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STRENGTHENING OF STRUCTURES BY HPFRCC LAMINATES

C. Antony Jeyasehar* and R. Balamuralikrishnan
Department of Civil and Structural Engineering, Annamalai University, Annamalainagar-608 002, Tamilnadu, India

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ABSTRACT

This paper presents the results of experimental, analytical and numerical studies concerning the flexural strengthening of RC beams using externally bonded High Performance Fiber Reinforced Cementitious Composites (HPFRCCs) like Slurry Infiltrated Fibre CONcrete (SIFCON) and Slurry Infiltrated Mat CONcrete (SIMCON). A total of ten reinforced concrete beams were cast and tested in the laboratory over an effective span of 3000 mm. Eight beams were strengthened with bonded SIFCON and SIMCON laminates at the bottom under virgin condition and tested until failure; the remaining two beams were 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. Comparisons were made between experimental, analytical and numerical results of SIFCON and SIMCON. The results show that the strengthened beams exhibit increased flexural strength, enhanced flexural stiffness, and composite action until failure.

Keywords: Composite beams; SIFCON; SIMCON; flexural strengthening; fiber reinforced concrete; metal fibers

1. INTRODUCTION

The cost of civil infrastructure constitutes a major portion of the national wealth. Its rapid deterioration has thus created an urgent need for the development of novel, long - lasting and cost - effective methods for repair and retrofit. 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. 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

* E-mail address of the corresponding author: chellam.ajs@gmail.com (C. Antony Jeyasehar)

waste of natural resources if upgrading or strengthening is a viable alternative *(Hollaway and Leeming 1999).* Many reinforced concrete buildings and structures need repair or strengthening to increase their load carrying capacities or enhance ductility under seismic loading *(Naaman and Reinhardt 1995; Hollaway and Leeming 1999).*

1.1 HPFRCCs

A promising new way of resolving this problem is to selectively use advanced composites such as High Performance Fibre 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, durability while also being faster and more cost - effective to construct than conventional methods. Normally two types of HPFRCCs available in the market namely SIFCON and SIMCON.

1.2 Slurry infiltrated fibre concrete (SIFCON)

SIFCON is a high-strength, high-performance material containing a relatively high volume percentage of steel fibres as compared to steel fibre reinforced concrete (SFRC). It is also sometimes termed as ‘high - volume fibrous concrete’. The origin of SIFCON dates to 1979, when Prof. Lankard carried out extensive experiments in his laboratory in Columbus, Ohio, USA and proved that, if the percentage of steel fibres in a cement matrix could be increased substantially, then a material of very high strength could be obtained, which he christened as SIFCON. While in conventional SFRC, the steel fibre content usually varies from 1 to 3 percent by volume, it varies from 4 to 20 percent in SIFCON depending on the geometry of the fibres and the type of application. The process of making SIFCON is also different, because of its high steel fibre content. While in SFRC, the steel fibres are mixed intimately with the wet or dry mix of concrete, prior to the mix being poured into the forms, SIFCON is made by infiltrating a low-viscosity cement slurry into a bed of steel fibres ‘pre-packed’ in forms / moulds. The matrix in SIFCON has no coarse aggregates, but a high cementitious content. However, it may contain fine or coarse sand and additives such as fly ash, micro silica and latex emulsions. The matrix fineness must be designed so as to properly penetrate (infiltrate) the fibre network placed in the moulds, since otherwise, large pores may form leading to a substantial reduction in properties. A controlled quantity of high - range water - reducing admixture (super plasticizer) may be used for improving the flowing characteristics of SIFCON. All types of steel fibres, namely, straight, hooked, or crimped can be used. The HPFRCCs were developed in the 1990's to improve performance characteristics of fibre reinforced concrete *(Naaman and Reinhardt 1995).* The dispersing of fibers and grouting process of SIFCON laminates are shown in Figure 1.

1.3 Slurry infiltrated mat concrete (SIMCON)

SIMCON can also be considered a pre - placed fibre concrete, similar to SIFCON. However, in the making of SIMCON, the fibres are placed in a “mat form” rather than as discrete fibres. The advantage of using steel fibre mats over a large volume of discrete fibres is that the mat configuration provides inherent strength and utilizes the fibres contained in it with very much higher aspect ratios. The fibre volume can, hence, be substantially less than that required for making of SIFCON, still achieving identical flexural strength and energy absorbing toughness.

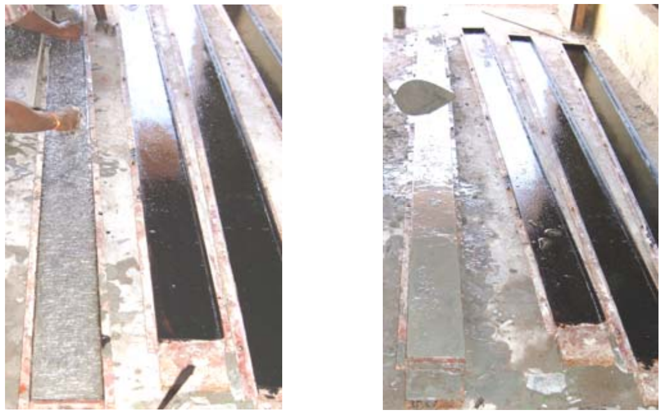


Figure 1. SIFCON laminates

Providing the fibres as a mat which is then infiltrated by high strength slurry, a new type of HPFRCC, called Slurry Infiltrated Mat CONcrete (SIMCON) can be produced (Figure 2). SIMCON is made using a non - woven “steel fibre mats” that are infiltrated with concrete slurry. Steel fibres produced directly from molten metal using a chilled wheel concept are interwoven into a 0.5 to 2 inches thick mat. This mat is then rolled and coiled into weights and sizes convenient to a customer’s application (normally up to 120 cm wide and weighing around 200 kg per metre).

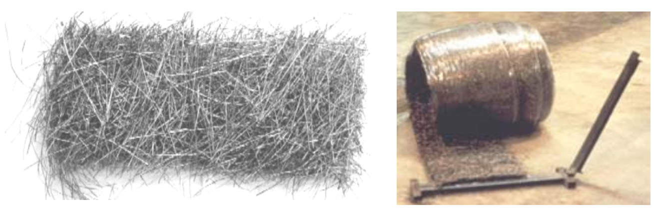


Figure 2. Steel fibre mat

By having the steel fibres in the form of a mat, placement and handling on a construction site are considerably easier *(Krstulovic and Al - Shannag 1999).* SIMCON is similar to that of SIFCON in that both use slurry infiltration methods. 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 SIFCON and SIMCON laminates.

2. EXPERIMENTAL PROGRAMME

2.1 Preliminary studies of SIFCON and SIMCON

The preliminary tests were conducted before casting the laminates based on ACI Committee

549-1997, ferrocement model code (FMC), and with reference to ACI - SP185, ACI - SP 172 to predict the mechanical properties of SIFCON and SIMCON. The properties of steel fibers are supplied by M/s STEWOLS & CO, Nagpur, India. The different combination SIFCON volume fraction (V_f) say 5.5 to 8.5 percent with increment of 0.5 percent and constant aspect ratio (l/d) of 70 were used to find optimum volume fraction. From the basic test (compression, tension and flexure) results, the laminate with optimum volume fraction $V_{f\,=}$ 8.0 percent and aspect ratio l/d = 70 performed well in all respects. From all the above test results, the mechanical properties used in this study are summarized below:

i. Density of SIFCON laminates = 1950 kg/m^3
ii. Steel fiber density = 7695.97 kg/m^3
iii. Optimum volume fraction = 8.0 percent
iv. Optimum aspect ratio = 70
v. Mean Compressive Strength of SIFCON laminates, f_{cm} = 90.20 N/mm^2
vi. Mean Tensile Strength of SIFCON laminates, f_{ct} = 14 N/mm^2
vii. Modulus of Elasticity of SIFCON laminates, E_r = 3.05×10^4 N/mm^2.

The different combination of SIMCON volume fraction say 4.0 to 6.0 percent with increment of 0.5 percent and three different aspect ratio l/d = 300, l/d = 400 and l/d = 300 & 400 cocktail fibers were used to find optimum volume fraction and aspect ratio. Similar basic tests were conducted. From the basic test (compression, tension and flexure) results, the laminate with optimum volume fraction V_f =5.5 percent and aspect ratio l/d = 300 performed well in all respects. From all the above test results, the mechanical properties used in this study are summarized below:

i. Density of SIMCON mat = 7695.97 kg/m^3
ii. Density of SIMCON laminates = 1800 kg/m^3
iii. Mean Compressive Strength of SIMCON laminates, f_{cm} = 88 N/mm^2
iv. Mean Tensile Strength of SIMCON laminates, f_{ct} = 17 N/mm^2
v. Modulus of Elasticity of SIMCON laminates, E_r = 2.70×10^4 N/mm^2

2.2 Casting of SIFCON and SIMCON laminates

In series 1, two numbers of SIFCON laminates of size 125×25×2950 mm were cast as per optimum volume fraction V_f = 8.0 and aspect ratio l/d = 70. 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 was 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 was used as super plasticizer. The hand dispersion of steel fibers as per volume fraction and aspect ratio and followed by grouting was carried out to complete the laminates. The completed SIFCON laminates (2 Nos.) are shown in Figure 3.

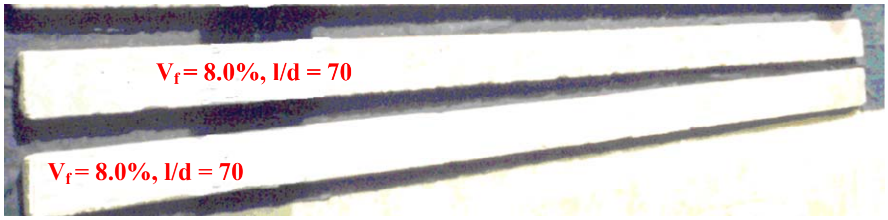


Figure 3. Completed SIFCON laminates

In series 2, six numbers of SIMCON laminates of size 125×25×2950 mm were cast with 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 were 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; 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 125×25×2950 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 (Figure 4).

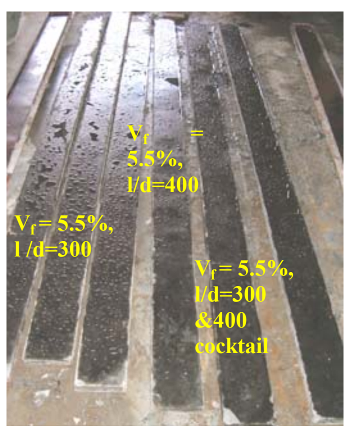


Figure 4. Finished SIMCON laminates

2.3 Casting of RC beams

Totally ten beams were cast and tested in the laboratory over an effective span of 3000 mm. Eight beams were strengthened with bonded SIFCON and SIMCON laminates at the bottom under virgin condition and tested until failure; the remaining two beams were used as control specimens. The beams were designed as under reinforced section (as per IS 456 - 2000), reinforced with 2 - Y12 at bottom, 2 - Y10 at top using 6 mm diameter stirrups at 150 mm c/c and M 20 concrete and Fe 415 grade steel are used. The details of test beams are presented in Table1. At the bottom 12 mm diameter cold twisted deformed steel bar are used as tension reinforcement having 0.2 percent proof stress of 512 N/mm^2, and two numbers of 10 mm diameter cold twisted deformed bars as hanger bars and 21 Nos. of 6 mm diameter, 2 legged stirrups (mild steel) provided at 150 mm c/c throughout the span as shear reinforcement. The mean strength of concrete 27.40 N/mm^2 used for beams.

The concrete mix proportion was 1:1.45:3.30 with water cement ratio 0.50. Ordinary Portland Cement (OPC) 53 grade, natural river sand conforming Zone III (IS 383-1970) and coarse angular aggregate of 20 mm size conforming Zone II (IS 383 – 1970) were used as the concrete ingredients. Before casting of beams, for each specimen 5mm electrical strain gauges of gauge factor 2.1 and gauge resistance 120 Ohm was fixed at mid span of tension reinforcement. The shuttering was removed after 24 hours from the time of casting and the specimens were cured using wet gunny bags. 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. The modulus of elasticity of concrete was 2.4×10^4 N/mm^2 and the poison's ratio was 0.19.

2.4 Bonding of SIFCON and SIMCON Laminates

Two numbers of SIFCON laminates and six numbers of SIMCON laminates of 25 mm thick were used for externally strengthening the RC beams. The soffit of the beams and bonding face of SIFCON and SIMCON laminates were sand blasted to remove the surface laitance and then blown free of dust using compressed air. After surface preparation, epoxy bonding systems were adopted to bond the laminates and bond line thickness 2.0 mm were kept constant for all the test specimens.

The strengthened beam with SIFCON and SIMCON laminate is schematically represented in Figure 5. Beams were tested in third - point loading (ASTM C78) the maximum stress is present over the center 1/3 portion of the beam under static monotonic loading which is schematically represented in Figure 6. The details of test beam are presented in Table 1.

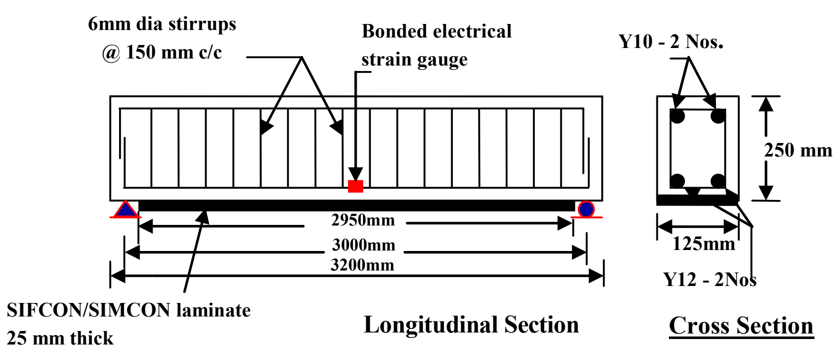


Figure 5. Details of test beam

The load-deflection relationships were obtained using deflection measurements from LVDTs and strain data collected from demec gauges for the control beams (CB1 and CB2), SIFCON strengthened beams (RBSF1 and RBSF2) and SIMCON strengthened beams

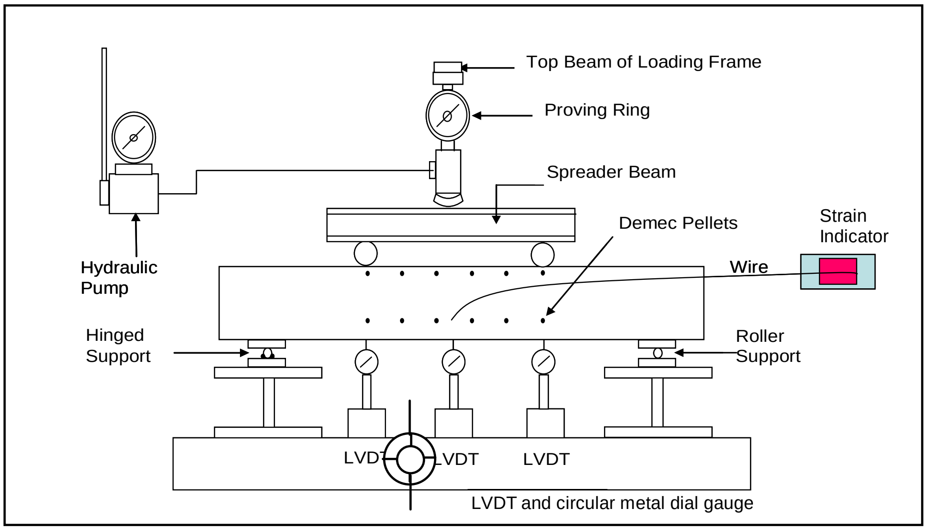


Figure 6. Static test set up

Table 1: Details of test beam

Sl. No.	Beam designation	Beam Type
1.	CB1 and CB2	Control beams
SERIES:1 Strengthened beam with externally bonded SIFCON laminates		
2.	RBSF1 and RBSF2	SIFCON laminated beams (V_f = 8 percent and l/d = 70)
SERIES:2 Strengthened beam with externally bonded SIMCON laminates		
3.	RBSM1 and RBSM2	SIMCON laminated beams (V_f = 5.5 percent and l/d = 300)
4.	RBSM3 and RBSM4	SIMCON laminated beams (V_f = 5.5 percent and l/d = 400)
5.	RBSM5 and RBSM6	SIMCON laminated beams (V_f = 5.5 percent and l/d = 300 and 400 cocktail)

(RBSM1 and RBSM2, RBSM3 and RBSM4, RBSM5 and RBSM6) under static monotonic loading, and are presented in Figures 7 and 8. From the load – deflection, it is seen that beams RBSF1, RBSF2 and RBSM1 and RBSM2 exhibit decreased deflection and appreciable flexural strength and enhanced ductility, energy capacity factor when compared to control beams. The first crack loads were obtained by visual examination only. It was found that failure did not occur at the laminate-concrete interface. The test results on the strength and deformation properties of the control specimens and strengthened beams are reported in Table 2. The ductility can be calculated from the load deflection response of the particular beam *(Pillai and Menon, 2002)*. The calculated results on the strength and deformation properties of the control specimens and strengthened beams are reported in Table 3.

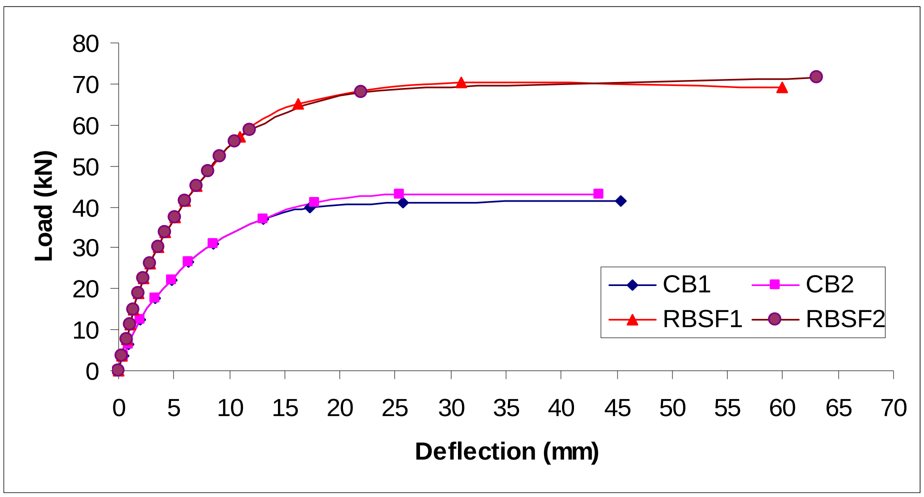


Figure 7. Load - deflection response of control beams and SIFCON laminated beams

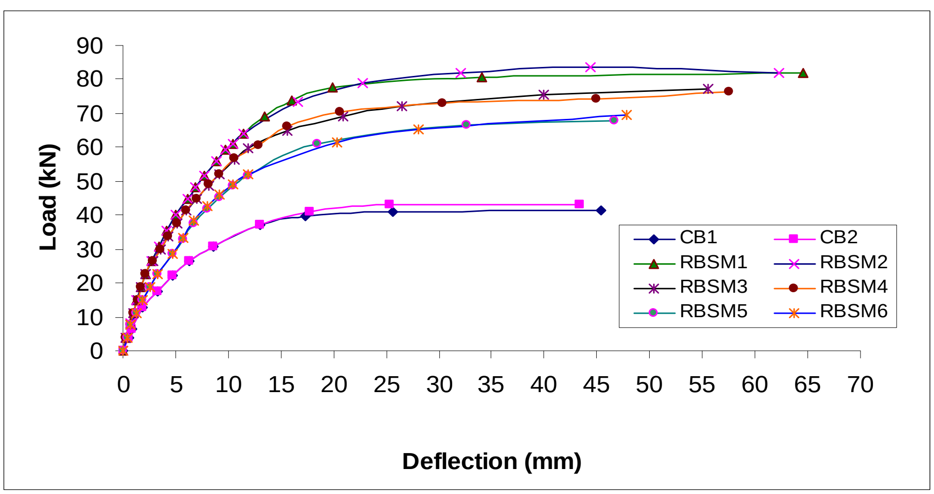


Figure 8. Load-deflection response of control beams and SIMCON laminated beams

Table 2: Details of test beam

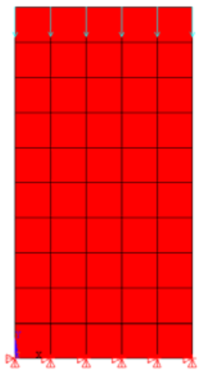
Beam code	First crack stage		Service stage		Yield stage		Ultimate stage		Average crack width at service load (mm)
	Load (kN)	Central deflection (mm)	Load (kN)	Central deflection (mm)	Load (kN)	Central deflection (mm)	Load (kN)	Central deflection (mm)	
CB1	15.00	6.38	30.00	27.50	33.75	23.00	41.25	45.00	0.18
CB2	14.90	7.40	28.00	28.80	33.80	22.70	42.00	43.20	0.17
RBSF1	32.50	8.64	46.33	40.33	54.00	31.01	69.50	60.50	0.12
RBSF2	32.25	8.67	46.43	40.50	54.10	30.05	69.75	60.75	0.13
RBSM1	45.0	9.28	55.0	43.66	69.75	34.47	82.50	65.50	0.08
RBSM2	45.15	9.22	55.20	43.00	69.85	34.70	82.58	64.57	0.08
RBSM3	40.00	8.00	52.0	37.33	67.0	29.40	78.0	56.00	0.11
RBSM4	40.12	7.92	52.12	37.00	67.25	29.20	78.20	55.50	0.11
RBSM5	37.25	6.61	46.12	30.85	58.58	24.35	69.50	46.28	0.12
RBSM6	37.50	6.75	46.00	31.47	58.5	24.84	69.0	47.21	0.12

Table 3: Strength and deformation properties

Beam code	Ductility (deflection) factor	Energy capacity factor	Post cracking-pre yielding stiffness (kNm^2)
CB1	1.90	1.65	1460
CB2	1.90	1.65	1470
RBSF1	3.04	2.52	2576
RBSF2	3.06	2.62	2566
RBSM1	3.10	2.15	3481
RBSM2	3.12	2.16	3482
RBSM3	2.48	1.90	3184
RBSM4	2.49	1.92	3187
RBSM5	2.21	1.80	2674
RBSM6	2.23	1.82	2679

3. 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 concrete element and link 8 for rebar, pipe 16 for dummy element and giving attachment with glue element *(ANSYS 7 user manual).* The models are generated for beams RBSF1, RBSM1 and control beams. Tee generated model for control beam is shown in Figure 9. A comparison of load-deflection and strain variation arising out of numerical analysis with that of experimental investigation has been presented in Table 4.



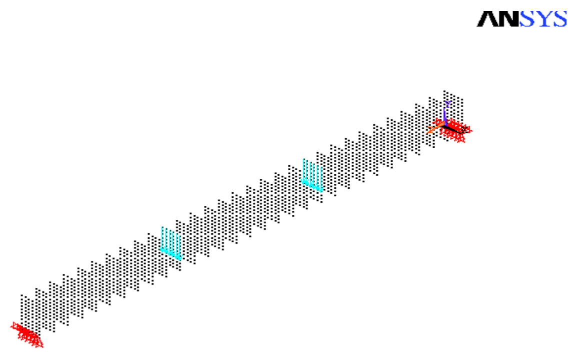


Figure 9. Element discretization, loading pattern and boundary conditions in FEA

4. THEORETICAL LOAD-DEFLECTION BEHAVIOUR (SECTION ANALYSIS)

The theoretical multilinear moment curvature (M-ϕ) relationships were derived for the perfect beam following the procedure given in Park and Paulay (1975). 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-linearity in stress strain curve of steel is proposed (*Antony Jeyasehar, 1999*) 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 RBSF1 and RBSM1 are shown in Figures 10 to 12. It can be seen that the predicted deflections are in fairly 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 3 and 4 show that the beam RBSM1 is performing well in all respects.

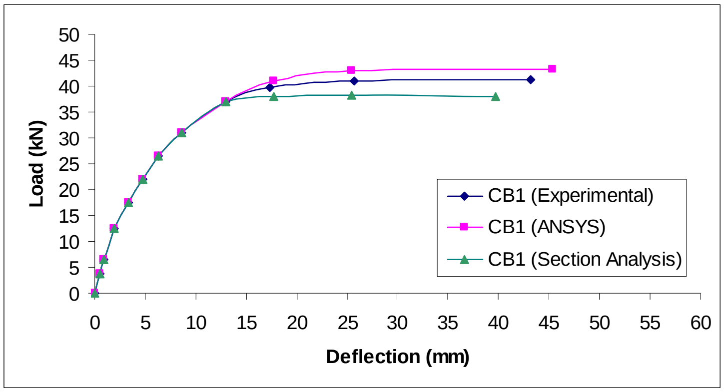


Figure 10. Comparison load – deflection curve for control beam CB1

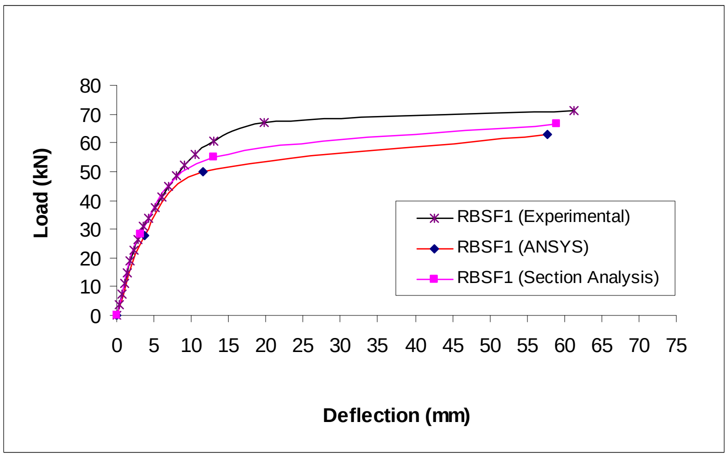


Figure 11. Comparison load – deflection curve for SIFCON strengthened beam

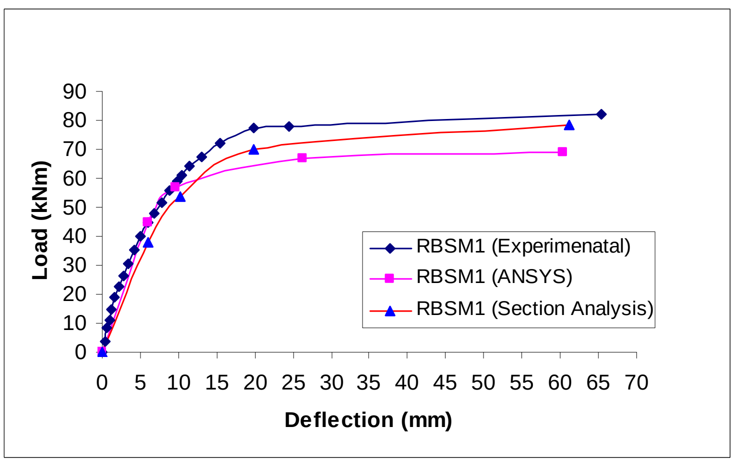


Figure 12. Comparison load – deflection curve for SIMCON strengthened beam

Table 4: Comparison 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	40.0	41.06	-	-	-
2.	RBSF1	69.75	60.50	65.50	69	51	60
3.	RBSM1	82.00	69.50	76.40	98	74	86

5. OVERALL PERFORMANCE EVALUATION

The performance of the beams (series 1 and 2) has been evaluated by considering the equivalent elastic forces using energy and deflection approaches *(Lakshmanan. N, 2003)*. The equivalent elastic forces P_{e1} and P_{e2} are computed considering the load deflection curve as shown in Figure 13

$$P_{e1} = \sqrt{[2A_e P_y] / \delta_y}$$
$$P_{e2} = P_y [\delta_u / \delta_y]$$

Where, A_e is an equivalent area (mm^2), P_y is yield load (kN), and δ_y and δ_u are deflections at yield and ultimate stages (mm). Hence it is felt that, to evaluate the overall performance of any repair measure, the following effectiveness factors may be used. The effectiveness factors F1 and F2 may be defined as,

$F_1 = P_{e1}$ (retrofitted) / P_{e1} (conventional) $\longleftarrow$ Energy Approach
$F_2 = P_{e2}$ (retrofitted) / P_{e2} (conventional) $\longleftarrow$ Deflection Approach

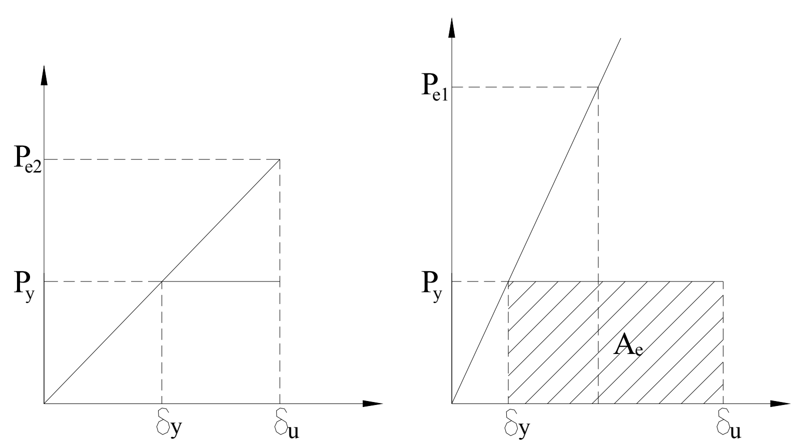


Figure 13. Computation of equivalent elastic force for ductile structures

The effectiveness factors evaluated using energy approach (F_1) and deflection approach (F_2) for the control beam (CB1 and CB2) and retrofitted beams series 1 and 2 say RBSF1and RBSF2, and RBSM1 to RBSM6) are given in Table 5. In both the series, F_1 varies from between 2.08 and 3.60, and F_2 varies between 1.95 and 3.37. It can be seen that SIMCON strengthened beams of V_f = 5.5 percent and l/d ratio 300 exhibits superior performance when compared to other beams.

Table 5: Effectiveness factors for beams (series 1-2)

Beam code	P_y	δ_y	δ_u	A_e	P_{e1}	P_{e2}	F_1	F_2
CB1	33.75	23.00	45.00	3819.32	105.77	66.00	1.00	1.00
CB2	33.80	22.70	43.20	3716.36	105.20	64.32	1.00	1.00
RBSF1	54.00	10.01	30.50	5419.32	241.80	164.54	2.30	2.50
RBSF2	54.10	10.05	30.75	5600.62	246.04	165.52	2.33	2.57
RBSM1	69.75	9.24	29.50	9400.12	376.18	222.57	3.55	3.37
RBSM2	69.85	9.28	29.57	9625.76	381.20	222.69	3.60	3.37
RBSM3	67.0	10.10	25.00	7225.76	309.55	165.84	2.92	2.51
RMSM4	67.25	10.17	25.50	7400.91	312.84	168.62	2.96	2.55
RBSM5	58.58	10.58	23.28	4387.62	220.43	128.90	2.08	1.95
RBSM6	58.5	10.50	23.21	4500.86	223.95	129.31	2.12	1.96

6. CONCLUSIONS

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

1. SIFCON and SIMCON laminates properly bonded to the tension face of RC beams can enhance the flexural strength substantially. The SIFCON strengthened beams exhibit an increase in flexural strength of 68 to 70 percent for laminates having volume fraction 8.0 percent and aspect ratio 70, and SIMCON strengthened beams exhibit an increase in flexural strength of 45 percent for laminates having volume fraction 5.5 percent and aspect ratio 300 and 400, 89 percent for volume fraction 5.5 and aspect ratio 400, and 98 percent for volume fraction 5.5 percent and aspect ratio 300.
2. At any given load level, the deflections are increased significantly thereby increasing the stiffness for the strengthened beams. At ultimate load level of the control specimens, the strengthened beams exhibit an increase of deflection up to 70 percent for both

SIFCON and SIMCON strengthened beams. This is reflected in the performance factors F_1, and F_2.

3. Among the three different volume fraction and aspect ratio of bonded SIMCON aminates, the strengthened beam RBSM1 of volume fraction 5.5 percent and aspect ratio 300 exhibit 98 percent increase in flexural strength when compared to the control specimen and has fairly close agreement with the experimental, theoretical calculations (section analysis) and numerical (ANSYS) results.
4. All the beams strengthened with SIFCON laminates with optimum volume fraction 8.0 percent and aspect ratio 70, and SIMCON laminates with optimum volume fraction 5.5 percent and aspect ratio 300, 400, and 300 and 400 experience flexural failures. None of the beams exhibit premature brittle failure.
5. A flexible epoxy system will ensure that the bond line does not break before failure and participate fully in the structural resistance of the SIFCON and SIMCON strengthened beams.

From the test results it can be seen that SIMCON strengthened beams performed well in all respects when compared to SIFCON strengthened beams.

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