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FLEXURAL AND CYCLIC BEHAVIOUR OF RC BEAMS RETROFITTED WITH CARBON FIBER REINFORCED POLYMER (CFRP) FABRICS

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ABSTRACT

This paper explores the flexural behaviour of carbon fiber reinforced polymer (CFRP) retrofitted reinforced concrete (RC) beams. For flexural strengthening of RC beams, a total of sixteen beams were cast and tested over an effective span of 3000 mm up to failure under static monotonic and compression cyclic loads. The beams were designed as under-reinforced concrete beams. Twelve beams were retrofitted with bonded CFRP fabrics in one layer, two layers and three layers which are parallel to beam axis at the bottom under virgin condition and tested until failure; the remaining four beams were used as control specimens. Static and cyclic responses of all the beams were evaluated in terms of strength, stiffness, ductility ratio, energy absorption capacity factor, compositeness between CFRP fabrics and concrete, and the associated failure modes. The theoretical moment-curvature relationship and the load-displacement response of the retrofitted beams and control beams were predicted by using FEA software ANSYS. Comparison has been made between the numerical (ANSYS) and the experimental results. The results show that the retrofitted beams exhibit increased flexural strength, enhanced flexural stiffness, and composite action until failure.

Keywords: Composite beams; CFRP fabrics; flexural strengthening; numerical (ANSYS); reinforced concrete.

1. INTRODUCTION

In recent years repair and retrofit of existing structures such as buildings, bridges, etc., has been amongst the most important challenges in Civil Engineering. The primary reason for strengthening of structures includes upgrading of its resistance to withstand underestimated loads, increase in the load carrying capacity for higher permit loads, such as due to increased

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perceived risk from seismic excitations, eliminating premature failure due to inadequate detailing, restoration of lost load carrying capacity due to corrosion or other types of degradation caused by aging, etc. The use of carbon fiber reinforced polymer (CFRP) in strengthening reinforced concrete (RC) structures has become an increasingly popular retrofit technique. The technique of strengthening reinforced concrete structures by externally bonded CFRP fabrics was started in 1980s and has since attracted researchers around the world [1].

Strengthening with externally bonded CFRP fabrics has shown to be applicable to many kinds of structures. Currently, this method has been applied to strengthen such structures as column, beams, walls, slabs, etc. The use of external CFRP reinforcement may be classified as flexural strengthening, improving the ductility of compression members, and shear strengthening. It is well known that reinforced concrete beams retrofitted with externally bonded fiber-reinforced polymer (FRP) or CFRP to the tension face can exhibit ultimate flexural strength greater than their original flexural strength. However, these FRP and CFRP retrofitted beams could lose some of their ductility due to the brittleness of FRP and CFRP plates. Retrofitted reinforced concrete beams with Glass Fiber-Reinforced Polymers (GFRP) or FRP plates [2] and [3]. They concluded that the flexural strength of reinforced concrete beams could be significantly increased by externally bonded GFRP of FRP plated to their tension surface. However, they indicated in their experimental research that the ductility of reinforced concrete beams using externally bonded GFRP or FRP was reduced, and the extent of reduction in ductility was dependent upon the original beams.

A relatively new technique involves replacement of the steel plates by fiber-reinforced polymers (FRP) in the form of fabrics or wraps [4], [5] and [6]. FRP offers the engineer an outstanding combination of properties such as low weight, easier site handling, immunity from corrosion, excellent mechanical strength and stiffness, and the ability of formation in long lengths, thus eliminating the need for lap joints [7] and [8]. Further, there has been a rapid progress in concrete technology that has resulted in the evolution of concretes having specified characteristics. The present study evaluates the performance of RCC beams with bonded CFRP fabrics in single layer and two layers at the soffit of the beam under static and and cyclic loading. CFRP fabrics have shown great promise to upgrade structural systems. An emphasis has been given to the strength and deformation properties of CFRP fabrics retrofitted RC beams. The theoretical moment-curvature relationship and the load - displacement response of the retrofitted beams and control beams were predicted by using FEA software ANSYS. Comparison is made between the numerical (ANSYS) and the experimental results and suitable conclusions are drawn based on the results obtained from laboratory experiments and numerical analysis.

2. EXPERIMENTAL INVESTIGATION

The test program consisted of casting and testing of sixteen beams, of which four were control beams, all of size 150×250×3200 mm length and designed as the beams of under reinforced section [9], reinforced with 2-12 # at bottom, 2–10 # at top using 6mm dia stirrups @ 150 mm c/c (Fig. 1). The beams were cast using M 20 grade concrete and Fe 415 grade steel.

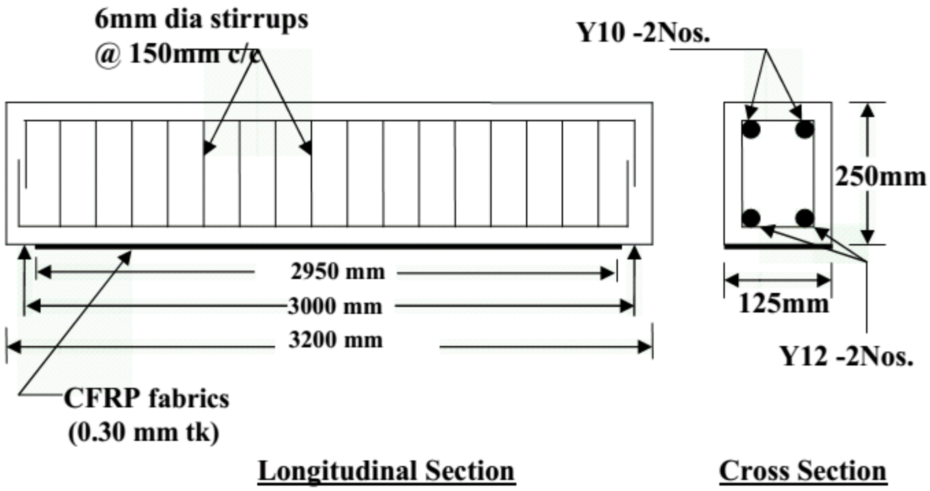

Figure 1. Longitudinal and cross section of retrofitted beam

Ordinary Portland cement, natural river sand and the crushed granite of maximum size 20 mm were used. High yield strength deformed (HYSD) bars of 12 and 10 mm diameter with mean strength of 512 N/mm^2 were used as longitudinal reinforcement and 6 mm diameter mild steel bars were used for internal links. The elastic modulus of the concrete is $2.4x10^4$ N/mm^2. After 28-day curing, companion cubes (150 mm) and cylinders (150 mm diameter x 300 mm height) cast along with the beams were tested in compression to determine the 28-day compressive strength and modulus of elasticity. In three series of retrofitted beams, first series having four beams with bonded CFRP fabrics in single layer which is parallel to beam axis, of which two beams were subjected to static loading, and remaining two beams were subjected to compression cyclic loading. In second series having four beams with bonded CFRP fabrics in two layers which are parallel to beam axis, of which two beams were subjected to static loading and remaining two beams were subjected to compression cyclic loading. In third series having four beams with bonded CFRP fabrics in three layers which are parallel to beam axis of which two beams were subjected to static loading and remaining two beams were subjected to compression cyclic loading under virgin condition and tested until failure. Each case two beams were taken for repeatability. The details of test beams are presented in Table 1.

The CFRP fabrics (Nitowrap EP (CF) from Fosroc Chemicals Limited) available in coil form of standard width of 1.0 m and orientation of fiber is unidirectional shown in Fig.2.

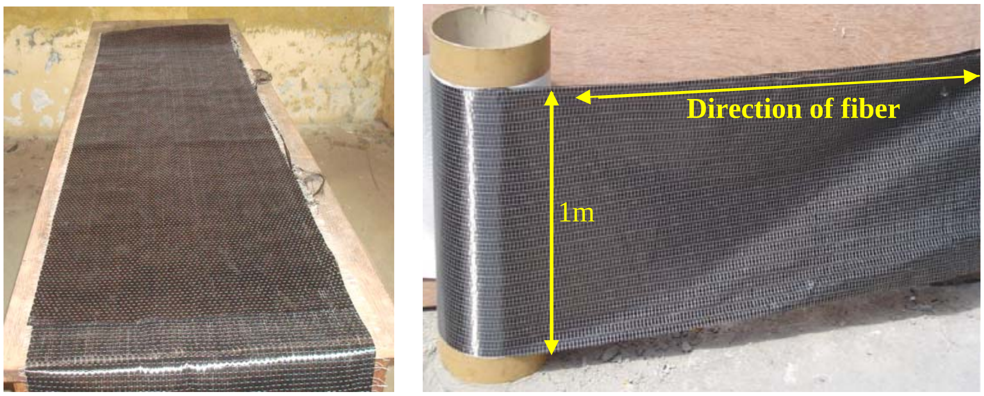

Figure 2. Carbon fiber

The soffit of the beams were sand blasted to remove the surface laitance and then blown free of dust using compressed air. The CFRP fabrics from is a carbon fiber composite wrapping system were adopted, in which Nitowrap (CF) is used in conjunction with an epoxy sealer cum primer Nitowrap 30 applied over the soffit of the beam, allow them to dry and then apply as a high build epoxy saturant Nitowrap 410 over the primer coat. The high build epoxy pot life is 2 hours at 30º C. The CFRP fabrics in single layer cut to size of 125×0.3×2950 mm

Table 1: Beam designation

Retrofitted Beam with Externally Bonded CFRP Fabrics										
Sl. No.	Beam Code	Beam Type and number of layers	Fabrics Thickness and Ultimate Elongation in Percentage	Fiber Orienta-tion	Tensile Modulus N/mm^2	Tensile Strength N/mm^2	Modulus of Elasticity N/mm^2	Density g/m^2	Types of Loading	Performance Evaluation
1.	CB1 and CB2	Control beam	-	-	-	-	-	-	Static loading	Strength, Stiffness, Ductility, Energy absorption capacity, Composite-ness and the Failure mode
2.	CB1 and CB2	Control beam	-	-	-	-	-	-	Compres-sion Cyclic loading	
3.	RBCF1 and RBCF2	GFRP retrofitted beam (one layer)	0.30 mm and 1.5	Unidirect-ional (parallel to beam axis)	$285x10^3$	3500	$1.55×10^5$	200	Static loading	
4.	RBCF3 and RBCF4	GFRP retrofitted beam (two layers)	0.30 mm and 1.5	Unidirect-ional (parallel to beam axis)	$285x10^3$	3500	$1.55×10^5$	200	Static loading	
5.	RBCF5 and RBCF6	GFRP retrofitted beam (three layers)	0.30 mm and 1.5	Unidirect-ional (paralle to beam axis)	$285x10^3$	3500	$1.55×10^5$	200	Static loading	

6.	RBCF7 and RBCF8	GFRP retrofitted beam (single layer)	0.30 mm and 1.5	Unidirect -ional (parallel to beam axis)	285x10^3	3500	1.55×10^5	200	Compres-sion Cyclic loading
7.	RBCF9 and RBCF10	GFRP retrofitted beam (two layer)	0.30 mm and 1.5	Unidirect -ional (parallel to beam axis)	285x10^3	3500	1.55×10^5	200	Compres-sion Cyclic loading
8.	RBCF11 and RBCF12	GFRP retrofitted beam (three layer)	0.30 mm and 1.5	Unidirect -ional (paralle to beam axis)	285x10^3	3500	1.55×10^5	200	Compres-sion Cyclic loading

Were placed over the beam which is parallel to beam axis and uniform pressing was done by grip roller head. The system is protected by a polyurethane top coat of Nitowrap 512 in case of atmospherically exposed structure. The retrofitted beams were tested after the interval of 7-days. The coin tap was conducted to identify areas of debond, if any. The same procedure was adopted bonding CFRP fabrics in two layers and three layers one over other which are parallel to beam axis and finished protective coating over third layer shown in Fig.3.

Figure 3. Finished with protective coating over third layer

Load, displacement and strains have been recorded. For each specimen electrical strain gauges were fixed at mid span of tension reinforcement and at the mid span of bottom surface of bonded CFRP fabrics in the longitudinal direction. Concrete having mean cube compressive strength of 27.54 MPa was used. For all the test beams, the parameters of interest were ultimate load, mid-span deflection, 1/3 span (both left and right) deflections, composite action, and failure modes. All the test beams were over-designed for shear to avoid the undesirable brittle failure. The CFRP fabrics thickness of 0.3 mm and bond line thickness 300 microns were kept constant for all the test specimens.

2.1 Testing and Measurements

All the beams were tested over a simply supported span of 3000 mm under four-point bending, the load of which was monotonically increased under static loading and compression cyclic loading. (Figs. 4 and 5). The vertical mid-span and 1/3rd span deflections were measured using mechanical dial gauges of 0.01 mm accuracy and electrical strain gauges were used for finding the steel strain and composite strain. The crack development and propagation were monitored and marked during the progress of the test. The crack widths were measured using a crack detection microscope of 0.02 mm precision.

Figure 4. Test set up for static loading

Figure 5. Test set up for compression cyclic loading

2.2 Summary of Test Results

The test results on the strength and deformation properties of the control specimens and retrofitted beams are reported in Table 2 and 3.

Table 2: Summary of test results

Beam Code	First Crack Stage		Service Stage		Yield Stage		Ultimate Stage		Average Crack Width at Service Load (mm)
	Load (kN)	Central Deflection (mm)	Load (kN)	Central Deflection (mm)	Load (kN)	Central Deflection (mm)	Load (kN)	Central Deflection (mm)	
CB1	15	3.40	27.50	14.66	34.37	18.33	41.25	22.00	0.11
RBCF1	20.00	3.35	33.67	13.95	41.25	16.20	50.50	20.93	0.09
RBCF3	25.00	3.30	40	12.82	50.00	15.15	60.00	19.88	0.08
RBCF5	32.00	3.00	46.67	11.91	61.50	13.89	70.00	17.87	0.06

Table 3: Derived information

Beam Code	Ductility Factor	Energy Capacity Factor	Post Cracking-Pre yielding Stiffness (kNm^2)	Mode of Failure
CB1	1.20	1.15	935	Flexure
RBCF1	1.30	2.20	1183	Flexure
RBCF3	1.31	2.40	1197	Flexure
RBCF5	1.28	2.80	1597	Flexure

A quantitative measure of ductility has to be with reference to a load-deflection response. Then, the ratio of the ultimate deformation to the deformation at the beginning of the horizontal path (or, at first 'yield') can give a measure of ductility. However, each choice of deformation (strain, rotation, curvature, or deflection) may give a different value for the ductility measure [10]. Yield load has been taken at the point of change of gradient of the load deflection curve. Service load has been obtained by applying normal partial safety factor to the ultimate load.

Energy absorption capacity can be measured under the area of stress-strain curve (load-deflection curve). The first crack loads were obtained by visual examination only. The experimental ultimate loads were obtained corresponding to the load beyond which the beam would not sustain additional deformation at the same load intensity. Based on the experimental results, it can be observed that significant increase in strength can be realised at all the load levels by externally bonding CFRP fabrics. This increase may be attributed to the increase in tensile cracking strength of concrete due to confinement. Further it is to be noted that increase in load carrying capacity is possible only when other modes of failure do not interfere. All the retrofitted beams were also carefully examined prior to and after testing. It was found that failure did not occur at the CFRP fabrics-concrete interface. This confirms that the composite action continued throughout the load spectrum.

The details presented in Tables 2 and 3 show that the beams RBCF5 is performing well in all respects and RBCF6 exhibited slight decrease in all the properties because of sustained load effect. The load-mid span deflection graphs were drawn for control and retrofitted beams both in static and compression cyclic loading as shown in Figs.6 to 11. From the graph it is seen that beam RBCF5 exhibits increased flexural strength and decreased deflection.

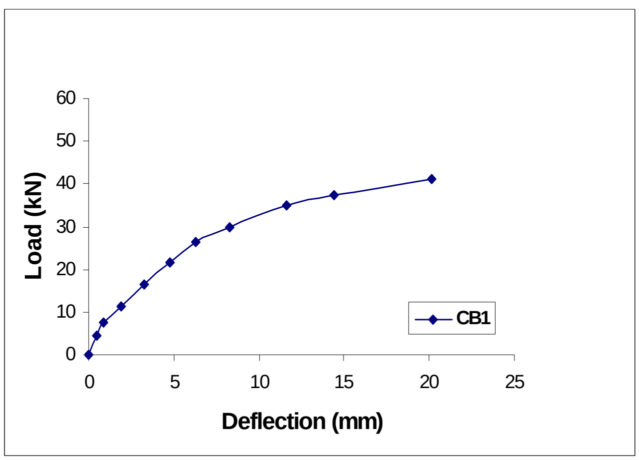

Figure 6. Load-deflection curves for CB1 (static loading)

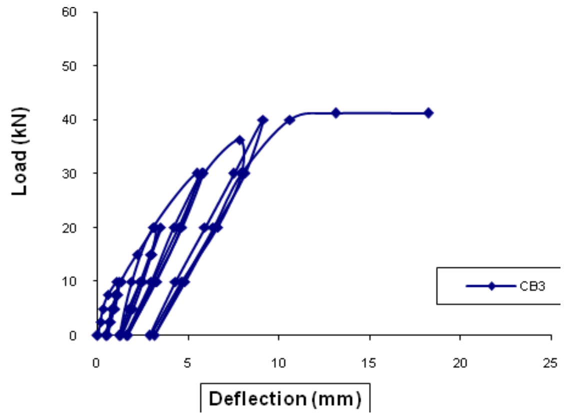

Figure 7. Load-deflection curves for CB3 (compression cyclic loading)

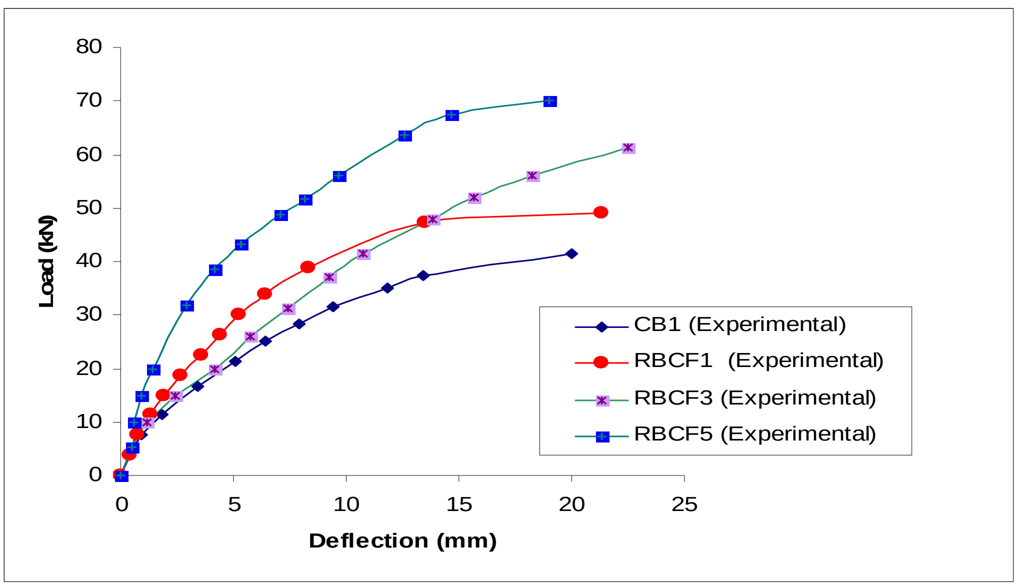

Figure 8. Load deflection curve for control beam and CFRP retrofitted beams in one, two and three layers (static loading)

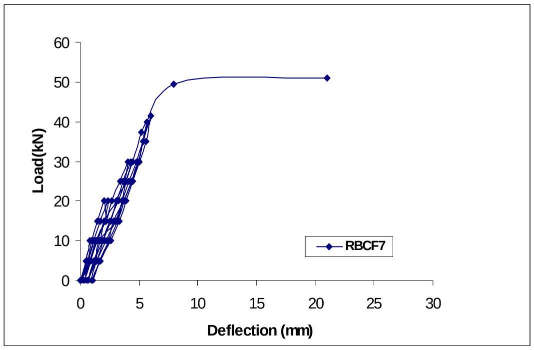

Figure 9. Load deflection curve for beam RBCF7 (one layer)

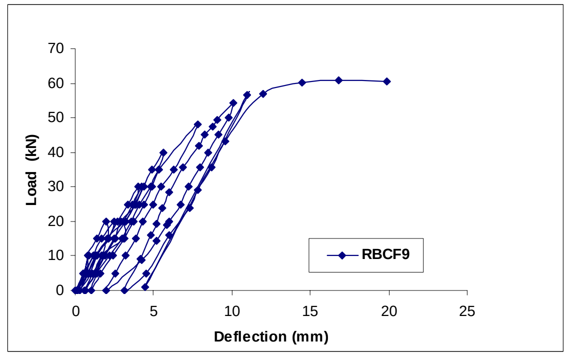

Figure 10. Load deflection curve for beam RBCF9 (two layers)

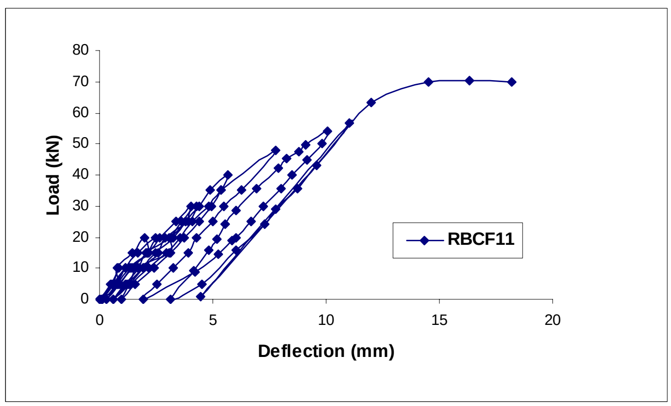

Figure 11. Load deflection curve for beam RBCF11 (three layers)

During the test, the crack patterns in the beams were noted and the crack patterns were closely analysed. The crack patterns of the beams are shown in Fig. 12 and also the crack width of control beams and retrofitted beams are reported in Table 2 and 3.

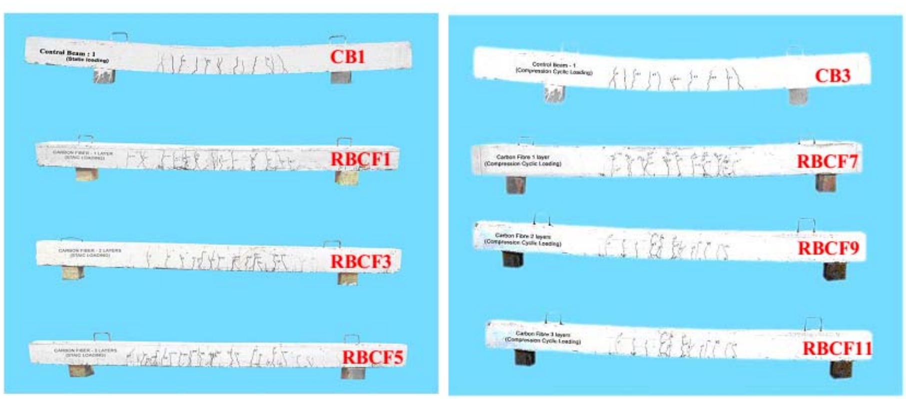

Figure 12. Crack pattern of tested beams (static and compression cyclic loading)

3. NUMERICAL (ANSYS) RESULTS OF LOAD-DEFLECTION BEHAVIOUR

FEA software ANSYS is adopted for predicting the load-displacement response of the control and retrofitted beams numerically. The mesh model defined 375 nodes and 47 elements. The programme offers solid 65 for beam element (Fig.13), link 8 for steel element (Fig.14) and solid 45 for CFRP fabrics element [11]. The generated model for beams CB1, RBCF1, RBCF3 and RBCF5. The element discretization, loading pattern and boundary conditions in FEA model (ANSYS) for RBCF5 beam is shown in Fig.15. A typical deflected shape at ultimate stage of retrofitted beam (RBCF5) is shown in Fig.16. The experimental and numerical (ANSYS) load-deflection curves are compared for both control beam CB1 and retrofitted beams RBCF1, RBCF3 and RBCF5 are shown in Fig.17. It can be seen that the predicted deflections are in close agreement with the experimental results. Comparisons of ultimate loads for experimental and numerical (ANSYS) results are shown in Table 4.

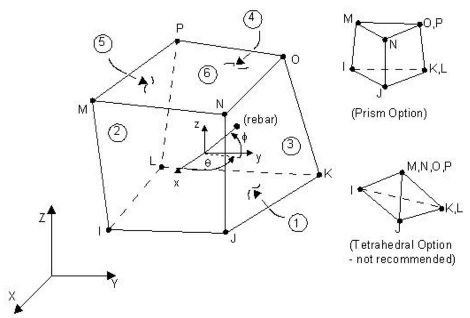

Figure 13. Solid 65 and solid 45 geometry

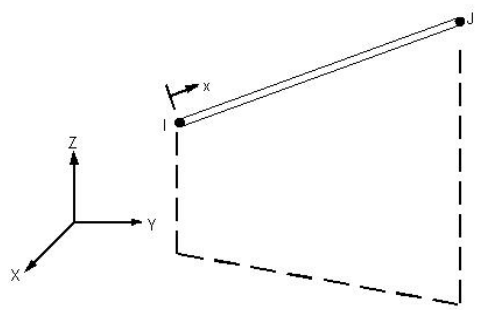

Figure 14. Link 8 geometry

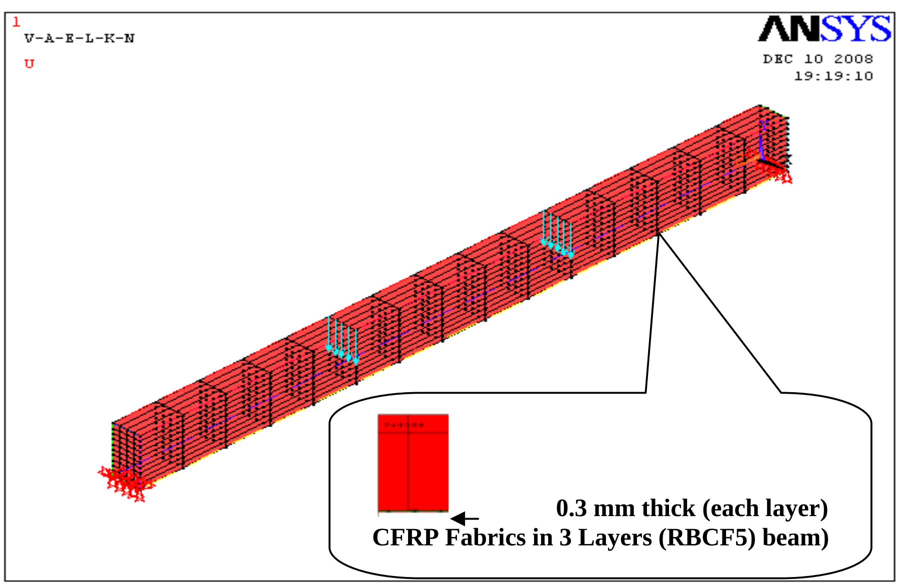

Figure 15. Element discretization, loading pattern and boundary conditions (RBCF5)

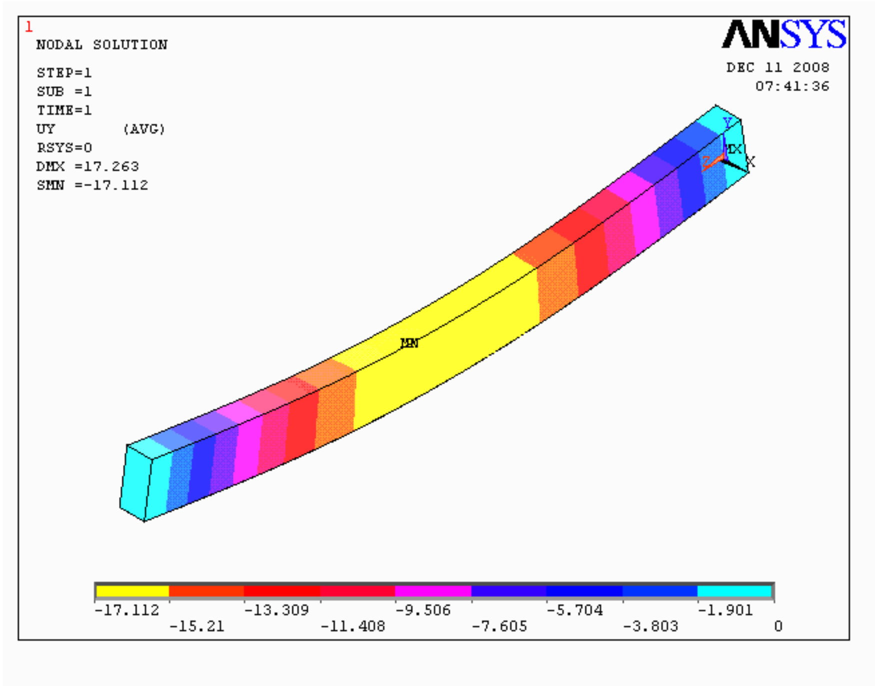

Figure 16. Deflected shape of retrofitted beam RBCF5 at ultimate stage

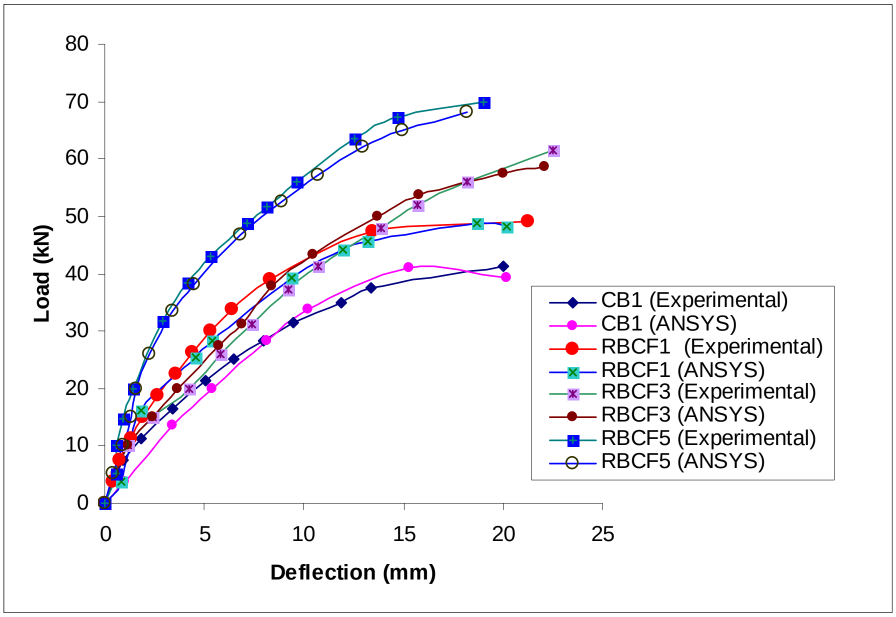

Figure 17. Load - deflection curve for control beam CB1 and retrofitted beams RBCF1, RBCF3 and RBCF5

Table 4: Comparisons of ultimate loads

Sl. No	Detail of Beam	Ultimate Loads in kN		Percentage Increase in Flexural Capacity	
		Experimental	Numerical (ANSYS)	Experimental	Numerical (ANSYS)
1.	CB1	41.25	41.00	-	-
2.	RBCF1	50.50	48.00	22	17
3.	RBCF3	60.00	58.00	45	41
4.	RBSF5	70.00	65.00	70	63

7. CONCLUSIONS

Based on the results obtained from experiments, and theoretical analyses, the following conclusions are drawn:

CFRP fabrics properly bonded to the tension face of RC beams can enhance the flexural strength substantially. The retrofitted beams exhibit an increase in flexural strength of 18 to 20 percent for single layer and 40 to 45 percent for two layers and 68 to 70 for three layers for both static and compression cyclic loading respectively.

At any given load level, the deflections are reduced significantly thereby increasing the stiffness for the retrofitted beams. At ultimate load level of the control specimens, the retrofitted beams exhibit a decrease of deflection up to 80 percent.

All the beams retrofitted with CFRP fabrics in one layer, two layers and three layers experience flexural failures. None of the beams exhibit premature brittle failure.

A flexible epoxy system will ensure that the bond line in single layer, two layers and three layers CFRP retrofitted beams does not break before failure and participate fully in the structural resistance of the retrofitted beams.

From the experimental results it is clear that minimum two layers of CFRP fabrics should be bonded to get the desired results. The retrofitted beam RBCF1(single layer), RBCF3 (two layers) and RBCF5 (three layers) exhibit 22 percent, 45 percent and 70 percent respectively increase in flexural strength when compared to the control specimen and has close agreement with the experimental and numerical (ANSYS) results.

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