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BEHAVIOUR OF RESTRAINED SIFCON TWO WAY SLABS PART 2: PUNCHING SHEAR

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ABSTRACT

In part 1 of this paper, flexural tests conducted on restrained SIFCON two way slabs were described and the load-deflection responses under flexural loading were reported. Three different types of slabs i.e. SIFCON slabs, FRC slabs and PCC slabs were investigated. It was found that flexural performance of SIFCON slabs is quite superior when compared to FRC and PCC slabs. Among SIFCON slabs those containing twelve percent fibres by volume exhibited excellent load carrying capacities, ductility and energy absorption capacities.

In part 2 of the paper, the effect of various volume percentage of steel fibre in SIFCON slab specimens subjected to punching shear was studied. The punching shear load was applied to simulate a column-footing connection. From experimentation, the failure loads, deflection and crack patterns in punching shear were studied. Fibre reinforced concrete (FRC) and plain cement concrete (PCC) slab specimens were used as control specimens. The results reported that SIFCON slabs with 12% fibre volume possess high performance than the other slab specimens in all respects. The experimental results are compared with the ACI and IS codes and the need for separate provisions for SIFCON in punching shear is emphasised. A regression model has been developed to predict the punching shear capacity of SIFCON slabs.

Keywords: SIFCON, FRC, PCC, Punching shear and Two-way slabs with clamped edges

1. INTRODUCTION

Slurry infiltrated fibrous concrete (SIFCON) introduced by David Lankard [1], it is a composite material utilizing short steel fibres in a cement based matrix. SIFCON differs from conventional steel fibre reinforced concrete in which the steel fibres are added directly to concrete mix in the ratio of 1-3% by volume. SIFCON on other hand with a bed of well compacted steel fibres in the range of 5-20% by volume. A low viscous cementitious slurry

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or cement mortar is infiltrated through the preplaced fibre bed. Though SIFCON is a relatively new material due to its high strength and ductility characteristics it has potential applications such as rehabilitation of bridge decks, pavement rehabilitation, explosive resistant containers for storing materials that could accidentally explode, earth quake retaining structures, security vaults and refractory applications, etc. due to its excellent energy absorption capacities [2,3]. Singh et al.[4], studied the stress-strain behaviour in compression and tension by preparing SIFCON with 10% volume fraction of fibres by adding fly-ash in the matrix. Naman and Baccouche[5] presented the shear response of dowel reinforced SIFCON. They observed that the shear strength of SIFCON is ten times higher than that of the plain matrix. The behaviour of reinforced concrete beams with SIFCON matrix has been studied by Naman et al.[6] and reported that the use of SIFCON eliminates the need of shear stirrups in RCC beams. Utility of SIFCON connections for seismic resistant frames has been investigated by Naman et al.[7]. The behaviour of SIFCON under pure torsion has been presented by Balasubramanian et al.[8]. SIFCON with straight, crimped and trough shaped fibres has been prepared and investigated for torsional resistance. In the part 1 of this paper [9], behavior of restrained SIFCON slabs in flexure has been presented. The effect of fibre reinforcement on the deformation and strength characteristics of punching shear failure on FRC slabs is presented by Swamy and Ali[10]. The fibres were used through out the slab or in punching shear zone of the column head and comparative tests were carried out on connections with bent up steel bars. The results show that fibres reduce deformations at all stages of loading, increase ultimate punching shear loads and produce ductile shear failure. Kuang and Morley[11] investigated the influence of degree of edge restraint, percent of steel reinforcement and span-depth ratio on structural behavior and punching shear capacities of the reinforced cement concrete slabs. Lim and Vijaya Rangan[12] reported that the effectiveness of stud shear reinforcement in increasing punching shear strength of reinforced cement concrete slab column connection. Harajli, Maalouf & Khatib[13] investigated the use of hooked steel fibres to improve the ductility of shear failure and ultimate shear capacity of slab column connections of flat slabs. Mansur, Ahmad and Paramasivam[14] reported the punching shear test on square ferro cement slabs. Ebead and Marzouk[15] introduced strengthening techniques for reinforced concrete two way slabs using steel plates and steel bolts against excessive flexure and shear stresses. Baris Binici and Oguzhan Bayrak[16] presented strengthening technique for increasing punching shear resistance in reinforced concrete flat plates using carbon fibre reinforced polymers (CFRPs). Lovrovich and Mclean[17] investigated the punching shear strength of reinforced concrete slabs with varying span-depth ratios and reported significant increase in punching shear strength as l/d ratio decreased below 6. From the comprehensive study, it is clear that very little information is available on SIFCON two way slabs and there is need to study their behaviour in punching shear.

2. EXPERIMENTAL PROGRAM

The experimental program comprises of casting and testing of nine reinforced SIFCON slabs, three fibre reinforced concrete slabs (2% fibre) and three plain cement concrete slabs

(M20 grade concrete) restrained on all four edges. The mix proportions of the various slabs are presented in Table 1. All the slabs are square and are of size 600×600×50mm.

Table 1. Mix proportions

S.No	Designation of slab	Mix proportion	Volume fraction of fibre	W/C ratio	Dosage of super plasticize r	Mode of vibration
1	SIFCON -8%	Cement and sand (1:1 by wt)	8%	0.45	1.5%	Hand tamping
2	SIFCON -10%	Cement and sand (1:1 by wt)	10%	0.45	1.5%	Hand tamping
3	SIFCON -12%	Cement and sand (1:1 by wt)	12%	0.45	1.5%	Hand tamping
4	FRC-2%	Cement, sand and coarse aggregate (1:1.54:3.17)	2%	0.5	-	Table vibration
5	PCC-0%	Cement, sand and coarse aggregate (1:1.54:3.17)	No fibres	0.5	-	Table vibration

3. MATERIALS

In the preparation of test specimens, 53 grade ordinary Portland cement (IS 12269), natural river sand (passing through 4.75mm IS sieve), black steel fibres (ultimate tensile strength 395 MPa) with 50 aspect ratio, poTable drinking water and stone aggregate (maximum size 20 mm) is used.The SIFCON slabs are produced with 8, 10, 12% volume fraction of fibres with a proportion of 1:1 cement mortar (water cement ratio 0.45). To increase the workability of cement mortar for SIFCON slabs, CONPLAST –300 super plasticizer was used. Stone aggregate 50% passing through 20 mm IS sieve and retained on 12.5 mm IS sieve and 50% of the aggregate passing through 12.5mm IS sieve and retained on 10 mm IS sieve was used in preparation of fibre reinforced concrete and plain cement concrete slab specimens. Concrete mix proportion adopted is 1:1.54:3.17(cement: fine aggregate: Coarse aggregate) with water cement ratio of 0.5. The concrete mix was designed by I.S. Code method to achieve designed 28 days cube strength of 20MPa.

3.1 Casting of test specimens

Steel moulds were used to cast the slab specimens of required size. Two L-shaped frames with a depth of 50 mm were connected to a flat plate at the bottom using nuts and bolts. Cross-stiffeners were provided to the flat plate at the bottom to prevent any possible deflection while casting the specimens. The gaps were effectively sealed by using thin card-boards and wax to prevent any leakage of cement-sand slurry in SIFCON slab specimens. The moulds are shown in Figure 1. Initially the steel mould was coated with waste oil so that the slab specimens can be removed easily from the moulds. Then the steel fibres are placed randomly in the mould such that they occupy the entire volume of the mould. In the mean time cement-sand slurry was prepared using CONPLAST-300 which was later poured into the mould uniformly over the pre-placed bed of fibres. The details of casting are shown in Figure 2. In case of fibre reinforced concrete slabs, fibres are first mixed in the dry mixture of cement and sand and then spread over the heap of coarse aggregate. Hand mixing was done after adding required quantity of water to achieve uniform dispersion of fibres and to prevent the segregation or balling of fibres during mixing. For both FRC and P.C.C. specimens, Table vibration was adopted. The test specimens were de-moulded after 24 hrs and were cured for 28 days in curing water ponds. After removing the slab specimens from the curing pond, they were allowed to dry under shade for a while and then they were coated with white paint on both sides, to achieve clear visibility of cracks during testing. The loading position on the top and the dial gauge position at the bottom of the slab were marked with black paint.

Figure 1. Slab mould

Figure 2. Casting of SIFCON slabs

3.2 Loading arrangement and testing

The setup for loading the slab consists of a solid plate of 100 x 100 x 20 mm placed at the center of the top face of slab specimen. Over this solid plate, solid circular rod of 50 mm diameter was kept to distribute the load from hydraulic jack to the slab specimen. The whole arrangement has been made to obtain the punching shear effect on the slab specimen, as shown in Figure 3. The loading platform consists of four welded steel beams of ISMB 200@254 N/m in square shape. These steel beams were stiffened using small size steel I-Sections (ISMB100@50N/m). This loading platform has been supported by brick walls on two sides and the other two sides are supported with two steel rods. The load was applied through hydraulic jack and was measured with a calibrated proving ring of 500 kN capacity. The vertical deflections were measured by using dial gauge with a least count of 0.01 mm. The vertical deflections were measured at the centre of the slab specimens.

The load has been applied incrementally. The load increment was selected such that there will be as many number of readings as possible. The load was applied in increments of 833.3 N which corresponds to one unit of proving ring. Deflections have been recorded for each load increment. The load at the first crack and the corresponding deflection at the bottom centre of the slab were recorded. The ultimate punching shear load and corresponding deflection at the centre were also observed and recorded.

Figure 3. Testing of slabs for punching shear

4. RESULTS AND DISCUSSION

The results of the experimental investigation are summarised in Table 2. The values presented here represent the average of punching shear strengths, load and deflection obtained for three specimens in each series. The effect of volume percentage of fibres on the ultimate punching shear load of the SIFCON slabs is shown in Figure 4. From Figure 4. it is observed that there is an increase in first crack strength in punching shear with the increase in volume fraction of fibres. The slab specimens reinforced with higher volume fraction of fibres behaved better than those containing lower volume fractions of fibres. The maximum first crack punching shear load of 54.99 kN has been achieved for slabs reinforced with 12% volume fraction of fibres. The increase from first crack load to ultimate load is ranging between 43 to 106 kN for SIFCON slabs which indicates the excellent load carrying capacity of SIFCON slab specimens in punching shear. FRC slab specimens and PCC slab specimens have failed at significantly lower loads. The percentage increase in first crack punching shear strength in SIFCON slab specimen when compared to FRC specimens is in the range of 1704 to 2191% for different volume fractions of fibres indicates their superiority. First crack in PCC slabs could not be captured due to its brittleness.

Table 2. Details of test results

S.No.	Nomenclature	First crack load (kN)	Deflection at first crack load (mm)	Ultimate load (kN)	Deflection at ultimate load (mm)
1.	SIFCON-8	43.33	3.93	81.00	20.50
2.	SIFCON-8	48.33	3.32	96.00	22.50
3.	SIFCON-8	54.99	3.40	106.00	24.00
4.	FRC-2	2.40	0.90	4.17	15.00
5.	PCC-0	--	--	2.50	--

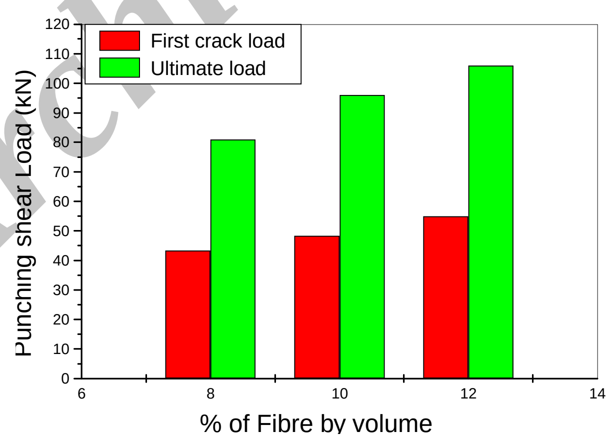

Figure 4. Effect of volume fraction of fibres

From Table 2 and Figure 4 it is observed that ultimate punching shear strength increases with increase of volume fraction of fibre in SIFCON slab specimens. The maximum ultimate punching shear load of 106kN has been obtained for SIFCON slabs with 12% volume fraction of fibres which is 30% higher than that of 8% volume fraction slab specimens. The ultimate punching shear strength of SIFCON slab specimens is about 1842 to 2441% when compared to FRC slab specimens with maximum values corresponding to 12% volume fraction of fibres. The increment when compared to PCC specimens is about 3140 to 4140%. From this it is observed that the SIFCON specimens behave quite well over FRC and PCC slab specimens in punching shear.

The central deflection response of various slab specimens is shown in Figure 5. and maximum central deflection values are presented in Table 2. From Figure 5, it is observed that there is a decrease in central deflection in SIFCON slab specimens when compared with the FRC slab specimens at a particular load. Among the SIFCON slab specimens, slab with 12% volume fraction of fibre show higher stiffness than the 8 and 10% volume fraction slab specimens. The SIFCON slabs have not only carried higher loads, but also sustained greater deflections till ultimate stage.

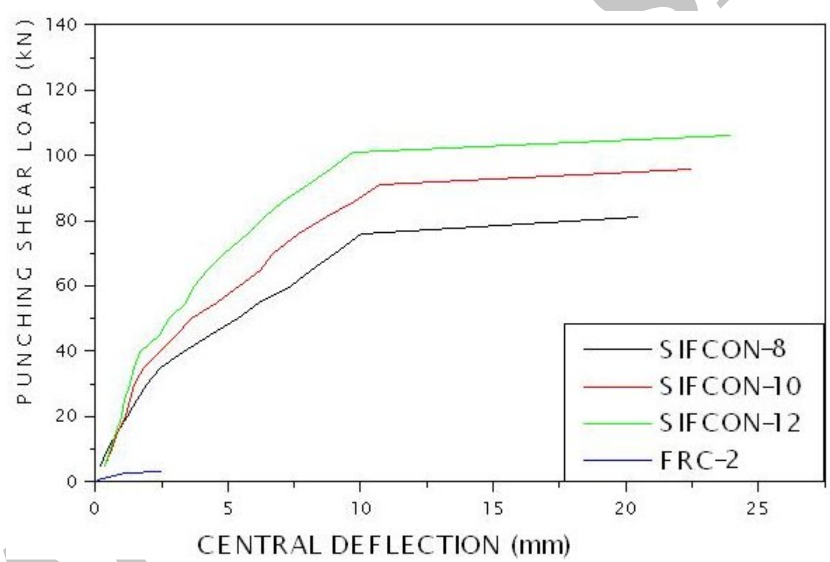

Figure 5. Load deflection response of different slab specimens

The crack patterns of different slab specimens are depicted from Figure 6. to Figure 9. From Figure 6 to Figure 8 it is observed that the crack pattern is almost similar in all SIFCON slabs. In all slabs, the first crack originated at the centre and propagates radially towards the edges and corners. At higher loads, already formed cracks get widened with formation of new cracks. The new formations of cracks are mainly concentrated at the point of application of punching load. More or less, cracks are mainly localized up to a particular distance/area from the loading point. The influence of this distance/area increases with increase in volume fraction of fibres in SIFCON slab specimens. A few cracks are identified on the top surface SIFCON slab specimens. Similar type of failure pattern was reported by the earlier researchers Swamy and. Ali[9], Kuang and Morley[10] and. Mansur, Ahmad and Paramasivam[13] for RCC and FRC slabs.

From Figure 9, it is observed that the FRC slab specimens show more number of cracks underneath the slab, but the influence area is not so clear as in the case of SIFCON slabs. The PCC slab specimens are broken in to fragments while the SIFCON slabs are intact even after failure. The SIFCON slab specimens exhibit superior performance compared to FRC and PCC slab specimens in punching shear. This is mainly due to the incorporation of higher volume fraction of fibres which leads to crack arresting and crack bridging mechanism in the matrix.

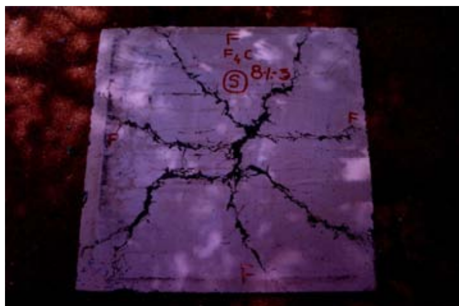

Figure 6. View of SIFCON-8% slab after failure in punching shear

Figure 7. View of SIFCON-10% slab after failure in punching shear

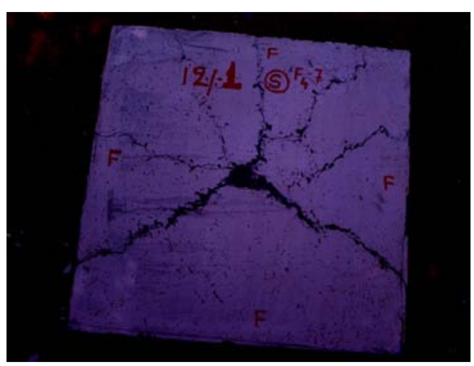

Figure 8. View of SIFCON-12% slab after failure in punching shear

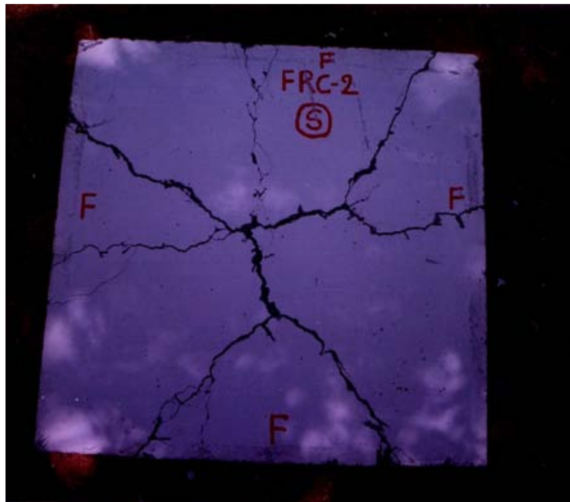

Figure 9. View of FRC-2% slab after failure in punching shear

5. COMPARISION WITH EXISTING CODAL PROVISIONS

Till to day, there is no code for SIFCON material in punching shear. However in the present analysis, the two major building codes ACI 318-2005 and IS 456-2000 have been considered for comparison. In the strict sense, the above two building code methods may not be applicable to SIFCON material.

As per the ACI 318-2005 code, the ultimate punching shear strength P_u is taken as the smallest value given by the following

$$P_u=(0.166+(0.332/B_c))\sqrt{f_c}\ u\ d \tag{1}$$

$$P_u=(0.166+(0.083\ \alpha\ d/u))\sqrt{f_c}\ u\ d \tag{2}$$

$$P_u=0.332\sqrt{f_c}\ u\ d \tag{3}$$

According to the Indian standard code IS: 456-2000, the expression for calculating the punching shear strength P_u by considering partial safety factor for material as unity is given as

$$\mathbf{P_u=K_s}\,\tau_c\,\mathbf{u\ d} \tag{4}$$

Where

$$\mathbf{K_s = (0.5+B_o) \leq 1} \tag{5}$$

$$\tau_c\,\mathbf{=0.25\ \sqrt{f_{ck}}} \tag{6}$$

The above two specified code provisions are used to calculate the ultimate punching shear load and the predicted values are depicted in Table 3. From Table 3 it can be observed that the experimentally observed values are higher than those calculated as per ACI and I.S code procedures. The experimental loads for SIFCON slabs are higher by 20 to 43% when compared with ACI code and 60 to 90% higher when compared with I.S code. From the results it can be concluded that the IS code is more conservative than the ACI code and there is a need to define specific procedures for computation of punching shear of SIFCON.

Table 3. Comparison of punching shear test results with standard codes of practice

S.No.	Nomenclature	Ultimate Punching Shear loads (kN)			EXP values/ ACI 318-2005	EXP values/IS 456-2000
		Exp values	ACI 318-2005	IS: 456-2000		
1.	SIFCON-8	73.16	67.08	50.40	1.10	1.45
2.	SIFCON-10	84.99	70.69	53.10	1.20	1.60
3.	SIFCON-12	90.82	74.12	55.80	1.22	1.63

6. REGRESSION MODEL FOR PUNCHING SHEAR STRENGTH OF SIFCON

A simple regression model has been developed from the results of present investigation for predicting the punching shear strength of SIFCON slabs. To develop the punching shear strength model, linear regression technique has been adopted. The linear regression is in the form of Y=A+BX where Y is independent variable, X is dependent variable and A and B are called regression coefficients. The A and B are determined from regression analysis in accordance with the principle of least squares method.

The proposed model for punching shear is as given below

$$\mathbf{P_u = \tau\, u_s\, d} \qquad (7)$$

It is convenient to express shear strength in terms of characteristic compressive strength (**f_{ck}**). For this purpose, control cube specimens of 150X150X150mm were cast, cured and tested for compressive strength. From the results of the present study, a simple regression model has been developed connecting shear stress **τ** with characteristic compressive strength **f_{ck}** and is presented as Equation (8).

$$\tau = 0.339 + 0.332\sqrt{f_{ck}} \qquad (8)$$

However the compressive strength (f_{ck}) of SIFCON is dependent on fibre volume fraction. In the present work three fibre volume fraction viz 8,10 and 12% have been used. It will be convenient to estimate f_{ck} with fibre volume fraction (F_v). Accordingly the following equation has been developed to estimate f_{ck} based on F_v using liner regression. This equation is given below.

$$\mathbf{f_{ck} = 25.32 + 2.505\, F_v} \tag{9}$$

Substituting the equation 9 in equation 8

$$\tau = 0.339 + 0.332\sqrt{(25.32 + 2.505\, F_v)} \tag{10}$$

The critical perimeter u_s can be defined as below with reference to Figure 10.

$$u_s = 4[\, b + 2d \tan\theta] \tag{11}$$

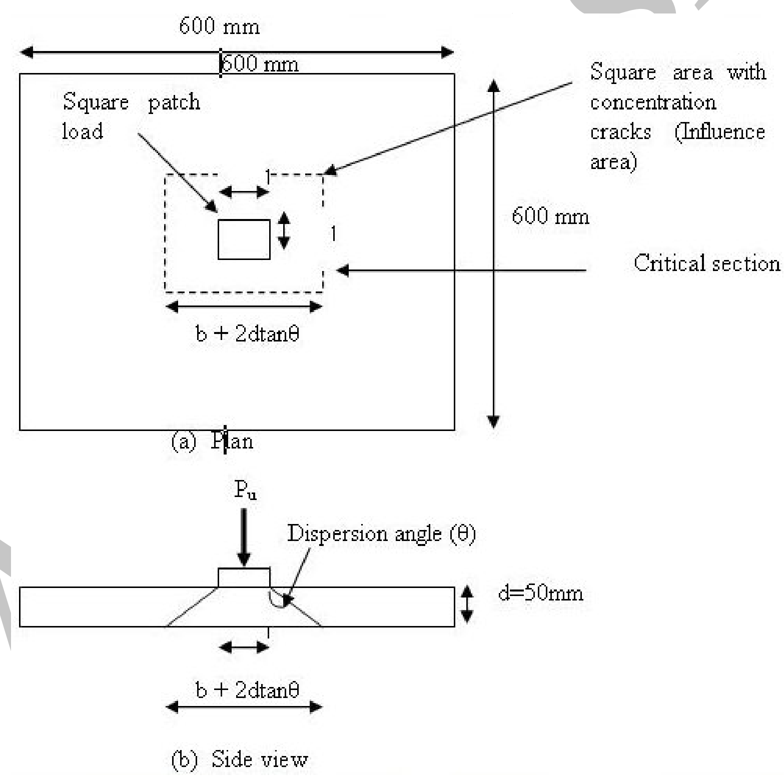

Figure 10. Dispersion angle for slabs under punching shear

From the present experimental work, it is observed that the dispersion angle θ depends on fibre volume fraction F_V. Accordingly a simple regression equation is developed to connect θ with F_V and is presented as equation 12.

$$\theta=18.23+1.575(F_v) \quad (12)$$

Substituting equation 10 in equation 9

$$u_s = 4[\, b+ 2d \tan(18.23+1.575(F_v))] \quad (13)$$

Substituting equation 10 and equation 13 in equation 7, a model for predicting punching shear strength is obtained as below.

$$P_u =\{(0.339 + 0.332\sqrt{(25.32 + 2.505\, F_v)})(4[\, b+ 2d \tan(18.23+1.575(F_v))]d\} \quad (14)$$

A comparison of the ultimate loads predicted by the regression model (Eq. 14) with experimental values, ACI and IS codes are presented in the Table 3 and Figure 11. From Table 3 and Figure 11 it can be observed that the proposed model compared well with the experimental ultimate loads. The ratio of experimental punching shear load to that predicted by regression model is presented in column 7 of Table 4. It can be observed that the ratio varies from 0.98 to 1.07. Thus, the proposed equation gives much better predictions for SIFCON slabs than the codes of ACI 318-2005 and IS 456-2000. This can also be observed from Figure 11.

Table 4. Performance of regression model

S.No.	Nomenclature	Exp Ultimate load (kN)	Ultimate Load predicted by Regression model (kN)	As per ACI 318-2005 (kN)	As per IS: 456-2000 (kN)	Exp value / Predicted value
1.	SIFCON-8	81.00	82.23	67.08	50.40	0.98
2.	SIFCON-10	96.00	90.24	70.69	53.10	1.06
3.	SIFCON-12	106.0	98.73	74.12	55.80	1.07

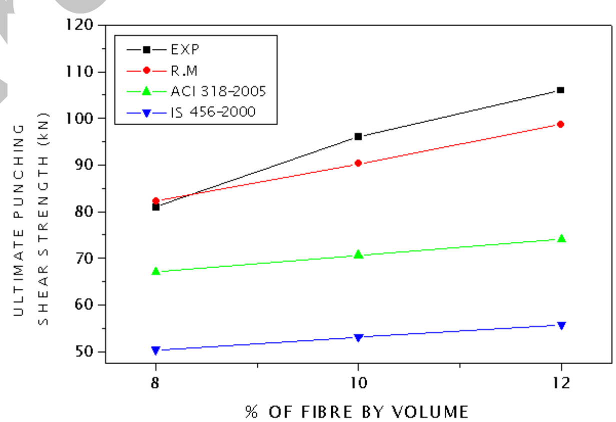

Figure 11. Performance of regression model

7. CONCLUSIONS

The major objective of this investigation is to study the punching shear behaviour of SIFCON slabs. SIFCON slabs with different volume fractions of fibres have been produced and tested. The superiority of SIFCON slabs over FRC slabs and PCC slabs has been demonstrated. Experimental results have been compared with the provisions of ACI and IS codes. A Regression model is proposed to estimate the punching shear strength of reinforced SIFCON slabs. Analyzing the results obtained from this investigation, the following conclusions are drawn:

- The punching shear carrying capacity of the SIFCON slabs is much higher than the fibre reinforced concrete and plain cement concrete slab specimens.
- With increase of fibre volume the punching strength carrying capacity increases in SIFCON slabs.
- The ultimate punching shear strength of SIFCON slab specimens is about 1842 to 2441% and 3140 to 4140% higher when compared with FRC-2 and PCC-0 slab specimens respectively.
- The zone of influence area (dispersion angle) increases with increase of volume fraction of fibres.
- The SIFCON slabs are intact even after ultimate failure but this is not so in PCC slab specimens.
- The SIFCON slabs with higher volume fraction of fibre sustain greater deflection with high ultimate punching shear load
- In SIFCON slabs the stiffness increases with increase of fibre volume and the stiffness of SIFCON slab specimens is very much higher than the FRC and PCC slab specimens.
- Existing codal provisions for punching shear are not suiTable for SIFCON slabs. There is need to develop specific codal provisions for punching shear of SIFCON slabs.

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NOTATION

P_u =Ultimate punching shear strength (N).
B_c = the ratio of long side to short side of the loaded area
f_c = specified compressive strength of concrete N/mm^2 and
α = 40 for symmetric punching.
u = Length of the critical perimeter (mm), taken at a distance of d/2 from the column/pedestal (for ACI and IS codal provision)
d = Effective depth of the slab (mm).
B_o = ratio of short side to long side of column
τ_c = Shear stress in concrete (N/mm^2)
f_{ck}= Characteristic cube compressive strength of concrete (N/mm^2)
$F_{v=}$fibre volume fraction in %
b = breadth of the patch load (mm)
d = total depth of slab (mm)(for SIFCON slabs)
u_s = length of the critical perimeter (mm) (depending on angle of dispersion for SIFCON slabs)
τ = Shear strength of SIFCON (N/mm^2)