

Experimental and Analytical Study on Bond Performance of Reinforced Bars Embedded in Fibre Reinforced Concrete

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ABSTRACT: The behaviour of reinforced concrete structures is influenced by the interaction between the concrete and reinforcement. The bond between steel and concrete is very important and essential so that they can act together without any slip in a loaded structure. Hence bond has been, and still is a topic of fundamental and applied research. Here a Study on the effect of steel and recron 3S fibre on the bond strength and bond stress- slip response of deformed steel bars embedded in fibre reinforced concrete was carried out both experimentally and analytically. Experimental study was carried out by doing pullout tests using Universal Testing Machine (UTM) on cubes of size 150x150x150mm. A total of 24 pullout specimens were cast and tested. The variables considered were, the volume fraction of hooked steel fibres, the volume fraction of recron 3S fibres and the diameter of reinforcement bars. The analytical study was carried out using ANSYS software by modeling a cubical specimen similar to experimental work. It was seen that steel fibres showed higher bond strength than recron 3S fibres and that of control specimen. The results obtained from analytical tests showed the same trend as that of experimental ones.

KEYWORDS: Bond stress, deformed bars, fibre reinforced concrete, pullout tests, steel fibres, recron 3S fibres.

I. INTRODUCTION

The behaviour of reinforced concrete (RC) structures depends up on the type of bond developed between the steel reinforcement and the surrounding concrete. The utility of reinforced concrete as a structural material is derived from the combination of concrete that is strong and relatively durable in compression with reinforcing steel that is strong and ductile in tension. Maintaining composite action requires transfer of load between the concrete and steel. This load transfer is referred to as bond and is idealized as a continuous stress field that develops in the vicinity of the steel-concrete interface. Bond stress is the tangential shear or friction developed between the reinforcement and the surrounding concrete that transfers the force onto the reinforcement. To ensure the integrity of various constituent or composite action of concrete and steel reinforcement, sufficient bond should be developed by the surrounding concrete with the reinforcement. Proper bond between the steel reinforcement and the surrounding concrete is also crucial for the overall strength and serviceability of RC members. The failure of RC structures may be due primarily to the deterioration of the bond. Hence it is necessary to study the bond characteristics.

II. LITERATURE REVIEW

From the review of the literatures it can be seen that a number of studies were carried out on the bond strength and behaviour of reinforcement bars in fibre reinforced concrete. The bond and slip characteristics of reinforcing bars embedded in fibre reinforced concrete (FRC) was studied by Harajli et.al.[1]. From the results he concluded that the presence of fibres (steel or polypropylene) in concrete restricts the growth of the splitting cracks and leads to a much higher bond resistance. Muhammed Hadi [2] who studied the Bond strength of High Strength Concrete with

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High Strength Reinforcing Steel reported that the pullout specimen with the smaller bar size has greater bond strength than the specimen with the larger diameter bar and it also showed that the bond strength and the initial stiffness increased as the amount of concrete surrounding the reinforcing bar increased. The bond strength of fly ash based geopolymer concrete and OPC concrete with reinforcing steel was evaluated by Prabir Kumar Sarker [3]. The varying parameters were compressive strength, concrete cover, bar diameter. He found that geopolymer concrete has higher bond strength than OPC concrete and bond strength increased with the increase in concrete cover and the concrete compressive strength. Dr Ala'a & Wjdan Dhaif [4] studied the behaviour of bond between concrete and plain steel reinforcement both experimentally and analytically (using ANSYS). He found that there is good agreement between the finite element solution and the experimental results and that bond strength increases by decreasing the diameter of steel bar embedded in concrete cylinder specimens of the same compressive strength. Appa Rao and Kadhiraivan [5] studied the influence of specimen geometry, bar diameter, strength of concrete, lateral confinement and embedment length on the bond properties of concrete by nonlinear finite element analysis. It was found that the bond strength of concrete decreases as the diameter of bar increases and as the concrete strength increases, the bond strength increases. Splitting failure was observed in unconfined concrete, while pullout failure was predominant in confined concrete. Ganesan et al. [6] investigated the bond stress - slip response of bars embedded in hybrid fibre reinforced high performance concrete. The investigation revealed that the confinement and bridging effects of hybrid fibres enhanced the bond stress of reinforcing bars embedded in HFRHPC composites when compared to plain HPC. All the studies mainly investigated the influence of bar diameter, embedment length, surface type of reinforcing bars, concrete type, curing age of concrete, concrete compressive strength, different confining conditions etc on bond strength. Study involving comparison of analytical and experimental works is limited. The studies generally concluded that the bond strength increased with, decrease in bar diameter, increase in concrete cover, increase in compressive strength, decrease in water cement ratio.

III. EXPERIMENTAL PROGRAMME

This experimental programme was carried out to evaluate the bond stress - slip behaviour and pullout strength of reinforced bars embedded in fibre reinforced concrete. A total number of 24 pullout specimens were cast (two specimen each for twelve different types). The details of specimens and variables are given in Table 1. The main variables considered were: (i) Volume fraction of crimped steel fibres (V_{fs}) viz; 0.5% and 0.1%, (ii) Volume fraction of polyester fibres (V_{fp}) viz; 0.1%, 0.2% and 0.3%, (iii) diameter of reinforcing steel bars (ϕ) viz; 16mm and 20mm. It was noted from literature review that, the volume content of steel fibres alone can vary up to 2% [7] and the optimum volume fraction of recron 3S fibres is in the range of 0.2 - 0.3% [8]. Based on the review the volume fraction of both the fibres was fixed. Two specimens were cast for each parameter and the average of the two was taken for analysis.

A. Materials Used

Portland Pozzolana Cement (PPC) flyash based of "ACC" brand, locally available M sand conforming to grading zone III of IS:383-1970 (reaffirmed 2002) and coarse aggregates of maximum size 20mm which was locally available was used in the project. CONPLAST SP 430 which complies with IS 9103:1999 & BS: 5075 Part 3-1985 was used as superplasticizer to obtain the required workability. The fibres used were i) Crimped steel fibres - DURAFLEX CR30 of Kasturi Metal Composites (P) Ltd and ii) Polyester fibres, Recron 3S, CT2024 of Reliance Industries Limited. Fig 1(a) and 1(b) shows the fibres used in the study. The properties of fibres given by the manufacturer are given in Table 2. Reinforcement bars used is Fe500 of Minar TMT brand. Table 3 gives the properties of reinforcement bars obtained by doing tension tests.

B. Mix proportions

In this experimental study concrete of M25 grade is used and for that mix design is done based on IS 10262:2009 [9]. The details of mix proportions are given in Table 4. Required quantities of cement, fine aggregates and coarse aggregates were first mixed thoroughly in a drum type mixer for a period of 2 minutes. During the mixing operation 80% of water was added first and mixed thoroughly and the remaining 20% water, mixed with superplasticizer was added later. The steel and polyester fibres were dispersed by hand to the mixture to achieve

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a uniform distribution throughout the concrete. Since the addition of fibres reduced the workability of concrete, the dosage of superplasticizer was adjusted to maintain required workability for all the mixes.

Table 1: Details of specimens and variables

Sl No	Specimen designation	V_{fs} (%)	V_{fp} (%)	Rebar diameter
1	CS Φ 16	0	0	16
2	PFRC1 Φ 16	0	0.1	16
3	PFRC2 Φ 16	0	0.2	16
4	PFRC3 Φ 16	0	0.3	16
5	SFRC1 Φ 16	0.5	0	16
6	SFRC2 Φ 16	1	0	16
7	CS Φ 20	0	0	20
8	PFRC1 Φ 20	0	0.1	20
9	PFRC2 Φ 20	0	0.2	20
10	PFRC3 Φ 20	0	0.3	20
11	SFRC1 Φ 20	0.5	0	20
12	SFRC2 Φ 20	1	0	20



Fig 1(a) Crimped steel fibres



Fig 1(b) Recron 3S fibres

C. Casting of specimens

The pullout specimens were prepared as per IS 516-1959 (reaffirmed 2004) [10]. The specimen consists of concrete cubes 150x150x150mm with a single reinforcing bar (16mm or 20mm dia) embedded vertically along the central axis in each specimen. The bar was projected down by about 10 mm from the bottom of the cube for measuring the slip of the reinforcement bar. Also, the bar was projected upwards by about 85 cm from the top face of the cube to provide an adequate length for gripping the specimen in the testing machine. The end of the reinforcing bars on which the tip of LVDT was fixed during the test was ground to a reasonably smooth surface normal to the axes of the bars. The specimens were also reinforced with a helix of 6mm diameter plain mild steel bar at a pitch of 25mm to prevent splitting failure. Moulds for casting were prepared using plywood. De moulding was carried out after 24 hours and then the specimens were immediately placed into curing tank for 28 days of curing. Fig 2 shows the casting of specimens and the cast ones before curing.

Table 2: Properties of fibres used

Fibre type	Shape	Length (mm)	Diameter (mm)	Aspect ratio	Tensile strength(MPa)
Steel	Crimped	30	0.6	50	750-1100
Recron 3S	Triangular	12	0.036	334	400-600

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Table 3: Properties of deformed reinforcement bars

Sl No	Nominal diameter of bar(mm)	Actual diameter of bar (mm)	Yield Strength (MPa)	Ultimate Strength (MPa)
1	16	16.04	545	609
2	20	20.12	485	660.5

Table 4: Mix proportion for M25 grade concrete

Cement	Water	Fine aggregate	Coarse aggregate	Superplasticizer
394 kg/m ³	177.3 kg/m ³	691.6 kg/m ³	1110.76 kg/m ³	4.73 kg/m ³



Fig 2: Casting of specimens

D. Testing of pullout specimens

The test was conducted as per IS 2770 Part 1:1967 – (reaffirmed 2002) [11] using a universal testing machine of 600kN capacity. While testing, the pullout specimen was mounted on the testing machine in such a manner that the bar is pulled axially from the specimen. As per IS 2770 the end of the bar at which the pull is applied shall be that which projects from the top face of the cube as cast.

The test framework setup is shown in Fig 3. Linear variable differential transformer (LVDT) was used to measure the displacement of the bar. Two LVDT's were fixed one at the loaded end and other at the free end of the bar for measuring the slip of the bar with respect to concrete. The LVDT at the free end was placed such that the pointed tip of the LVDT touches the exposed end of rebar on the back end of the specimen to record bar slip. Load was applied to the reinforcing bars monotonically at a rate not greater than 22.5 kN/min. The loading was continued until the specimen failed. The recording of loads and deformations were carried out. The loads recorded were then converted to bond stress. Assuming a uniform bond stress distribution over the embedment length in concrete, the average bond stress between the reinforcing bar and the surrounding concrete τ_b was calculated as ,

$$\tau_b = \frac{P}{\pi d_b l_b}$$

where, τ_b is the bond stress in (MPa), P is the applied load (N), d_b is the diameter of bar (mm) and l_b is the embedded length of bar (mm).

E. Behaviour of specimens

In all the specimens pullout type of failure was observed for both experimental tests as well as finite element analysis. No yielding was occurred in the steel bar. Pull out failure is likely to occur when the concrete in between reinforcing

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steel bar ribs (concrete key) is weak and surrounding concrete is strong [12]. The splitting type of failure was not seen in the specimens due to the presence of helical reinforcement in the form of confinement. The splitting type of failure does not provide pullout bond strength. Fig 4 (a) shows the pullout failure in control specimen (specimen without fibres) in which there is substantial cracking of concrete. Whereas in the case of SFRC specimen the crack is reduced which shows the ability of fibres in controlling the crack.

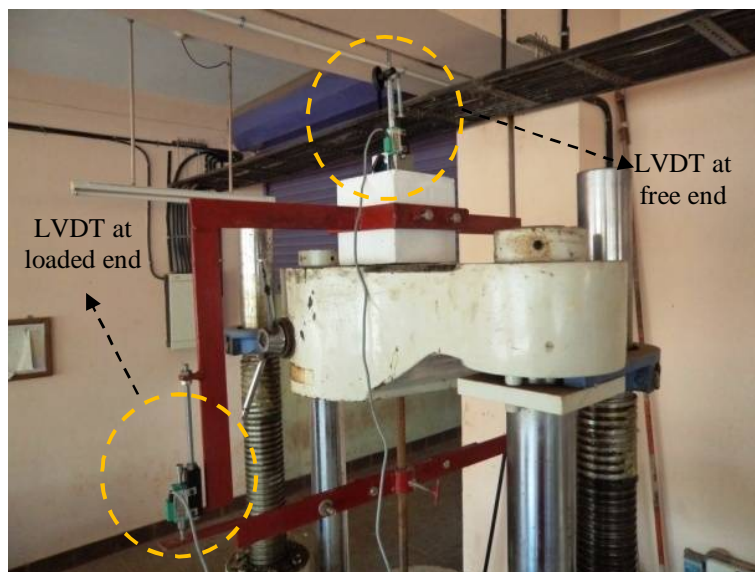


Fig 3: Test setup



a) Control specimen b) SFRC2 specimen

Fig 4: Pullout type of failure

IV. ANALYTICAL PROGRAMME

The analytical work was done using the finite element programme ANSYS. Concrete and reinforcement are discretized by three dimensional elements in modeling of bond [13]. In this work the pullout specimens were modeled in the Autocad system and then imported to ANSYS 16.1. Here based on the experimental work the control specimen as well as specimens of all other mixes were modeled and analysed.

A. FE Modeling of Pull-out Specimen

While modeling the specimen in Autocad, a cube of size 150x150x150mm was considered. In the modeling process, four different parts were modeled separately and then bonded together. The concrete surrounding the reinforcement bar was separately modeled as a cylindrical concrete specimen in which helical reinforcement was embedded. The parts modeled separately are i) Reinforcement bar, ii) Outer concrete, iii) Inner concrete and iv) Helical reinforcement. To resemble the experimental scenario, concentric steel bar of both 16mm and 20mm diameter and length 1000mm was modeled. After modeling all the parts were combined together to act as a complete pullout specimen by giving proper contact between them. The contact between inner concrete and helical reinforcement was given as bonded. The contact between inner and outer concrete was also given as bonded. Frictional contact was given between inner concrete and reinforcement bar since frictional factor plays a major role at the interface of deformed bar and concrete. A frictional coefficient of 0.7 was given for the analysis purpose, since the value ranges from 0.45-0.7 (based on the literature reviews). After successfully giving contacts, the model was meshed. The meshed specimen model is shown in Fig 5. To obtain precise results, in concrete vicinity of reinforcement, meshing was done much finer at the interface between concrete and reinforcement. At the face of the specimen a mesh size of 20mm was used whereas at the interface of bar and concrete a mesh size of 5mm was used in order to get more accurate results. A total of twelve specimens were modeled (with varying parameters such as bar reinforcement, volume fraction of fibres etc.) as that of the experimental work.

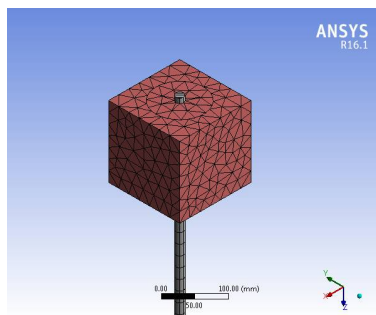


Fig 5: Meshed specimen model

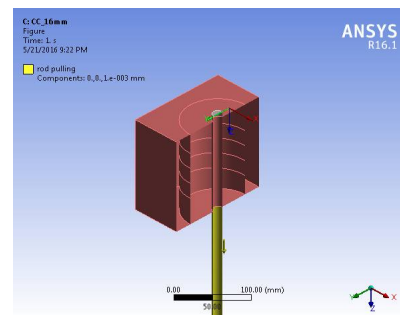


Fig 6: Specimen showing pulling of rod

B. Element Types

ANSYS literally provides hundreds of element types. To identify these element types, each element type is assigned a code name (eg: SOLID186, BEAM188 etc). By default the workbench automatically chooses appropriate element types from an element library according to the type of structural bodies involved in the project [14]. Here in this pullout specimen, concrete was modeled using SOLID 186. For modeling helical reinforcement, element named BEAM188 was used. Contact elements CONTA174 and TARGE170 were used for bonding bar and concrete.

C. Loading and boundary condition

As an initial loading a pull of 3 mm was applied on the reinforcement bar. The support conditions were given to the cube specimen by restraining translation in one direction. The displacement of reinforcement was given only in Z direction (i.e. downward similar to experimental set up).

D. Material properties

For FEA analysis the following properties of concrete were given in the engineering data section for further solving., i) Compressive strength , ii) Elastic Modulus , iii) Poisson's ratio and iv) Density. For each type of specimen the values of the above said properties except Poisson's ratio had been found out experimentally and were provided in the required field. In the case of reinforced steel bar the properties which was fed include i) Yield strength , ii) Elastic Modulus, iii) Poisson's ratio and iv) Density.

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E. Analysis of pullout specimen

After assigning the material properties and giving load and boundary conditions, the specimen was set for analysis. Fig 6 shows the pulling of rod in analysis. After analysis, the total deformation, force required for deformation, total stresses and strains etc was obtained from the solutions and results area. The force required for the slip was taken from the results section and a graph was drawn between bond stress and slip.

V. RESULTS AND DISCUSSIONS

A. Bond Stress

The value of bond stress at a slip of 0.025mm and 0.25mm which is the requirement as per IS 2770 Part (1):1967 (reaffirmed 2002) and the ultimate load and ultimate bond stress of all the specimens which failed due to pullout of reinforcement bars are shown in Table 5. For all the specimens very little slip was noted till the specimens reached the ultimate load. Only at the time of failure of specimen there was considerable slip. Hence for the sake of comparison of bond stress as per IS 2770 slip at 0.025mm and slip at 0.25mm was noted. The results from table show that the bond stress for polyester fibre reinforced concrete (PFRC) was more than the control specimen and that for steel fibre reinforced concrete was more than PFRC for both 16 and 20mm bars. This extend of increase was more pronounced in the case of 16mm bars where it increased by 47.6 % for 1% steel fibres. However the extend of increase was small ie 37.39 % for 20mm bars. The increase in bond stress values due to the increase in fibre content may be due to the fact that the increase in volume fraction of fibres increases the confinement and bridging effects in the matrix which will improve the bond stress values.

Table 5: Experimental test results

Sl no	Specimen designation	Bond stress at 0.025mm slip (MPa)	% Increase or decrease in bond stress compared to CS	Bond stress at 0.25mm slip (MPa)	% Increase or decrease in bond stress compared to CS	Ultimate load (kN)	Ultimate bond stress (MPa)	Failure mode
1	CSΦ16	12.50	-	11.40	-	95	12.57	Pullout
2	PFRC1Φ16	13.20	5.60	12.80	12.28	100	13.24	Pullout
3	PFRC2Φ16	13.90	11.20	13.60	19.3	105	13.90	Pullout
4	PFRC3Φ16	14.30	14.40	13.70	20.17	108	14.30	Pullout
5	SFRC1Φ16	15.90	27.20	13.80	21.05	122.5	16.21	Pullout
6	SFRC2Φ16	18.45	47.60	17.30	51.75	140	18.53	Pullout
7	CSΦ20	11.50	-	10.2	-	110	11.61	Pullout
8	PFRC1Φ20	11.85	3.04	11.4	11.76	112.5	11.87	Pullout
9	PFRC2Φ20	12.30	6.96	11.6	13.72	117.5	12.40	Pullout
10	PFRC3Φ20	12.95	12.61	11.6	13.72	125	13.19	Pullout
11	SFRC1Φ20	13.60	18.26	12.4	21.57	130	13.72	Pullout
12	SFRC2Φ20	15.80	37.39	15.4	50.98	150	15.83	Pullout

It can be noted from Table 5 that, for a given embedded length and mix the bond stress for smaller diameter bars is more than that of larger diameter bars. This may be because of the larger concrete cover to bar diameter ratio available in the case of small diameter bars which may contribute more to the bond resistance of the bar. When the cover to the reinforcement is increased, then crack initiation load increases and subsequently bond strength improves. The bond stress for 20mm bar is about 8-36% lesser than that of 16mm bar when the different mixes are considered.

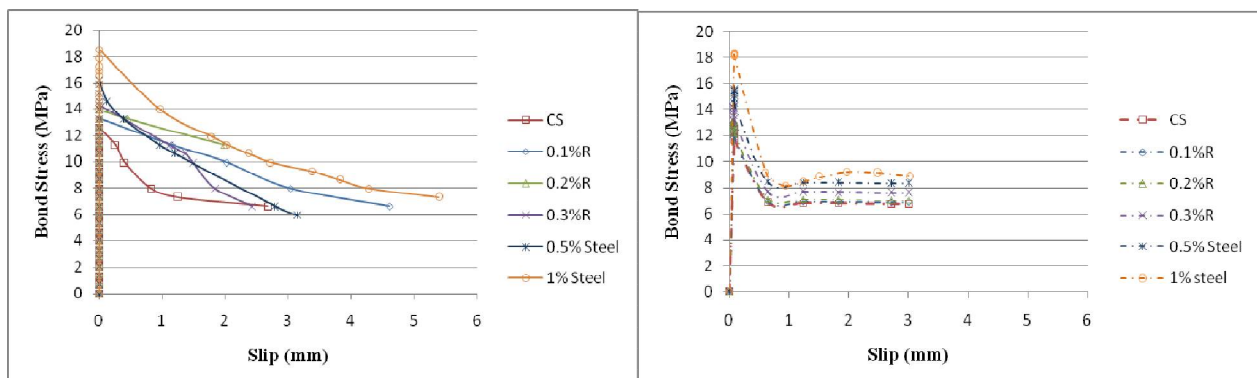
Significant improvement in bond stress was seen in the case of 16 and 20mm bars when the steel fibre volume fraction was increased from 0.5% to 1%. In the case of 16mm bar, there was an increase of 27.2% compared to control specimen for 0.5% steel fibre, whereas a significant improvement of 47.6% was seen compared to CS when steel fibre volume was increased to 1%. Similarly in the case of 20mm bars there was an increase of 18.26% and 37.39% compared to CS for 0.5% and 1% steel fibre respectively.

For specimens with same bar diameters improvement in bond stress was observed when the fibre volume fraction was increased from 0.1% to 0.3% in case of recron fibres. For 16mm bar when the fibre fraction was 0.1%, 0.2% and 0.3% the bond stress increased 5.6%, 11.2%, 14.4 % respectively. In the case of 20mm bar when the fibre fraction was 0.1% the bond stress showed an increase of 3.04%, whereas for 0.2% and 0.3% of fibre fraction the bond stress showed an increase of 6.96% and 12.61% respectively compared with control specimen.

B. Bond stress-slip behaviour

Generally bond stress slip relationship represents the bond behaviour in reinforced concrete members. Adhesion of FRP bars to concrete is the principal component that describes the bond performance of the bar at initial loading stages. Once adhesion between bar and concrete breaks, the bar starts to slip and friction between the outer layer of the bar and concrete controls the bond mechanism.

The load versus slip values were recorded for all types of specimens during testing and the values were plotted in graph. All curves were found to have almost the same trend. The Figs 7 (a) and (b) below shows the experimental and analytical graph respectively for the bond stress versus slip behaviour of specimens with 16mm bars. Whereas Figs 8 (a) and (b) shows the experimental and analytical graph respectively for the bond stress versus slip behaviour of specimens with 20mm bars. From the graph it can be seen that the curves for both experimental and analytical works shows similar trend. All curves showed an initial ascending branch up to maximum stress τ_{max} . It also showed a falling branch or softening branch, after the maximum bond stress was attained. This portion of curve was characterized by a significant decrease in the bond stress accompanied by an increase in bar slip. From the graphs obtained from experimental work it can be seen that post cracking behaviour for specimens with 0.5% steel fibres are almost similar to the post cracking behaviour of specimens with 0.1, 0.2 and 0.3% recron fibres. So it can be inferred that 0.5% steel fibres can be effectively replaced with recron 3S fibres which are cheap and easily available in the market. It also has very little weight compared to that of steel fibres.



a) Experimental

b) Analytical

Fig 7: Bond stress vs slip behaviour of specimens with 16mm bar

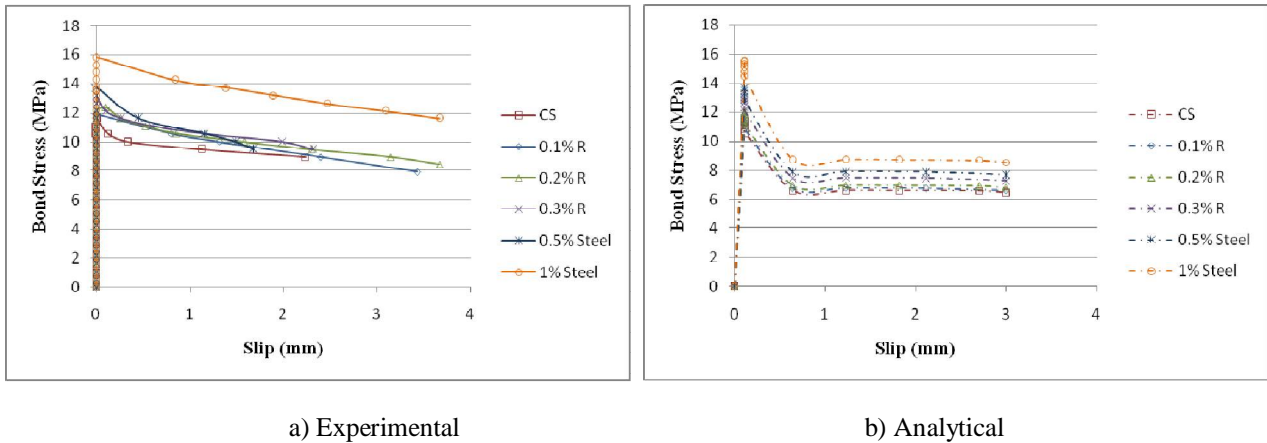


Fig 8: Bond stress vs slip behaviour of specimens with 20mm bar

C. Comparison of results

The experimental and analytical test results of 12 types of pullout specimens for 16mm and 20mm bars are tabulated and compared in Table 6. The ultimate load at which the specimen failed and the corresponding ultimate stress for both experimental and analytical work is given. From the table it is clear that the bond stress decreases with increase of bar diameter. Also small differences are seen in the results of experimental and analytical work. The difference in result predicted by FEA and those obtained experimentally may be attributed to the difficulty of determining the actual coefficient of friction at the interface of reinforcement bar and concrete. Fig 9 (a) and (b) shows the graphical comparison of the experimental and analytical results for 16mm and 20mm bars respectively.

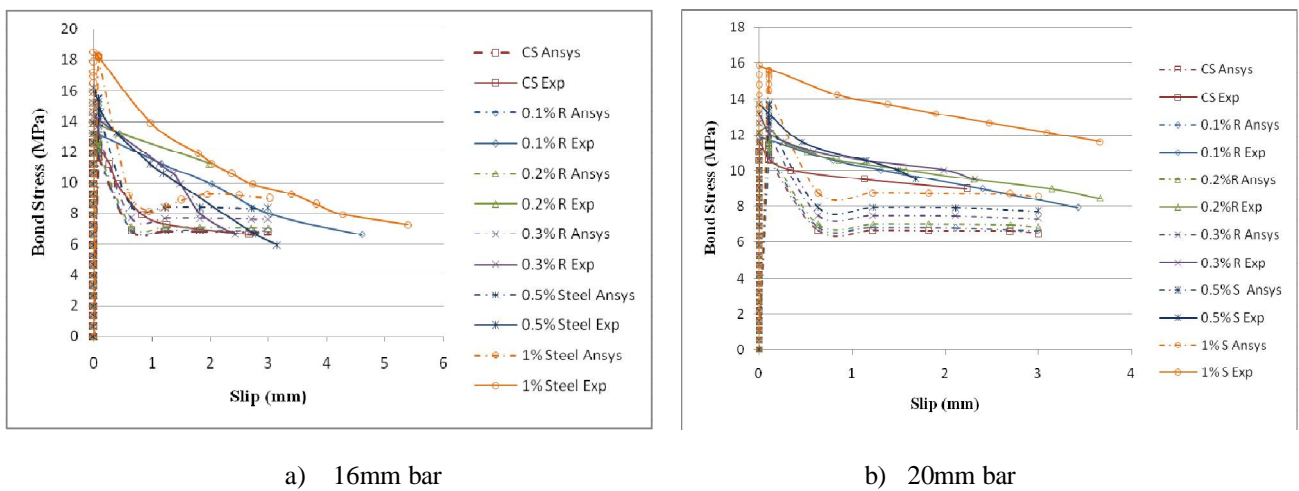


Fig 9: Comparison of experimental and analytical work of specimens

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Table 6: Comparison of experimental and analytical results

Specimen Designation	Ultimate Load (kN)		% Increase / Decrease in load compared to FEA	Ultimate Bond Stress (MPa)		% Increase/ Decrease in bond stress compared to FEA
	FEA	EXP		FEA	EXP	
CSΦ16	94.40	95	0.63%	12.50	12.57	0.63%
PFRC1Φ16	96.15	100	3.85%	12.73	13.24	3.85%
PFRC2Φ16	99.00	105	5.71%	13.10	13.90	5.71%
PFRC3Φ16	106.85	108	1.06%	14.14	14.30	1.06%
SFRC1Φ16	116.9	122.5	4.57%	15.47	16.21	4.57%
SFRC2Φ16	137.95	140	1.46%	18.26	18.53	1.46%
CSΦ20	107.97	110	1.85%	11.39	11.61	1.85%
PFRC1Φ20	110.40	112.5	1.87%	11.65	11.87	1.87%
PFRC2Φ20	113.65	117.5	3.28%	11.99	12.40	3.28%
PFRC3Φ20	122.69	125	1.85%	12.95	13.19	1.85%
SFRC1Φ20	129.8	130	0.12%	13.70	13.72	0.12%
SFRC2Φ20	147.44	150	1.71%	15.56	15.83	1.71%

The graph for 16 mm and 20mm bar specimens shows that the value of bond stress for each type of specimen from experimental work is more than that of analytical work. This is acceptable, as the bond strength from analytical work which is predicted one, is less than experimental result, the analysis done by FEA is on the safer side. Thus it can be used for predicting the bond strength of various specimens by changing the parameters.

VI. CONCLUSIONS

Based on the experimental and analytical results of the study presented in this paper the following conclusions are made.

- (1) The addition of polyester and steel fibres improved the bond stress for both 16mm and 20mm bars compared to the control specimen. But the increase in bond strength was more in the case of steel fibres.
- (2) The trend of bond-slip relation was found independent of the bar diameter. The curves for 16mm and 20mm bar showed same trend.
- (3) For both experimental and numerical analyses, bond strength decreases by increasing the diameter of steel bar embedded in cubical specimens of same compressive strength.
- (4) Since the post peak behaviour of specimens with 0.5% steel fibres is almost similar to recron 3S fibres, the specimens with 0.5% steel can be effectively replaced with recron 3S fibres which are cheap and easily available in the market.

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- (5) The difference between the results predicted by FEA and those obtained experimentally is attributed to the difficulty of determining the frictional properties at the interface of bar and concrete.
- (6) Since the analytical results were almost similar to experimental values, it is possible to use the analytical procedure for predicting the bond strength for various specimens.

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