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CYCLIC BEHAVIOUR OF REINFORCED CONCRETE BEAMS RETROFITTED WITH EXTERNALLY BONDED SIFCON LAMINATES

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ABSTRACT

The aim of the research work is to present the results of experimental and analytical studies concerning the cyclic behaviour of reinforced concrete (RC) beams retrofitted with externally bonded Slurry Infiltrated Fibrous Concrete (SIFCON). This study presents a method for retrofitting of reinforced concrete beams to enhance the actual load carrying capacity using High Performance Fibre Reinforced Cementitious Composites (HPFRCCs) laminates SIFCON and which are directly bonded to the tension face at the soffit of the beam by epoxy adhesives and are tested under compression cyclic loading. A total of four beams of size 125 mm width × 250 mm depth × 3200 mm length with effective span of 3000 mm are cast and tested in the laboratory. The laminates of size 125 mm width × 25 mm depth × 2950 mm length are bonded in between the beam supports. Two beams were retrofitted with SIFCON laminates (RBSF1 and RBSF2) and remaining two beams were tested under compression cyclic loading (CB1 and CB2) as a base line specimen. Cyclic 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. Comparison was made between the numerical (ANSYS) with the experimental results. The results show that the strengthened beams exhibit increased flexural strength, enhanced flexural stiffness, and composite action until failure.

Keywords: Composite beams; HPFRCCs; SIFCON; Metallic fibres; ANSYS.

1. INTRODUCTION

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

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or strengthening is a viable alternative [1]. Many reinforced concrete buildings and structures need repair or strengthening to increase their load carrying capacities or enhance ductility under seismic loading [2]. 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. SIFCON fall in this category of HPFRCCs.

SIFCON is a high - strength, high - performance material containing a relatively high volume percentage of steel fibres as compared to SFRC. It is sometimes termed as ‘high - volume fibrous concrete’ also.

The origin of SIFCON 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 [3].

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, 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 was developed in the 1990's to improve performance characteristics of fibre reinforced concrete. The discrete fibres and grouting process of SIFCON laminates are as shown in Figs.1 and 2.

Figure 1. Discrete steel fibres

Figure 2. Grouting process of SIFCON laminates

The resulting composite material possesses very high strength as well as ductility. In addition it has been demonstrated that SIFCON is highly resistant to dynamic loads such as blast pressure and ballistic penetration [4]. SIFCON can be considered as a special type of fibre concrete with high fibre content. SIFCON has excellent potential for application in areas where high ductility and resistance to impact are needed. Only very limited information is available about its behavior under different types of loading [5].

The shear response of SIFCON with and without dowel reinforcement subjected to monotonically increasing shear loading [6]. Specimens tested include plain slurry, plain concrete, dowel reinforced concrete, SIFCON and dowel reinforced SIFCON. Two different volume fraction of fibres were used (6 percent and 11 percent). Special emphasis is placed an analyzing the contribution of steel fibres and dowel bar reinforcement to the strength, ductility, and energy - absorbing capacity of the composite. The results show that dowel reinforced SIFCON has an outstanding response under shear loading. It has an ultimate shear strength of up to 35 MPa and an energy - absorbing capacity of up to 1200 times that of plain concrete and up to 12 times that of dowel reinforced concrete.

HPFRC based repair of structural concrete and his study experimentally evaluates the performance of reinforced concrete flanged beam elements damaged in flexure or shear and subsequently repaired using different repair materials [7]. In particular, the use of glass and carbon FRP fabric and high performance self - compacting concrete containing fibre cocktails (30 mm and 13 mm length of fibres), HPFRC in the form of U - jackets to restore the capacity of damaged structural concrete elements has been examined. Measures in the form of ductility and repair index that indicate effectiveness of different repair materials and deployment procedures have been presented. The repair procedure has been extended to beam column elements damaged under cyclic loadings.

2. EXPERIMENTAL PROGRAMME

2.1 Preliminary studies on SIFCON laminates

The following tests were conducted 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:

Tensile properties of steel fibres
Compressive strength
Tensile strength
Flexural strength
Modulus of Elasticity under compression
Modulus of Elasticity under tension

The properties of steel fibres supplied by M/s STEWOLS and CO, Nagpur, India are shown in Table 1.

Twenty one laminates of size 125 × 25 × 500 mm were cast with different volume fraction (V_f), say 5.5, 6.0, 6.5, 7.0, 7.5, 8.0 and 8.5 percent and constant aspect ratio (l/d) 70 which are schematically represented in Fig. 3.

Table 1: Tension Test on Steel Fibres

Description	Ultimate tensile strength (MPa)	Ultimate strength as per ASTM A820 (MPa)
Round steel fibres 0.45 mm diameter	940	345

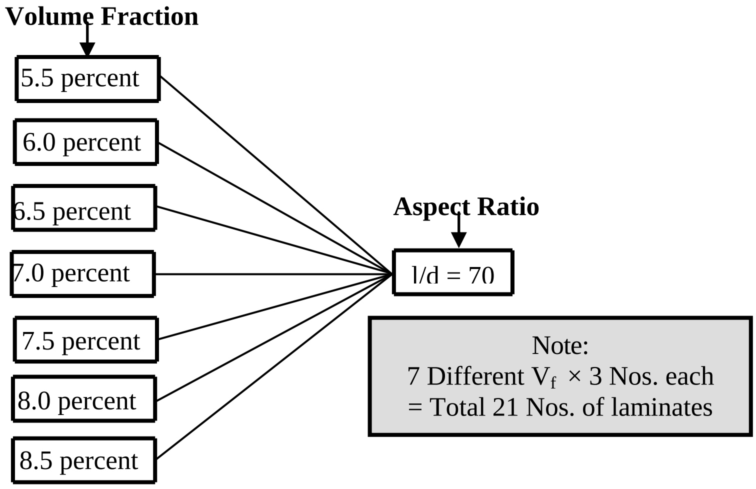

Fig.3 Schematic representation of SIFCON laminates

The compressive strength test results are shown in Table 2. The test results V_f = 8.0 percent gives better results, when the volume fraction (V_f) and consequent fibre content increases, the penetration capacity of cement matrix into the fibre reduces and this could be the reason for reduction in strength for higher volume fraction (V_f) say 8.5.

Table 2: Compressive Strength (cube and cylinder), Modulus of Elasticity (cylinder), and Tensile Strength (long dog bone - shaped specimen) of SIFCON

Sl. No.	**Volume fraction (V_f)**	**Ultimate Stress MPa (cube)**	**Ultimate Stress MPa (cylinder)**	**Modulus of Elasticity Er MPa**	**Tensile Strength MPa**
1.	Plain cement matrix V_f = 0.0	27.54	25.35	2.40×10^4	6
2.	V_f = 5.5 percent	65.85	62.08	2.60×10^4	10.88
3.	V_f = 6.0 percent	70.02	65.10	2.70×10^4	11.22
4.	V_f = 6.5 percent	75.16	68.50	2.75×10^4	12.50
5.	V_f = 7.0 percent	82.10	75.50	2.90×10^4	13.20
6.	V_f = 7.5 percent	85.35	78.65	2.95×10^4	13.55
7.	**V_f = 8.0 percent**	**90.20**	**82.62**	**3.05×10^4**	**14.00**
8.	V_f = 8.5 percent	87.36	84.12	3.00×10^4	13.75

The details of flexure (bending) test results for SIFCON laminates (125 × 25 × 500 mm) are presented in Table 3. The load - deflection curve has a short linear elastic response and a considerable plateau at the peak. The fibre length and fibre volume fraction influence key for strength and the ductility.

Table 3: Summary of Flexure Test Results for SIFCON Laminates (125 × 25 × 500 mm)

Sl. No.	Volume Fraction (%)	Aspect Ratio (l/d)	First Crack Stage				Ultimate Stage	
			Load (kN)	**Deflection (mm)**	**Stress (N/mm^2)**	**Stiffness (kNm^2)**	**Load (kN)**	**Deflection (mm)**
1.	5.5	**70**	**2.56**	1.62	**10.91**	**1.80**	5.32	3.15
2.	6.0		**2.60**	1.34	**11.08**	**2.19**	6.21	3.50
3.	6.5		**2.72**	1.25	**11.59**	**2.46**	6.90	4.50
4.	7.0		**2.84**	1.21	**12.12**	**2.68**	8.28	4.86
5.	7.5		**2.95**	1.15	**12.58**	**2.90**	9.06	4.90
6.	**8.0**		3.60	**1.05**	15.35	3.88	**11.14**	**6.60**
7.	8.5		**3.40**	1.00	**14.50**	**3.86**	10.13	5.23

Stiffness equation up to yield point has been calculated as follows:

$$\delta_c = \frac{Px}{48EI}\left(3L^2 - 4x^2\right) \text{ where } x = \frac{L}{3} \quad (1a)$$

$$\text{Stiffness}\left(EI\right) = \frac{PL^3}{56.25\delta_c} \text{ Where } \delta_c = \text{ Central deflection} \quad (1b)$$

Here also moment of inertia of uncracked section is assumed at the first crack stage.

From the test results it is found that V_f = 8.0 percent and l/d ratio 70 gives better performance with regard to ultimate load (U.L) and stiffness at yield stage. When the volume fraction (V_f) and consequent fibre content increases, the penetration capacity of cement matrix into the fibre reduces and this could be the reason for reduction in strength and other behaviour of V_f = 8.5 percent and l/d ratio 70.

From the basic test (compression, tension and flexure) results, the laminate with volume fraction V_f= 8.0 percent and aspect ratio l/d = 70 performed well in all respects. From the above all test results, the mechanical properties used in this study are summarized below:

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

3. CASTING OF SIMCON LAMINATES

3.1 Casting of RC beams

The mean strength of concrete used for beams was 27.54 MPa. 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 to Zone III as per IS 383 - 1970 and coarse angular aggregate of 20 mm size conforming Zone II were used as the concrete ingredients. After 28 - days of curing, companion cubes (150 mm) and cylinders (150 mm diameter × 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 28173 N/mm^2 and the Poisson's ratio was 0.19. The test programme is presented in Table 4. The beams are designed as under reinforced section (as per IS 456 - 2000), reinforced with high yield strength deformed bars of two 12 mm diameter on tension side. The reinforcement is having 0.2 percent proof strength of 512 N/mm^2, modulus of elasticity of 1.95 × 10^5 N/mm^2 and Poisson's ratio of 0.27. Two numbers of 10 mm diameter hanger bars with yield strength of 415 N/mm^2 and 6 mm diameter, 2 legged stirrups (mild steel) at 150 mm c/c throughout the span, with yield strength of 250 N/mm^2 as shear reinforcement were used (Fig. 4).

Table 4: Details of Control Beams and Strengthened Beams with SIFCON Laminates

Sl. No	Beam Code	Beam Type	Steel fiber (SIFCON)			Laminate Properties				Types of Loading under Virgin Condition	Performance Evaluation
			Dia (mm)	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. & 2.	CB1& CB2	Control beam	-	-	-	-	-	-	-	Compression Cyclic loading	Strength, Stiffness, Ductility, Energy absorption capacity, Compositeness and the Failure mode
3. & 4.	RBSF1 & RBSF2	SIFCON laminated beam	0.50	8.0 percent	70	90.20	14	3.05×10^4	1950		

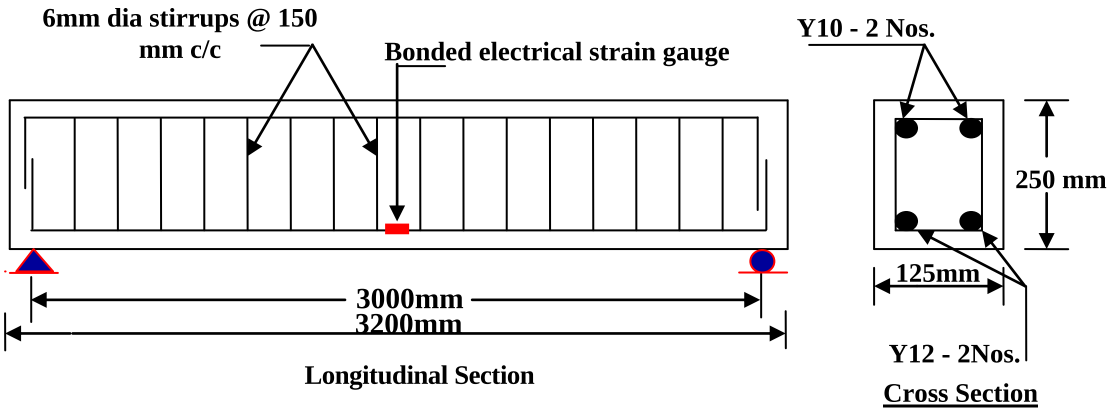

Figure 4. Reinforcement details of RC beam

Two numbers of SIFCON laminates of size 125 × 25 × 2950 mm as per optimum volume fraction V_f = 8.0 and aspect ratio l/d = 70.The hand dispersion of steel fibers and grouting process are adopted. The completed SIFCON laminates are shown in Fig. 5.

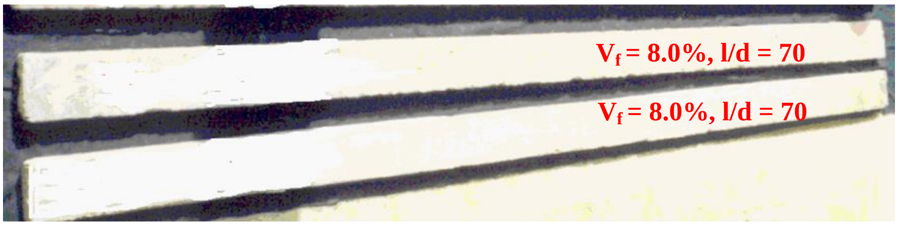

Figure 5. Completed SIFCON laminates

4.2 Bonding of SIFCON laminates

Two numbers of SIFCON laminates of 25 mm thick are used for externally strengthening the RC beams. The soffit of the beams and bonding face of SIFCON laminates are sand blasted to remove the surface laitance and then blown free of dust using compressed air. After surface preparation, a two - part epoxy adhesive [8] (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 is used to bond laminates to the beam soffits. The adhesive has an ultimate tensile strength of 34.80 N/mm^2 (ASTM D638), flexural modulus 3377 N/mm^2 (ASTM D790), flexural strength 32.0 N/mm^2 (ASTM D790), elastic modulus of 1500 N/mm^2 (ASTM D638), density 1.35 g/cc (IS4456) the adhesive components are mixed thoroughly and are applied to the surface using a trowel as shown in Fig. 6.

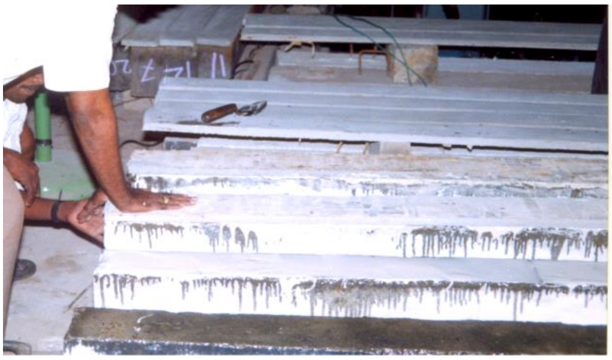

Figure 6. Bonding of beam soffit with SIFCON laminates

The SIFCON laminates already cast are placed over the beam and held in position by dead weights. For ease of work, the beams are inverted and the laminates placed at the top in the laboratory. But in the field the laminate has to be bonded at the bottom of the beam. The laminate has to be fixed after proper gluing at the bottom of the beam and can be jacked up. The strengthened beams are tested after an interval of 14 - days. Curing time (air curing) required for epoxy resin is maximum of seven days and the temperature is less than 35º C but the test has been conducted after 14 days even though 7 days of curing for epoxy resin is normally adopted. The coin tap is conducted to identify areas of debond, if any. The SIFCON laminate thickness of 25 mm and bond line thickness 2.0 mm are kept constant for all the test specimens.

4. EXPERIMENTAL SETUP, TESTING AND MEASUREMENTS

Beams are tested in four - point bending (ASTM C78) under compression cyclic loading which is represented in Fig. 7. The compression cyclic loading is conducted by servo control cyclic loading machine of 100 kN capacity. The beams are tested till the ultimate load is reached. The load is given in increments of 2.5 kN up to failure.

Figure 7. Compression cyclic loading setup of CB1

At each stage of loading, the deflections are measured using LVDTs, crack widths (first five) in the constant bending moment zone are measured using a crack detection microscope of 0.02 mm precision and the strains are measured using demec gauge and noted. The crack development and propagation are monitored and marked during the progress of the test.

The load - deflection relationships were obtained using deflection measurements from LVDTs. The load - mid span deflection curves are drawn for control (unstrengthened) and strengthened beams under compression cyclic loading conditions as shown in Figs. 8 and 9. From the load - deflection it is seen that beam RBSF1 and RBSF2 (under compression cyclic loading) exhibit increased deflection and appreciable flexural strength and enhanced ductility, stiffness and energy capacity factor when compared to control beams.

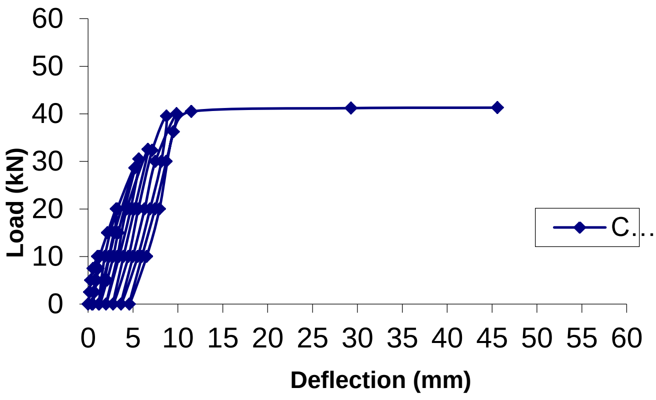

Figure 8. Load –deflection response of control beam

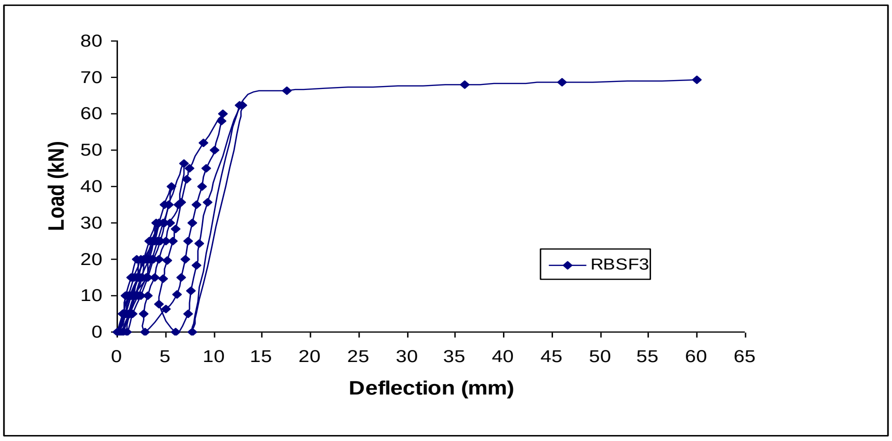

Figure 9. Load - deflection response of SIFCON strengthened beam

The first crack loads are obtained by visual examination only. The experimental ultimate loads are obtained corresponding to the load beyond which the beam would not sustain additional deformation at the same load intensity. The experimental service load can be calculated from experimental ultimate load divided by partial safety factor and experimental yield loads are obtained corresponding to the stage of loading beyond which the load - deflection response is not linear. The experimental ultimate loads are obtained corresponding to the stage of loading beyond which the beam will 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 SIFCON 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 are also carefully examined prior to and after testing. It is found that failure does not occur at the laminate - concrete interface. This confirms that the composite action continues throughout the load spectrum.

The test results on the strength and deformation properties of the control specimens and strengthened beams are reported in Table 5. The derived information is also presented in Table 6.

Table 5: Summaries of test results (SIFCON)

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	16.00	6.10	27.33	28.66	35.00	22.00	41.00	43.00	0.19
CB2	16.20	6.50	27.40	28.67	35.20	22.50	41.10	43.00	0.19
RBSF1	32.00	8.25	46.00	37.43	54.50	30.00	69.00	56.15	0.12
RBSF2	32.12	8.00	46.16	38.00	54.25	31.00	69.25	57.00	0.13

Table 6: Derived information (SIFCON)

Beam Code	Ductility (deflection) Factor	Energy Capacity Factor	Post Cracking - Pre yielding Stiffness (kNm^2)	Mode of Failure	Types of loading
CB1	1.81	1.62	1520	Flexure	Compression cyclic
CB2	1.82	1.67	1530	Flexure	Compression cyclic
RBSF1	3.03	2.52	2610	Flexure	Compression cyclic
RBSF2	3.00	2.50	2600	Flexure	Compression cyclic

5. MODES OF FAILURE

During the test, the crack patterns in the beams are noted and the crack patterns are closely analysed. All the beams strengthened with SIFCON laminates with varying volume fraction experience flexural failure.

None of the beams exhibits premature brittle failure. The maximum crack width near yield stage varies between 0.18 mm and 0.19 mm for beam CB1 to CB4, and between 0.12 mm and 0.15 mm for SIFCON strengthened beams (RBSF1 and RBSF2). The maximum crack spacing is 75 to 100 mm for all beams.

6. DISCUSSIONS

The first crack loads are obtained by visual examination only. At this load level, the strengthened beams show an increase of 70 percent with respect to the control specimens. At service load level, the strengthened beams exhibit an increase up to 63 percent with respect to control specimens. At yield load level, the strengthened beams exhibit an increase up to 40 percent with respect to control specimens.

At experimental ultimate load level, the strengthened beams show an increase of 70 percent with respect to the control specimens. Based on the experimental results, it can be observed that significant increase in strength can be realized at all load levels by externally bonding SIFCON laminates. This increase may be attributed to the increase in the composite moment of inertia of the section and to the increase in tensile cracking strength of concrete due to confinement. Further, it is to be noted that the increase in load carrying capacity is possible only when other modes of failure do not interfere. The strengthened beams exhibit a decrease in deflection of 70 percent at first crack load level of the control specimens, 75 percent at service load level of the control specimens, and 75 percent at yield load level of the control specimens, and 70 percent decrease in ultimate load level of the control specimens. The post - cracking stiffness is significantly higher for the strengthened beams. This may be due to the significant increase in the moment of inertia and hence the flexural rigidity imparted by the laminate when the concrete below the neutral axis becomes ineffective. Also the laminate provides a mechanism by which the tensile stresses are distributed to the uncracked concrete in the tension zone thereby improving its performance.

All the tested beams failed in flexure mode only. The beams experienced considerable flexural cracking and vertical deflection near to failure. Well - distributed closely spaced cracking was observed. None of the beams exhibited sudden brittle failure. The strengthened beams exhibit an increase of flexural capacity of 90 percent at first crack load level of the control specimens, 68 percent at service load level of the control specimens, 60 percent at yield load of the control specimens and 68 percent at ultimate load level of the control specimens.

These results clearly demonstrate the effect of the laminates in restraining the opening of cracks and maintaining the general integrity of the section. All the strengthened beams are also carefully examined prior to and after testing. It is found that failure does not occur at the laminate - concrete interface. This confirms that the composite action continues throughout the load spectrum. The test results show strengthened beams exhibit nearly 60 percent increases in ductility and 40 percent increase in energy capacity of the control beams. The strengthened beam shows that the post cracking pre - yielding stiffness is more than 75 percent with respect to control beams.

7. NUMERICAL ANALYSIS (ANSYS)

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 program offers SOLID65 for beam element, SOLID45 for laminates and LINK8 for steel [9]. The non - linear finite element modelling adopted using ANSYS proves to be an acceptable predictive tool for the analysis of RC beams strengthened with externally bonded laminates. The numerical solution in terms of load - deflection variation for SIFCON strengthened beams exhibits a decrease by 20 percent variation with the experimental results. It shows a fairly good agreement with the experimental results.

8. OVERALL PERFORMANCE EVALUATION

The performance of the beams (series 1 to 3) has been evaluated by considering the equivalent elastic forces using energy and deflection approaches [10]. The equivalent elastic forces P_{e1} and P_{e2} are computed considering the load - deflection curve as shown in Fig. 10.

$$P_{e1} = \sqrt{[2A_e P_y] / \delta_y} \tag{1c}$$

$$P_{e2} = P_y [\delta_u / \delta_y] \tag{1d}$$

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). It is felt that, to evaluate the overall performance of any repair measure, the following performance factors may be used.

The performance factors F1 and F2 may be defined as,

$$F_1 = P_{e1}\,(\text{retrofitted}) / P_{e1}\,(\text{conventional}) \quad \longleftarrow \quad \text{Energy Approach} \tag{1e}$$

$$F_2 = P_{e2}\,(\text{retrofitted}) / P_{e2}\,(\text{conventional}) \quad \longleftarrow \quad \text{Deflection Approach} \tag{1f}$$

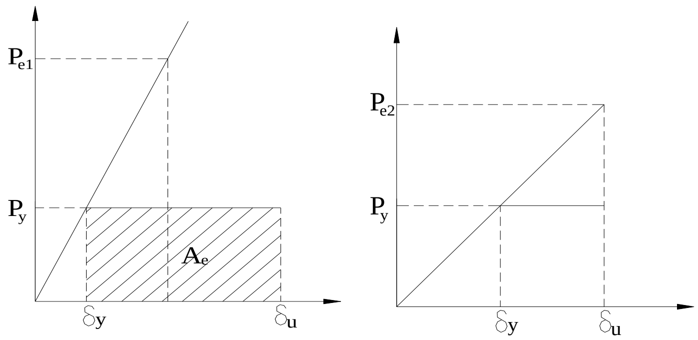

Figure 10. Computation of equivalent elastic force for ductile structures

The effectiveness factors evaluated using energy approach (F_1) and deflection approach (F_2) for the control beam (CB1 and CB2) and retrofitted beams RBSF1and RBSF2 are presented in Table 7. In all the series, F_1 is 2.30 and F_2 is 2.33. It can be seen that SIFCON strengthened beams of V_f = 8.0 percent and l/d ratio 70 exhibits superior performance when compared to other beams.

Table 7: Effectiveness Factors for Beams

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	31.00	60.50	5419.32	264.80	151.80	2.50	2.30
RBSF2	54.10	31.01	60.75	5600.62	271.82	153.78	2.57	2.33

9. CONCLUSIONS

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

i. The HPFRCC laminates such as SIFCON 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.

ii. At any given load level, the deflection decreases significantly which again causes increase in stiffness. At ultimate load level of the control beams, the strengthened beams.

iii. All the beams strengthened with SIFCON laminates with optimum volume fraction 8.0 percent and aspect ratio 70, experience flexural failure. None of the beams exhibit premature brittle failure of the laminates.

iv. SIFCON strengthened beams shows improved ductility with respect to control beams because of the presence of metal fibres.

v. 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 strengthened beams throughout the load spectrum. An examination of crack distribution indicates that the crack widths are less in the SIFCON strengthened beams than in the control beam.

vi. The overall performance of the beams evaluated by the performance factor F1 (energy approach) for SIFCON strengthened beams exhibit a range between 2.5 to 2.6 and the values of F2 (deflection approach) for strengthened beams exhibits a range between 2.30 to 2.35.

vii. A non - linear finite element modelling adopted using ANSYS proves to be an acceptable predictive tool for the analysis of RC beams strengthened with externally bonded laminates. The numerical solution in terms of load - deflection variation for SIFCON strengthened beams exhibits a decrease by 20 percent variation with the experimental results. It shows a fairly good agreement with the experimental results.

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