from the literatures that only few research works have been carried out on RC beams to strengthen/retrofit using GFRP laminates. Hence, in this study, GFRP is used, because it is ductile and economical than other FRP and also it is considered to be an alternative solution to retrofit the concrete elements. Though a lot of research works have been done on HFRC, but no research is reported on adding of different proportions of low modulus fibres along with high modulus fibres in the concrete. Steel and glass fibres are identified as high modulus fibres to resist macro cracks, while polypropylene fibres are low modulus material since it reduces the micro cracks. The analysis is carried out with three types of fibres (steel, glass and polypropylene) in a suitable combination and their different mix proportions are provided in Table 1. The study was carried out to enhance the flexural capacity of HFRC beams retrofitted with externally bonded GFRP laminates under static loading condition. The analytical modelling by using FEA is to validate the behaviour of the experimentally tested beams.

Table 1 Various mix proportions of fibres

MIX ID	*Fibres mix proportion by volume (%)*		
	Steel fibres	*Glass fibres*	*Polypropylene fibres*
AO	0	0	0
B1	1	0	0.15
B2	1	0	0.30
B3	1	0	0.45
C1	0	0.03	0.15
C2	0	0.03	0.30
C3	0	0.03	0.45

4 Test program

4.1 Material properties

Ordinary Portland cement of 53 grades with specific gravity 3.12 was used for preparation of test specimens, which satisfies the requirement of IS 12269 (1987) specifications. Locally available river sand was used as fine aggregate which passed through 2.36 mm size sieve having specific gravity 2.69 and fineness modulus 2.75 conforming to grading zone 3 of IS 383 (1970) specifications. Crushed angular granite stone with 12 mm maximum size was used as coarse aggregate conforming to IS 383 (1970) specifications and having specific gravity 2.72 and fineness modulus 6.6. The potable water was used for mixing and curing the concrete. Polycarboxylic ether based high-performance super-plasticiser was used in concrete. A dosage range of 500–1,500 ml per 100 kg of cement is used to achieve good workability and durability with specific gravity of 1.08 as per IS 9103 (1999) and ASTM C494-type F. Fibres like steel, glass and polypropylene were used in suitable combination. The various mix proportions of fibres and their properties are provided in Table 1 and Table 2, respectively. The uni-directional GFRP laminates of thickness 3 mm was used. A commonly used bonding material namely epoxy adhesive was used to ensure bond quality between concrete and its layers. The properties of the GFRP laminates and epoxy adhesive as supplied by the manufacturer are shown in Table 3. The longitudinal reinforcement consisting of high yield strength deformed bars of 12 mm and 10 mm diameters have yield strength of 420 MPa and 412 MPa, respectively. The shear reinforcement consisting of mild steel bars of 8 mm diameter have yield strength of 250 MPa.

Table 2 Properties of steel, glass and polypropylene fibres

	Steel	*Glass*	*Polypropylene*
Length (mm)	48	6	12
Diameter (mm)	0.75	0.014	0.05
Density (Kg/mm^3)	7,680	2,680	980
Modulus of elasticity (GPa)	200	72	3.5
Tensile strength (MPa)	1,100	1,700	400

4.2 Test specimens

Concrete with cube compressive strength of 25 MPa was used to carry out testing. The concrete mix ratio for test specimens consists of 437.7 kg/m^3 of ordinary Portland cement, 624 kg/m^3 of fine aggregate, 1,172 kg/m^3 of coarse aggregate with water cement ratio of 0.45 calculated as per the design guidelines of IS 10262 (2009).

The specimens were cast in 150 mm cubes for compressive strength test and pull-out test, 100 × 100 × 500 mm beams for flexural strength test and 150 mm diameter × 300 mm long cylinders for splitting tensile strength test. The specimens were cast in 152 mm diameter × 63.5 mm thickness disc for impact strength test.

Table 3 Properties of GFRP laminates and epoxy adhesive

Materials	*Property*	*Values*
GFRP laminates	Sheet form	Uni-directional roving
	Glass content %	60–90
	Specific gravity	1.7–2.2
	Tensile strength, MN/m^2	530–1,730
	Tensile modulus, GN/m^2	28–62
	Compressive strength, MN/m^2	310–480
	Flexural strength, MN/m^2	600–1,800
Epoxy adhesive	Viscosity at 25ºC, Mpa s	500–650
	Density at 20ºC, g/cm^2	1.15
	Flash point, ºC	>120
	Epoxy index, eq/Kg	5.20–5.50

A total of six nos. of beams were cast and tested as two sets (sets A and B), each containing three nos. of beams. The beams were designed to be weak in flexure and strong in shear to examine the flexural behaviour. In set A, out of three beams, one served as control beam and the remaining two beams were reinforced with hybrid steel-polypropylene fibres and hybrid glass-polypropylene fibres, whereas in set B, the beams were preloaded until flexure cracks appeared up to 75% of ultimate load (fixed damage degree) of set A beams and retrofitted with GFRP laminates in the clear span of bottom of the beam. All the test beams had similarity in overall cross-sectional dimensions, internal longitudinal and shear reinforcement. The details of test specimen (sets A and set B beams) are given in Table 4. The beams were 150 × 200 mm in cross-section and 2,100 mm in length. Each concrete beam was reinforced with two 10 mm diameter bars in bottom (tension zone) and two 8 mm diameter bars in top (compression zone) along with a shear reinforcement (lateral ties) of 8 mm diameter bar at a spacing of 100 mm centre-to-centre. The typical geometry and reinforcement of the beams are shown in Figure 1. The RC beams are designed as per IS 456 (2000). The design and wrapping schemes for flexural retrofitting of beams using externally bonded FRP systems is done based on ACI Committee 440 (2008) specifications. Details of the preloaded beams retrofitted with GFRP laminate in the bottom are shown in Figure 2.

Table 4 Details of beam specimen

Set	*Beam reference*	*Beam designation*
A	AOF	Control beam
	B2F	Hybrid steel-polypropylene hybrid beam
	C2F	Hybrid glass-polypropylene hybrid beam
B	AOFR	Preloaded control beam retrofitted with GFRP laminate
	B2FR	Preloaded hybrid steel-polypropylene hybrid beam retrofitted with GFRP laminate
	C2FR	Preloaded hybrid glass-polypropylene hybrid beam retrofitted with GFRP laminate

The preloaded beams were bonded with GFRP laminate after the fixed damage degree, has been applied. The surfaces of the beams are cleaned using a mechanical grinder. Then the epoxy adhesives are coated on the cleaned surface of the preloaded RC beams and GFRP laminate. Finally, the GFRP laminate are attached in the tension side of the preloaded RC beams. The preloaded beams retrofitted with GRFP laminates are equipped for testing, after the beams are allowed to dry for a minimum period of seven days.

Figure 1 Beam reinforcement details (unit: millimetre)

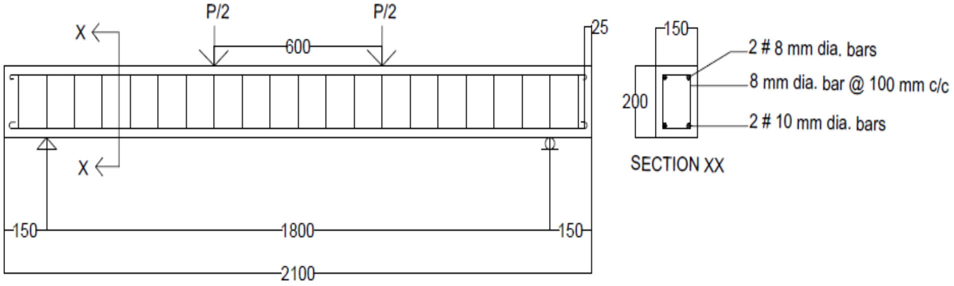
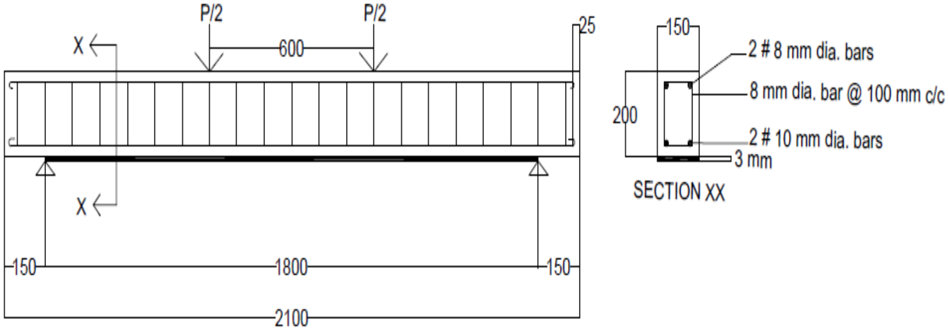


Figure 2 Preloaded beams retrofitted with GFRP laminate in the bottom (unit: millimetre)



4.3 Test methods

The compressive strength and flexural strength were determined in accordance to IS 516 (1959). The splitting tensile strength was determined as per IS 5816 (1999). The impact resistance of the hybrid fibre reinforced concrete (HFRC) specimen was determined by using drop weight method of impact test recommended by ACI Committee 544 procedure. The bond strength was determined by conducting pull-out test and the specimen were prepared as per IS 2770 (Part 1) (1967). The contact length between the concrete and steel bar was kept as 5 cm. For each specimen, a single reinforcing bar was placed in the centre of the cube. Deformed bars of diameter 12 mm were used to study the bond strength. The experimental bond strength obtained is compared with theoretical assessment. The theoretical bond strength was calculated using the formula provided in BS 8110-1: Part 1 (1997, 2002) and is as follows:

$$f_{bu} = \beta\sqrt{f_{cu}}$$

where f_{bu} is the theoretical bond strength in N/mm^2; β the bond coefficient (β = 0.50 for deformed bars) f_{cu} the compressive strength of concrete in N/mm^2.

All the test beams were subjected to four-point bending in a loading frame. The beam supports at the two ends with a span length of 1,800 mm. The loads were applied at points dividing the span length into three equal parts through hydraulic jack at a regular interval. Two dial indicators with an accuracy of 0.01 mm under the point loads and LVDT were fixed at the mid span to measure the deflections of the beam. Crack detection microscopes with 0.02 mm precision were used to measure the crack widths of the beam. The cracks of the testing beams were mapped during loading and at the time of failure. The beams were tested up to the ultimate load and the deflection is noted. The arrangement of beam test set-up is shown in Figure 3.

Figure 3 Beam test setup (see online version for colours)

4.4 Test results and discussion

4.4.1 Compressive, split tensile and flexural strength test

The compressive, split tensile and flexural strength of 28 day samples for the various mixes is obtained in the range of 35.9–44.6 N/mm^2, 2.9–5.5 N/mm^2 and 4.5–8.3 N/mm^2 respectively and the test results are shown in Table 5. These three tests are conducted to find the optimum percentage of hybrid fibres in concrete. The addition of hybrid fibres in concrete improved the compressive, split tensile and flexural strength. Among the various mixes, B2 (1% steel fibres and 0.30% polypropylene fibres) and C2 (0.03% glass fibres and 0.30% polypropylene fibres) exhibited a better performance. The compressive, split tensile and flexural strength of B2 and C2 mixes are found to be increased about 24.2%, 89.6% and 84.4% and 16.4%, 31% and 40% than the plain concrete (A0) respectively. From the test results, B2 and C2 mixes are identified as optimum and used for casting beam specimens. From Table 5, it appears that at low dosage rates of polypropylene fibres (0.1% and 0.30%) does not significantly detract from, and even improves compressive, split tensile and flexural the strength of concrete matrix. However, higher dosage rate (0.45%) decreases the strength due to higher volumes of fibres interfering with the cohesiveness of the concrete matrix. Similar result was earlier experienced by Ahmed et al. (2006) when employing higher dosage of polypropylene fibres.

Table 5 Compressive, split tensile and flexural strength test results

Mix ID	*Compressive strength (N/mm^2)*		*Split tensile strength (N/mm^2)*		*Flexural strength (N/mm^2)*	
	7 days	*28 days*	*7 days*	*28 days*	*7 days*	*28 days*
A0	24.1	35.9	2.0	2.9	3.5	4.5
B1	30.0	42.4	2.8	4.3	5.6	6.5
B2	32.1	44.6	4.0	5.5	6.7	8.3
B3	29.5	41.5	2.6	4.0	5.3	6.4
C1	27.5	40.1	2.2	3.4	4.0	5.1
C2	29.1	41.8	2.4	3.8	5.0	6.3
C3	26.8	39.0	2.1	3.2	3.8	5.3

4.4.2 Impact strength test

Irrespective of fibres type, the impact energy is affected by fibres addition in concrete. With reference to previous research work, Wang and Huang (2012) also reported the similar outcome. Moreover, addition of fibres in concrete mixture had no significant effect on first crack under impact test, but ultimate crack was greatly enhanced. The first crack (N1), ultimate crack (N2) and impact energy for various tested specimens are shown in Table 6. From the impact test results, it is identified that incorporating fibres in the concrete arrest the initiation and propagations of cracks. Because of higher fibres content, B3 and C3 mix specimens take more blows for the first crack and failure crack than plain concrete specimen. The impact energy increases with increase in dosage of hybrid fibres in concrete. The impact energy of A0, B3 and C3 mixes obtained are 80.16 Nm, 460.92 Nm and 240.48 Nm, respectively. As a result, impact energy of the HFRC is high as compared to the control specimen. Consequently, regarding to fibres types and volume fraction, hybrid steel-polypropylene had better performance in reinforcing the concrete to reach the highest impact resistance. Based on test results, hybrid steel-polypropylene fibres was more efficient in increasing impact energy when compared with hybrid glass-polypropylene fibres. This is due to the consequence of positive interaction between steel and polypropylene fibres. Because, steel fibres has higher elastic modulus and tensile stress compared to glass fibres, so the hybrid steel-polypropylene fibres with higher volume fraction has the capability to the impact resistance.

4.4.3 Pull-out test

The results for the pull-out test are given in Table 7. The 28-day bond strength for deformed bar ranged from 6.89 to 9.01 N/mm^2 for the various mixes. In pull-out test, as for deformed bars, all samples failed by cracking at the concrete cover. Similar pattern of failure was reported by Teo et al. (2007). Due to incorporation of fibres in concrete there is a good bonding between the concrete and hybrid fibres. Consequently, higher bond strength along with maximum slip is obtained for HFRC when compared with plain concrete specimens. The ultimate bond strength of 9.01 N/mm^2 and 7.95 N/mm^2 is obtained for the B2 and C2 mix specimens respectively. Similar to compressive, split tensile and flexural strength, higher dosage rate of polypropylene fibres affects the bond strength of HFRC. From the experimental results, it was found that the bond strength of specimens with deformed bars was approximately 19%–20% of the compressive strength. The experimental bond strength was much higher than the theoretical bond strength as stipulated by BS 8110-1: Part 1 (1997, 2002).

Table 6 First crack, ultimate crack and impact energy for the various tested specimens

MIX ID	*First crack (N1)*	*Ultimate crack (N2)*	*Impact energy (Nm)*
A0	1	3	80.16
B1	4	9	260.52
B2	6	14	400.80
B3	7	16	460.92
C1	2	7	180.36
C2	2	8	200.40
C3	3	9	240.48

Table 7 Results of pull-out test using deformed bars

MIX ID	*Compressive strength, N/mm^2*	*Experimental bond strength, N/mm^2*	*Theoretical bond strength, N/mm^2*	*Experimental/ theoretical bond strength*	*Slip at ultimate load, mm*
A0	35.9	6.89	3.00	2.30	2.56
B1	42.4	8.22	3.26	2.52	3.04
B2	44.6	9.01	3.34	2.70	3.21
B3	41.5	7.96	3.22	2.47	2.92
C1	40.1	7.69	3.17	2.43	2.82
C2	41.8	7.95	3.23	2.46	2.89
C3	39.0	7.42	3.12	2.38	2.77

4.4.4 Flexural behaviour of HFRC beam retrofitted with GFRP laminates

4.4.4.1 Load carrying capacity

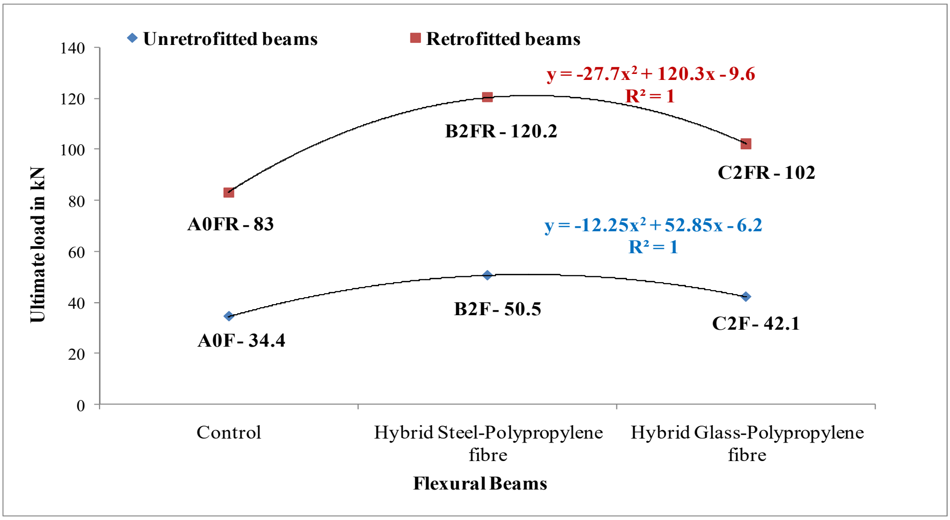
The yield load, ultimate load and its corresponding deflection values for all the tested beams are shown in Table 8. Figure 4 shows the experimental results of control, HFRC and retrofitted beams in terms of ultimate load. The use of hybrid fibres in concrete arrests the micro cracks as well as macro cracks. Due to this phenomenon, the ultimate load carrying capacity increases in the HFRC beams. From Figure 4, it is observed that, the flexural behaviour of hybrid steel-polypropylene fibres and hybrid glass-polypropylene fibres reinforced concrete beams (B2F and C2F) showed an increase in ultimate load of about 47% and 22% respectively over the control beams (A0F). The experimental result exhibits that the retrofitted beams considerably increase the load carrying capacity than unretrofitted beams. The beams retrofitted with GFRP laminates in the soffit (A0FR, B2FR and C2FR) increases ultimate load by 141%, 138% and 142% than unretrofitted beams (A0F, B2F and C2F).

The hybrid steel-polypropylene FRC beams retrofitted with and without GFRP laminates (B2FR and B2F) showed an enhancement in ultimate load of about 18% and 20% when compared with hybrid glass-polypropylene FRC beams retrofitted with and without GFRP laminates (C2FR and C2F). This increase is significant and it can be attributed due to high tensile strength of steel fibres than glass fibres.

Table 8 Load, deformation, ductility and stiffness

Test beam ID	*Yield load (kN)*	*Ultimate load (kN)*	*Yield deflection (mm)*	*Ultimate deflection (mm)*	*Deflection ductility*	*Energy ductility*	*Stiffness (kN/mm)*
A0F	26.1	34.4	8.6	18.1	2.10	3.31	1.90
B2F	38.6	50.5	3.0	11.5	3.83	8.33	4.39
C2F	32.5	42.1	7.1	21.4	3.01	5.52	1.97
A0FR	61.4	83	9.6	22.6	2.35	3.54	3.67
B2FR	88.4	120.2	3.5	14.1	4.03	7.18	8.52
C2FR	73.3	102	7.6	25.6	3.37	5.51	3.98

Figure 4 Ultimate loads of control, HFRC and retrofitted beams (see online version for colours)



Finally, it was observed that, the retrofitted HFRC beams performed superior in load carrying capacity than the same set of retrofitted control beams. The hybrid steel-polypropylene and hybrid glass-polypropylene fibre reinforced beams retrofitted with GFRP (B2FR and C2FR) showed an improvement in ultimate load of about 45% and 23% respectively in ultimate load over the retrofitted control beam (A0FR). The reason is the strengthening effect of GFRP was attained effectively with hybrid fibres in concrete beams. It enhanced the performance and controlled the crack localisation and propagation in concrete. The relationship between ultimate load (y) in kN and various beam designation (control, hybrid steel-polypropylene and hybrid glass-polypropylene fibre) for unretrofitted and retrofitted beams (x) can be obtained as $y = -12.25X^2 + 52.85X - 6.2$ and $y = -27.7X^2 + 120.3X - 9.6$ as shown in Figure 4.

Figure 5 Load-deflection response of unretrofitted beams (see online version for colours)

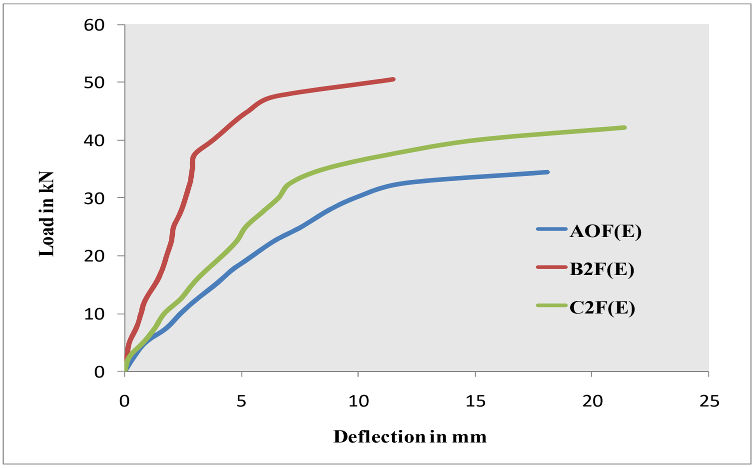
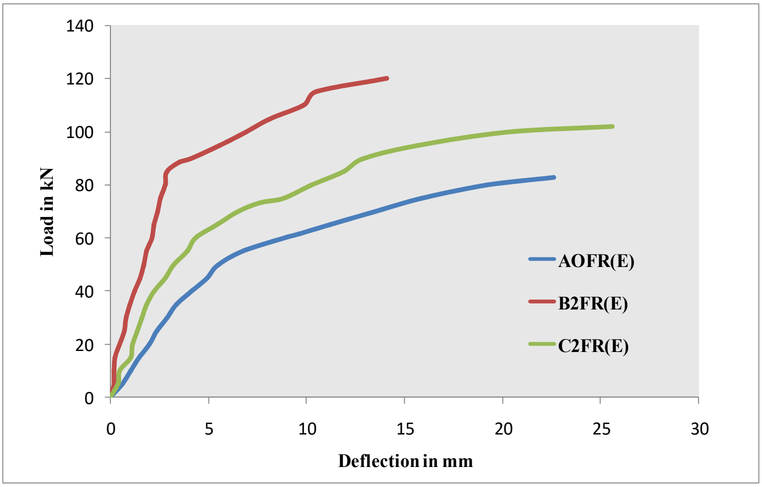


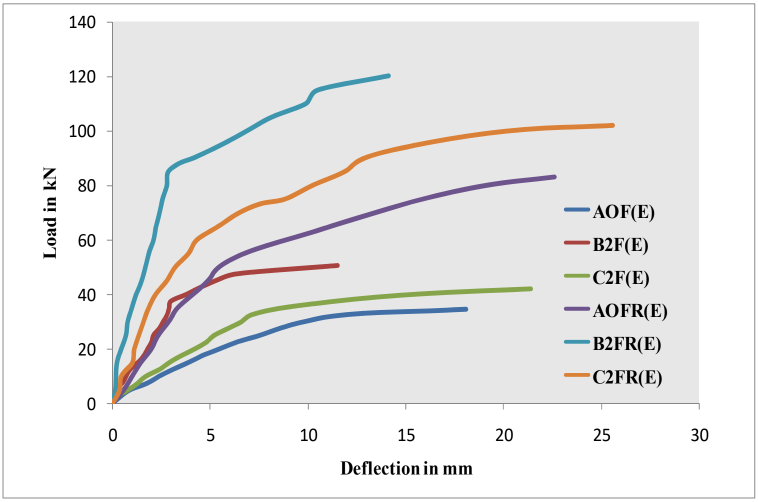
Figure 6 Load-deflection response of retrofitted beams (see online version for colours)



4.4.4.2 *Load-deflection relationship*

For comparison and better representation, of load verses mid span deflection curve for all the tested beams were plotted in Figure 8. Figures 5 and 6 show the load-deflection response of unretrofitted and retrofitted beams. From Figure 5, it is clear that the hybrid steel-polypropylene FRC beam carries higher load carrying capacity with lower deformation as compared to hybrid glass-polypropylene FRC beam and control beam. The above mentioned similar response is captured in Figure 6 for retrofitted beams. It is observed from Figure 7, that initially all the retrofitted beams perform like the control beam with the internal steel reinforcing bars carries the majority of the tensile force in the beam. When the internal steel yields, the additional tensile force is carried by the GFRP laminates and an increase of the load carrying capacity is obtained. From Figure 7, it was observed that, retrofitted control beam takes excessive load with a reduced amount of deformation than the HFRC beam (B2F and C2F). From this study, it was concluded that the retrofitted concrete beams perform superior than unretrofitted beams. A0F(E), B2F(E), C2F(E) and A0FR(E), B2FR(E), C2FR(E) represents the experimental results of the corresponding beams.

Figure 7 Load verses mid span deflection curve for all the tested beams (see online version for colours)



4.4.4.3 *Crack width, crack pattern and failure modes*

The maximum crack width occurs at the point of application of ultimate load. The crack width values for the tested beams A0F, B2F, C2F (unretrofitted) and A0FR, B2FR, C2FR (retrofitted) are 0.82 mm, 0.54 mm, 0.60 mm and 1.3 mm, 0.85 mm, 0.94 mm, respectively. Figure 8 reveals an increase in load carrying capacity and a decrease in crack width. Due to incorporation of hybrid fibres in concrete beam exhibits widely spaced and lesser number of cracks. Moreover, Kumar and Mahendran (2016) reported that, arresting the micro cracks as well as macro cracks depends on the ability of hybrid fibres. The results exhibit that HFRC beams carries higher load with lesser crack width. The relationship between ultimate load in kN (y) and crack width in mm (x) for unretrofitted and retrofitted beams as shown in Figure 8 is obtained as $y = -52.41X + 75.93$ and $y = -74.12X + 178$. The identified optimum mixes B2 and C2 along with A0 were used for casting of beam specimens A0F, B2F, C2F. As shown in Figure 9, increase in the concrete compressive strength from 35.9 MPa to 41.8 MPa tends to reduce the crack width by 27%, while the crack width tends to decrease by 11% when the concrete compressive strength increase from 41.8 MPa to 44.6 MPa. Hence, the relationship between concrete compressive strength in MPa (y) and crack width in mm (x) is obtained as $y = -29.92X + 60.31$. The crack pattern at collapse for the tested beams is shown in Figure 10. According to design, the control beam fails in flexure. The crack initiated in the vertical direction as flexural crack in the tension zone and as the load increases, beams failed in flexure ultimately. From the observation, it is found that the related response is applicable for all the tested beams. The retrofitted beams show cracks at relatively closer spacing than unretrofitted beams due to confinement of GFRP in the tension zone. The unretrofitted beams are failed due to concrete crushing, whereas in retrofitted beams delamination has taken place. Figures 11(a) and 11(b) depict the sample failure modes for unretrofitted (concrete crushing failure) and retrofitted (delamination failure) concrete beams.

Figure 8 Crack width variation with ultimate load for different beam designation (see online version for colours)

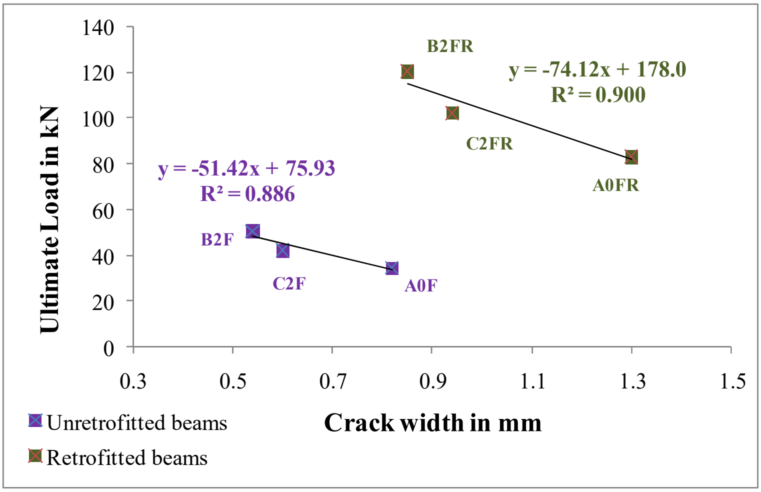


Figure 9 Crack width variation with effect of concrete compressive strength (see online version for colours)

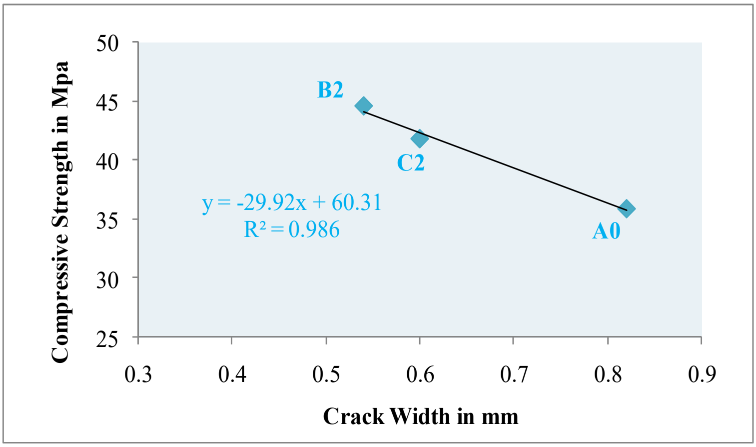
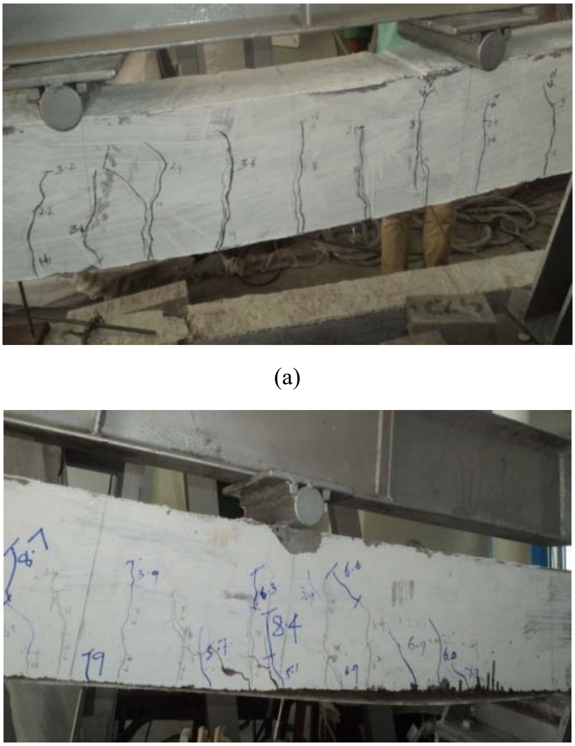


Figure 10 Crack pattern at collapse for the tested beams (see online version for colours)

Figure 11 Modes of failure for unretrofitted and retrofitted concrete beams, (a) concrete crushing failure (b) delamination failure (see online version for colours)



(a)

(b)

4.4.4.4 Ductility characteristics

Ductility relationships for all the tested beams are presented in Figure 12. Ductility is the ability of the structural component to undergo maximum deformation without major loss in strength. Ductility is generally measured in terms of deformation and energy. Attari et al. (2012) define the term deflection ductility as the ratio of ultimate deformation to the yield deformation, whereas the energy ductility was calculated based on the area arrived from the load-central deflection curve up to ultimate divided by the area of the load deflection curve up to yield. The experimental results exhibit that the effect of adding hybrid fibres influences the behaviour of beams with increase in the ductility characteristics when compared to control beam. Because of the presence of the GFRP, the increase in ductility has direct bearing with flexural capacity. From Table 8, it is concluded that, there is significant improvement in ductility performance in the retrofitted beams than unretrofitted beams.

Figure 12 Ductility relationship (see online version for colours)

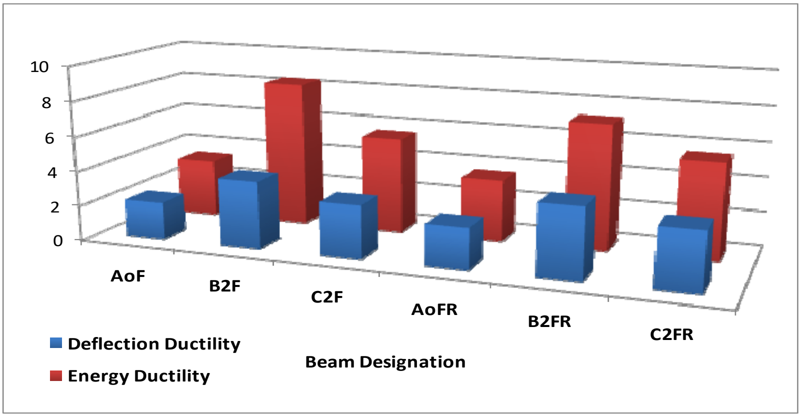
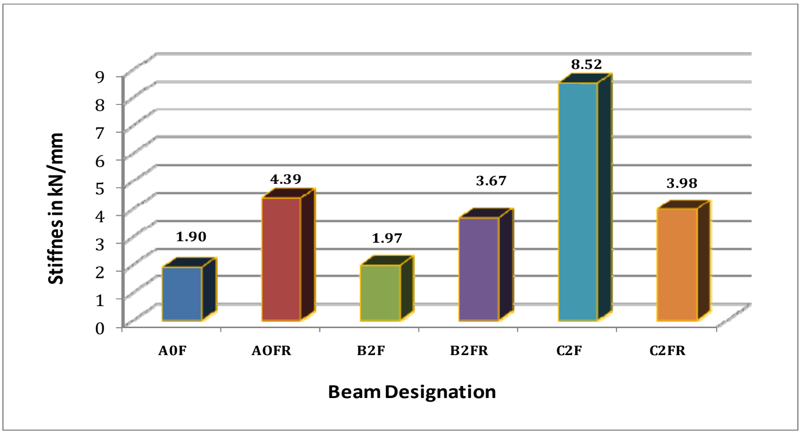


Figure 13 Stiffness value of all the tested beams (see online version for colours)



4.4.4.5 Stiffness characteristics

The stiffness is defined as the ratio of ultimate load to its corresponding maximum deformation. Stiffness characteristics of the tested beams are presented in Figure 13. As shown in Table 6, inclusion of different types of fibres (hybrid fibres) in concrete beam increases the load carrying capacity with lower deformation. As a result, a stiffness characteristic is improved in HFRC beams substantially than control beam. Incorporating of hybrid fibres in concrete beams increases the beam stiffness; while bonding of GFRP laminates in the concrete and HFRC beam, further increases the stiffness followed by improvement in flexural strength.

5 Analytical investigation – validation of experimental test results

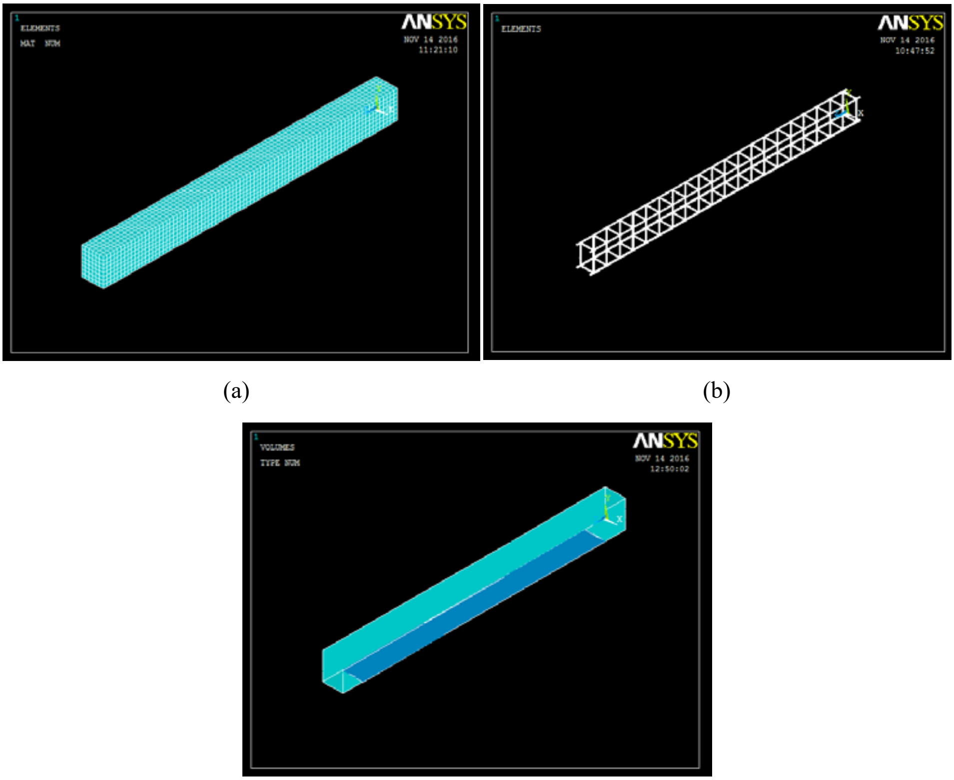
The FEA was conducted in this study, to simulate the flexural behaviour of the experimentally tested beams. Finite element (FE) modelling process is carried out using well known commercially available FEA software, ANSYS. Here the actual modelling is created in FE software by Discretisation approach. An eight-node solid element, Solid65, was used to model the concrete. A Link8 element was used to model the steel reinforcement. A layered solid element, Solid46, was used to model the FRP composites. FEA using nonlinear FE models of cracked concrete, steel bars and GFRP is used to predict the behaviour of FRP retrofitted beam. Figures 14(a), 14(b) and 14(c) show the ANSYS modelling for concrete, steel and GFRP respectively. The two point static load is applied to the beam model with increasing order up to the ultimate load to obtain the ultimate strain value of the concrete as shown in Figure 15.

The load-deflection curve is considered the key feature in studying the beam behaviour as it involves response parameters such as beam ultimate loads and its corresponding maximum deflection. Therefore, correlating the load-deflection relationships of the analytical results with that of the experimental results is considered an effective method to verify the FE model.

Table 9 Comparison of experimental test results with FEA results

S. no.	*Beam ID*	*Experimental results*		*FEA results*		*Percentage difference in ultimate load*	*FEA results/ experimental results*	
		Ultimate load Pu(E) in kN	*Ultimate deflection Du(E) in mm*	*Ultimate load Pu(A) in kN*	*Ultimate deflection Du(A) in mm*		*Pu(A)/ Pu(E)*	*Du(A)/ Du(E)*
1	A0F	34.4	18.1	31.5	16.8	8.43	0.92	0.93
2	B2F	50.5	11.5	45.8	12.4	9.31	0.91	1.08
3	C2F	42.1	21.4	45.3	22.5	7.60	1.08	1.05
4	A0FR	83	22.6	79.6	20.5	4.10	0.96	0.91
5	B2FR	120.2	14.1	126.4	12.6	5.16	1.05	0.89
6	C2FR	102	25.6	105.2	28	3.14	1.03	1.09
Mean							0.99	0.99
Standard deviation							0.05	0.08
Coefficient of variation							5.31%	8.53%

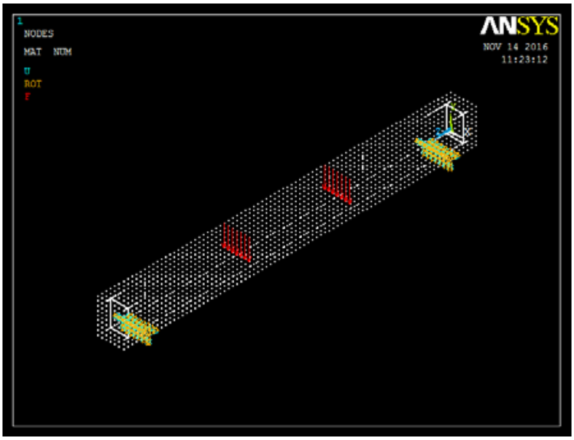
Figure 14 (a)–(c) ANSYS modelling for concrete, steel and GFRP (see online version for colours)



(a) (b)

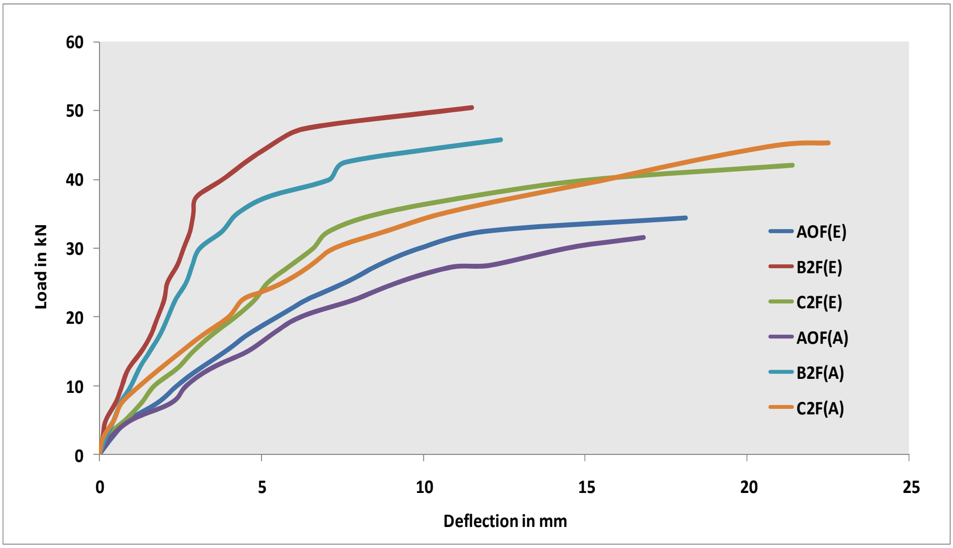
(c)

Figure 15 Static load applied on the beam model (see online version for colours)

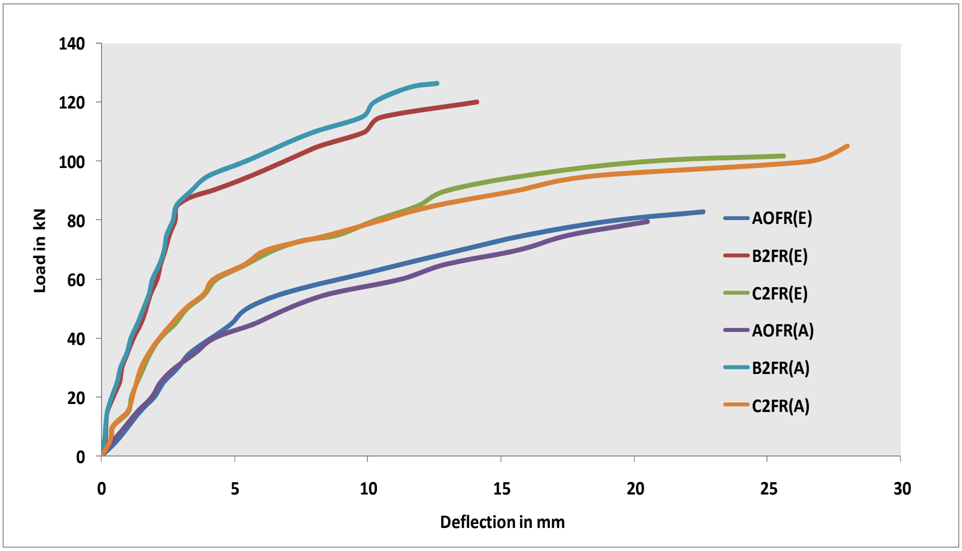


The ultimate loads and mid span deflections predicted by FEA were compared with the experimental results as shown in Table 9 and it was found that a good correlation was obtained between the experimental results and the results obtained from ANSYS. It can be seen that the FE model predicts the behaviour of beams well with good accuracy.

Figure 16 (a)–(b) Load-deflection curve for unretrofitted and retrofitted concrete beams (see online version for colours)



(a)



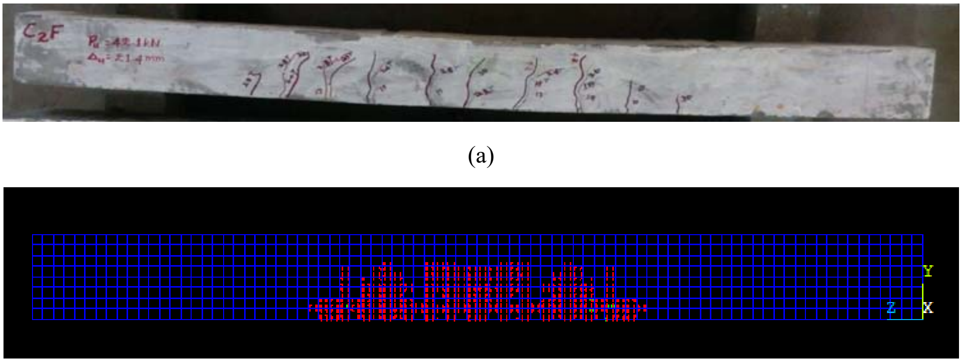
(b)

From Table 9, very good conformity was found in maximum load carrying capacity. Variation of results, for analytical and experimental values, ranged between 3.14% to 9.31%. Similar verdict was recorded by Hashemi et al. (2007). From the same table, it was also found that the average value of ratio of analytical ultimate loads and the experimental ultimate loads is 0.99. The standard deviation observed is 0.05 and coefficient of variation is 5.31%. Similarly, the experimental deflections are compared with the theoretical values obtained for corresponding loads. The average value of ratio of theoretical deflection and the experimental deflection is 0.99 with a standard deviation of 0.08 and coefficient of variation of 8.53%. The coefficient of variation obtained between experimental and analytical for ultimate load and its corresponding deflection exhibits minimum variation.

The load-deflection response recorded by the FE model was compared to the experimental results where good concurrence has been achieved. A comparison between the load-deflection curves obtained from FEA and experiment for the unretrofitted and retrofitted beams are shown in Figures 16(a) and 16(b). From the figure, it is clear that, the extensive behaviour of the FE models represented by the load-deflection curves show good agreement with the experimental beam test results. The slight variation in the load-deflection curves may be due to the two reasons. In the experimentally tested beams micro cracks may be there that could be produced by drying shrinkage in the concrete whereas the FE model does not comprise the effect of micro cracks. The second reason is that, in the FEA ideal bonding is assumed between the concrete and the steel reinforcement, but the equivalent hypothesis would not be true for the experimentally tested beam.

For all the experimentally tested beams, cracks were initially observed in the tension zone. Under rising load, cracks propagated in a vertical direction and additional new cracks appeared through the shear span as shown in Figure 10. Similar findings were recorded by Adam et al. (2015). The crack pattern was predicted well using FE software ANSYS and found to be very close to the crack pattern obtained in all the experimental investigations. Considering the beam sample, C2F (hybrid glass-polypropylene FRC beam) the crack pattern at failure obtained from both analytical and experimental work exhibits similarity as shown in Figure 17.

Figure 17 (a) Experimental observed crack patterns for beams specimen C2F (b) FEA predicted crack patterns for same beam specimen (lines indicate crack orientations and dots indicates crushing of concrete) (see online version for colours)



(a)

(b)

From the above analysis, it was verified that the FEA can predict the load carrying capacity, deformation and crack pattern similar to the experiment with minor variation.

6 Conclusions

The effect of addition of hybrid fibres in concrete on various strength characteristics was studied. The flexural behaviour of HFRC beams retrofitted with externally bonded GFRP laminates was experimentally investigated by incorporating optimum dosage of hybrid fibres. The following conclusions are drawn based on analysis of test results:

- The addition of hybrid fibres improved the mechanical properties of concrete. The compressive, split tensile and flexural strength of B2 (1% steel fibres and 0.30% polypropylene fibres) and C2 (0.03% glass fibres and 0.30% polypropylene fibres) mixes are found to be increased about 24.2%, 89.6% and 84.4% and 16.4%, 31% and 40% than the plain concrete (A0) respectively. From the test results, B2 and C2 mixes are identified as optimum and used for casting beam specimens.
- Increase in hybrid fibres content improved the bonding between concrete and the fibres. It also increased the impact strength and arrests the initiation and propagation of cracks in concrete.
- Incorporating hybrid fibres in concrete arrests the micro cracks as well as macro cracks. Due to this phenomenon, the ultimate load carrying capacity increases in the HFRC beams. The flexural behaviour of hybrid steel- polypropylene fibre and hybrid glass-polypropylene FRC beams (B2F and C2F) showed an increase in ultimate load of about 47% and 22% respectively over the control beams (A0F). The HFRC beams exhibited wide spacing and lesser crack width with corresponding increase in compressive strength when compared to control beam.
- The HFRC beams exhibited wide spacing and lesser crack width with corresponding increase in compressive strength when compared to control beam.
- The retrofitted beam considerably increases the load carrying capacity than unretrofitted beams. The beams retrofitted with GFRP laminate in the soffit (A0FR, B2FR and C2FR) increases ultimate load by 141%, 138% and 142% than unretrofitted beams (A0F, B2F and C2F).
- The retrofitted HFRC beams (B2FR and C2FR) show an improvement in load carrying capacity by 45% and 23% than the same set of retrofitted control beams (A0FR). The reason is the strengthening effect of GFRP was attained effectively with hybrid fibres in concrete beams. It enhanced the performance and controlled the crack localisation and propagation in concrete.

- Because of the presence of hybrid fibres in the concrete beam, there is an increase in stiffness and ductility which has direct bearing with flexural strength, while bonding with GFRP further improves its characteristics.
- In all the cases of test results, hybrid steel-polypropylene FRC shows an enhanced performance than hybrid glass-polypropylene FRC. This increase is significant and it can be attributed due to high elastic modulus and tensile strength of steel fibres than glass fibres.
- The flexural behaviour of FE models represented by the load-deflection curves show good agreement with the experimental beam test results.
- The experimental test results analytically validated using FEA software package ANSYS showed that the similar crack pattern can be captured with minor variation.

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