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Behavior of CFRPC strengthened reinforced concrete beams with varying degrees of strengthening

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Abstract

This paper summarizes the results of experimental and analytical studies on the flexural strengthening of reinforced concrete beams by the external bonding of high-strength, light-weight carbon fiber reinforced polymer composite (CFRPC) laminates to the tension face of the beam. Four sets of beams, three with different amounts of CFRPC reinforcement by changing the width of CFRPC laminate, and one without CFRPC were tested in four-point bending over a span of 900 mm. The tests were carried out under displacement control. At least one beam in a set was extensively instrumented to monitor strains and deflections over the entire range of loading till the failure of the beam. The increase in strength and stiffness provided by the bonded laminate was assessed by varying the width of laminate. The results indicate that the flexural strength of beams was significantly increased as the width of laminate increased. Theoretical analysis using a computer program based on strain compatibility is presented to predict the ultimate strength and moment–deflection behavior of the beams. The comparison of the experimental results with theoretical values is also presented, along with an investigation of the beam failure modes.

Keywords: B. Adhesion; A. Laminates; B. Strength; Flexural behavior

1. Introduction

In recent years, the concrete construction industry has faced a very significant challenge in view of the deterioration of infrastructure. A large number of bridges, buildings and other structural elements require rehabilitation and repair. Effect of environment, increase in both traffic volume and truck weights and design of older structures, which may have been adequate compared with old codes but are not adequate with current codes, are all factors that contribute to infrastructure becoming either structurally deficient or functionally obsolete.

There is currently a range of techniques available for extending the useful life of structurally deficient and functionally obsolete structures. One such technique is adding fiber reinforced plastic composites (FRPCs) as external reinforcement. FRPCs have been used to retrofit concrete members like columns, slabs beams and girders in structures such as bridges, parking decks and buildings. Among these, the application of FRPCs to strengthen the concrete beams has perhaps received the most attention from the research community.

Beams retrofitted with FRPCs have been investigated primarily for their strength enhancement. Saadatmanesh and Ehsani [1], Ritchie et al. [2], and Meier and Kaiser [3] proved beyond doubt the effectiveness of using composite laminates as an external reinforcement for strengthening. Experiments conducted so far used both glass fiber and carbon fiber laminates. The works reported by Meier and Kaiser [3], Meier et al. [4], Shahawy et al. [5,6], Takada et al. [7] have used carbon fiber laminates. Ritchie et al. [2] studied the effectiveness of strengthening using different types of FRPC laminates. Laminates made of glass, carbon and aramid fibers have been used and the increase in ultimate strength is found to be ranging from 28 to 97% of that of unstrengthened beams for different types of laminates. Faza and Ganga Rao [8] reported an increase of 200% in strength when CFRPC laminates are wrapped around beams. Ross et al. [9] verified the results of CFRPC strengthened reinforced concrete beams with those obtained from inelastic analysis as well as finite element analysis. Spadea et al. [10] studied the improvement in ductility

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Table 1
Concrete mix details

Aggregate-cement ratio	6
Coarse aggregate to fine aggregate ratio	1
Fly-ash	20% by weight of cement
Water cement ratio (including fly-ash)	0.5

when end anchorages for laminate are used. Buyukozturk and Hearing [11] have stressed the need for better understanding of the failure modes of strengthened beams. The purpose of this paper is mainly to contribute to the experimental database. Moreover, a theoretical model for prediction of the behavior of laminate strengthened beam is validated with experiment. Beams are strengthened with different levels of CFRPC reinforcement by varying the width of laminate. The flexural behavior is studied in terms of ultimate load, serviceability, strains of different components and crack patterns along with failure modes.

2. Experimental study

The experiment consisted of fabricating reinforced concrete test beams, applying the CFRPC laminate layers of different widths and testing them under four point bending. The beams were instrumented to record their response history until failure.

2.1. Test materials

Concrete and mild steel bars were used in preparation of beam specimens. Unidirectional CFRPC laminates were used with an epoxy adhesive for strengthening. The details of these materials are briefly discussed here.

2.1.1. Concrete

Concrete having average compressive strength of 30 MPa is specified for all the concrete beams. Ordinary Portland cement, locally available sand and crushed basalt rock were used for making concrete. The maximum size of coarse aggregate used was 12.5 mm. Since the fine aggregates were coarse in nature (fineness modulus = 3.56), fly ash was added to get the smooth working surface finish. The details of the mix are given in Table 1.

2.1.2. Steel

Mild steel bars of 5.5 mm diameter were used. Three typical samples representing this reinforcement were tested for their tensile strength and Young's modulus. The Young's modulus, yield strength and percentage of elongation at failure were found to be $2.09 \times 10^{+5}$ MPa, 267 MPa and 34.78%, respectively.

2.1.3. CFRPC laminate and epoxy adhesive

The CFRPC laminate samples were tested for their tensile strength, Young's modulus and for percentage of elongation at failure. Table 2 gives the details of laminate and epoxy adhesive properties. The 20% difference in tensile strength of CFRPC laminate may be attributed to difference in the test environmental conditions like temperature.

2.2. Test beams

2.2.1. Design

The design of the concrete beam was carried out according to specifications of Indian code IS:456-1978 code [12]. The steel reinforcement was chosen to approach the lower limit of an under-reinforced beam. The plain mild steel bars for reinforcement were chosen in such a way that they have the lowest possible yield stress (267 MPa). This ensures the early transfer of bending tensile forces to composite laminate. The dimensions of the beam were 100 mm wide, 100 mm deep and 1000 mm length (Fig. 1). The span of the beam (900 mm) was limited by the maximum span that can be tested in the universal testing machine.

The internal longitudinal reinforcement consisted of four 5.5 mm diameter bars with yield stress of 267 MPa. This reinforcement correspond to 20% of balanced (0.2B) reinforcement. Tensile tests were performed on the reinforcing bars and these values were used for theoretical predictions. Shear reinforcement consisted of two-legged stirrups of the same steel used as longitudinal steel. The beam was over designed in shear to avoid a brittle shear failure due to the increased shear load on the strengthened beam.

Table 2
CFRPC laminate and epoxy adhesive properties

Materials	Property	Values supplied by the manufacturer	Values found in the laboratory
CFRPC laminate	Tensile strength (MPa)	1793	1440
	Tensile modulus (MPa)	1.38×10^5	1.23×10^5
	Elongation at ultimate (%)	1.3	1.21
Epoxy adhesive	Tensile strength (MPa)	60	–[a]
	Adhesion	24 MPa > 2 (Concrete)	–[a]
	Flexural strength (MPa)	100	–[a]
	Flexural modulus (MPa)	2140	–[a]

[a] Not found in the laboratory.

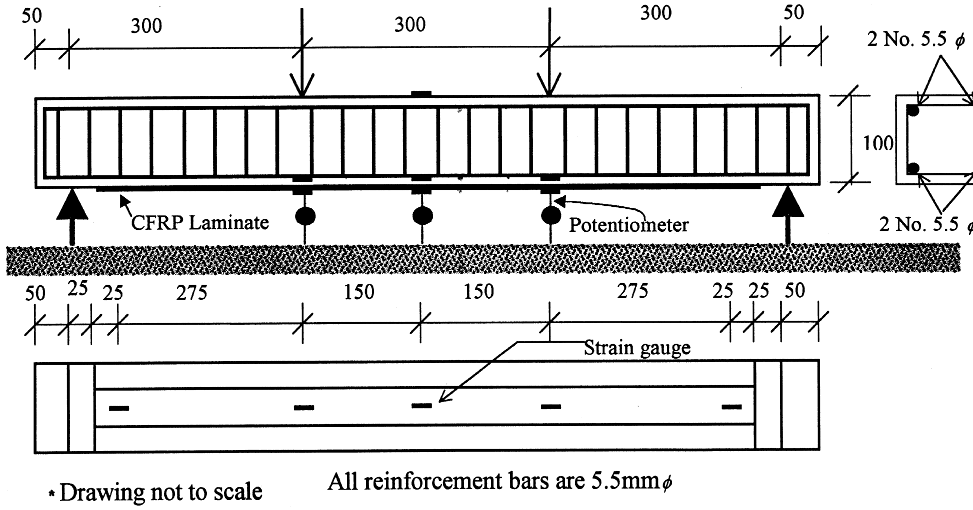

Fig. 1. Details of the test beam.

2.2.2. Fabrication

To have dimensionally accurate beams of size $100 \times 100 \times 1000\ mm^3$, six mild steel moulds were made as per IS:516-1959 specifications [13]. These beams were cleaned and oiled before casting of the beams. Before commencement of casting of concrete beams, a set of rich cement mortar cover blocks were made and cured sufficiently in water. These cover blocks were useful for maintaining uniform cover of concrete throughout the length of beam. At the center of the small block, a copper wire was inserted to facilitate it for tying to reinforcement. Three cover blocks were used (one at the center and two at the ends) for each beam for maintaining the uniform concrete cover to reinforcement.

Strain gages on steel reinforcement were fixed before casting of beams. The gage locations of reinforcement are shown in the Fig. 1. These gages were protected from moisture by coating them with rubber solution and then covering with butyl rubber. The ends of lead wires were sealed with M-seal to prevent the entry of moisture while curing the beams. A total of 60 beams (six in each batch) were cast in 10 batches. The same concrete mix was used for all batches.

2.2.3. Bonding of the CFRPC laminates

All loose particles of concrete surface at the tension side of the beam were chiseled out by using a chisel. Then the surface was roughened with wire brush before cleaning it with air blower to remove all dust particles. Also it was ensured that no moisture was visible on the surface. The two component primer mixed in the ratio of 2:1 by volume was applied on the prepared concrete surface. After waiting for a minimum of 1 h, the two component structural epoxy (1:1 by volume) paste was applied to fill all voids and uneven areas. It was ensured that the surface was free from all ridges and unevenness areas and was smooth. These ridges and uneven areas were removed using a trowel and the structural epoxy paste. Once the voids were filled, it was allowed to dry for 18 h and then uneven areas in the epoxy were smoothened.

Lines were drawn on epoxy coated surface with pencil for correct positioning of the laminate. Using a 3.5 mm V-notched trowel, a layer of the structural epoxy paste was applied to the beam and laminate surfaces. The composite laminate was attached starting at one end and applying enough pressure to press out any excess epoxy from the sides of the laminate. Excess epoxy was removed from sides of the laminate. Epoxy thickness was not specifically controlled, but excess epoxy squeezed out all along the edges of the laminate ensured complete epoxy coverage. The epoxy was then allowed to cure for a minimum of one week before testing.

2.3. Strengthening scheme

Three types of beams were strengthened to different levels by changing the width of CFRPC laminate. The widths of CFRPC laminate were chosen in such a way that, the strengthened beams correspond to under-reinforced, nearly balanced and over-reinforced sections. Three different widths, 10, 20 and 40 mm were used to obtain the above three types of beams. The CFRPC laminate in each type of beam was converted to equivalent steel reinforcement to have the idea of percentage of balanced reinforcement. The percentage of equivalent steel in beams strengthened with 10, 20 and 40 mm width CFRPC laminates correspond to 52% (0.52B), 89% (0.89B) and 142% (1.42B) of balanced steel approximately. Similarly the flexural reinforcement of virgin (unstrengthened) beam correspond to 20% (0.2B) of balanced steel.

3. Theoretical analysis

An incremental deformation technique assuming strain

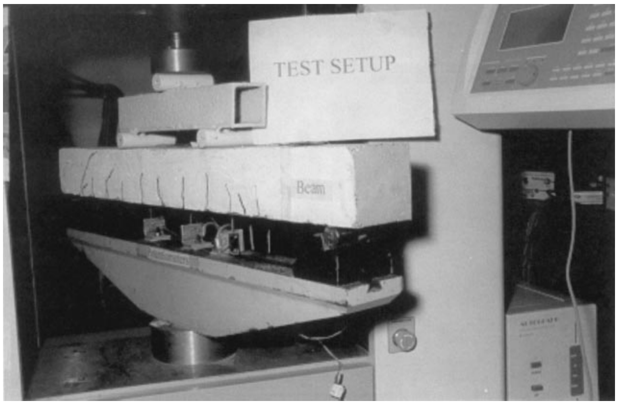

Fig. 2. Typical four-point bending setup.

compatibility was used to predict the flexural behavior of the beams. The neutral axis was obtained by using the iteration and summation of various force components in the beam. Following four assumptions were made in developing the model:

1. The bond between laminate and concrete is perfect.
2. The beam fails by either concrete compression or tensile failure of the laminate.
3. The tensile strength of concrete is neglected.
4. Plane sections remain plane before and after bending.

The model first assumes the top layer concrete strain in compressive region. For this strain the neutral axis depth was calculated by using equilibrium condition and iteration technique. Once the neutral axis depth and compressive strain of concrete are known, the program uses the force in tension steel and CFRPC laminate to calculate moment and curvature of beam. The deflection at center of the beam was found by curvature–area theorem. Experimentally obtained stress–strain curve of steel was used to obtain the force in steel at various levels of strain in steel. The failure of the beam is considered whenever the concrete has reached a failure strain of 0.0035 or the CFRPC laminate reaches its ultimate strain. A computer program was developed to perform the above numerical procedure.

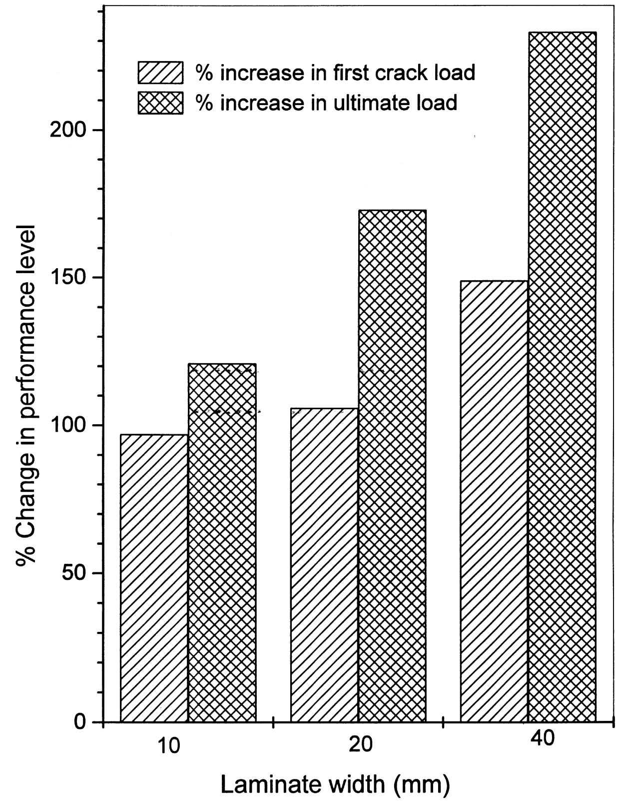

Fig. 3. Performance of strengthened beams compared to virgin beams at first crack and ultimate loads.

4. Instrumentation and test procedure

A total of 12 different strain gages were installed on reinforcing bars (6), CFRPC laminate (5) and concrete (1). Deflections at mid-span and under point loads were measured by using potentiometers. All gages were connected and monitored by data acquisition system. Instrumentation details and test set-up are shown in Figs. 1 and 2. The beam surfaces at the supports and under point loads were cleaned with sand-paper to have smooth surface to avoid any eccentricity in loading. The beams were tested under four-point static loading over a span of 900 mm. The loads were applied at 150 mm on either side of the center of the beam by universal testing machine (UTM) with displacement control at the rate of 0.05 mm/min. Strains, deflections and applied load were recorded for every 30 s. The

Table 3
Various parameters for different beams

Type of beam	Expt. first crack moment (kN–m) avg.	Expt. ult. moment (kN–m) avg.	Avg. deflection at ultimate load (mm)	Avg. expt. beam stiffness (kN–m/mm)	Avg. expt. service moment (kN–m)
0.2B	0.57	1.311	9.55	0.472	0.574
0.52B	1.125	2.903	8.38	0.726	0.621
0.89B	1.175	3.584	7.59	0.854	0.711
1.42B	1.422	4.366	6.25	0.988	

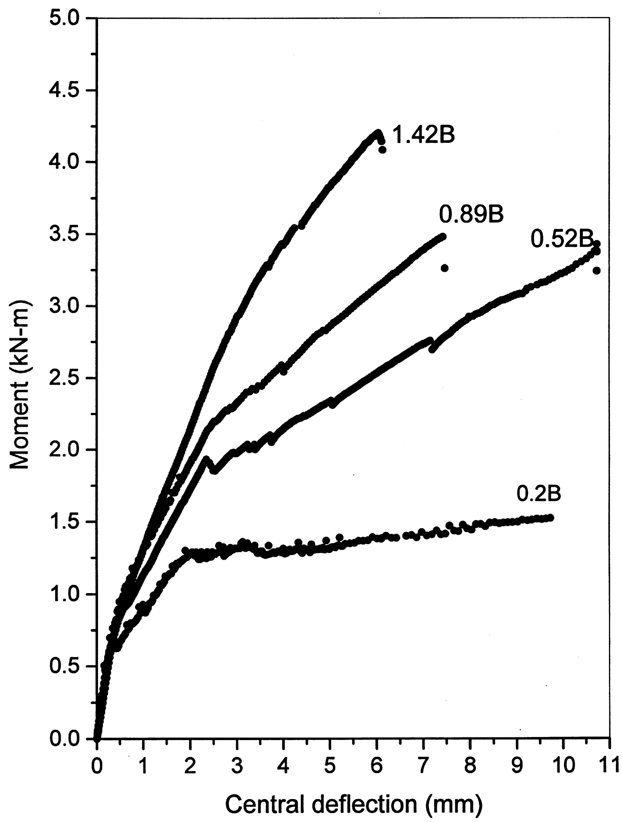

Fig. 4. Moment versus deflection curve for beams with different levels of strengthening.

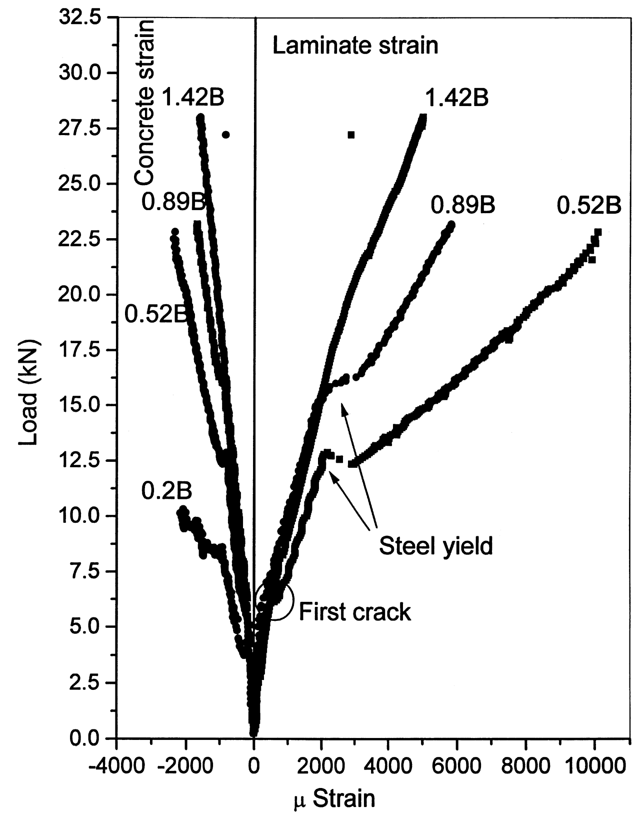

Fig. 5. Experimental load versus concrete and laminate strains for different beams.

load cell of UTM was connected to data acquisition system. The data acquisition system was customized through software developed under Lab-Windows/CVI environment. All channels were scanned 1000 times before taking their average for every set of readings. All beams were white washed to mark crack patterns while loading. Load at first crack appearance was noted down. Subsequent crack patterns were marked on the beam surfaces as they develop during testing. A total 12 beams were tested under four-point bending to investigate effect of laminate width variation.

5. Results

5.1. First cracking and ultimate moments

Observed first cracking moments and ultimate moments are presented in columns 2 and 3 of Table 3. The percentage increase in these moments compared to virgin beam are shown in Fig. 3. The increase in first crack moment of strengthened beams can be attributed to increased stiffness due to the laminate restraining effect. The cracking and ultimate moments increased monotonically with increased strengthening. The theoretical ultimate moments were substantially higher for 0.89B and 1.42B beams compared to experimental moments. This higher prediction of ultimate capacity by the present model can be attributed to assumption of a perfect bond between concrete and CFRPC laminate. All beams failed by typical peeling of the laminate due to flexural-shear crack. The continuous increase in ultimate load of these beams is due to increase in shear capacity because of external strengthening.

5.2. Deflections and stiffness

Fig. 4 shows the moment–deflection relationship for beams with different levels of strengthening. Although the initial stiffness of the beams remains unchanged, the stiffness has changed considerably after the onset of cracking. The increase in stiffness is proportional to the laminate width. Column 5 of Table 3 gives measured stiffness of various beams at a deflection of span/350, respectively. The value span/350 is the serviceable deflection limit as per IS:456-1978 [12]. Here the stiffness is a measure of moment per unit deflection corresponding to point on moment–deflection curve where the deflection is equal to span/350. Also, the measured ultimate deflections decreased progressively with increasing laminate width as shown in column 4. Fig. 3 shows the significant increase in the stiffness of strengthened beams over the virgin beam. The percentage increase in stiffness is directly proportional to the degree of strengthening. The percentages increase in stiffness were 53.8, 80.9, 109 for 0.52B, 0.89B, 1.42B beams, respectively.

Table 4
Laminate and concrete strains of strengthened beams

Type of beam	Average max. laminate strains	Theoretical laminate strains	% of failure strain (expt.)	Average max. concrete strains	Theoretical concrete strains
0.52B	8665	11 615	74	2065	2217
0.89B	5765	10 997	49	1615	3444
1.42B	4940	7783	42	1505	3428

5.3. Serviceability

The effect of CFRPC laminates on the serviceability behavior of different strengthened beams is evaluated by comparing loads carried by these beams corresponding to the same deflection at mid-span sustained by the control beam at its service moment of 0.497 kN m. This service moment is calculated based on IS:456-1978 [12]. The control beam at service load has a mid-span deflection of approximately 0.24 mm. The corresponding moments of strengthened beams are presented in column 6 of Table 3. The increase in load capacity of the beams can be observed with increase in the level of strengthening. There is almost 45% increase in service load capacity for the 1.42B beam compared to the 0.2B beam as shown in Fig. 3. This shows the distinct effect of CFRPC laminates in stiffening the beams at serviceability limit-state.

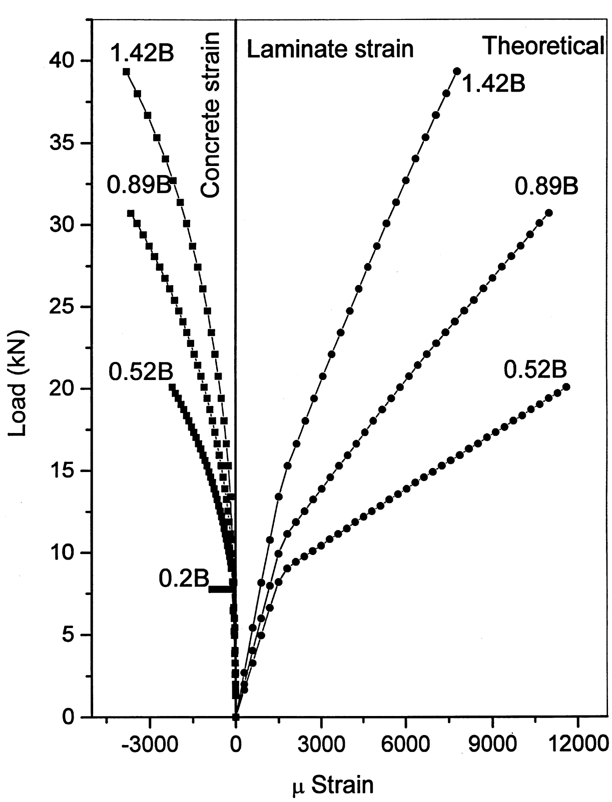

Fig. 6. Theoretical load versus laminate and concrete strain for different beams.

5.4. Concrete, steel and laminate strains

5.4.1. Laminate strains

The applied load versus mid-span strain in concrete at top compression fibers and bottom CFRPC laminate fibers is shown in Fig. 5. The measured and theoretical laminate strains are given in columns 2 and 3 of Table 4, respectively. It can be observed from these values that the strain in laminate increases as the laminate width reduces. The maximum measured tensile strain in bottom fibers was observed in 0.52B beam, which was about 75% of failure strain of the laminate. The ultimate tensile strains in 0.89B and 1.42B beams were nearly half of the rupture strain of laminate. These results suggest that there is an optimum width below which the laminate strains are excessive resulting in excessive deflections and curvature. At any given load beyond first crack, the beams exhibit smaller strain values with increasing degree of strengthening. From Fig. 5, it can be observed for various beams the appearance of first crack. Till the first crack the laminate has not taken much load as the strain is almost zero in this region as the curve is almost vertical. From the first crack the laminate started taking load by the fact that the curve had started showing some moderate inclination till the steel yield. From this point onwards the curve has taken a steep slope which indicates the laminate has started taking substantial load. This kind of behavior was clearly shown by 0.52B and 1.42B beams.

The theoretical variation of top (concrete) and bottom (laminate) fiber strains for various strengthened beams are shown in Fig. 6. This figure shows two slope lines for laminate strain variation. The first part of all lines indicates the load taken by laminate until steel yields. The subsequent part indicates the load taken by laminate after the steel yield. The second part is steeper compared to first, because the load taken by laminate will be more after steel yield. Fig. 7 shows the comparison of measured and predicted strain for typical 0.89B beam. The strains at ultimate load from theory are substantially higher than the experimental values both for top and bottom fibers. This can be explained by the fact that the model does not take into account the failure by delamination of laminate, which is the case of failure for all strengthened beams. Also, the model failed to predict the three-slope curve as it does not consider crack detection.

The variation of ultimate laminate strains (only for 0.89B

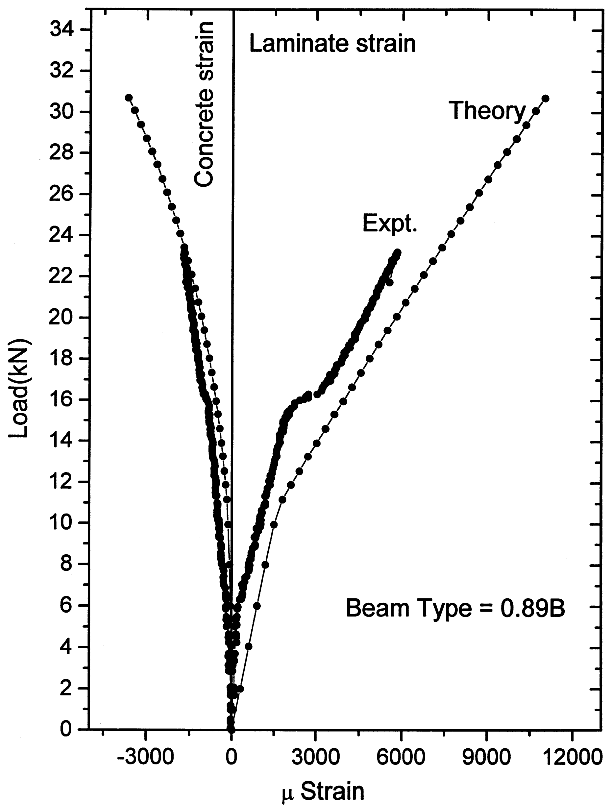

Fig. 7. Comparison of load versus concrete and laminate strain for beam with 20 mm width laminate.

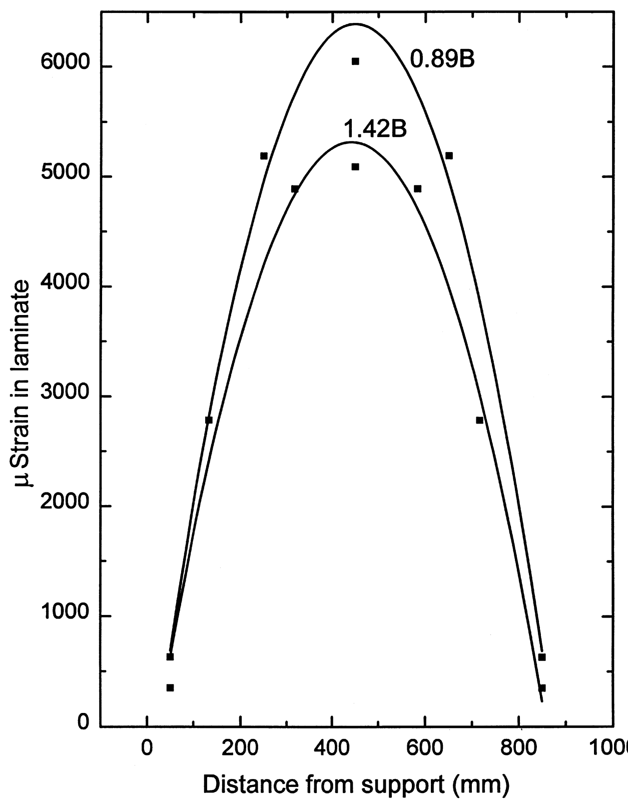

Fig. 8. Variation of laminate strain along the length of beam at ultimate load.

and 1.42B beams) along the length of beam is shown in Fig. 8. The ultimate strain seems to vary parabolically along the length of the beam.

5.4.2. Concrete strains

The test and theoretical concrete strains at ultimate load are given in columns 5 and 6 of Table 4, respectively. The 0.52B beam has higher strain compared to other two beams indicating this beam has undergone more curvature at ultimate load. There is not much of difference between test strains for 0.89B and 1.42B beams. From this fact it can be concluded that below a certain width of the laminate, the curvature will be excessive which is not good from serviceability point of view. The concrete strain in case of 0.42B beam is less than the remaining two beams. This is due to failure of this beam by laminate rupture as predicted by model, which did not happen in experiment where it failed by laminate peeling due to flexural-shear crack.

5.4.3. Steel strains

Load capacities of different beams at steel yield are given in column 2 of Table 5. The percentages of ultimate load at which steel has yielded are 49, 51, and 52 for 0.52B, 0.89B, and 1.42B beams, respectively. This ratio is useful in calculating the various types of ductilities for strengthened beams. From column 5, it can also be observed that there is a steady increase in steel yield load compared to virgin beam as the level of strengthening increases.

5.5. Crack pattern and failure modes

The crack patterns at collapse for the tested beams are shown in Fig. 9. The virgin beam exhibited widely spaced and lesser number of cracks compared to strengthened beams. The strengthened beams have also shown cracks at relatively close spacing. This shows the

Table 5
Steel yield loads

Type of beam	Steel yield load (kN)	Ultimate load (kN)	% of ultimate load	% increase in steel yield load
0.2B	6.14	9.88	62.14	–
0.42B	10.33	21.20	48.70	68.24
0.89B	11.89	23.20	51.25	93.65
1.42B	15.07	28.88	52.18	145.43

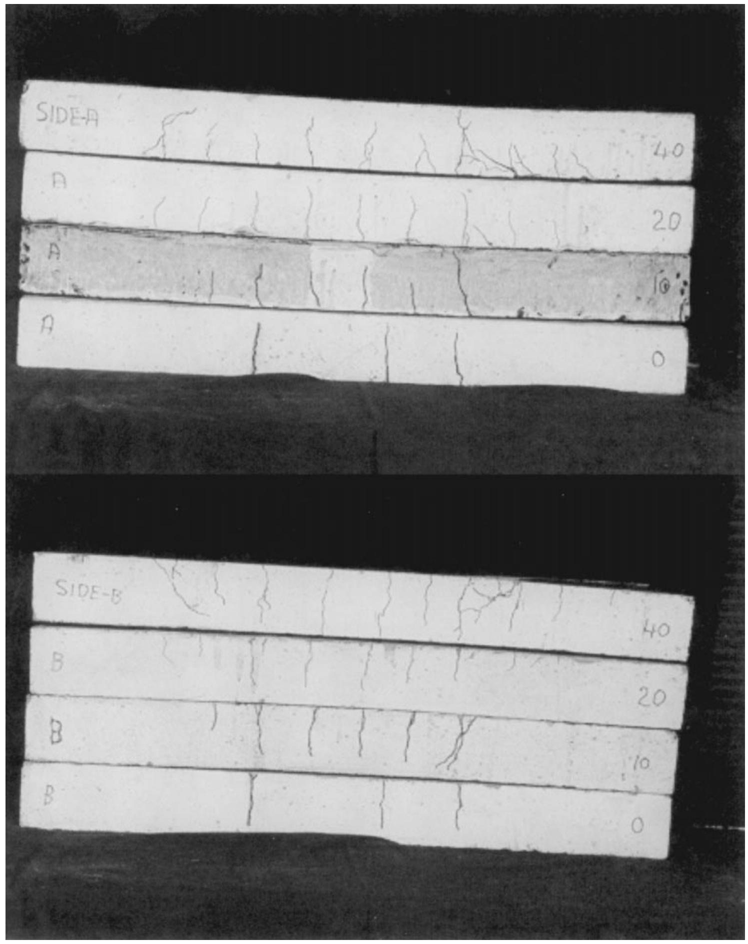

Fig. 9. Crack pattern of strengthened beams.

enhanced concrete confinement due to the CFRPC laminates. This composite action has resulted in shifting of failure mode from flexural failure (steel yielding) in case of virgin beam to peeling of CFRPC laminate in case of strengthened beams. The debonding has taken place due to flexural-shear cracks (shear span to effective depth ratio is less than six) by giving cracking sound. A crack normally initiates in the vertical direction and as the load increases it moves in inclined direction due to the combined effect of shear and flexure. If the load is increased further, cracks propagate to top and the beam splits. This type of failure is called flexure-shear failure.

5.6. Ductility

Three different ductility ratios namely deflection, curvature and energy were calculated for all types of specimens. Here the load at which steel has yielded has taken as the benchmark for measuring various ductilities. Ductility ratios were obtained by dividing the ductility indices by corresponding ductility index of virgin beam. The ductility ratios for various beams are presented in Table 6. It can be noted from Table 6 that as the laminate width increases the ductilities of beams reduce. This is true in all the three cases of ductility ratios. The lowest ductility ratios were found to be from deflection criteria. The ductility of 1.42B beam is

Table 6
Experimental and theoretical ductility ratios

Type of beam	Deflection ductility		Curvature ductility		Energy ductility	
	Expt. (avg.)	Theory	Expt. (avg.)	Theory	Expt. (avg.)	Theory
0.2B	1	1	1	1	1	1
0.52B	0.67	0.97	0.88	0.98	0.77	0.89
0.89B	0.51	0.92	0.62	0.95	0.57	0.65
1.42B	0.34	0.85	0.38	0.78	0.49	0.58

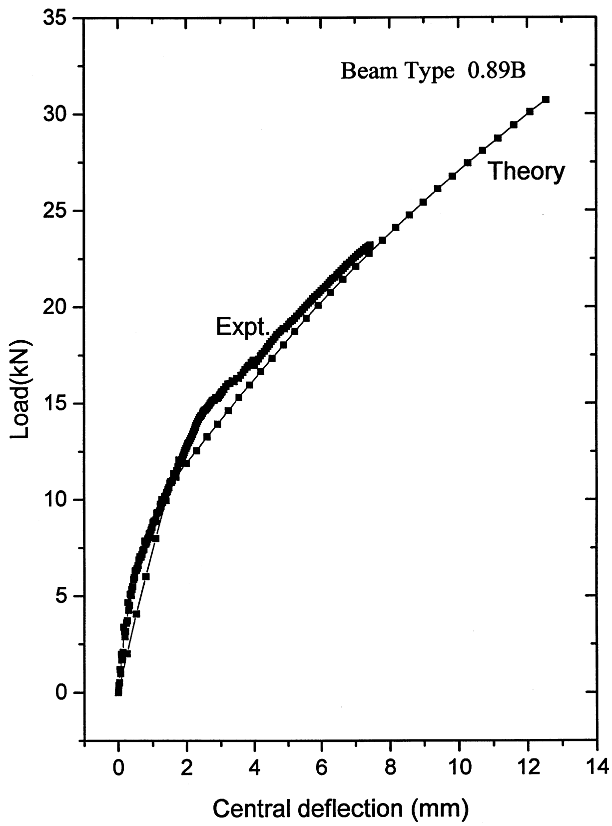

Fig. 10. Comparison of load versus deflection for beam with 20 mm width laminate.

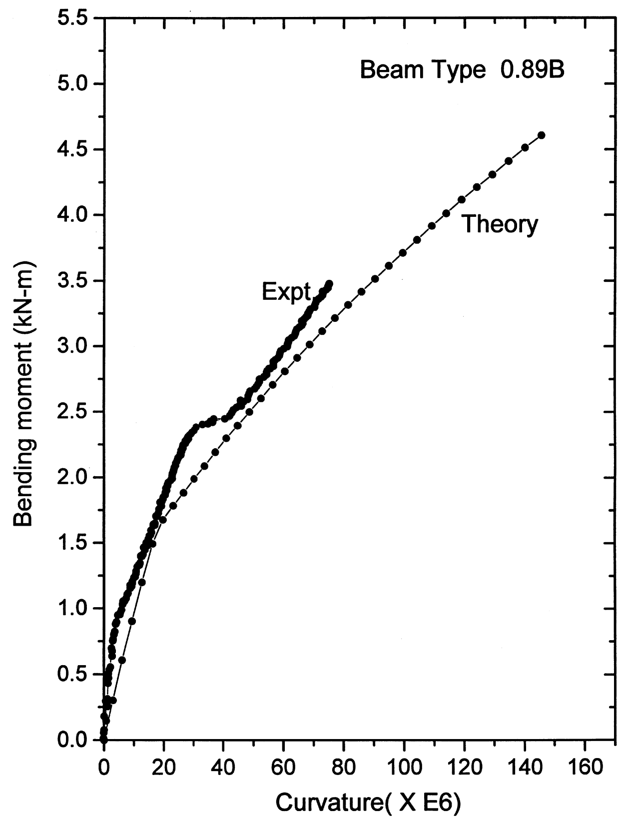

Fig. 11. Comparison of bending moment versus curvature for beam with 20 mm width laminate.

about 35, 38, 50% of 0.2B beam by deflection, curvature and energy ductility criteria, respectively.

5.7. Comparison of experimental and theoretical results

Comparison of the experimental and predicted load–deflection curve for the 0.89B beam is shown in Fig. 10. It can be seen from this figure that the model has predicted the load deformation behavior with in reasonable limits. But the ultimate moments for all strengthened beams were not in close agreement with the experimental values. This can be explained due to the fact that the model does not take into account the debonding of laminate. It assumes perfect bond till the beam fails either by concrete compression or due to the rupture of CFRPC laminate. Fig. 11 shows the comparison of moment versu curvature relation for 0.89B beam. Similarly, Fig. 7 shows the comparison of load versus laminate and concrete strains at the center. From these figures it can be concluded that the model has predicted curvature, laminate and concrete strains of strengthened beams with reasonable accuracy.

6. Conclusions

1. The first crack ultimate moments of strengthened beams were significantly higher than that of virgin beam indicating the reinforcing effect of the CFRPC laminate. The maximum increase in first crack and ultimate moments were about 150 and 230%, respectively.
2. There is a substantial increase in the stiffness of strengthened beams and the maximum increase is about 110% in case of over-reinforced strengthened beam. The deflections at ultimate load seem to reduce as the degree of strengthening increases. This has resulted in reduced ductility of strengthened beams. The ductility ratios by deflection criteria seem to be lower compared to curvature and energy ductility ratios.
3. As the degree of strengthening increases, the laminate strain and concrete strain at the center have reduced indicating the reduced curvature of the beam. The maximum strain in case of highest laminate width beam is less than half of its failure strain. This indicates the under utilization of CFRPC material. For effective utilization of this material, end anchorage has to be used to avoid delamination.
4. The path of the load–deflection curve seems to be fairly in close agreement with the theoretical curve. But the model has predicted higher ultimate load. This can be ascribed to the assumption of perfect bond between concrete and laminate. Also the model has predicted strains (both laminate and concrete) and curvatures of the beam with reasonable accuracy.

5. All strengthened beams failed by typical peeling of CFRPC laminate due to flexural shear cracks. The cracks at ultimate load of strengthened beam were more in number compared to cracks of virgin beam indicating clearly the composite action due to CFRPC laminate.

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