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A Comparative Study of RC Beams Strengthened with GFRP Laminates

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Abstract

Four types of GFRP laminates are available for strengthening reinforced concrete (RC) beams. These are 4-layerd symmetric cross-ply (SCP), symmetric angle-ply (SAP), anti-symmetric cross-ply (ASCP), and anti-symmetric angle-ply (ASAP) laminates. The flexural behavior of simple RC beams has been studied experimentally and the results validated using ANSYS. Five sets of five beams each of grade M20 were cast for the purpose. Degree of enhancement in the flexural capacity, ductility and stiffness of the strengthened beams has been determined. The symmetric cross-ply laminate is found to be the most suitable laminate for enhancement of strength and stiffness for strengthened RC beams.

Key words: Flexure, GFRP, Laminate, ANSYS, Strengthened

1. Introduction

Most buildings show distress during their service life and require strengthening using on-site structures. The distress may be due to accidental loading, or loads of a higher magnitude than the design ones, or where design or construction errors might put their safety or performance under question [1]. Further, with time a change in ownership and use the load pattern may result in distress in some of structural elements requiring local strengthening.

Several techniques, such as shotcrete, jacketing and others are in use for post-strengthening of the existing/distressed structural elements. Recently noncorrosive, high strength but lightweight fiber-reinforced polymer composites (FRPs) are becoming popular in strengthening RC structures. Their use which started in the mid-1980s, has gained momentum and since then investigations about post-strengthening of RC members by externally bonding FRP is being carried out across the globe [2-8].

Chiew *et al*. [9] showed the effectiveness of glass fiber-reinforced polymer (GFRP) in strengthening undamaged concrete beams. Mahmoud and Mihilmi [10] presented an analytical method to predict flexural capacity of externally bonded FRP beam and prepared a nomograph to facilitate design of RCC members strengthened with FRP.

Rahimi and Hutchinson [11] studied the suitability of FRP for externally bonded reinforcement of concrete structures subjected to flexural loading. They observed that stiffness and strength of the strengthened beams enhanced considerably.

Hu *et al*. [12] used ABAQUS finite element programme to predict the ultimate load capacity of RC beam strengthened with FRPs. They concluded that use of FRPs significantly increases the stiffness of the RC beams.

Although strengthening of RC beams with FRP has been investigated by many researchers, the numerical studies are still being carried out to study behavior of such beams for a better understanding. The present work focuses on the experimental investigation of flexural behavior of RC beam strengthened with four layered symmetric and anti-symmetric cross-ply and angle-ply GFRP laminates, and then validating the findings using ANSYS.

2. Analysis of the Section

Aim of this study is to predict the failure load of strengthened beam. In the present analysis tensile strength of concrete is ignored and the maximum strain in concrete is assumed to be 0.0035. In place of rectangular stress diagram, actual parabolic stress diagram is considered. The FRP reinforcement is assumed to have a linear elastic relationship till failure. A plane section before loading is assumed to remain plane after loading. Further, it is assumed that there is no slip between GFRP and concrete. Shear deformation within adhesive layer is neglected. The cross-section details, strain and stress distribution diagrams of proposed RC beam strengthened with GFRP laminates are shown in Fig. 1.

The compressive force due to concrete on the cross section is given as:

$$C = 0.67 f_{ck} b \left[\frac{3}{7} x + \left(\frac{2}{3}\right)\left(\frac{4}{7}\right) x \right] = 0.542 f_{ck} bx \quad (1)$$

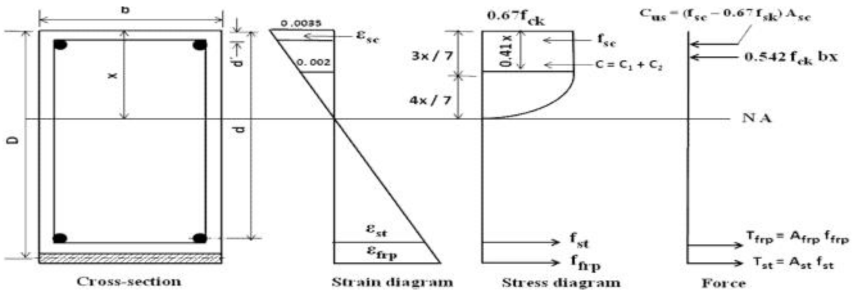

Fig.1 Details of doubly reinforced rectangular beam strengthened with GFRP

Depth of neutral axis is given as

$$x = \frac{A_f f_f + A_{st} f_{st} - (f_{sc} - 0.67 f_{ck}) A_{sc}}{0.542 f_{ck} b} \quad (2)$$

Moment of resistance of the strengthened beam is expressed as

$$M_u = 0.542 f_{ck} bx \, (D - 0.41x) + (f_{sc} - 0.67 f_{ck}) A_{sc} (D - d') - A_{st} f_{st} (D - d) \quad (3)$$

where, A_{sc} = area of compression steel, A_{st} = area of tension steel, A_f = area of GFRP laminate, f_f = observed ultimate strength of GFRP laminate, f_{ck} = characteristic strength of cube, b = width of beam, D = depth to the centroid of GFRP laminate , d = depth to the centroid of the tensile steel, d' = concrete cover M_u = ultimate moment, f_{sc} = yield strength of steel in compression, f_{st} = yield strength of steel in tension.

The moment of resistance of RC beams strengthened with four layered symmetric cross-ply (SCP) [0°/90°/90°/0°], anti-symmetric cross-ply (ASCP) [0°/90°/0°/90°], symmetric angle-ply (SAP) [45°/-45°/-45°/45°] and anti-symmetric angle-ply (ASAP) [45°/-45°/45°/-45°] laminates are calculated using Eqn. (3) which uses the properties of different types of GFRP laminates and the other constituent materials. The moment of resistance of RC beams and strengthened RC beams are given in Table 1.

Table 1 Moment of resistance of strengthened RC beams

S. No.	Strengthening scheme	f_{ck} (N/mm^2)	f_f (N/mm^2)	Moment of resistance (kNm)	Failure load (kN)
1	SCP	27.26	148.0	24.09	96.36
2	SAP	26.52	112.0	20.34	81.36
3	ASCP	26.96	122.0	21.40	85.60
4	ASAP	30.00	101.0	19.26	77.04

The first crack and ultimate moment of the flexure deficient reference beam, as shown in Fig. 2, are calculated using Eqn. (4) and Eqn. (5), respectively.

$$M_{cr} = f_{cr} \frac{I_g}{y_t} \quad (4)$$

where $f_{cr} = 0.7\sqrt{f_{ck}}$

$$M_u = 0.87 f_y A_{st} \left[1 - \frac{A_{st} f_y}{b d f_{ck}} \right] \quad (5)$$

where, M_{cr} = moment at first crack, f_{cr} = modulus of rupture, I_g = moment of inertia of the gross section about the centroidal axis, neglecting the reinforcement, y_t = the distance from centroidal axis of gross section, neglecting the reinforcement to extreme fiber in tension.

First crack load and failure load of flexure deficient reference beam are calculated as 12.52 kN and 22.55 kN, respectively.

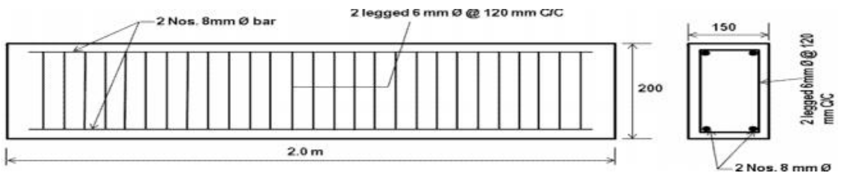

Fig. 2 Details of beam specimen designed for flexure failure

3. Experimental Program

The experimental program encompasses details of the materials used and the procedure adopted for casting beams and pasting of laminates.

3.1 Materials Used

(i) Concrete: Standard cubes of 150 mm sides were cast from each batch of concrete used for making beams. 28 days average cube strength for different batches obtained are shown in Table1.

(ii) Steel: Five samples of the steel rebars were tested under uniaxial tension. The average yield stress of the bars is found to be 506 N/mm^2.

(iii) GFRP laminates were tested under uniaxial tension. The specimens exhibited linear-elastic behavior up to failure. Tensile strength values of respective GFRP laminates are shown in Table 1.

iv) Epoxy: Araldite GY 257 and Aradur 140 mixed in the ratio of 2:1 was used for bonding the GFRP sheets over the RC beams.

3.2 Experimental Procedure

A line diagram of test arrangement for the beam specimens under four-point loading is shown in Fig. 3. The test beams have simply supported span of 2000 mm. Equal concentrated loads acting downwards were applied at 500 mm from each support. To accomplish this, I-girder beams were placed centrally over two rollers which in turn were placed over the test beam at a distance of 500 mm from each end support. The girder was subjected to loads, in regular increments of 2 divisions (least count of 0.5 kN) on the dial scale, through a jack pointing centrally over the test beam. Deflection gauges were placed under applied load-points as well as at mid-point of the beam. The test program consisted in testing the beams of series V and R under incremental loading till failure.

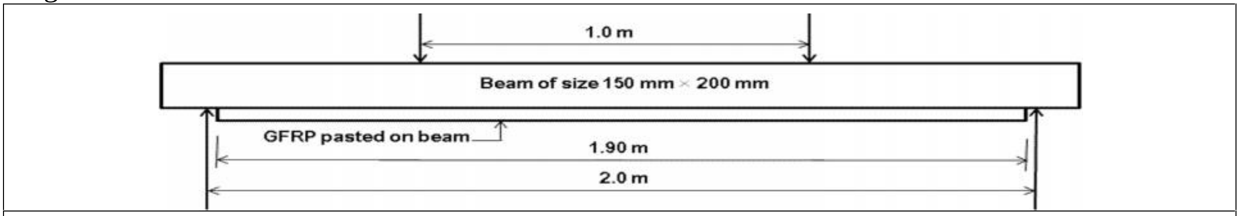

Fig. 3 Line diagram for the test set-up for flexure deficient beams

In the first phase of testing, five beams of series V marked as V_1, V_2, V_3, V_4 and V_5 were loaded up to the failure in increments of 1kN. Mid-deflections were recorded at each load increment. Crack patterns were also observed.

3.2.2 Strengthened Beam

In the second phase, four sets of beams, each set consisting of five beams, strengthened with four different types of GFRP laminates on their tension sides were tested. Total twenty beams in sets of five each were tested, deflections at mid-span and quarter-span were recorded and crack patterns observed.

Fig. 4 GFRP laminates pasted at tension side of RC beams

The tension face of beam was smoothened by mechanical grinding, and dust was brushed off. Epoxy resin in the ratio of 2:1 (Hardener: Resin) by weight was applied and spread over the tension face of the beam as well as on the surface of the GFRP laminate. Laminate was pasted up to the point well away from the location of the roller support to avoid any interaction between the support and laminate. To effectuate good bonding between the beam and the laminate, the outer face of the laminate was hard-pressed with 40 mm thick wooden plank against the beam by clamping it at five positions as shown in Fig. 4. After drying for forty eight hours, clamps were removed and the beams were ready for testing. The beams prepared in the manner described above were subjected to incremental load.

4. Experimental Observations

Behaviour of the beams, throughout the test, up to failure is described on the basis of the recorded data, observed crack patterns, and the mode of failure of the reference beams and strengthened beams. The area under the respective load deflection curves represents the absorbed energy [13]. The area under load deflection curve corresponding to first crack load and at which failure takes place is defined as initial absorbed

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energy and final absorbed energy, respectively. The area under the load deflection curve up to 8 mm deflection is defined as energy at serviceability.

4.1. Reference Beams

The beams were tested to compare the results of GFRP strengthened beams and hereafter will be known as reference beams. Set of five beams denoted by V were tested. Incremental load was applied. No crack was visible in the reference beams until an average load of about 14 kN. On loading further up to the failure, after appearance of the first crack small cracks started to develop vertically in the mid-span region displaying no specific spacing pattern. All cracks continued to grow in both width and length in the direction towards the top. With increase in load, larger cracks travelled up to depth of the beam. This trend continued until failure occurred at an average load of about 35 kN. Failure mode of the reference beam is shown in Fig. 5. Fig. 6 shows the load-deflection behaviour for each reference beam. Linear behaviour with almost constant rate of deflection up to the first crack load and thereafter up to failure was observed. Summary of the experimental observations of the reference beam is given in Table 2.

Fig. 5 Failure mode of reference beam

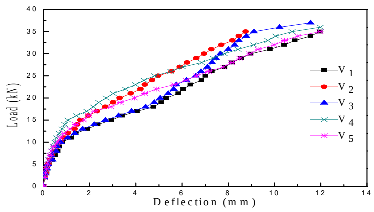

Fig. 6 Load-deflection behavior for reference beams

Table 2 Experimental observations of each specimen of reference beams

S. No.	Specimen Detail	First crack load (kN)	Deflection (mm) corresponding to first crack	Failure load (kN)	Final deflection (mm)	Failure Mode
1.	V_1	13	1.9	35	11.96	Flexure
2.	V_2	17	2.32	37	8.75	Flexure
3.	V_3	12	1.35	37	11.56	Flexure
4.	V_4	14	1.9	35	11.98	Flexure
5.	V_5	15	1.6	35	11.86	Flexure
6.	(Average) V	14.2	1.81	35.8	11.22	Flexure

4.2 Strengthened Beam

Beams having flexural deficiency were strengthened with different types of GFRP laminates on its tension side are referred as strengthened beams. These strengthened beams were also loaded gradually leading to failure. Beams were strengthened with symmetric cross-ply, symmetric angle-ply, anti-symmetric cross-ply and anti-symmetric angle-ply laminates. In each set, five beams were tested. Crack patterns and possible failure modes were investigated after each load increment. In all the cases strengthened beams were never able to reach the ultimate moment of resistance as the GFRP laminate debonded leading to the failure of RC beams in flexure. The first crack in the strengthened beam was observed at 21.5 kN. Unlike the reference beam, the cracks were smaller in width and length. Small, flexural cracks began to form in the mid-section region. They continued to travel up to the depth of the beam with increase in load. Most of the cracks crossed up approximately 50% of the beam depth before debonding occurred. A few larger cracks that formed in the mid-

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span region, reached about 75% of the beam depth in case of beams strengthened with symmetric laminates. While in case of beams strengthened with anti-symmetric laminates, larger cracks reached up to 90% of depth. Failure of the beams occurred with knocking sound due to debonding of GFRP laminates; debonding started from one end. Failure modes of respective beams are shown in Figs.7-10. Figures 11- 14 show the load-deflection curve for the strengthened beams. The beams displayed linear behaviour till first crack and beyond this the linear behaviour continued with reduced stiffness. The beam continued to deflect with little increase in load carrying capacity until the GFRP laminate debonded with cracking sound. Summary of the experimental observations of the strengthened beams is given in Table 3.

Fig. 7 Failure mode of beam strengthened with symmetric cross-ply laminate

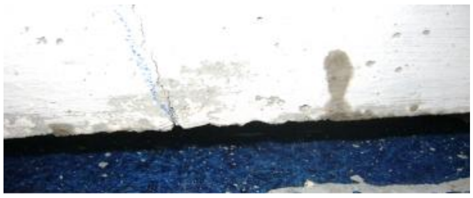

Fig. 8 Failure mode of beam strengthened with symmetric angle-ply laminate

Fig. 9 Failure mode of beam strengthened with anti-symmetric cross-ply laminate

Fig. 10 Failure mode of beam strengthened with anti-symmetric angle-ply laminate

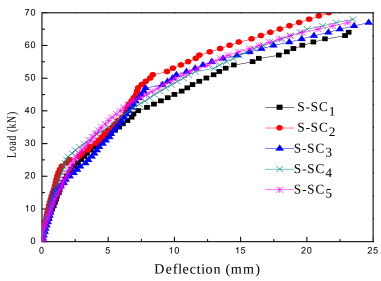

Fig. 11 Load-deflection behaviour of beams strengthened with symmetric cross-ply laminate

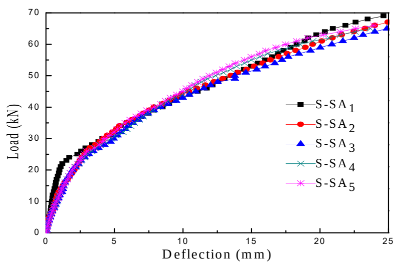

Fig. 12 Load-deflection behaviour of beams strengthened with symmetric angle-ply laminate

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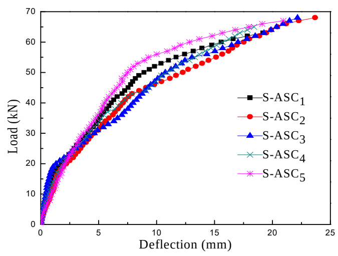

Fig. 13 Load-deflection behaviour of beams strengthened with anti-symmetric cross-ply laminate

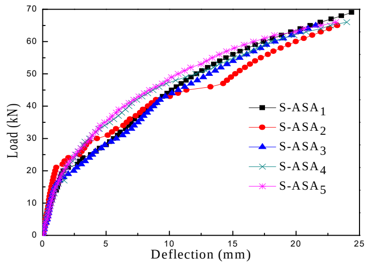

Fig. 14 Load-deflection behaviour of beams strengthened with anti-symmetric angle-ply laminate

Table 3 Average values of first crack load, failure load, deflection and failure mode of strengthened beams

S. No.	Specimen Detail	First crack load (kN)	Deflection (mm) corresponding to first crack	Failure load (kN)	Final deflection (mm)	Failure Mode
1.	S-SCP	21.8	1.6	67	23.44	Debonding
2.	S-SAP	21.8	2.22	66.8	24.77	Debonding
3.	S-ASCP	21	2.61	64	22.10	Debonding
4.	S-ASAP	21.4	1.72	66.4	23.4	Debonding

5. ANSYS Modeling

Strengthened beams are analysed with ANSYS software. Graph drawn from values found through software were compared with that of experiments. The Solid65 element, Solid46 element and Link8 element are used for concrete material, GFRP laminates, and steel reinforcement, respectively [14].The full-size beam model having dimension 2000 mm × 200 mm ×150 mm is shown in Fig. 15. Model of longitudinal and shear reinforcements are shown in Fig. 16.

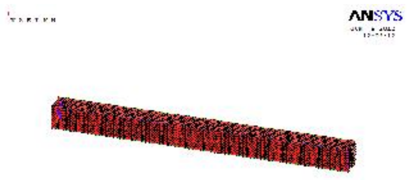

Fig. 15 Model of strengthened RC beam

Fig. 16 Model of reinforcement in strengthened RC beam

A convergence study was carried out on a reference beam model, with four numbers of element, i.e. 600, 2400, 4800 and 6000, to determine an appropriate mesh density. Figure 17 shows the results of the convergence study. It can be seen that very good convergence of the deflection is achieved at 4800 elements. Therefore, 4800 element model is selected for the reference beam model and used as the basis of the other GFRP strengthened beam models as well. The overall mesh of the concrete and GFRP laminates is shown in Fig. 18.

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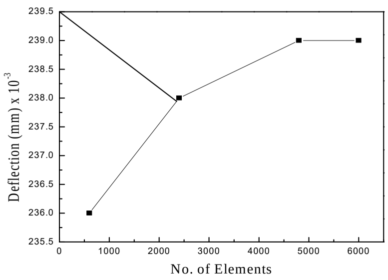

Fig. 17 Convergence study: displacement at mid-span of beam

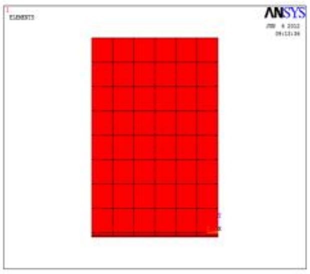

Fig. 18 Meshing for strengthened RC beam

To have the perfect bond, the link element for steel reinforcement is connected between nodes of each adjacent concrete solid element, so that the two materials share the same nodes [15]. No mesh of the reinforcement is needed because individual elements are created in the modeling through the nodes created by the mesh of the concrete volume. The meshing sizes of concrete and steel reinforcement are 25 mm. Nodes of the GFRP layered solid elements are connected to those of adjacent concrete solid elements in order to satisfy the perfect bond. The model of RC strengthened beam with load and boundary condition is shown in Fig. 19. Finally the solution is obtained.

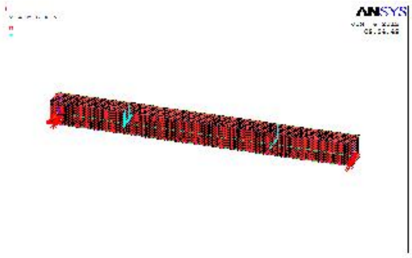

Fig. 19 Load and boundary conditions of strengthened beam

6. Discussion

In each case of strengthened beam, debonding of GFRP laminates with RC beams took place prior to failure stage. Consequently, experimental failure load was observed to be lower than the theoretical calculated load and is given in Table 4.

Table 4 Comparison of ultimate failure load of strengthened beams

S.No.	**Strengthened beam**	**Ultimate Failure Load (kN)**		**Difference (%)**
		Theoretical	**Experimental**	
1	S-SCP	96.36	67.0	30.4
2	S-SAP	81.36	66.8	17.8
3	S-ASCP	85.6	64.0	25.2
4	S-ASAP	77.04	66.4	13.8

An important issue in the strengthening of RC beams with FRP plates is the ductility of the strengthened beams. The ductility of post-strengthened beam depends on the performance factor (PF), which is product of deformability factor (DF) and strength factor (SF). DF is determined by dividing the deflection at ultimate limit state by the deflection at serviceability limit state. SF is the ratio of the ultimate load and the serviceability load. To ensure ductile behavior of the post-strengthened beams PF of a beam should be more than four (Garcez *et al*. 2008). The point where the deflection of the beam is equal to span/250 is defined as the serviceability limit (IS 456:2000). In the present case the limiting deflection corresponding to serviceability limit is 8 mm. Tables 5 shows average values of absorbed energy, PF, SF and DF for reference beams and strengthened beams.

Average values of absorbed energy, increase in load carrying capacity of the beams at serviceability stage and failure stage and performance factor of each series of the beams are calculated based on experimental observation and a comparison is shown in Table 5. It is observed that all the strengthened beams show increased load carrying capacity with respect to reference beam. At serviceability stage, it is also noticed that beams strengthened with symmetric cross-ply (S-SCP), symmetric angle-ply (S-SAP), anti-symmetric cross-ply (S-ASCP) and anti-symmetric angle-ply (S-ASAP) laminates have shown improved load carrying capacity of all strengthened beams by approximately 51%, 32%, 16% and 34%, respectively, where as the ultimate load carrying capacity of all the strengthened beam increases by more than 75%.

Table 5 Comparison of absorbed energy, deformability factor (DF), strength factor (SF) and performance factor (PF) of beams

Beam detail	**Serviceability stage**			**Failure stage**			**PF**
	Load (kN)	**Absorbed Energy (kNmm)**	**Increase in Load (%)**	**Load (kN)**	**Absorbed Energy (kNmm)**	**Increase in Load (%)**	
V	29.8	155.04	_	35.8	215.3	-	1.68
S-SC	45.20	225.12	51.67	67.00	1076.46	87.15	4.34
S-SA	39.6	188.6	32.88	66.8	1051.60	86.59	5.22
S-ASC	34.8	189.8	16.77	64.0	923.33	78.77	5.11
S-ASA	40.2	205.04	34.89	66.4	1002.14	85.47	4.85

Energy absorbed by the beams is found to increase from the first crack stage till the failure stage. Energy absorption at both the stages is the highest in case of beams strengthened with symmetric cross-ply laminates. Increase in absorbed energy at serviceability stage for beams strengthened with symmetric cross-ply, symmetric angle-ply, anti-symmetric cross-ply and anti-symmetric angle-ply laminates are found to be approximately 45%, 21%, 22% and 32%, respectively. For strengthened beam, increase in absorbed energy at ultimate stage for beams strengthened with symmetric cross-ply, symmetric angle-ply, anti-symmetric cross-ply and anti-symmetric angle-ply laminates is approximately 399%, 388%, 328% and 365%, respectively. Also, substantial increase in absorbed energy at failure stage in case of retrofitted beams with four types of laminates is observed and increase is more than 150% where as insignificant increase in absorbed energy is found at serviceability stage.

The influence of the external strengthening on the development of the cracks is also significant. From the comparison of the crack patterns of the strengthened and reference beams, the crack propagation is found to reduce due to GFRP laminates. Number of cracks in strengthened specimens just prior to failure was not reduced when compared to that of the reference beam before failure. It was also observed that cracks were much wider on the reference beams at different load stages in comparison to strengthened beams.

Each of the strengthened beam displayed increased ductility when compared to the reference beams. All the strengthened beams have performance factors more than four, showing adequate ductility. Performance of beams strengthened and retrofitted with symmetric cross-ply is observed to be the best at all the stages with regards to strength followed by beams strengthened/retrofitted with symmetric angle-ply laminates. Ductility of the beams strengthened and retrofitted with laminates has found to be increased in comparison to reference beam. However the performance factor of beam retrofitted with symmetric cross-ply laminates and anti-symmetric angle-ply laminates are less than four, showing decrease in ductile behavior.

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At ultimate loads, all the strengthened beams display a decrease in deflection as compared to that of the reference beams (tested at failure load of reference beams). From serviceability view point, the performance of strengthened beams is better than that of retrofitted beams.

Performance of beams strengthened and retrofitted with symmetric cross-ply is observed to be the best at all the stages with regards to strength followed by beams strengthened/ retrofitted with symmetric angle-ply laminates.

Load-deflection curves of strengthened beams were plotted using data from analysis by ANSYS software. The load-deflection curves depict two distinct parts; the initial almost straight portion denoting elastic behaviour and other, the non-linear one without sudden change of curvature. It is the non-linear part, albeit close to the elastic limit, where in initial cracks were observed. A comparison between values obtained experimentally and numerical results are shown in Figs. 20-24. Since specimen of every series show similar pattern, it was decided to have average values obtained experimentally for each series. In linear phase, the ANSYS analysis is in good agreement with experimental one. The analysis predicts the beam to be stronger, because of the absence of micro cracks in ANSYS model and assumed perfect bond condition between concrete and reinforcement as well as between concrete and laminates. As the perfect bond assumption does not take into account the shear strain between different materials, it over estimates the strength of the beam. Debonding failure of beams, which was observed in the laboratory, is not observed in ANSYS because of the perfect bond model.

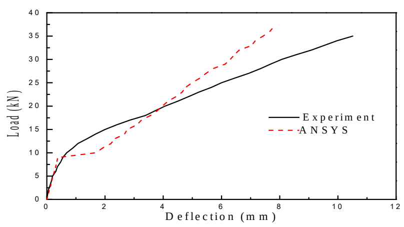

Fig. 20 Comparison of load-deflection behaviour of flexure deficient reference beam

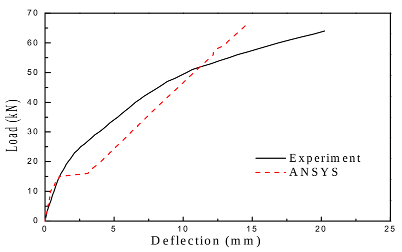

Fig. 21 Comparison of load-deflection behavior of beam strengthened with symmetric cross-ply laminate

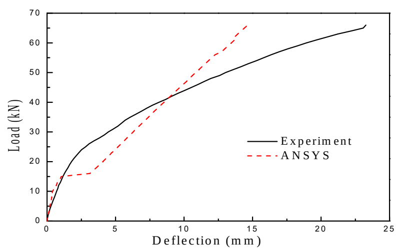

Fig. 22 Comparison of load-deflection behaviour of beam strengthened with symmetric angle-ply laminate

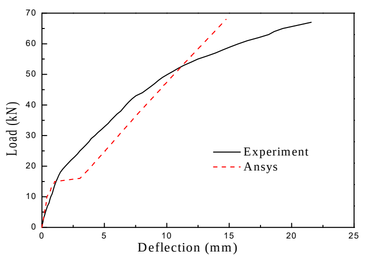

Fig. 23 Comparison of load-deflection behaviour of beam strengthened with anti-symmetric cross-ply laminate

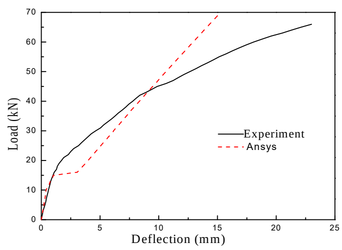

Fig. 24 Comparison of load-deflection behavior of beam strengthened with anti-symmetric angle-ply laminate

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7. Conclusions

Following major conclusion can be drawn from the research work.

- Strengthening beams in flexure with different type of GFRP laminates is found to be effective and can be used as an alternative for enhancing the capacity of RC beams and to achieve improved behaviour of cracked beams.
- Among all of laminates used for strengthening, the symmetric ply composite is found to be the most suitable for enhancing strength with least deflection.
- Ductility of strengthened beams is enhanced.
- Strengthening retards the progress of cracks.

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