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Structural behaviour of HFRC beams retrofitted for shear using GFRP laminates

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Abstract. This paper summarizes the experimental study of the shear behaviour of Hybrid Fibre Reinforced Concrete (HFRC) beams retrofitted by using externally bonded Glass Fibre Reinforced Polymer (GFRP) laminates. To attain the set-out objectives of the present investigation, steel fibre of 1% and polypropylene fibre of 0.30% was used for hybrid steel-polypropylene fibre reinforced concrete: whereas for hybrid glass-polypropylene fibre reinforced concrete, glass fibre by 0.03% and polypropylene fibre of 0.03% by volume of concrete was used. In this study, 9 numbers of beams were cast and tested into three groups (Group I, II & III). Each group containing 3 numbers of beams, out of which one serve as a control beam or a hybrid steel-polypropylene fibre reinforced concrete beam or a hybrid glass - polypropylene fibre reinforced concrete beam and the remaining two beams were preloaded until shear cracks appeared up to 75% of ultimate load and then preloaded beams (damaged beams) were retrofitted with GFRP laminates at shear zone in the form of strips, as one beam in vertical position and another beam in inclined position to restrict the shear cracks. Finally, the retrofitted beams were loaded until failure and test results were compared. The experimental tests have been conducted to investigate various parameters of structural performance, such as load carrying capacity, crack pattern and failure modes, load-deflection responses and ductility relations. The test results revealed that beams retrofitted using GFRP laminates considerably increased the load carrying capacity. In addition, it was found that beams retrofitted with inclined strip offers superior performance than vertical one. Comparing the test results, it was observed that hybrid steel-polypropylene fibre reinforced concrete beam retrofitted with GFRP laminates showed enhanced behaviour as compared to other tested beams.

Keywords: shear behavior; glass fibre reinforced polymer (GFRP) laminates; steel; glass and polypropylene fibres

1. Introduction

The term Fibre Reinforced Concrete (FRC) is defined by ACI Committee 544 as a concrete made of hydraulic cements containing fine and coarse aggregates and discontinuous discrete fibres. Wafa (1990) emphasized the use of fibres to be selected based on various factors such as fibre 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. Hybrid fibre is combinations of two or more types of fibres which improve the properties of concrete further. But it mainly depends on implementation of suitable fibre combination.It has been demonstrated as of late (Xu and Hannant 1992, Kakemi and Hannant 1995, Mobasher and Li 1996) that by utilizing the idea of hybridization with two different fibres incorporated into a common cement matrix, the hybrid composite can offer more attractive engineering properties because the presence of one fibre enables the most efficient utilization of the potential properties of the other fibre. Ganesan *et al*. (2014) found that the use of hybrid fibres in concrete arrests the micro cracks as well as macro cracks. Low modulus fibre arrests the micro cracks and control the formation of macro cracks, where as high modulus fibre control macro cracks. Hosny *et al*. (2006) demonstrated that, Fibre Reinforced Polymers (FRP) has been used to strengthen/retrofit the reinforced concrete (RC) structural elements that have been increasing in the last two decades. Research and design guidelines concluded that externally bonded FRP could increase the capacity of RC elements efficiently. The advantages of FRP include their high strength and stiffness, light weight, and good resistance to fatigue and corrosion. The adhesives are used to bond the FRP composites to the surface of the concrete structure.

2. Related research work

It is realized that concrete is relatively a brittle material. Bentur *et al.* (1990) explained that the reinforcement of concrete with randomly distributed short fibres improves the toughness of cementitious matrices by preventing or controlling the initiation, propagation, or coalescence of cracks. Yaoa *et al*. (2003) examined and found that among the three types of fibres (carbon, steel and polypropylene), carbon fibre have the highest compressive strength,

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Table 1 Properties of fibres

Fibre type	Steel	Glass	Polypropylene
Length (mm)	48	6	12
Diameter (mm)	0.75	0.014	0.05
Density (Kg/mm^3)	7680	2680	980
Modulus of elasticity (GPa)	200	72	3.5
Tensile Strength (Mpa)	1100	1700	400

Table 2 Properties of GFRP laminates and epoxy adhesive

Materials	Property	Values
GFRP laminate	Sheet form	Uni-directional roving
	Glass content %	60-90
	Specific gravity	1.7-2.2
	Tensile strength, MN/m^2	530–1730
	Tensile modulus, GN/m^2	28-62
	Compressive strength, MN/m^2	310-480
	Flexural strength, MN/m^2	600-1800
Epoxy adhesive	Viscosity at 25°C, Mpa s	500-650
	Density at 20°C, g/cm^2	1.15
	Flash point, °C	>120
	Epoxy Index, eq/Kg	5.20-5.50

polypropylene fibre have 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. Sharmila *et al.* (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 fibre, the mixture of different types of fibres increases the load carrying capacity, energy absorption capacity, stiffness and ductility characteristics substantially.

Ayman *et al.* (2007) conducted various theoretical investigations to predict the shear capacity of reinforced concrete beams strengthened externally with FRP wet lay-up laminates or procured strips. Sobuz *et al.* (2012) demonstrated that the externally bonded carbon fibre reinforced polymer (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. Obaidat *et al.* (2011) presented the experimental results on the shear behaviour of structurally damaged full-scale reinforced concrete beams retrofitted with CFRP laminates. The main variables considered were the internal reinforcement ratio, position of retrofitting and the length of CFRP. The experimental results, generally, indicate that beams retrofitted in shear by using CFRP laminates are structurally efficient and are restored to stiffness and strength values nearly equal to or greater than those of the control beams. Tersawy (2013) carried out investigation on RC beams of three different sets, as-built beams (unstrengthened), beams strengthened with vertical carbon fibre-reinforced polymer (CFRP) wraps and beams strengthened with inclined CFRP wraps. The results of the experimental work indicated that externally inclined bonded CFRP wraps enhanced the shear strength of beams significantly. Belarbi *et al.* (2012) realized that only few experimental work has been carried out on RC beams to strengthen/retrofit using GFRP laminates. In this investigation Glass Fibre Reinforced Polymer (GFRP) is used. Because it is more ductile and cheaper than other FRP, it is considered to be an alternative solution to retrofitthe concrete elements. The epoxy adhesives are used for bonding the GFRP laminates to the surface of the beam.

In this exploration, hybridization of fibre is done using two fibres having a high and low modulus of elasticity respectively. Steel fibre and glass fibre have high modulus of elasticity; whereas polypropylene fibre has a low modulus of elasticity. Steel fibres are used to improve the tensile strength that restricts the widening of macro cracks and thus increasing the energy absorption capacity. Moreover the glass fibre is used to increase the energy absorption capacity and to eliminate the problem of early age plastic shrinkage cracks and polypropylene fibre, in addition it is used to control cracks and to get better impact resistance of the concrete.

Incorporating fibres into the concrete increases the cost up to 5% when compared to conventional concrete. This increase in cost is not a big deal as it is vividly noted that the use of fibres into the concrete results in overall increase in its performance characteristics.Several studies have been conducted to examine the flexural strengthening of RC members with externally bonded FRP, studies on shear strengthening have been limited. The aim of this study is to assess and analyze the shear behaviour of control and HFRC beams after retrofitting with externally bonded Glass FRP laminatesas a form of strips in vertical and inclined position under static loading condition.

3. Experimental investigation

3.1 Material properties

Ordinary Portland cement of 53 grades with specific gravity 3.12 was used for preparation of test specimens, which satisfies the requirements 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 and conforming to grading zone III 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

Table 3 Details of test specimen

Group	Beam reference	Designation	Damage degree (%)
	A_OS	Control Beam	--
I	A_OSR (V)	Preloaded control beam retrofitted with GFRP laminates as vertical strip in shear zone	75%
	A_OSR (I)	Preloaded control beam retrofitted with GFRP laminates as inclined strip in shear zone	75%
	B_2S	Hybrid steel-polypropylene Fibre Reinforced Concrete beam	--
II	B_2SR (V)	Preloaded beam retrofitted with GFRP laminates as vertical strip in shear zone	75%
	B_2SR (I)	Preloaded beam retrofitted with GFRP laminates as inclined strip in shear zone	75%
	C_2S	Hybrid glass-polypropylene Fibre Reinforced Concrete beam	--
II	C_2SR (V)	Preloaded beam retrofitted with GFRP laminates as vertical strip in shear zone	75%
	C_2SR (I)	Preloaded beam retrofitted with GFRP laminates as inclined strip in shear zone	75%

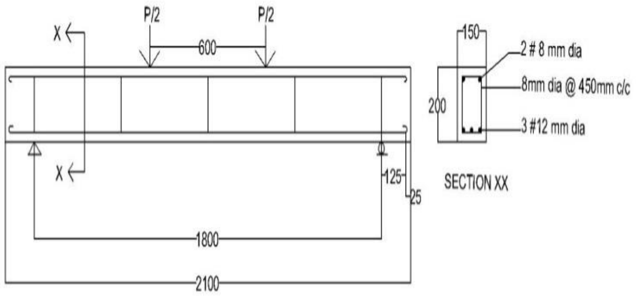

Fig. 1 Beam reinforcement details (Unit: millimeter)

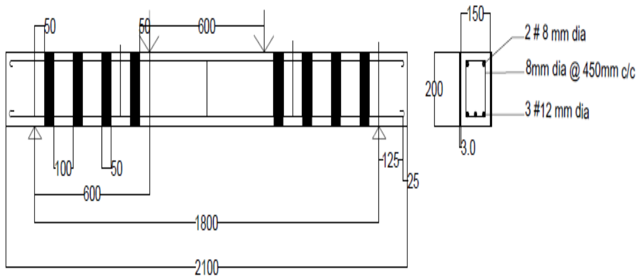

Fig. 2 Preloaded beams retrofitted with GFRP laminates as vertical strip (Unit: millimeter)

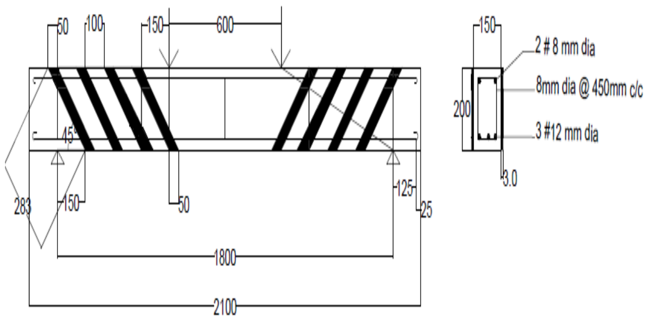

Fig. 3 Preloaded beams retrofitted with GFRP laminates as inclined strip (Unit: millimeter)

high-performance super-plasticizer was used in concrete. A dosage range of 500-1500 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 and their properties are shown in Table 1. 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 layers. The properties of the GFR Plaminates and epoxy adhesive as supplied by the manufacturer are shown in Table 2. The longitudinal reinforcement consisting of high yield strength deformed bars of 12 mm and 10 mm diameters have a yield strength of 420 and 412 Mpa respectively. The shear reinforcement consisting of mild steel bars of 8 mm diameter have a yield strength of 250 MPa.

3.2 Test program

Concrete mix proportion was calculated as per the design guidelines of IS 10262:2009. Concrete with the cube compressive strength of 25 MPa and water cement ratio of 0.45 was used.

Totally 9 numbers of RC beams were used for this investigation. The beams were divided into three groups. Each group consists of 3 numbers of beams. The details of test specimens are given in Table 3. The typical geometry and reinforcement of the beams are shown in Fig. 1.

The beams were designed to have insufficient shear strength to obtain a pure shear failure; strong in flexure. The beams were employed for shear retrofitting. Zhang and Hsu (2005) reported that FRP strips and fabrics of different configurations, exhibit various contributions in shear strengthening of RC beams. Compared with the control beam, 45^o and 90^o strip orientation in shear zone increase about 80% and 60% in shear capacity, which is the most efficient system among the other strengthening configuration. The paper finally summarizes that the use of FRP-strengthened beams not only increase in shear strength, but also increase in ductility. Jaber *et al.* (2007) experimentally found that the failure of the beams with FRP bonding over the entire shear span was sudden with little warning over the different configurations of FRP systems for shear strengthening. Thus, in the present study, for shear retrofitting, GFRP laminates are bonded in the form of vertical (90^o orientation) and inclined (45^o orientation) strips to arrest the propagation of cracks in the shear zone

Fig. 4 Surface preparation

Fig. 5 Epoxy coating

Fig. 6 Bonding of GFRP

Fig. 7 The arrangement of test set

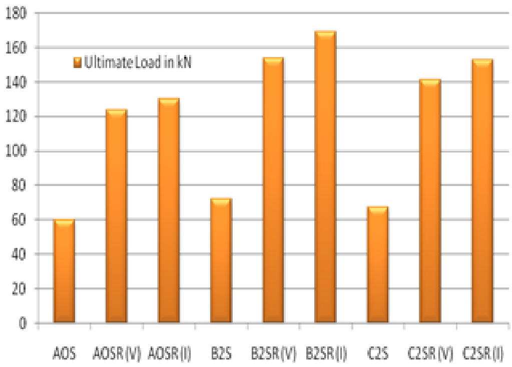

Fig. 8 Ultimate load values

Table 4 Load and deflection values

Test beam ID	Yield load (kN)	Ultimate load (kN)	Yield deflection (mm)	Ultimate deflection (mm)
A_OS	45.5	60.1	6.7	12.1
A_OSR (V)	90.6	124.1	7.5	17.5
A_OSR (I)	94.4	130.3	7.4	18.4
B_2S	54.7	72.3	2.8	9.0
B_2SR (V)	110.6	154	3.0	12.9
B_2SR (I)	119	169	3.1	13.5
C_2S	50.4	67.5	5.9	15.5
C_2SR (V)	102.3	141.2	5.9	21.9
C_2SR (I)	109	153	6	23

on the both side faces of the beam. The design and wrapping schemes for shear retrofitting of beams using externally bonded FRP systems is based on ACI 440.2R-08 (2008). Details of the preloaded beamsretrofitted with GFRP laminates in shear zone as strips in vertical and inclined position is shown in Figs. 2 and 3 respectively.

3.3 Retrofitting of test specimens

The preloaded beams were bonded with GFRP laminates after the concrete reached an age of 28 days. Before bonding the laminates on the beam, the concrete surfaces are cleaned and prepared using a mechanical grinder. Fig. 4 shows the surface preparation of test specimen. In order to prepare adhesives, the epoxy resins and hardener are mixed until proper integration is obtained.

Then the adhesives are coated on the surface of GFRP laminates and preloaded RC beams. Finally GFRP laminates are attached to the preloaded RC beams as strips in the shear zone. The epoxy coating and bonding of GFRP laminates to the test specimen is shown in Figs. 5 and 6 respectively. The retrofitting beams are allowed to dry for a minimum period of 7 days. Once the drying process is completed, the preloaded beams retrofitted with GRFP laminates are equipped for testing until the failure occurs.

3.4 Test set up and loading procedure

All the beams were tested under four point bending in a loading frame of 1000 kN capacity. The loads were applied through 100 kN capacity hydraulic jack at a regular interval. The beam supports consisting of a pin support and a roller support at the two ends. The specimen overall length is 2100 mm with a span length of 1800 mm and the load was applied at points dividing the length into three equal parts. Deflectometers were fixed at the mid span and below the loading points to measure the deflection using dial gauges of 0.01 mm accuracy. Mechanical strain gauges were used

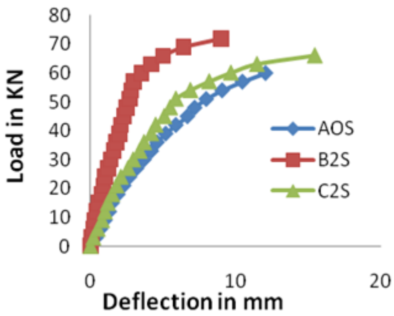

Fig. 9 Load-deflection curve for shear beam

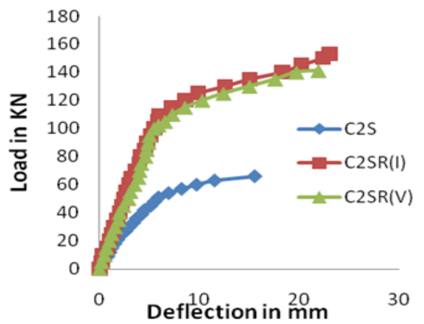

Fig. 12 Load-deflection curve for group III

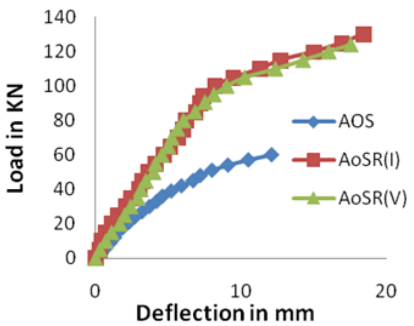

Fig. 10 Load-deflection curve for group I

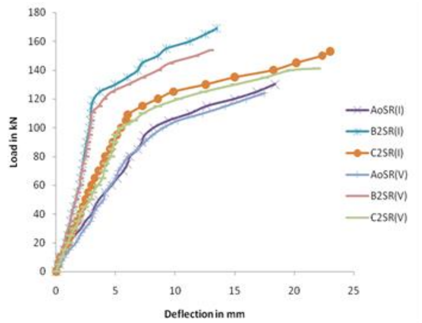

Fig. 13 load-deflection curve for beams with different GFRP arrangements

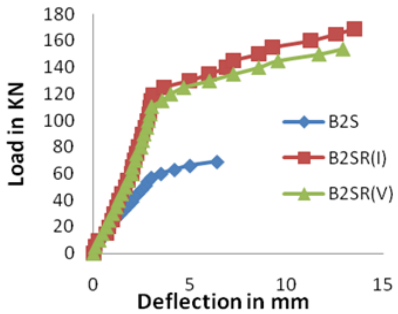

Fig. 11 Load-deflection curve for group II

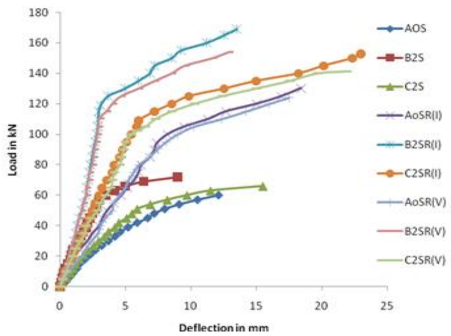

Fig. 14 Load-mid pan deflection curve for all the tested beams

to measure strain readings. Crack detection microscopes with 0.02 mm precision were used to measure the crack widths of the beam.

The test specimens were tested up to the ultimate load and the deflection is noted. The arrangement of test set up is shown in Fig. 7. The preloaded beams are also tested by this loading frame. The load necessary to attain the fixed damage degree, has been applied. Then the GFRP laminate has been bonded on the shear zone of the preloaded beam and the load has been applied up to failure.

4. Results and discussion

4.1 Load carrying capacity

The yield load, ultimate load and its corresponding deflection values for all the tested beams are shown in Table 4. Fig. 8 shows the experimental results of controlled, 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, the ultimate load carrying capacity increases in the hybrid fibre reinforced concrete beams.

From the Fig. 8, it is clear that the ultimate load increases about 21% in B_2S and 12% in C_2S than control beam (A_0S). The B_2S shows an improvement by 20% when compared with C_2S with the ultimate load carrying capacity. The increase is significant and it may be due to high tensile strength of steel fibre than glass fibre. The experimental result exhibits that, the hybrid steel-polypropylene, hybrid glass-polypropylene fibre incorporated beam retrofitted with GFRP laminates as strips in vertical and inclined direction increases about 24%, 14% and 30%, 17% respectively in ultimate load over the retrofitted control beam. It is observed from Table 4, that A_0SR (I), B_2SR (I), C_2SR (I) experience slight increase in the ultimate load carrying capacity by 4.2%, 7.6%, 8.4% than A_0SR (V), B_2SR (V), C_2SR (V).

Fig. 15 Crack pattern & failure modes of tested beam

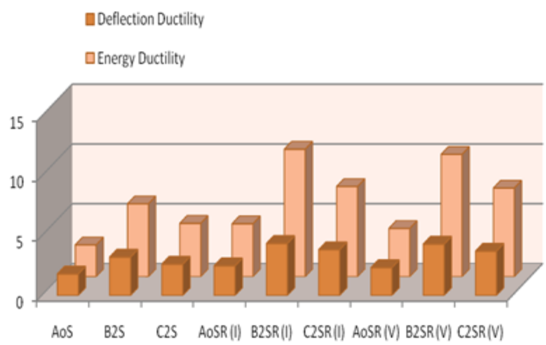

Fig. 16 Ductility comparisons of all the tested beams

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 Fig. 14. Fig. 9 shows the load-deflection response of shear beams. From the graph, it is clear that HFRC beams achieved a substantial gain in load carrying capacity than control beam. From Table 4, it is clear that the hybrid steel-polypropylene fibre reinforced concrete beam carries higher load carrying capacity with lower deformation as compared to hybrid glass-polypropylene fibre reinforced concrete beam. Figs. 10, 11 and 12 shows the load-deflection curve for Group I, II & III beams. It is observed from Figs. 10, 11 and 12, that initially all the retrofitted beams perform like the control beam with the internal steel reinforcing bars carries the majority of the shear force in the beam. When the internal steel yields, the additional shear force is carried by the GFRP laminate and an increase of the load carrying capacity is obtained Sobuz *et al.* (2012). The load-deflection curve for beams with different GFRP arrangements is given in Fig. 13. From the figure it illustrates that, compared to the hybrid fibre incorporated beams retrofitted with GFRP laminate as strips in an inclined direction shows better performance than beams retrofitted in vertical direction.

4.3 Crack pattern and failure modes

The crack patterns at collapse for the tested beams are shown in Fig. 15. According to design, the control beam fails in shear. Retrofitted beams failed in shear ultimately, but the crack usually initiates in the vertical direction as flexural crack located in the tension zone and as the load increases, it extends into inclined direction in the shear zone due to the effect of shear.

HFRC beams exhibited widely spaced and lesser number of cracks due to effect of fibres as compared to control beam. The GFRP strips arrest the propagation of cracks in the shear zone. As a result, retrofitted beams shows cracks at relatively closer spacing than non-retrofitted beams. This shows the enhanced concrete confinement due to the GFRP laminates. The non-retrofitted beams are failed due to concrete crushing, while in retrofitted beams delamination has taken place due to shear cracks by giving cracking sound.

4.4 Ductility relations

Ductility is the capability of the material or structural component to undergo maximum deformation without significant 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. Ductility comparisons of all the tested beams are presented in Fig. 16.

The experimental results exhibit that inclusion of hybrid fibres in reinforced concrete beams significantly increases the ductility when compared to control beam. Because of the existence of the GFRP strips, the shear capacity is increased followed by an increase in the ductility when compared to non-retrofitted beams. Inclined strips arrest the propagation of cracks due to diagonal tension. Due to this, the ductility increases further in a better way than vertical strips.

5. Conclusions

From the present experimental work, the following conclusions can be drawn:

1) Based on the test results, it is evident that the HFRC beams reached higher level in ultimate load than control beam. The ultimate load increases about 21% in B_2S and 12% in C_2S than A_0S.

2) The hybrid steel-polypropylene fibre reinforced concrete beam carries higher load carrying capacity with lower deformation as compared to hybrid glass-polypropylene fibre reinforced concrete beam. B_2S shows an improvement by 20% when compared with C_2S with the ultimate load carrying capacity.

3) The experimental result exhibits that, HFRC beams retrofitted with GFRP laminates achieved a substantial gain in load carrying capacity than retrofitted control beams. B_2SR (V), C_2SR (V) and B_2SR (I), C_2SR (I) increases about

24%, 14% and 30%, 17% in ultimate load over the A_0SR (V) and A_0SR (I).

4) The beams retrofitted with GFRP laminate as strips in an inclined direction shows better performance than beams retrofitted in vertical direction. A_0SR (I), B_2S (I), C_2SR (I) experience slight increase in the ultimate load carrying capacity by 4.2%, 7.6%, 8.4% than A_0SR (V), B_2SR (V), C_2SR (V).

5) As compared to control beam, the HFRC beams exhibited widely spaced and lesser number of cracks. Due to enhanced concrete confinement of GFRP laminates, the beams show cracks at relatively closer spacing than non-retrofitted beams.

6) The non-retrofitted beams are failed due to concrete crushing, while in retrofitted beams delamination has taken place.

7) Because of the existence of the GFRP strips, the shear capacity is increased followed by an increase in the ductility when compared to non-retrofitted beams.

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