Retrofitting of RC Beams with Externally Bonded Simcon Laminates

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Abstract: This paper presents the results of experimental and analytical studies concerning the flexural strengthening of RC beams using externally bonded **S**lurry **I**nfiltrated **M**at **CON**crete **(SIMCON)** laminates. A total of four reinforced concrete beams were cast and tested in the laboratory over an effective span of 3000 mm. Three beams were strengthened with bonded **SIMCON** laminate at the bottom under virgin condition and tested until failure; the remaining one beam was used as control specimen. Static responses of all the beams were evaluated in terms of strength, stiffness, ductility ratio, energy absorption capacity factor, compositeness between laminate and concrete, and the associated failure modes. The theoretical moment-curvature relationship for the test specimen and the load-displacement response of the strengthened beams and control beam were predicted by using FEA software ANSYS. Comparison was made between the numerical (ANSYS) with the experimental and theoretical results. The results show that the strengthened beams exhibit increased flexural strength, enhanced flexural stiffness, and composite action until failure.

Key Words: Composite beams, Fiber reinforced concrete, SIMCON, Flexural retrofit, Metal fibers.

1. INTRODUCTION

The cost of civil infrastructure constitutes a major portion of the national wealth. The rapid deterioration of reinforced concrete structures has thus created an urgent need for the development of novel, long-lasting and cost-effective methods for repair, retrofit and new construction. As the number of civil infrastructure systems increases worldwide, the number of deteriorated buildings and structures also increases. Complete replacement is likely to be an increasing financial burden and might certainly be a waste of natural resources if upgrading or strengthening is a viable alternative [1].

A promising new way of resolving this problem is to selectively use advanced composites such as High-Performance Fiber Reinforced Cementitious Composites (HPFRCCs). With such materials novel repair, retrofit, and new construction approaches can be developed and that would lead to substantially higher strengths, seismic resistance, ductility, corrosion resistance and durability while also being faster and more cost-effective to construct than conventional methods [2]. In the present days life extension of structures through strengthening is becoming an essential activity. A host of strengthening systems has to be devised and adopted over the years. The choice of the strengthening system depends on the specific performance requirements. Plate bonding technique has gained widespread acceptance as a potential solution. Reinforcing concrete with steel greatly increases its usefulness as building materials. Although rebar and wire mesh provide the bulk of this reinforcement, steel fiber has gained an increasing share in the market. One promising new development uses steel fiber mats (Fig. **1**) to reinforce the concrete matrix. The new approach called **SIMCON** produces concrete components with extremely high flexural strength [3]**.** Since **SIMCON** is manufactured using pre-made continuous fiber mats, delivered in large rolls, fiber placement is substantially simplified.
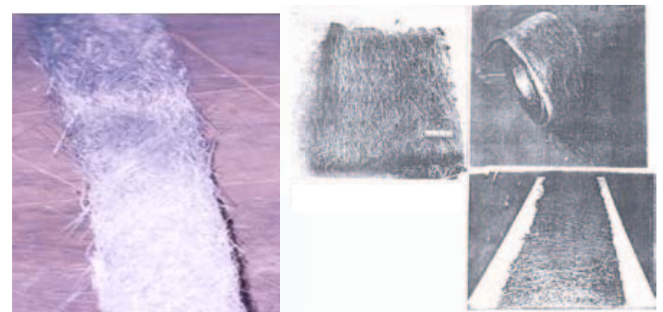

Fig. (1). Steel fiber mat.

Earlier, development SIFCON (Slurry Infiltrated Fiberous Concrete) was used in the field for retrofit and new construction. However, high placement cost and lack of fiber uniformity associated with manual distribution of discontinuous fibers have prevented its widespread field use [4]. All the above limitations can be overcome using **SIMCON**, which exhibits the improved features similar to SIFCON at a much lower fiber volume fraction. Since it is manufactured using pre-made continuous fiber mats, delivered in large rolls, fiber placement is substantially simplified [5].

SIMCON can also be considered a preplaced fiber concrete, the only difference being that the fiber is placed in a mat rather than discrete fibers. The fiber volume percent for manganese carbon steel mats ranged from 1.2 to 3.6 percent, while the stainless steel mats were placed to a density of 5.7 percent [6]. These fiber volumes can be increased somewhat by changing the fiber geometry. Fiber mat thickness ranges

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from 12 mm to 50 mm. The result of manufacturing process is a filter-like fiber mat in which 60-70 percent of fibers are aligned in a longitudinal direction while the remaining 30-40 percent of fibers are oriented at an angle of up to 50 degrees to the longitudinal direction. The width of roles are in between 300 and 350 mm with weights up to 2.224 kN for fibers made of steel with lengths of 300 mm or 350 mm, with a density of 7842 kg/m^3 [7].

SIMCON laminates have shown great promise to upgrade structural systems. The present study has been taken up for evaluating the effects of strengthening Reinforced Concrete (RC) beams with externally bonded **SIMCON** laminates. An emphasis has been given to the strength and deformation properties of **SIMCON** laminated RC beams. The theoretical moment-curvature relationship for the test specimen and the load-displacement response of the strengthened beams and control beam was 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 theoretical analysis.

2. EXPERIMENTAL INVESTIGATION

Preliminary experimental study was conducted to determine the optimum volume fraction and aspect ratio of fiber mat. Fourty-five laminates of size 125×25×500 mm were cast with different volume fraction (V_f), say 4.0 percent, 4.5 percent, 5.0 percent, 5.5 percent, and 6.0 percent and different aspect ratio (l/d) say 300, 400, and cocktail of 300 and 400. Among these combination the test results is found that V_f = 5.5 percent gives better performance with regard to ultimate load (U.L) and stiffness.

In this study uniform and mixed aspect ratio, say 300, 400, and cocktail of 300 and 400 were used, so that the length of the fiber is 150 and 200 mm, respectively, in such a way that as per volume fraction 60 percent of fibers aligned in the longitudinal direction and the remaining 40 percent of fibers aligned in the inclined direction not exceeding 50 degrees with the horizontal. Every mat has four or five layers of fibers as per V_f and the individual fibers are bonded with low viscosity epoxy resin that should not affect the voids between the individual fibers for achieving perfect cement grout. The final form of the fiber mat is just like filter mat. After spraying the resin the mat was held in position by compression machine under 50 kN at 30 minutes and then allowed for 24 hours air curing. Then the fiber mats were kept in the mould and were grouted; the cement slurry was

mixed in a mortar mixer with super plasticizer for improving workability with reduced water cement ratio and to have adequate fluidity in order to facilitate construction of specimens. Hence great care has been taken in choosing the constituent materials based on different trial mix. Mixing ratio of the cement slurry is given below:

Sand /cement	- 0.50
Water/cement ratio	- 0.30
Super plasticizers / Cement	- 0.025

Conplast 430 is used as super plasticizer. The purposes for which the admixture is used are as follows: water reduction, which increases strength and reduces permeability; improvement in impermeability; and air entrainment, which increases resistance to freezing and thawing. It is used for binding individual fiber and it posses very high mechanical and adhesive strength properties most desirable for civil engineering applications. Hand compaction and gravity feeding were used to produce thorough penetration of slurry into the preplaced steel fibers. Curing of **SIMCON** laminates was accomplished by covering with plastic sheets for 24 hours, followed by water submersion for 28-days after the curing period. The completed SIMCON laminates of size 125×250×2950 mm has one volume fraction and three aspect ratios, viz: V_f = 5.5 percent and aspect ratio 300, V_f = 5.5 percent and aspect ratio 400 and V_f = 5.5 percent and cocktail aspect ratio of 300 and 400 (Fig. **2**). Total of 4 beams, 125×250×3200 mm in size, were cast and tested in the laboratory over an effective span of 3000 mm. Of the above four beams, one beam was used as control specimens (CB1), and three beams (RB1, RB2 and RB3) were strengthened with bonded SIMCON laminates (125×250×2950 mm) at the bottom under virgin condition and tested until failure. The details of test beams are presented in Table **1**.

The beams are under reinforced section [8], reinforced with 2-12 # at bottom, 2–10 # at top using 6mm dia stirrups @ 150 mm c/c (Fig. **3**). M 20 concrete and Fe 415 grade steel are used.

The soffit of the beams were sand blasted to remove the surface laitance and then blown free of dust using compressed air. After surface preparation, the adhesive components were mixed thoroughly and applied to the surface using a trowel. The SIMCON laminates already cast were placed over the beam and held in position by dead weights. The strengthened beams were tested after the interval of 14-days. The coin tap was conducted to identify areas of
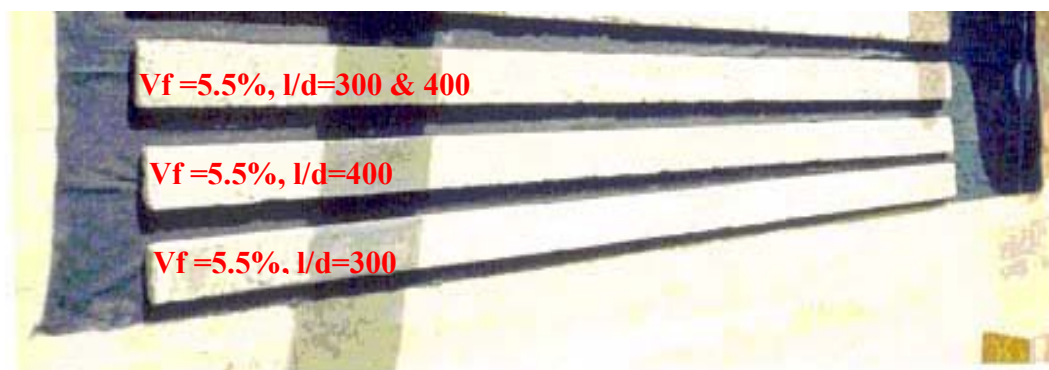

Fig. (2). SIMCON Laminates.

Table 1.   Beam Designation

Sl. No	Beam Number	Beam Type	Laminate Details		Laminate Properties			
			Volume Fraction (V_f)	Aspect Ratio (l/d)	Compressive Strength N/mm^2	Tensile Strength N/mm^2	Modulus of Elasticity N/mm^2	Density kg/m^3
1.	CB1	Control Beam	-	-	-	-	-	-
2.	RB1	SIMCON laminated beam	5.5 percent	300	88	17	2.2×10^4	7695.97
3.	RB2	SIMCON laminated beam	5.5 percent	400	85	15	2.1×10^4	7675.65
4.	RB3	SIMCON laminated beam	5.5 percent	300 and 400	80	14	2.0×10^4	7670.52
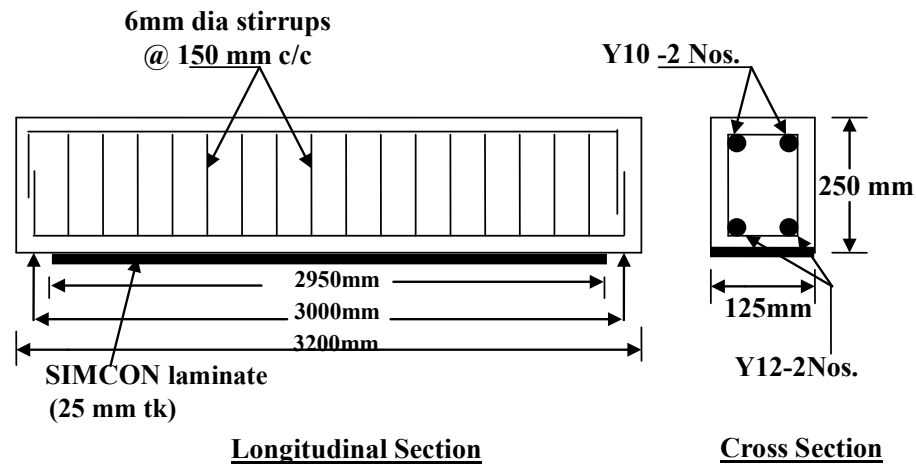
Fig. (3). Longitudinal and Cross Section of Strengthened.

debond, if any. Beams were tested in four point bending as shown in Fig. (**4**).

Fig. (4). Test Set Up for Static Loading.

   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 SIMCON laminates in the longitudinal direction. Concrete having mean cube compressive strength of 27.54 MPa was used. 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 2.4×10^4 N/mm^2. Three numbers of SIMCON laminates of 25 mm thick were used for externally strengthening the RC beams. A two-part epoxy adhesive (corocretin 1HS – BV comp A1 as a base material and corocretin 1HS – BV comp B1 as a hardener with filler for corocretin A1 – 100/200 and filler for corocretin B1- 300 mesh) with paste like consistency was used to bond laminates to the beam soffits. The adhesive had an ultimate tensile strength of 34.80 N/mm^2 and elastic modulus of 1500 N/mm^2. 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 SIMCON laminate thickness of 25 mm and bond line thickness 2.0 mm were kept constant for all the test specimens.

3. TESTING AND MEASUREMENTS

   All the beams were tested under four point bending, the load of which was monotonically increased. 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.

4. SUMMARY OF TEST RESULTS

The test results on the strength and deformation properties of the control specimen and strengthened beams are reported in Table **2** and **3**.

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 [9].

Energy absorption capacity can be measured under the area of stress-strain curve (load-deflection cure). 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 SIMCON laminates. 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 strengthened beams were also carefully examined prior to and after testing. It was found that failure did not occur at the laminate-concrete interface. This confirms that the composite action continued throughout the load spectrum. The load-mid span deflection graphs were drawn for control and strengthened beams as shown in Fig. (**5**). From the graph it is seen that beam RB1exhibits increased deflection and flexural strength.

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	3.38	27.5	14.08	34.37	17.60	41.25	21.13	0.11
RB1	45.0	6.88	55.0	18.67	69.75	23.33	82.50	28.00	0.08
RB2	40.0	5.14	52.0	16.67	67.0	20.80	78.0	25.00	0.11
RB3	37.5	4.68	46.0	15.47	58.5	19.38	69.0	23.21	0.12

Table 3.

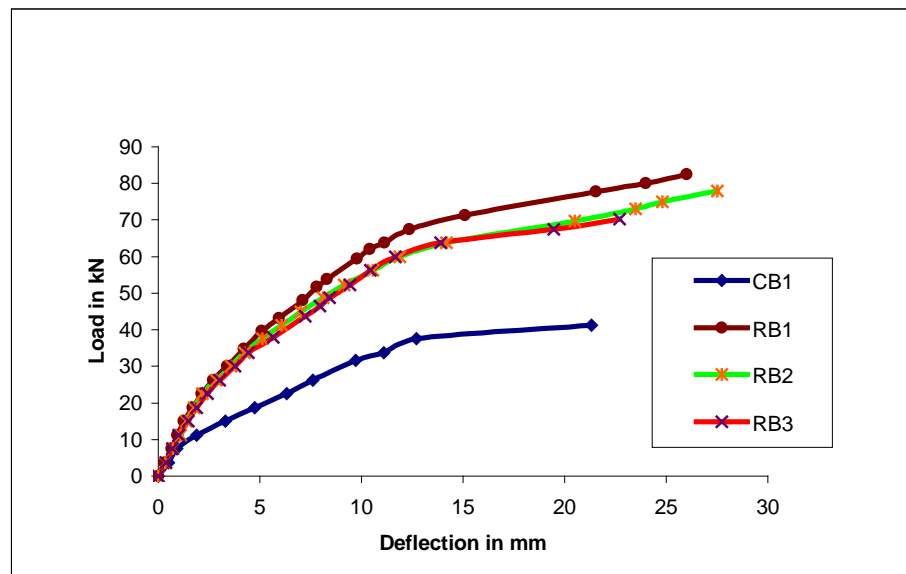| Beam Code	Ductility Factor	Energy Capacity Factor	Post Cracking-Pre yielding Stiffness (kNm^2)	Mode of Failure
CB1	1	1	860	Flexure
RB1	1.7219	1.644	2785	Flexure
RB2	1.3415	1.242	2545	Flexure
RB3	1.384	1.366	2335	Flexure

Fig. (5). Load-Deflection Curves.

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. (**6**) and also the crack width of control beam (CB1) and strengthened beams (RB1, RB2 and RB3) are reported in Table **2** and **3**.

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

FEA software ANSYS is adopted for predicting the load-displacement response of the control and strengthened beams numerically. The mesh model defined 375 nodes and 47 elements. The programme offers solid 65 for beam element (Fig. **7**), link 8 for steel element (Fig. **8**) and solid 45 for laminate element [10]. The generated model for beam RB1 is

shown in Fig. (**9**). A typical deflected shape of strengthened beam RB1 is shown in Fig. (**10**). A comparison of load-deflection and strain variation arising out of numerical analysis with that of experimental investigation has been presented in section 6.

6. THEORETICAL LOAD-DEFLECTION BEHAVIOUR (SECTION ANALYSIS)

The theoretical multilinear moment curvature (M-ϕ) relationships were derived for the control beam following the procedure given in Park and Paulay 1975 [11]. The three important stages or points identified in the M-ϕ curve are the cracking stage, yielding stage, and ultimate stage. In this study one more stage which corresponds to the start of non-
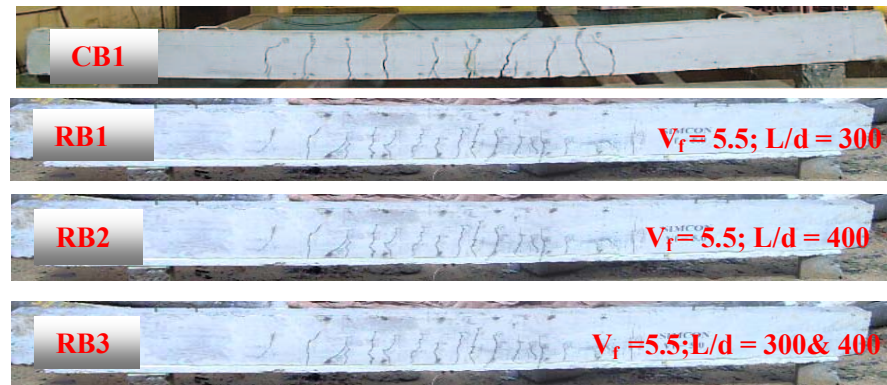

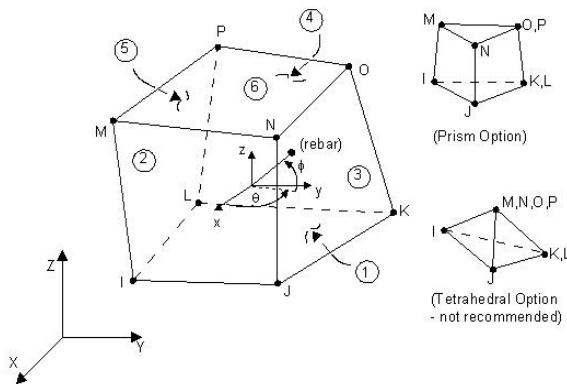**Fig. (6).** Crack Pattern of Tested Beams (CB1, RB1, RB2 & RB3).
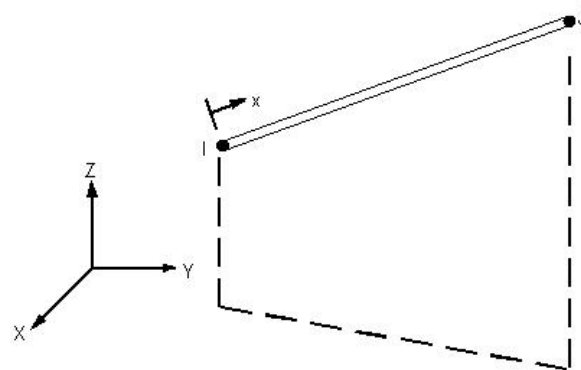

Fig. (7). Solid65 and Solid45 Geometry.
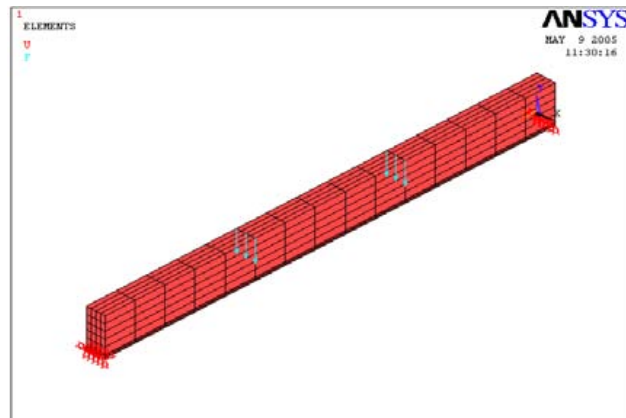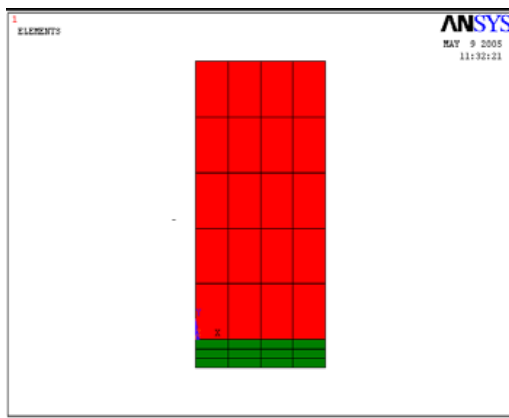
Fig. (8). Link8 Geometry.

Fig. (9). Element Discretization, Loading Pattern and Boundary Conditions in FEA.

linearity in stress strain curve of steel is proposed [12] and thus making it a multilinear curve. From the multi linear M-ϕ relationship multilinear load-deflection curve was derived by adopting a curvature distribution similar to that of a bending moment variation and conjugate beam method of analysis. The same procedure was adopted for uncracked beams bonded with SIMCON laminates of different aspect ratio. The experimental, numerical (ANSYS), and theoretical load-deflection curves are compared for both control beam (CB1) and strengthened beams RB1 in Figs. (**11**) and (**12**). It can be seen that the predicted deflections are in close agreement with the experimental results. Comparisons of ultimate loads for experimental, numerical (ANSYS), and theoretical (Section Analysis) results are shown in Table **4**. The details presented in Tables **2** and **3** show that the beam RB1 is performing well in all respects.
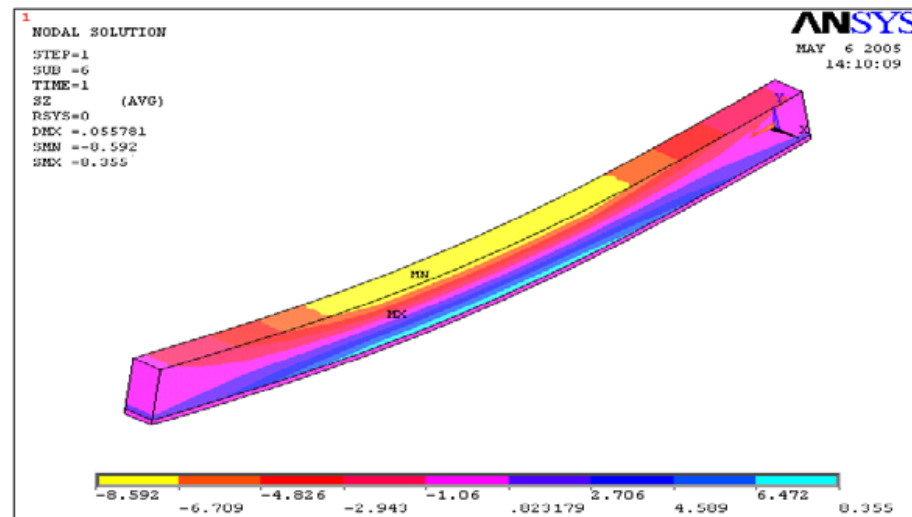

Fig. (10). Deflected Shape of Strengthened Beam RB1 (ANSYS).
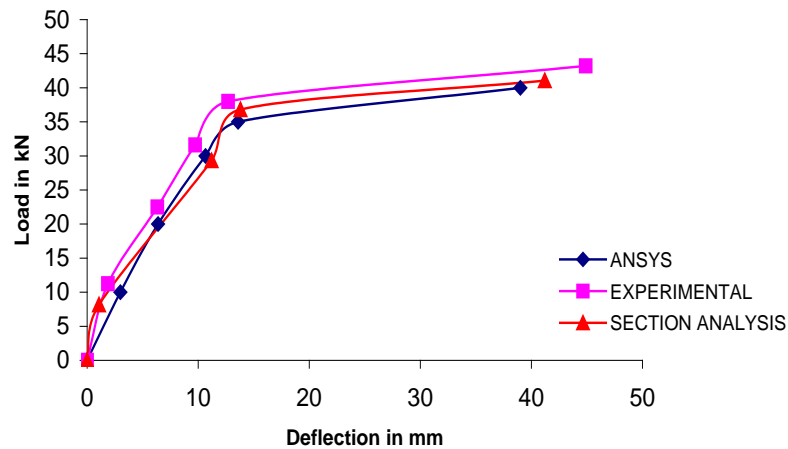

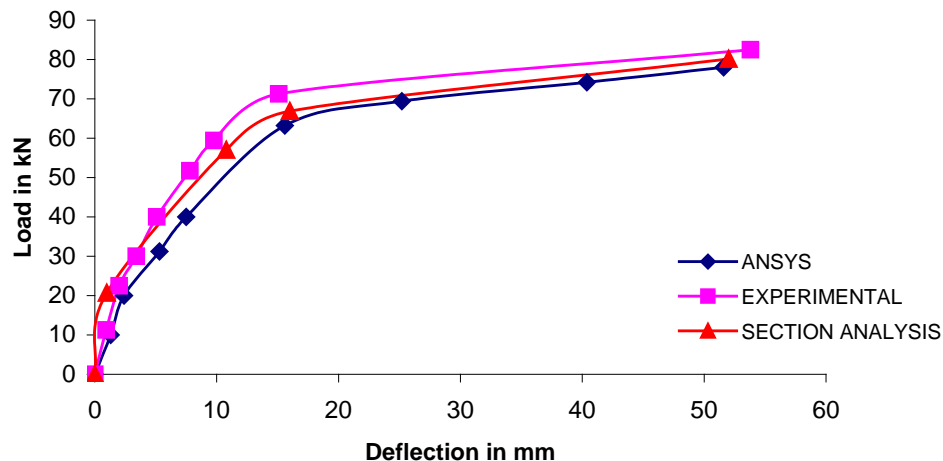**Fig. (11).** Load – Deflection Curve for Control Beam CB1.

Fig. (12). Load – Deflection Curve for strengthened Beam RB1.

Table 4.   Comparisons of Ultimate Loads

Sl. No	Detail of Beam	Ultimate Loads in kN			Percentage Increase in Flexural Capacity		
		Experimental	Numerical (ANSYS)	Theoretical (Section Analysis)	Experimental	Numerical (ANSYS)	Theoretical (Section Analysis)
1.	CB1	41.25	40.00	41.06	-	-	-
2.	RB1	82.50	78.00	80.14	100	95	95.18
3.	RB2	78.00	75.50	76.40	89.09	88.75	86.07
4.	RB3	60.00	58.00	59.10	45.45	45	43.94

7. CONCLUSIONS

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

1. **SIMCON** laminates properly bonded to the tension face of RC beams can enhance the flexural strength substantially. The strengthened beams exhibit an increase in flexural strength of 45.45 percent for laminates having volume fraction 5.5 percent and aspect ratio 300 and 400, 89.09 percent for volume fraction 5.5 and aspect ratio 400, and 100 percent for volume fraction 5.5 percent and aspect ratio 300.

2. At any given load level, the deflections are reduced significantly thereby increasing the stiffness for the strengthened beams. At ultimate load level of the control specimens, the strengthened beams exhibit a decrease of deflection up to 87 percent.

3. All the beams strengthened with **SIMCON** laminates with optimum volume fraction 5.5 percent and aspect ratio 300, 400, and 400 and 300 experience flexural failures. None of the beams exhibit premature brittle failure.

4. A flexible epoxy system will ensure that the bond line does not break before failure and participate fully in the structural resistance of the strengthened beams.

5. Among the three different volume fraction and aspect ratio of bonded **SIMCON** laminates, the strengthened beam RB1 of volume fraction 5.5 percent and aspect ratio 300 exhibit 100 percent increase in flexural strength when compared to the control specimen and has close agreement with the experimental, theoretical calculations (section analysis) and numerical (ANSYS) results.

6. The ultimate loads from the finite element analysis are lower than the ultimate loads from the experimental results by 3.10 percent to 5.80 percent. The ultimate loads from the theoretical calculations (section analysis) are lower than the ultimate loads from the experimental results by 0.50 percent to 2.90 percent.

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