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GREEN RETROFITTING OF REINFORCED CONCRETE BEAMS EMPLOYING SUSTAINABLE NATURAL SISAL FIBRE COMPOSITES AS ALTERNATIVE TO ARTIFICIAL FIBRE COMPOSITES FOR ENHANCED SHEAR STRENGTH

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Abstract

Sustainability and renewability in constructional materials and also utilization of such materials for various engineering purpose is the need of the hour. Green retrofitting with the aid of green fibre reinforced polymer (FRP) materials, made up of natural bio fibres like sisal would contribute to sustainable development. Non fossil-fuel carbon precursor organic fibres, i.e. sisal FRP composites were used for retrofitting of reinforced concrete (RC) beams, designed to undergo shear failure. Study in this field aimed at understanding the effect of natural sisal FRP retrofitting scheme over carbon FRP and glass FRP retrofitting schemes. Two wrapping configurations i.e. full wrapping and strip wrapping technique both in U-shaped wrap configurations, were used here for evaluating the shear strengthening effect. The effectiveness of the retrofitting scheme using natural sisal FRP was compared to that of carbon FRP and glass FRP in terms of ultimate shear strengths, load-deflection behavioural curves and obtained failure modes of the tested reinforced concrete beams. Failure mode study of retrofitted RC beams displayed promising performance by sisal FRP similar to that of carbon FRP and glass FRP. Also sisal FRP promoted ductile failure of beams with sufficient warnings and huge deflections unlike carbon FRP, which underwent sudden FRP rupture and Glass FRP, which underwent sudden debonding. Test results of this research indicate that lower embodied energy, renewable, sustainable, environment friendly and green materials like natural sisal fibre FRP, can be effectively utilized for reinforced concrete strengthening in contrast to other artificial FRP products such as carbon FRP or glass FRP.

Key words: FRP, retrofitting, shear strength, strengthening, sustainability

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1. Introduction

Strengthening restores the original structures and strengthens it with adequate load bearing capacity, enabling the structure to undergo an improvement in the load carrying capacity before the structure can undergo any type of failure, thereby increasing the service life and performance of the structure. Strengthening a structure i.e. any building component prior to its failure is called retrofitting. The need for seismic retrofitting particularly arises due to the following reasons, when buildings are not designed in accordance to the seismic codes of a particular country, when there has been a subsequent updating in the seismic building design codes and also in the codes of practice, subsequent updating of one area into a higher seismic zone, deterioration in the building strength and aging, requirement of modifications in the existing structure, a change in the building use, requirement for facilitating extra floors and levels i.e. enhancement in the floor levels in the building, requirement for facilitating higher super-imposed load

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carrying capacities in terms of live-load, dead load etc and when the building is severely deficient in carrying the large amount of design seismic forces or wind forces etc. and finally for the incorporation of lateral seismic forces and capacities to bear them without undergoing collapse (Handbook on Seismic Retrofit of Buildings, 2007).

Fibre reinforced polymer (FRP) have been successfully utilized for the retrofitting and strengthening of various structural components (Ceroni, 2010; Chalioris, 2007; Dong et al., 2013; Karayannis and Sirkelis, 2008; Lau and Zhou, 2001; Monteiro et al., 2018; Sheikh, 2002), and are vigorously used worldwide by the construction or infrastructural companies. Specially past research based on carbon fibre reinforced polymer composite (CFRP) retrofitting techniques of various structural elements carried out by various researchers(Al-Amery and Al-Mahaidi, 2006; Barros et al., 2007; Chalioris, 2008; Deifalla and Ghobarah, 2010; Esfahani et al., 2007; Gholami et al., 2013; Hashemi and Al-Mahaidi, 2012) have rendered the carbon fibre composite as one of the most utilized retrofitting material, due to high strength enhancements and also enhancements in other structural properties. Research carried out by past researchers have also highlighted the potentials of glass FRPs for structural strengthening (Almusallam, 2006; Ciocan et al., 2014; Correia et al, 2007, 2011; Panda et al., 2013; Sundarraja and Rajamohan, 2009). The glass fibre reinforced polymer composite (GFRP) retrofitting methodologies have displayed good potential in terms of strength enhancements and hence these too are used on a large scale basis, for the purpose of structural retrofitting.

The branch of science and technology, based on sustainability or sustainable development has emerged, keeping the current environmental concerns in mind, this basically is aimed at the incorporation of scientific research, education, and technological advancements and their coexistence, so as to meet this per-view. Technological and scientific growth and development in addition to higher consumer demands due to population rise, continues to increase demands on global resources, which ultimately models down to major issues of material availability keeping in mind the concept of environmental sustainability. Certain attributes of natural fibres make them environmentally friendly and a sustainable option (Van Dam, 2009). Attributes such as biodegradability, sustainability, renewability, recyclability and carbon dioxide neutrality also health friendly and good economic viability are some of the most influencing parameters contributing to their environmental friendly characteristics (Andrian et. al., 2012; Ciuca et. al., 2017; Sahari and Sapuan, 2011; Shi et al., 2013;Singh et al., 2009; Vilaplana et al., 2010; Xu et al., 2008). Natural fibres have very low embodied energy (Meredith et al., 2012), i.e. sum total of the energy used at each step of the process needed to create a particular finished product. The carbon footprints as well as the embodied energy of natural fibres are very low as compared to artificial ones (Ansell, 2011). Synthetic fibres are non-bio-degradable, and when they are disposed of in landfills, they cause pollution by releasing heavy metals and other pollutants into the ground water as well as in the soil (Torgal et al., 2012; Torgal and Labrincha, 2013). Natural fibres and the plants from where they are extracted aids in capturing carbon. More and more growth and development of plantations in various areas also lead to massive rural employment, thus engaging many rural households from the planting of the tress, to the fibre extraction process, also to the fibre textile weaving and their subsequent manufacturing process. All these lead to rural engagements which also have several other associated societal advantages, thus boosting the rural economy.

Enormous research is being devoted to the utilization of bio-fibres as reinforcing components for thermoplastics and thermoset composites so as to reduce the environmental impact created by artificial fibre reinforced polymer composites in various engineering application fields (Begum and Islam, 2013; Fidelis et al., 2013; Jacob, 2005; Langford, 2011; Mantia and Morreale, 2011;Marsh, 2008; Satyanarayan et al., 2007; Saxena et al., 2011). Natural fibre composite utilization can aid us to generate a sustainable technology for reinforced polymer composite application in the construction industries which considers the concept of environmental sustainability in practices. Because of the enormous environmental advantages associated with the utilization of natural fibers, and also because of the immense potential that these bio-fibre based composites possess, they have been very recently, successfully incorporated in the structural retrofitting or strengthening of various important structural components for enhancement in both flexural as well as shear strengths(Sen and Reddy, 2013; 2014). Natural fibre utilization is also being carried in other important aspects of construction, so as to work in tandem with enhanced structural strength and environmental sustainability, so that sustainability in constructional field can be attained (Dhir et al., 2006; Fan et al., 2012; Glavind, 2009; Hota and Liang, 2011; Juárez et al., 2010; Madurwar et al., 2013; Pietrosemoli and Monroy, 2013; Puitel et al., 2013; Torgal, 2014). Out of all the natural fibres, sisal fibres have found wide spread applications in polymer composites, because of superior fibre as well as composite properties (Li et al., 2000; Milanese et al., 2011; Prasad and Mohana, 2011; Ramesh et al., 2013;Rong et al., 2001; Silva et al., 2008). For structural repairs materials such as carbon and glass fabrics are mostly utilized all over the world and these materials have higher embodied energy and also possess higher energy consumption for their manufacturing. Thus, a replacement in these materials with sustainable, renewable, plant based fibrous products having lower embodied energy, as suitable constructional materials will aid us in achieving environmental sustainability, lessen the environmental impacts, and will also promote sustainable and green constructional practices.

The main objective of the present study was to evaluate the shear strength enhancement in reinforced concrete (RC) beams retrofitted using natural sisal FRP composites and to compare its effectiveness with that of artificial FRP composites of carbon and glass FRPs. The main focus was to promote the green retrofitting methodology by developing an alternate structural strengthening material derived from sustainable resources i.e. from plant based origin, and processing into fibre reinforced polymer composite, and subsequently utilizing these natural fibre reinforced composites for structural retrofitting purpose.

The following specific objectives were defined and met with: to obtain the ultimate shear strength of the reinforced concrete beams, which have been pre-strengthened (i.e. retrofitted) with FRP made up of natural sisal fibre (in fabric form). The ultimate shear strength thus obtained is compared with the ultimate shear strength of reinforced concrete beams which have been pre-strengthened (i.e. retrofitted) with FRP made up of artificial carbon fibre (in fabric form), and also with that of reinforced concrete beams which have been pre-strengthened (i.e. retrofitted) with FRP made up of artificial glass fibre (in fabric form).

Various other parameters such as fracture modes of failure at the ultimate load stage of all these beams, and also the enhancement in the ultimate shear load efficacies of all these beams were evaluated and compared. In order to promote and develop green retrofitting practices, various well studied conclusions were drafted for providing suitable guidelines to practicing engineers.

2. Material and methods

The natural sisal fibres, which are basically extracted from the leaves of the sisal plant, was fabricated in fabric form in Extra Weave Private Ltd, Kerala, India. MBrace® FRP fibres, mainly of two different types, i.e. Carbon fibre having thickness of 200gsm and Glass fibre, having thickness of 900 gsm (all fibres in fabric forms) were collected from BASF, Mumbai, India. Also all other constituents used for FRP fabrication, such as MBrace saturant (Epoxy), concresive 2200 (repairing grout), and MBrace primer (for primer application purpose) were all, obtained from BASF. The MBrace saturant mainly consists of Part A Resin (epoxy), and Part B, hardener. Both part A, epoxy resin and part B, hardener was used as the matrix material together, in combination. MBrace® saturant is an epoxy resin which is used in conjunction with MBrace® FRP sheets. The BASF provided FRP fabrication and strengthening system, fabricated using the BASF fabrics (made up of carbon and glass fabrics, separately) results in the fabrication of a high performance system of composite structure, which can be suitably utilized for structural repair, pre or post strengthening of structures, structural up-gradation and also blast mitigation etc. The mixing up of the epoxy and the hardener in the designated manufacturer's ratio thereby produces the high performance composite system in conjunction with the fibres. The properties of carbon fibre, glass fibre, supplied by the manufacturer are summarized in Table 1. The mechanical treatment in the form of heat treatment was carried for the sisal fabric mats. These mats were placed into the oven at 80°C for 48 hours. It has been shown by studies conducted earlier that natural fabrics/fibres when subjected to thermal/heat treatment results in better mechanical properties over non-treated natural fibre used in making of FRP composites (Cristaldi et al., 2010; Jacob et al., 2009; Milanese et al., 2012), and hence heat/thermal treatment is considered as one of the most suitable treatment method for enhancing the mechanical properties of natural fabric or textile composites.

Basically two numbers of mechanical strength characterizations i.e. tensile strength test, and flexural strength test was carried out for all the three different types of FRP composites i.e., sisal, carbon and glass FRP composites. The tensile strength for FRP composites fabricated using natural fibres was done based upon the ISO 527-4:1997(E), since sisal fibre in fabric form falls under the category of Type –2 materials.The tensile strength test of the FRPs fabricated by using carbon and glass fibres respectively, was done based upon the ISO 527-5:1997(E), since both these artificial fibres are under the category of Type –A materials.

Table 1. Properties of carbon fibre, glass fibre and saturant

Mechanical property	***Carbon fibre***	***Glass fibre***	***Saturant***
Description	MBrace Carbon Fibre (CF 240)	MBrace Glass Fibre (EU 900)	2 parts; Part A – Epoxy and Part B-Hardener
Modulus of Elasticity	240 kN/mm^2	73 kN/mm^2	-
Tensile Strength	4900 N/mm^2	3400 N/mm^2	-
Weight of fibre	200g/m^2	350g/m^2	-
Density	1.7 g/cm^3	2.6g/cm^3	1.06 kg/Lt (Mixed density)
Thickness	0.117mm	0.067mm	-
Ultimate Strain %	1.55	4.5	-
Colour	Black	White	Blue
Bond strength	-	-	>2.5 N/mm2 (Failure in concrete)

After the tensile strength tests, the flexural strength of the textile composites were determined. The flexural test was conducted as per ISO 14125:1998 standard, using a load cell of high sensitivity. Sisal falls under the group of Class II Type material, and carbon falls under the group of Class IV and glass falls under the group of Class III, all the specimen dimensiosns for the individual FRP token tests for flexural testing was followed based upon ISO 14125:1998. Table 2 gives the values of the tensile strength and flexural strength of sisal FRP, carbon FRP and glass FRP.

Table 2. Properties of sisal FRP, carbon FRP and glass FRP

Mechanical property	*Sisal FRP*	*Carbon FRP*	*Glass FRP*
Tensile strength (N/mm^2)	223.367	923.056	678.571
Flexural Strength (N/mm^2)	350.034	1587.134	666.871

ACC manufactured Ordinary Portland Cement (OPC) belonging to grade of 53 was used for the casting of the reinforced concrete beams. The cement used was as per IS: 12269-1987. River sand, which was sieved and cleaned along with crushed (angular) coarse aggregates of 12mm size (maximum size), was used for the casting of the reinforced concrete beams. The mix proportion i.e. mix-design of concrete as per IS 10262- 2009, for a concrete design strength of $20N/mm^2$ was carried out. The mix proportion was found to be 1: 2.07:1.87 for cement, sand and coarse aggregates, for water cement ratio 0.5. The workability tests performed revealed a slump value of 75mm. Large numbers of concrete cubes were cast, which revealed the 7 days compressive strength as 6.322 N/mm^2, for 11 days it was 11.263 N/mm^2 and for 28 days it was 22.309 N/mm^2. Hot rolled deformed Fe 415 HYSD bars having 8mm diameter was used. These bars were tested for their tensile strength, which revealed a value of 415 N/mm^2. Fe 415 HYSD 8mm diameter bars were used as longitudinal reinforcement and stirrups.

All the set of beams used for the experimental purpose (i.e. to estimate their ultimate shear strength) were cast with the same reinforcement design so as to understand their respective FRP's contribution in enhancing the shear strength. The beams were cast in three batches. In accordance, the RC beam design was carried out as per IS-456:2000. Fig.1 represents the reinforcement details, which were followed for all the RC beams. The beams were designed such that shear failure in the beam took place before flexural failure. Hence beams were strengthened in flexure, for ensuing shear failure. Double flexural moment was considered in the design so that shear failure takes place before flexural failure. Considering double factored moment, 4 numbers of 8mm dia bars were provided at the central span of 1000mm in the tension zone of the beam, and curtailment of 2 bars were carried out at the support i.e. at the end span of 200mm. This ensured higher factor of safety from flexural failure. To ensure shear failure, normal factored shear force was considered in the design, and it resulted in 2 legged 8mm stirrup bars at 130mm C/C throughout the length of the beam. Hanging bars of 2 numbers of 8mm dia bars were provided in the compression zone in the beam. Indian standard consideration restricts the maximum percentage of reinforcement in RC beams to 2.5%, and here the longitudinal reinforcement ratio i.e. considering both tensile and compressive reinforcements, it was ensured that all the RC beams remain under-reinforced.

A summary of the test beams has been shown in Table 3. The beams were prepared by grinding 3 side surfaces with the help of a grinding machine, this was done so as to roughen the beam surfaces. Then, the beams were cleaned and finally wiped to remove any dust or loose particles. Small surface defects in concrete were repaired using concresive 2200.Then a coat of MBrace Primer was applied on all the three sides of the beams in group B and C. The primer coat was allowed to air cure for 8 hours. Next, Resin Part A and Hardener Part B in ratio 3:1, of the two component MBrace saturant, were mechanically premixed until homogeneous. Then the neatly measured and cut pieces of MBrace® fibre reinforcements that is carbon fabric was applied on the beam models CS1,CS2,CS3,CS4 and MBrace® fibre reinforcements, that is glass was applied on the beam models GS1,GS2,GS3,GS4, lastly reinforcements of woven sisal fibre textile was applied on the beam models SS1,SS2,SS3,SS4.

Firstly the resin-hardener mix was prepared and the first coat of the resin-hardener mix was applied on all the beams. This was followed by placing of different natural fabrics or artificial fabrics in the chosen dimension on respective beam models. Then another coat of resin-hardener mix was applied on these fabrics with the help of roving mechanism through plastic laminating roller. It was ensured that no air bubbles are entrapped at the interpahse between the epoxy-concrete-fabric interfaces. Air curing was carried out for two-weeks before the experimentation of the retrofitted beams. The entire strengthening process of the wrapping of FRPs on the beams, have been demonstrated in Fig. 2.

3. Experimental

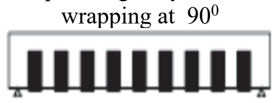
Two point loading system was adopted for the determination of ultimate shear strength of the RC beams. In this loading, the beam is loaded at every third span, this type of loading aids find ensuring pre bending in reinforced concrete beams, and generates zone of pure flexure at the mid span and zones of pure shear near the support ends. Each beam was placed on the loading frame in such a way that, the center of the beam and the center of the loading frame were aligned in a single line.

The effective span of the beam was 1300mm, and the two point loading was distributed by means of two mild steel rollers placed on the beam at the locations as shown in Fig. 4.

Above the two steel rollers, mild steel I-section was placed for the distribution of load equally on the two rollers. On top of the I section, additional mild steel I section was placed for building up of height in the loading frame.

On top of the second I section, the hydraulic jack was placed. Next the proving ring was placed on top of the hydraulic jack. Both the I-sections, hydraulic jack and also the proving ring were all tied to the frame individually using strong jute ropes. Dial gauges with least count of 0.001mm were placed at two locations, one was placed under the load and the other at the beam mid-span. Load increment was gradually carried out.

Table 3. Experimental beam summary

Test Beams	*Type of Wrapping used*	*Fabric used for making the FRP*	*Beam designation*
Group A	None 	None	ConS1,ConS2
Group B	U- shaped Single layer FRP full wrapping at 90^0 	Natural Sisal fabric	SS1,SS2
		Artificial Carbon fabric	CS1,CS2
		Artificial Glass fabric	GS1,GS2
Group C	U- shaped Single layer FRP strip wrapping at 90^0 	Natural Sisal fabric	SS3,SS4
		Artificial Carbon fabric	CS3,CS4
		Artificial Glass fabric	GS3,GS4

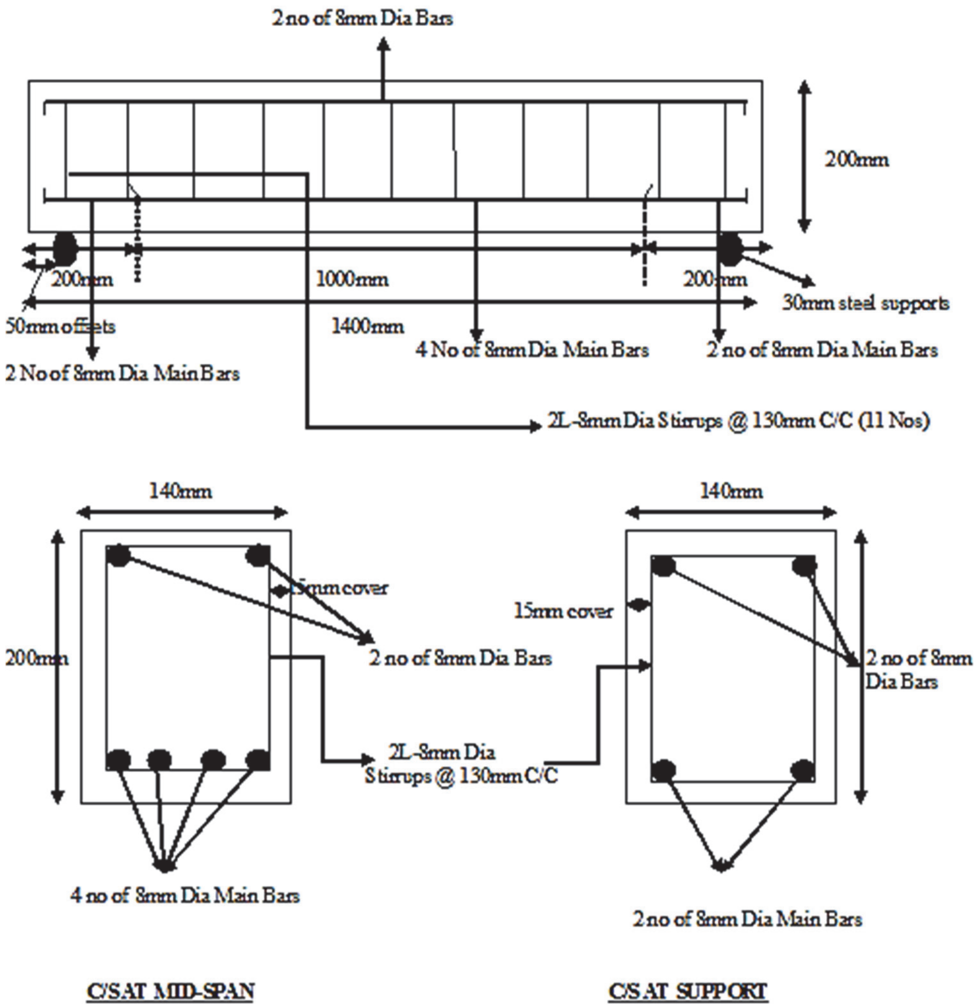


Fig. 1. Reinforcement detailing of group A, B and C beams, all designed to undergo shear failure

(a)

(b)

(c)

(d)

(e)

(f)

Fig. 2(a) Surface preparation of beams by grinding; **(b)** Primer application; **(c)** Application of epoxy hardener mix, **(d)** Bonding of woven glass fabric, **(e)** Bonding of woven carbon fabric; **(f)** Bonding of woven sisal fabric

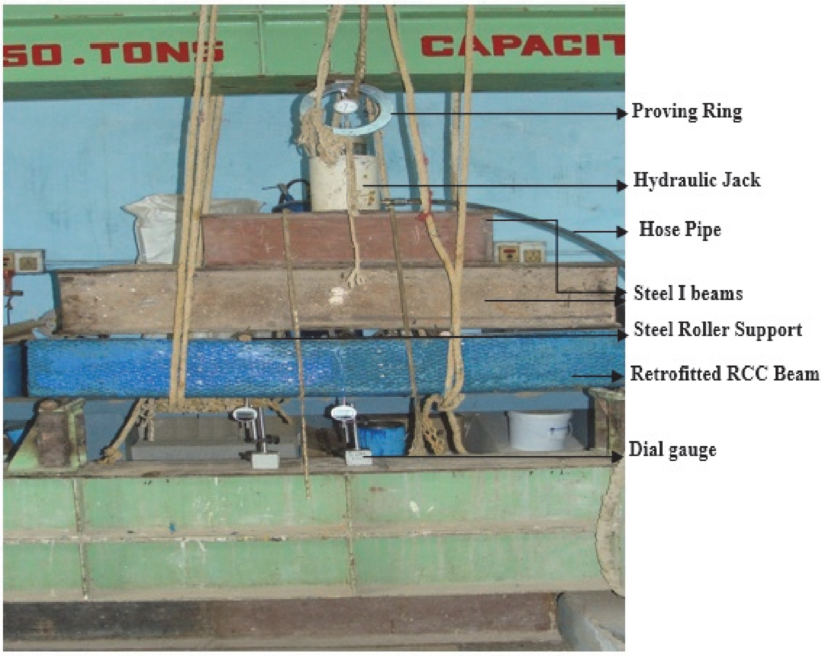


Fig. 3. Laboratory experimental beam-loading set-up

Load was applied with an increment of 5 kN gradually at a time. The gradual increase in load and the deformation readings in both the dial gauges were recorded throughout the test. The first crack loads, complete crack patterns, type of ruptures, and the ultimate failure loads, were all recorded in each test, for all the beams. The experimental set-up under the two point loading system or third point loading is as shown in the Fig. 3. At the end of each load increment, deflection, ultimate load, type of failure etc., were carefully observed and recorded.

4. Results and discussion

All the three sets of beams in group A, B and C were tested to find out their ultimate shear strength capacity so as to evaluate their ultimate shear strength. Different types of mode of failures were observed during the experiments of RC beams strengthened using natural sisal FRP, CFRP, and GFRP, which were subjected to high shear loads, aimed at making the beams undergo shear failure. The ultimate load carrying capacity, that is the ultimate shear strength of all the beams along with the nature of failure and deflections are given in Table 4. The fractured beam specimens belonging to various groups are as shown in Fig. 4.

It was observed that group A test beams, ConS1 and ConS2, underwent shear failure. Since in these beams no FRP wrapping was done as these are designated controlled beams, hence it can be concluded that indeed the beams were designed in such a manner such that shear failure prevailed prior to flexural failure. Hence the shear capacities of all these beams could be accessed. 45^0 inclined cracks were seen developing from near the support region, and undergoing extension in inclined 45^0 angles towards the point of load application. A large numbers of such shear cracks developed as the load increased. The average ultimate strength of these controlled beams 90 kN. The pattern of failure that both these controlled beams underwent was very similar and Figs. 5(a) and (b) shows the shear failure of these beams with large number of shear cracks.

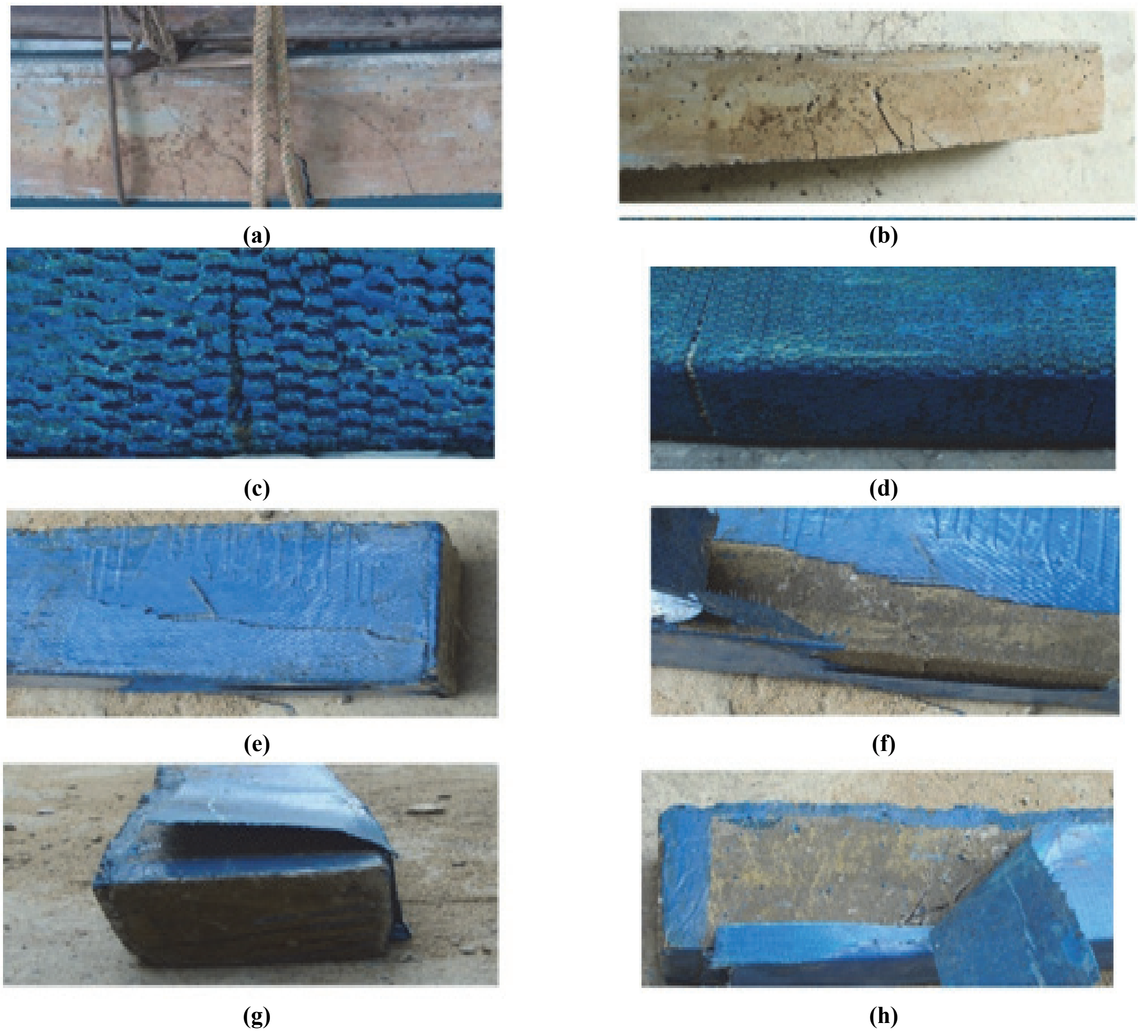


Fig. 4. (a) Shear failure of CS1 under the load, (b) Shear failure of CS2, (c) Tearing failure of SS1 at the shear zone, (d) Failure of SS1 in the shear zone, (e) CFRP rupture in shear zone of CS1, (f) Shear crack in shear zone of CS1, (g) Debonding of GFRP in GS1, (h) Shear cracks in shear zone of GS1

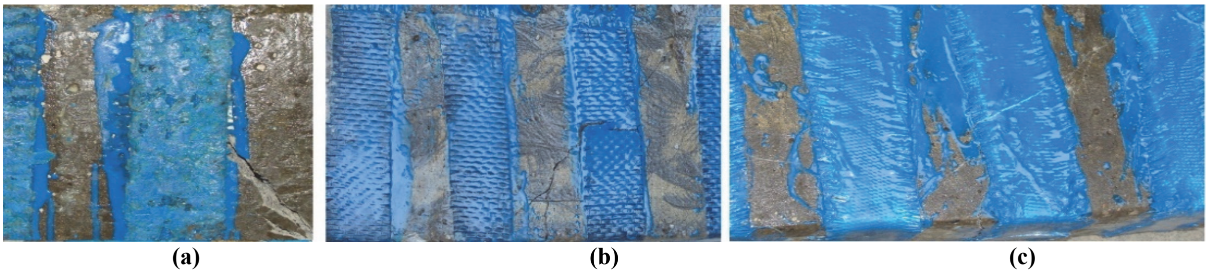


Fig. 5. (a) Shear crack in RC beam area in SS4, (b) Shear crack in CS3 cutting across CFRP, (c) Shear crack in GS3 cutting across GFRP

Table 4. Summary of all the experimental results

Group	*Beam Designation*	*Average deflection under the load at failure (mm)*	*Average deflection at midspan, at failure (mm)*	*Average first cracking load (kN)*	*First crack description*	*Average ultimate failure load (kN)*	*Increase of ultimate load capacity (%)*
Group A	ConS1 ConS2	7.457	8.643	55	At Beam	90	-
Group B	SS1 SS2	9.586	10.105	135	At FRP	160	77.8%
	CS1 CS2	9.664	9.772	150	At FRP	170	88.9%
	GS1 GS2	9.023	10.576	140	At FRP	165	83.4%
Group C	SS3 SS4	5.463	6.656	70	At Beam	120	33.4%
	CS3 CS4	8.036	8.782	80	At Beam and FRP	130	44.5%
	GS3 GS4	7.008	7.816	75	At Beam and FRP	120	33.4%

When load was applied on SS1 and SS2, then firstly the matrix started cracking, then on further increment of load, the sisal fibres in sisal FRP started to crack, then again on further load increment the cracks in sisal FRP started to widen, with absolutely no de-bonding of FRP at all from any sides of the beam, the vertical crack was in the sisal FRP alone, in the shear zone, that is near the support and then this crack started slowly moving from the bottom face of the beam to the top face. Both the failure modes depicted by SS1 and SS2 was very ductile in nature, with large deflections. Since, there was no de-bonding of sisal FRP, hence the cracks in the RC beam itself could not be visualized. The ultimate load carrying capacity was reached by further widening of the single crack, near both ends of the support region, without the generation of any other alternate cracks on the woven sisal FRP. Hence, in each beam, two numbers of cracks were observed at both the shear regions in beam. The average ultimate strength of group B beams SS1 and SS2 was 160 kN. Both the beams SS1 and SS2 failed in similar manner and Figs. 4(c) and (d) depicts the clear representation of the failure mode of these beams. SS1 and SS2 displayed an average shear strengthening effect of 77.8%.

When load was applied on CS1 and CS2, then firstly the rupture of carbon FRP was observed near the support, at the shear zone. Both the beams underwent failure at the shear zones, firstly the RC beam developed shear cracks, large number of inclined cracks, 45^0 inclined to the horizontal reference of the beams developed at the support region, extending at 45^0 angles towards the load i.e. towards the upper face of the beam. These shear cracks in the RC beam were visible after the debonding of carbon FRP from the beam face, near the support. At high loads, the rupture of carbon FRP was very sudden, and it was followed by debonding, also followed by the generation of large number of alternate inclined shear cracks of 45^0 at the support region, in the shear zone, this is how the ultimate load carrying capacity was reached. The failure modes depicted by both these beams CS1 and CS2 were very sudden and brittle in nature with no warning at all. Both the beams CS1 and CS2 failed in similar manner and Figs. 4(e) and (f) depicts the clear representation of the failure mode of these beams. The average ultimate strength of group B beams CS1 and CS2 was 170 kN. CS1 and CS2 displayed an average shear strengthening effect of 88.9%.

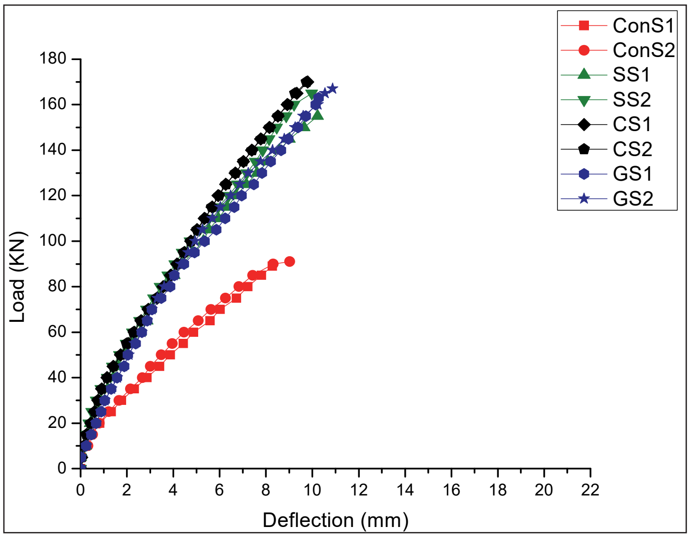
When load was applied on GS1 and GS2, then firstly the debonding of glass FRP was observed near the support. At high loads, the cracking of glass fibres within the glass FRP was observed followed by sudden debonding of glass FRP. The debonding started at the support region, and continued throughout the longitudinal direction i.e., throughout the entire length of the beam. The complete debonding of glass

FRP exposed the shear cracks in the RC beams, GS1 and GS2. This proved that the reinforced concrete beam underwent failure at the shear zone, and large number of inclined cracks, 45^0 inclined to the horizontal reference of the beams was observed for both GS1 and GS2, at the support region, extending at 45^0 angles towards the load i.e. towards the upper face of the beam. These shear cracks in the RC beam were visible after the debonding of glass FRP from the beam face, throughout the length of the beam. Then on further increment of load, these inclined cracks of 45^0, in the RC beam underwent further widening, also followed by the generation of large number of alternate inclined shear cracks of 45^0 at the support region, in the shear zone, this is how the ultimate load carrying capacity was reached. The failure modes depicted by both these beams GS1 and GS2 were very sudden and brittle in nature with no warning at all. Both the beams GS1 and GS2 failed in similar manner and Figs. 4(g) and (h) depicts the clear representation of the failure mode of these beams. The average ultimate strength of group B beams GS1 and GS2 was 165 kN. GS1 and GS2 displayed an average shear strengthening effect of 83.4%.

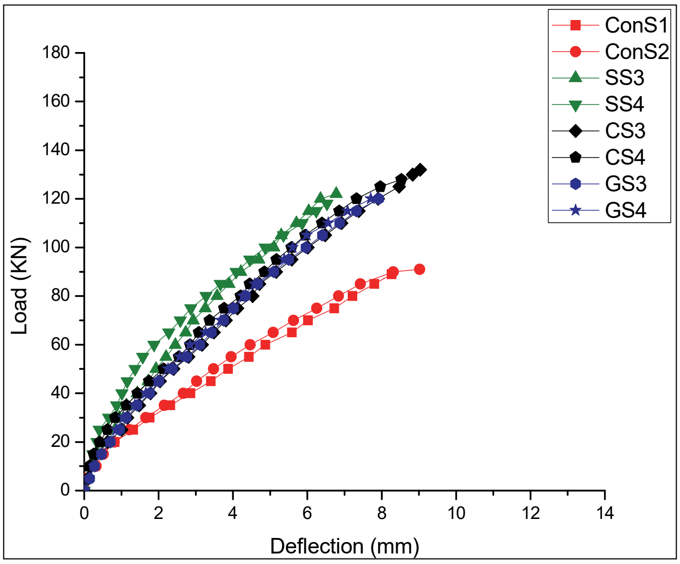
The third set of beams that is group C, in which the beams were strengthened by strip, U wrapped sisal FRP, SS3 and SS4, strip U wrapped carbon FRP, CS3 and CS4, and strip U wrapped glass FRP, GS3 and GS4, all beams were tested to find out their ultimate load carrying capacity. It was seen that all the beams SS3,SS4,CS3,CS4 and GS3,GS4, showed that their ultimate load carrying capacity was higher than that of Group A beams, but lower than that of group B beams. In all the beams of group C, it was observed that initially, cracks first developed in the RC beams only and not on the FRP at all, be it sisal FRP, carbon FRP or glass FRP. This indicated that the presence of bonded FRP on RC beams, be it even natural FRP like sisal, or artificial FRP like carbon and glass, imparted additional strength to the beams, and there by enhanced their ultimate shear load carrying capacity. When load was applied on SS3, SS4, CS3, CS4 and GS3, GS4, then large number of inclined shear cracks, 45^0 inclined to the horizontal reference of the beams developed in the RC beam area, and not even a single shear (45^0 inclined) crack developed in the natural sisal FRP, nor did the natural sisal FRP undergo rupture or any sort of debonding from the face of the beams. Fig. 5(a) presents the failure mode of the beam SS4. But similar behaviour was not observed for the RC beams CS3,CS4 and GS3,GS4, at higher loads, it was observed that for all the artificial FRP, strip wrapped beams, at higher loads, the shear cracks, i.e. 45^0 inclined cracks, crossed over from the RC beam area, to the artificial FRP area in 45^0 angular cracking, and reached the top surface of the beam, i.e., the artificial FRP like carbon FRP or glass FRP both underwent diagonal cracking throughout their width, without any rupture or debonding. Figs. 5(b) and (c) depicts the clear representation of the failure mode of the beams CS3 and GS3 respectively. The average ultimate strength of group B beams SS3 and SS4 was 120 kN. Even GS3 and GS4 displayed an average ultimate strength of 120 kN. The average ultimate strength of group B beams CS3 and CS4 was 130 kN. The strip wrapping technique too was successful in improving the shear capacity of the RC beams, and displayed a shear strengthening effect of 33.4% by both SS3, SS4 as well as GS3,GS4, and an effect of 44.5% was observed in CS3,CS4.

The load vs. The mid-span deflection of all the RC beams i.e. both retrofitted and un-retrofitted beams were made observation of and compared. Similar comparison of load vs. Mid-span deflections were also made pertaining to different FRP configurations, i.e. full wrapping in comparison to strip wrapping of FRP configuration. Since the same reinforcement design was carried out in the casting of all the beams, hence their shear carrying capacitites could be easily compared. The load vs.

The mid-span deflections of the FRP fully wrapped beams was the most superior as compared to un-retrofitted beams and also in comparison to FRP strip wrapped RC beams. The load-deflection behavior of controlled and all the retrofitted beams are as shown in Fig. 6.



(a)



(b)

Fig. 6. (a) Load vs. midspan deflection variation of controlled beam, sisal fully wrapped beam, carbon fully wrapped beam and glass fully wrapped beam, (b) Load vs. midspan deflection variation of controlled beam, sisal strip wrapped beam, carbon strip wrapped beam and glass strip wrapped beam

5. Conclusions

The experimental results reported in this paper aid us in drawing the following conclusions:

1. Full wrapping technique displayed the maximum increase in the ultimate shear strength of the RC beams. SS1 and SS2 displayed shear strengthening effect of 77.8%, CS1 and CS2 displayed shear strengthening effect of 88.9% and GS1 and GS2 displayed shear strengthening effect of 83.4%. The strip wrapping technique too was successful in improving the shear capacity of the RC beams, and displayed a shear strengthening effect of 33.4% by both SS3,SS4 as well as GS3,GS4, and an effect of 44.5% was observed in CS3,CS4. As the degree of strengthening increased, in view of full wrapping and strip wrapping, the load carrying capacity increased with an improvement in the load deflection behavior. Similar effect of strengthening can be observed when the RC beams were retrofitted and checked for the flexural strength evaluation (Sen and Reddy, 2014). Fully wrapped sisal FRP retrofitted RC beams displayed a flexural strengthening effect of 112.5%, that retrofitted by fully wrapped carbon FRP displayed a flexural strengthening effect of 150%, and finally that retrofitted by fully wrapped glass FRP displayed a flexural strengthening effect of 125%. Hence the flexural strengthening effect was more pronounced than the shear strengthening effect.

2. The use of FRP for shear strengthening of the RC beams, be it natural FRP like sisal or artificial FRP like carbon and glass, facilitated the formation of initial cracks at higher loads than their respective controlled beams. It can be concluded that the performance of sisal FRP in adding to the shear strength of the RC beams was very effective and executed performance of comparable magnitude to that of CFRP and GFRP shear retrofitting schemes.

3. There was a significant enhancement of ultimate shear strength of fully wrapped sisal FRP retrofitted beams, also the failure mode obtained by the use of natural FRP, like sisal FRP, was totally a ductile failure mode, with huge deflections before failure, hence sufficient warning was executed prior to failure, although the shear mode of structural failure is a brittle mode of failure, but wrapping of natural sisal FRP aided us to converting a brittle mode to shear failure to a ductile mode. But the failure modes depicted by artificial FRP retrofitting schemes, i.e. CFRP and GFRP retrofitting schemes were brittle ones. CFRP retrofitted beams underwent sudden CFRP rupture followed by CFRP debonding, and GFRP retrofitted beams underwent GFRP debonding, where the debonding continued throughout the sides and length of the beams. One of the most important aspect of structural failure mode, is obtaining a ductile mode of failure and such was observed by the use of sisal FRP retrofitting scheme and totally aided us in avoiding any catastrophic failure of RC beam failure under shear. Similar type of brittle failure was observed for RC beams retrofitted using artificial carbon FRP and glass FRP respectively under flexural strength evaluation (Sen and Reddy, 2014). The RC beams retrofitted using carbon FRP underwent sudden FRP rupture in the maximum bending moment zone, whereas the RC beams retrofitted using glass FRP underwent sudden FRP debonding from the sides. Unlike artificial FRP bonded RC beam's failure modes, sisal FRP retrofitted RC beams underwent a ductile failure mode under flexural strength evaluation (Sen and Reddy, 2014) and failed with huge deflection with sufficient warnings, and even at failure the sisal

FRP remained bonded to the RC beams without undergoing any FRP rupture or debonding.

4. The ultimate shear strength of the retrofitted beams were found to be greater than that of the control beams, thus aiding us to conclude that the presence of externally bonded natural FRP like sisal FRP, or artificial FRP like carbon FRP and glass FRP, were able to contribute positively in the shear load carrying capacity, for beams subjected to large shear forces. Higher deformations were seen for full wrapped sisal FRP retrofitted beams, highlighting the fact that natural FRP retrofitted beams absorb energy before their failures, and do not undergo rupture or debonding type of brittle failures.

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