

# Experimental and Analytical approach to Study the Effect of Tension Stiffening and Cracking in Fibre Reinforced Concrete

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**ABSTRACT:** Tension stiffening is a structural property of reinforced concrete that refers to the contribution of concrete between cracks to the overall stiffness of the member. In this study tension stiffening is experimentally evaluated considering the variables like the diameter of reinforced steel and incorporation of metallic and non-metallic fibres which depends on many factors such as size, type, elastic properties, aspect ratio, and volume fraction of fibres. For calculating the crack spacing, CEB-FIP code provision was considered and compared with the values of experimentally tested tension stiffening prism specimen. The successful implementation of the tension stiffening behaviour is demonstrated through the prediction of deformation of reinforced steel as per uniaxial load using a general nonlinear FE analysis package (ANSYS) by modelling and analysing reinforced concrete prism member. Based on the study, it has been found that the addition of fibres has increased the tension stiffening effect considerably. Crack spacing increased and number of cracks and crackwidth were decreased with the increase in fibre content.

**KEYWORDS:** Tension stiffening, Fibre reinforced concrete, Bar diameter, Crack spacing, Nonlinear FE analysis.

## I. INTRODUCTION

Bond of reinforcing bars to the surrounding concrete influences the behaviour of reinforced concrete structures in many ways. It can be a key element for the ultimate load carrying capacity of reinforced concrete structures since it affects the anchorage of bars. The deformation of a rebar embedded in concrete is significantly influenced by the bond between the two materials. In fact, it is well known that, after cracking, bond transfers tensile stresses from the rebar to the surrounding concrete (between cracks) that stiffen the response of a RC member subjected to tension; this stiffening effect is referred to as "tension stiffening". Tension stiffening refers to tension carrying ability of concrete between cracks, contributing to the stiffness of a reinforced concrete member before the reinforcement yields. Cracking causes a softening behaviour in plain concrete. As cracking progresses, concrete loses its stiffness at a relatively high rate. However, this softening behaviour is counteracted by the steel reinforcing bars in the tension zone of concrete. The tensile stress in concrete gradually decreases as cracking develops. When fibres are added into concrete, an additional significant mechanism influences the transmission of tensile stresses across cracks, arising from the bridging effect of fibres that provide a considerable post-cracking residual strength to FRC; hence, the concrete tensile stresses at a crack remain significant until a critical crack width, depending on the fibre types, dosage and toughness, is reached. Fibres significantly enhance the bond between concrete and rebar's and also act to reduce crack widths.

Bischoff [1] investigated the post cracking response of reinforced concrete tension members made with both plain and steel fibre-reinforced concrete (SFRC). Loading was either monotonic or cyclic, and shrinkage effects are included in analysis of the member response. Tension-stiffening results are used to determine the average tensile response of concrete after cracking, and an expression is developed to predict this smeared behaviour as a material property for cracked SFRC, as well as to estimate crack spacing. Fields and Bischoff [2] studied axial tension members made of both normal- and high-strength concrete and to investigate tension stiffening and cracking of reinforced concrete to determine experimentally if any relationship exists between concrete strength and post-cracking behaviour. Tension stiffening

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represents the tensile strength of concrete between cracks in a reinforced concrete member and can significantly affect member stiffness, deflection, and crack widths under service loads. Yun et al [3] described the influence of cement-based composites' ductility and damage-tolerant capacity on the tension stiffening performance and cracking process of reinforced cement-based composite tension ties. The effect of loading scheme (monotonic and repeated loading) was also investigated. Wu and Gilbert [4] showed that tension stiffening is most often included in models of reinforced concrete by modifying the constitutive laws of the tensile concrete. In reality, tension stiffening is caused by the bond stress that develops at the steel concrete interface between the primary cracks. A modified CEB-FIP bond model was incorporated into a non-linear finite element program to accurately model tension stiffening at the serviceability limit states. This research is intended to investigate the tension stiffening effect and cracking formation and development of FRC members toward a consistent modelling of the cracking phenomena in these materials. Paper is organized as follows. Section II describes the scope of present investigation. Section III gives clear idea of experimental programme. Section IV shows results and discussions and Section V presents conclusion.

## II. SCOPE OF PRESENT INVESTIGATION

The main objective of this research is to do an experimental and analytical (nonlinear FE analysis) investigation on the behaviour of fibre reinforced concrete tension ties to that of normal strength concrete ties. Mainly they are,

- Load-deformation behaviour
- Crack spacing

## III. EXPERIMENTAL PROGRAMME

The experimental work consisted of casting and testing 24 reinforced concrete prismatic tension members made of M25 grade concrete having cross-sectional dimensions of 60 x 60 mm and a length of 600 mm. 12 numbers of specimens were reinforced with 8 mm diameter bar and 12 numbers of specimens were reinforced with 10 mm diameter bar of grade Fe 500. The reinforcing bar was extended 150 mm on either side for proper gripping in the testing equipment. In addition of hooked end steel fibre with volume fraction of 0.5%, 1% and a non-metallic recron 3s (CT-2024) polyester fibre is added up to a total fibre volume fraction of 0.1 %, 0.2%, and 0.3%.

### A. Material used

Portland Pozzolana cement (PPC) conforming to IS: 1489(Part 1): 1991 (Reaffirmed 2005) [5], M sand with a specific gravity of 2.44 conforming to Grading Zone III of IS 383: 1970 (Reaffirmed 2002) [6], and coarse aggregate having a maximum size of 12 mm with a specific gravity of 2.69 were used for the investigation. Hooked End Steel fibres and Recron 3S polyester fibres used for this study are shown in Fig 1(a) and Fig 1(b), and their properties are given in Table 1. In this study as per IS: 9103-1999 [7] Conplast SP430 with specific gravity 1.22 was used as super plasticizer to obtain good workability.



Fig: - 1 (a)



Fig: - 1 (b)

Fig: - 1 Fibres used, (a) Hooked End Steel fibres (b) Recron 3S polyester fibres

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Table: - 1- Properties of fibres

Type of fibre	Hooked end steel fibre	Recron 3S polyester fibre
Length (mm)	30 mm	12 mm
Equivalent Diameter (mm)	0.6 mm	0.036
Aspect ratio	50	334
Tensile strength (MPa)	1100	400 - 600

### B. Mixture proportions

Mix designs for M25NSC (Normal strength concrete), M25SFRC (Steel fibre reinforced concrete) and M25PFRC (Polyester fibre reinforced concrete) have been worked out using the methods available from the literature. The same mixture proportions were used for all the specimens. The addition of fibres reduced the workability of concrete and the dosages of super plasticizer were adjusted to maintain the workability. In Table 2 the details of mixture proportions are given

Table: - 2- Mix proportion for M25 grade, kg/m<sup>3</sup>

Cement	Fine aggregate	Coarse aggregate	Water	Super plasticizer
431.64 kg/m <sup>3</sup>	778.73 kg/m <sup>3</sup>	900.74 kg/m <sup>3</sup>	194.24 kg/m <sup>3</sup>	3.453 kg/m <sup>3</sup>

### C. Mixing and Casting of the specimens

In Fig. 2(a) and Fig. 2(b) sketches for 8 mm and 10 mm reinforced specimens and cast of direct tension specimens were shown. For both 8 mm and 10 mm bar specimens, wooden formwork was prepared by using wooden plywood and they were fixed using nails and screws for the required dimension. Holes were provided on the side faces of the formwork so that they accommodate the reinforcing bars. The concrete used for casting of the specimens were mixed in a concrete mixer.

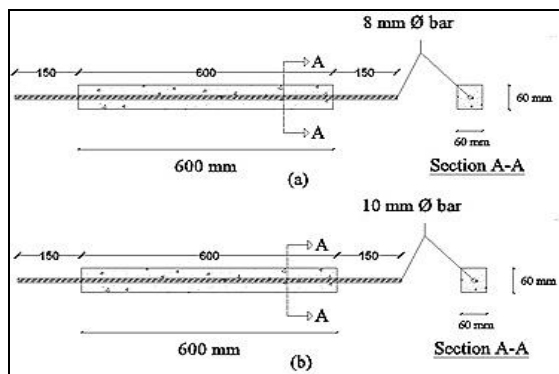


Fig: - 2 (a)



Fig: - 2 (b)

Fig:-2 (a) Sketches for 8 mm and 10 mm reinforced specimens and (b) cast of direct tension specimens

### D. Test setup and Instrumentation

After 28 days of curing, the specimens were white washed so that the cracking pattern is clearly visible during the time of test conducting. Fig 3(a) and Fig 3(b) shows specimens are ready for testing and the test setup. The specimens were tested under uniaxial tension in a universal testing machine (UTM) with a capacity of 600 kN. The axial elongation of the specimen was monitored by a linear variable differential transducer (LVDT), having a range of displacement is found to be 12 mm, fixed on the face of the specimen over a gauge length of 550 mm. The displacement was noted using a digital displacement indicator. A grid with a spacing of 100 mm was drawn on the front face of the specimen before testing to identify the crack locations continuously during the test. The location of each visible crack was

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marked on the specimen immediately after its appearance during the test. The crack spacing was measured by taking the average of crack spacing on all four sides after failure of the specimen. The testing was done under a load-control condition and continued until yielding occurred. In Table 3 the details of tested specimens and variables are given.

Table: - 3 Details of specimens

Serial No	Specimen designation	Rebar diameter (mm)	Volume fraction of fibres %		No.of specimens
			Hook End Loose Steel fibre	Polyester fibre	
1	NSC1	8	0	0	2
2	SFRC1		0.5	0	2
3	SFRC2		1	0	2
4	PFRC1		0	0.1	2
5	PFRC2		0	0.2	2
6	PFRC3		0	0.3	2
7	NSC2	10	0	0	2
8	SFRC3		0.5	0	2
9	SFRC4		1	0	2
10	PFRC4		0	0.1	2
11	PFRC5		0	0.2	2
12	PFRC6		0	0.3	2

**Note:** - NSC- Normal strength concrete, SFRC- Steel fibre reinforced concrete, PFRC- Polyester fibre reinforced concrete



Fig:-3 (a)



Fig:-3 (b)

Fig:-3 (a) Specimens ready for testing and (b) test setup

**E. Finite element modelling**

ANSYS, commercially available Finite Element (FE) software, of version 16.1 was used for the analysis of prismatic tension members. The actual behaviour of concrete should be simulated using the chosen element type. For the present type of model Conta174 and Targe170 elements were chosen. Fig 4(a) and Fig 4(b) shows Geometries of Conta174 and Targe170. Conta174 is used to represent contact and sliding between 3-D "target" surfaces and a deformable surface. The element is applicable to 3-D structural and coupled field contact analyses. The element also allows separation of bonded contact to simulate interface delamination. In this project, this element replaces Fe 500 TMT reinforcement bar in tension stiffening prism specimen. Targe170 is used to represent various 3-D "target" surfaces for the associated contact element replaces the M25 grade concrete [8].

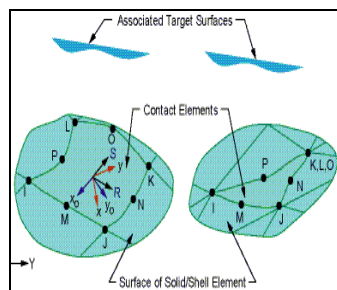


Fig: - 4 (a)

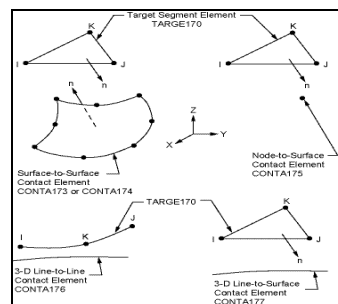


Fig: - 4 (b)

Fig: - 4 Geometries of (a) Conta174 and (b) Targe170 elements

**F. Nonlinear static analysis**

In linear static analysis the applied load should be within elastic limit, and therefore stress is proportional to strain so no deformation will take place. Also the stiffness will be constant  $k = c$ . Tension stiffening tests are carried out mostly in nonlinear static analysis because, applied load will be beyond the elastic limit so the study of the failure conditions of the test specimens is carried out by nonlinear finite element analysis. And if stress is not proportional to strain then the material undergoes deformation and also stiffness is not constant, i.e.  $k \neq c$ . The usefulness of the finite element method for nonlinear analysis very much depends on various numerical parameters which influence the solution.

**G. FEA model tension stiffening prism specimen**

In both experimental and analytical approach, load-deformation behaviour was getting as a result. In Fig 5(a) and 5(b), considering the geometry and uniaxial force reaction over the FEA model tension stiffening prism specimen and the deformation are indicated. From the solution information we can collect all the relevant results required for the study. In Table 4 details of analytically modelled direct tension specimens are provided.

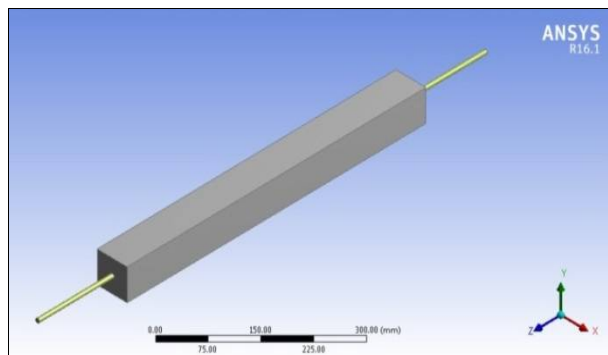


Fig:-5 (a)

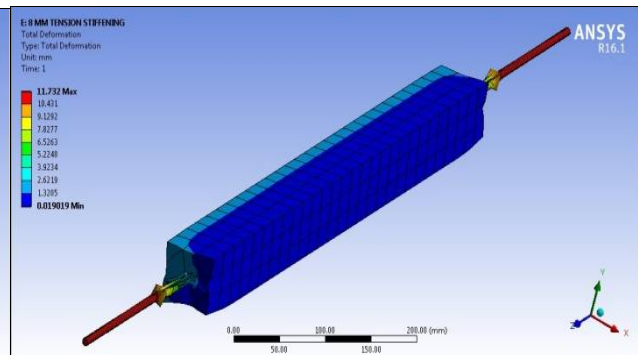


Fig:-5 (b)

Fig: - 5(a) Geometry and (b) Effect of Deformation in FEA model tension stiffening prism specimen

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Table: - 4 Details of specimen-Analytical

8 mm diameter bar model specimens	10 mm diameter bar model specimens
NSC1A	NSC2A
SFRC1A	SFRC3A
SFRC2A	SFRC4A
PFRC1A	PFRC4A
PFRC2A	PFRC5A
PFRC3A	PFRC6A

**Note:** - “A”- Denoted as “Analytical” in all specimens.

## IV. RESULTS AND DISCUSSIONS

In this section the results of the direct tension specimens reinforced with 8 mm and 10 mm bars and fibre reinforced with steel fibres and polyester fibres based on experimental test analysis and analytical analysis using ANSYS software have been presented. Based on laboratory test results the cracking data were obtained by counting the number of cracks at the time of failure. It should be noted that the crack spacing were obtained by taking the average of crack spacing on all four sides. Detailed investigations of the tension stiffening behaviour of specimens are described. The axial load-strain behaviour and the tension stiffening bond factor plotted for all the specimens. The analytical results using the FEA models for tension stiffening behaviour are compared with the experimental results to observe their validity and their accuracy against the experimental data obtained.

### A. Crack pattern

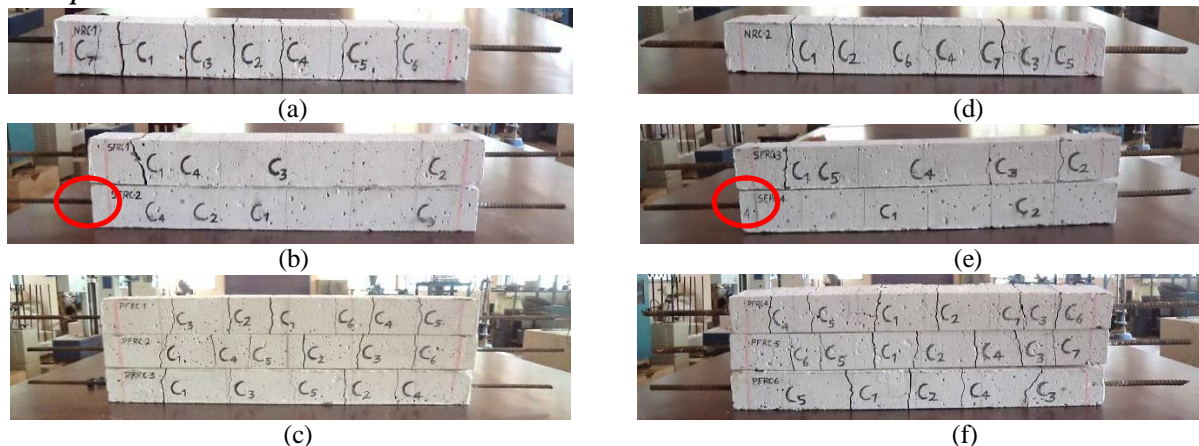


Fig 6 Crack patterns of Specimens (a) NSC1, (b) SFRC1 and SFRC2 and(c) PFRC1, PFRC2 and PFRC3 and Crack patterns of Specimens (d) NSC2, (e) SFRC3 and SFRC4 and (f) PFRC4, PFRC5 and PFRC6

Fig 6(a), Fig 6(b) and Fig 6(c) shows the crack patterns of 8 mm bar and in Fig 6(d), Fig 6(e) and Fig 6(f) shows the crack patterns of 10 mm bar containing tested prism specimens. In Table 5 shows the test results obtained from the experimental study. In both cases of NSC1 and NSC2 specimens, the first crack appeared near the middle portion of the specimen. As the load increased, the first crack widened and additional cracks appeared. The development of cracks was not uniform on all sides of the specimen. Longitudinal splitting cracks also appeared. In steel fibre reinforced concrete (SFRC) specimens, a less number of finer cracks are developed. Polyester fibre reinforced concrete (PFRC) specimens exhibited less cracks with reduced width as the volume fraction of polyester increased. This could be attributed to the ability of polyester fibres in arresting the micro cracks and the bridging action of the fibres at cracks was noted in specimens containing steel fibres. In SFRC specimens with 1% steel fibre have the ability for carrying tension so that not much cracks have been created after the yield load, In SFRC2 and SFRC4

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specimen neck (red mark in figure) has been formed over the reinforcement bar which shows increased tension stiffening property.

Table 5 Test results

Specimen	First crack load (kN)	Yield load (kN)
NSC1	8	28.6
SFRC1	13	30
SFRC2	28	31.8
PFRC1	10	29
PFRC2	11	29.2
PFRC3	14	29.8
NSC2	16	42.4
SFRC3	18	44.5
SFRC4	28	48
PFRC4	18	43.1
PFRC5	18	43.7
PFRC6	20	44.2

### B. Load-deformation behavior

The load-deformation response of the entire specimens can be obtained by plotting axial load with member strain. Fig 7 shows the experimental and analytical response of all specimens containing 8 mm diameter bar compared with bare bar and in Fig 8 shows the experimental and analytical response of all specimens containing 10 mm diameter bar compared with bare bar. When considering experimental test results for all the specimens, the behaviour was linear up to the first crack and initial stiffness, of specimens was higher than the stiffness of bare bar. It can be noted from Fig 7(a) and Fig 8(a) that, after the formation of first crack, the specimen containing steel fibres exhibited increased stiffness compared to NSC without fibres. In Fig 7(b) and Fig 8(b) shows load-deformation response of 8 mm and 10 mm diameter bar SFRC specimens containing 0.5 % steel fibre and in Fig 7(c) and Fig 8(c) shows load-deformation response of 8 mm and 10 mm diameter bar SFRC specimens containing 1 % steel fibre. The test result shows that, when fibre content increased from 0.5% to 1%, the stiffening effect increases markedly. In Fig 7(d), Fig 7(e) and Fig 7(f) shows load-deformation response of 8 mm diameter bar PFRC specimens containing polyester fibre with corresponding volume fraction of 0.1%, 0.2% and 0.3% and in Fig 8(d), Fig 8(e) and Fig 8(f) shows load-deformation response of 10 mm diameter bar PFRC specimens containing polyester fibre with corresponding volume fraction of 0.1%, 0.2% and 0.3% in each. PFRC specimens also exhibited an increased tension stiffening effect compared to the NSC specimen. For all the fibre reinforced concrete specimens, the strains are much lesser than that the bare reinforcement, even after cracking, which shows the tension stiffening effect of the matrix at the un-cracked sections and the contribution of fibres to the axial load-carrying capacity. This may be attributed to the ability of polyester fibres in delaying the formation and propagation of micro cracks and that of steel fibres in carrying stresses across the macro cracks. Among PFRC specimens with 0.3% polyester fibres showed higher tension stiffening effect than those with 0.1% and 0.2%. Also the specimens contains 0.3% polyester fibre shows much more strength than the specimens contains 0.5% steel fibres. In SFRC specimens with 1% steel fibre, it can be seen that most effective this test procedure that have the ability for carrying tension and makes reduction in crack formation so that not much more cracks has been created after the yield load shown. In both 8 mm and 10 mm bar specimen with 1% steel fibres, neck formation was seen which shows increase in tension stiffening property. It can be observed that the steel fibre reinforced composites exhibit high values of first crack load compared to NSC and PFRC specimens. SFRC tensile members present a different structural behavior with respect to plain concrete and PFRC tensile members. In fact, after cracking, fibers provide a noticeable increment of concrete toughness, guaranteeing a considerable residual strength between cracks; this phenomenon is generally neglected in plain concrete, due to its brittleness. The improved toughness of SFRC determines an increment of the average tensile stress of the undamaged concrete portions between two consecutive cracks; hence, the tension stiffening increases. The residual post-cracking strength provided by steel fibers contributes to the reduction of the transmission length, measured from a crack, which is necessary to transfer tensile stresses in concrete by means of bond

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between rebar's and surrounding concrete; hence, the average crack opening diminishes. Load at yielding was approximately the same for the NSC and bare bar, whereas it is little higher in SFRC and PFRC. Specimens with fibres exhibit tension stiffening even after yielding of the reinforcing steel because of the ability of fibres to carry tensile stresses across the cracks. ANSYS is commonly using finite element analysis software. So the finite element prism model created in ANSYS software and tried to investigate the specimen's behaviour under tensile loading. The entire graph shows same trend or same manner in load-deformation behaviour. In FEA analysis also the SFRC specimens shows tension stiffening behaviour more than that of NSC and PFRC.

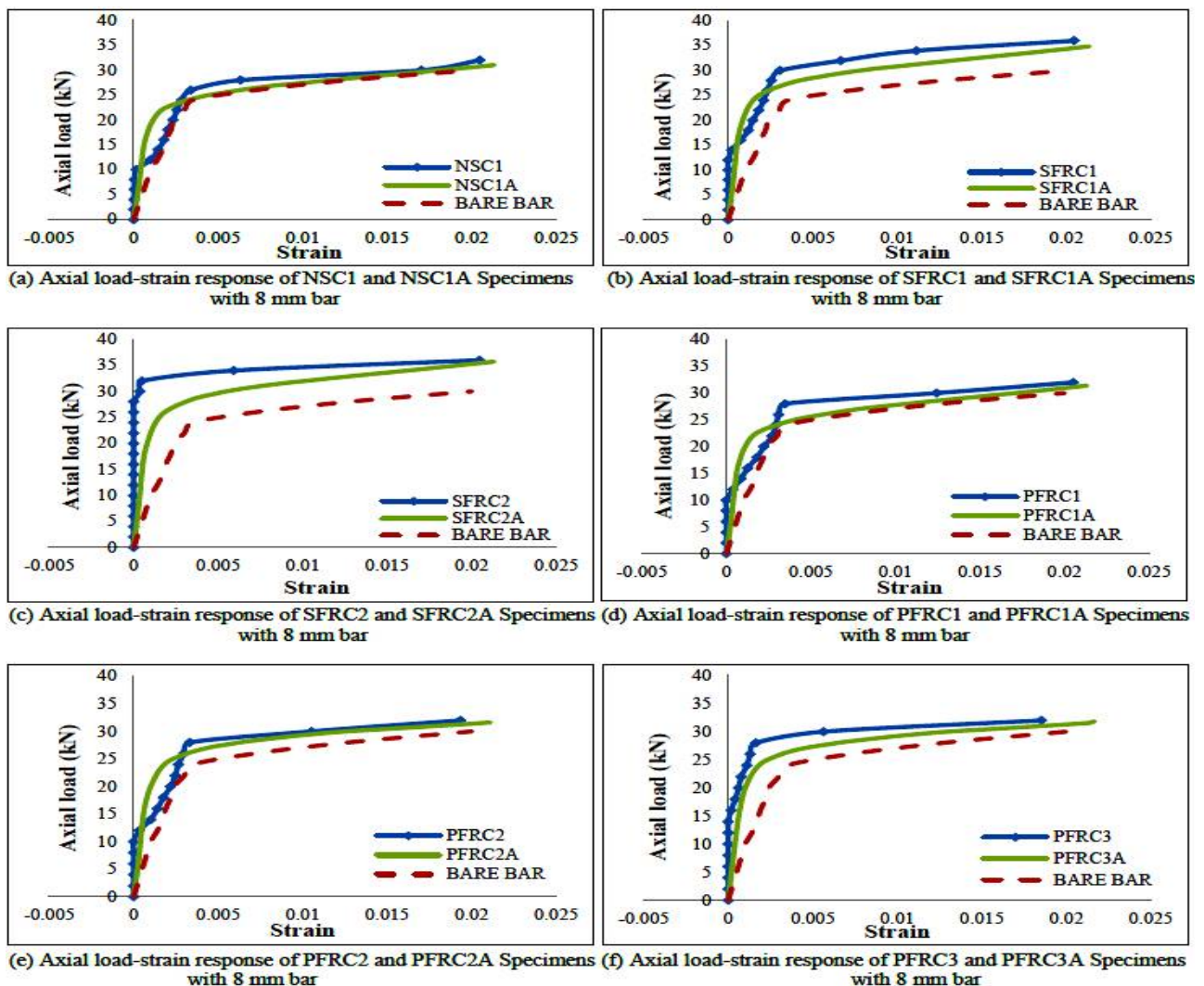
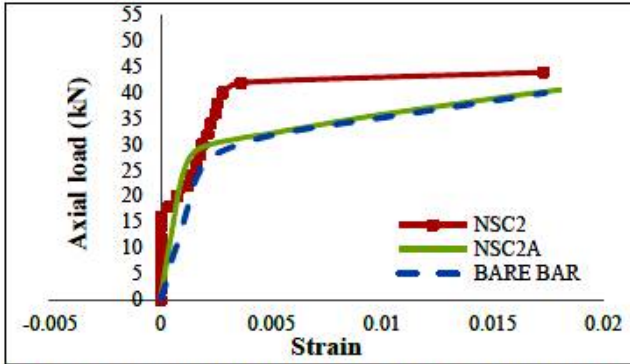


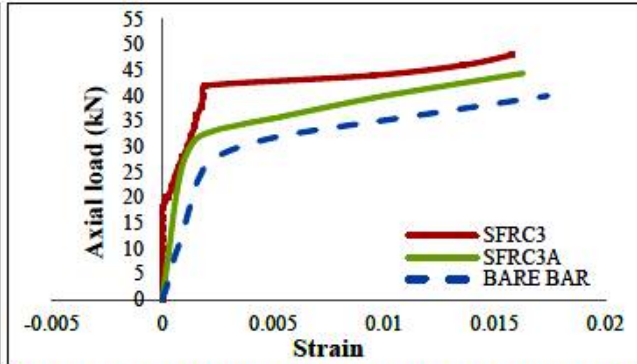
Fig: - 7 Axial load-strain response of all the specimens containing 8 mm bar

From the graphical representations both experimentally and analytically modelled specimens comparison in load-deformation is indicating that both showing tension stiffening effect compare with the bare bar As per the analysis it is clear that the ANSYS FEA models have some limitations that, the analysis can show only the tension stiffening behaviour.

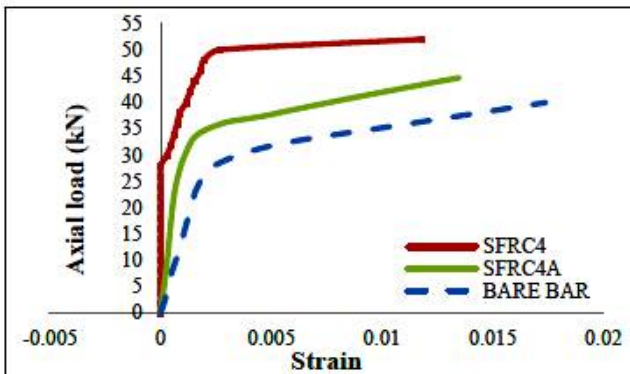




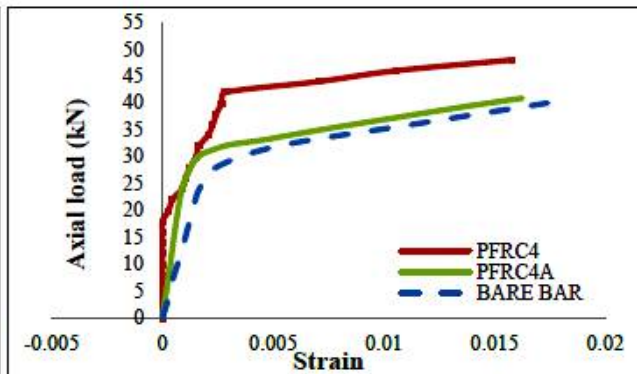
(a) Axial load-strain response of NSC2 and NSC2A Specimens with 10 mm bar



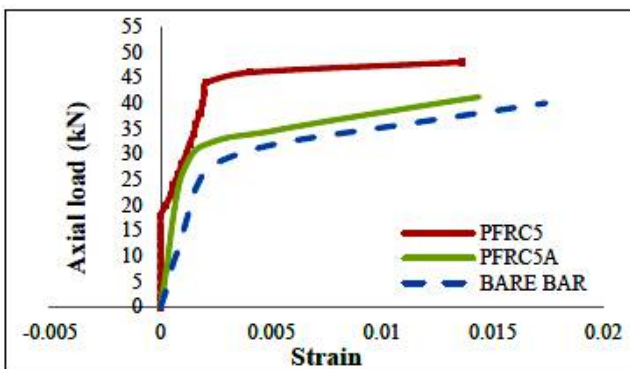
(b) Axial load-strain response of SFRC3 and SFRC3A Specimens with 10 mm bar



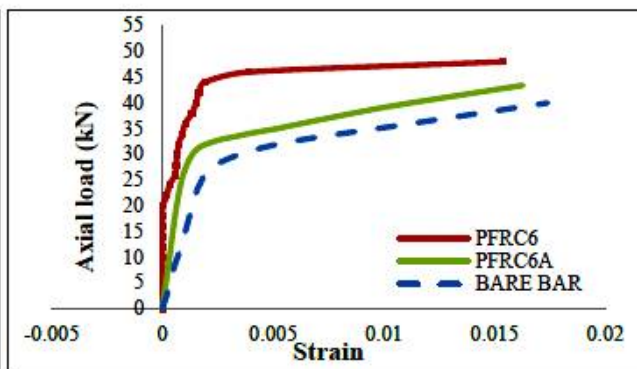
(c) Axial load-strain response of SFRC4 and SFRC4A Specimens with 10 mm bar



(d) Axial load-strain response of PFRC4 and PFRC4A Specimens with 10 mm bar



(e) Axial load-strain response of PFRC5 and PFRC5A Specimens with 10 mm bar



(f) Axial load-strain response of PFRC6 and PFRC6A Specimens with 10 mm bar

Fig: - 8 Axial load-strain response of all the specimens containing 10 mm bar

From the starting itself the graph is smooth curve in nature. Beyond the elastic region up to a limit this curves are higher than experimentally tested specimen's graph, except in the case of SFRC specimens with 1% fibre and PFRC specimens with 0.3% fibre. From above figures it is clear that the experimental specimen shows more tension stiffening behaviour than the FEA model specimen. Within the limitations ANSYS, FEA model also shows tension stiffening

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behaviour. These plots clearly emphasize the influence of the two different longitudinal steel bar diameters (8 mm and 10 mm) were adopted for this study. When considering the bar diameters, 8 mm bar has less ability to control the sudden local instability at the crack formation, as that of 10 mm bar.

### C. Crack spacing

Cracks are unavoidable and reinforcement is needed to control the behaviour after cracking and to limit crack widths. Large crack widths are not aesthetic but may also lead to accelerated reinforcement corrosion in severe environments, leakage in water-retaining/resisting structures, insanitary conditions, or obstructions and interruptions in production processes. Cracking may be caused by external applied forces, imposed deformations, by shrinkage or thermal strains which are externally and/or internally restrained, or by a combination of these. When cracking is caused by an external applied force the crack width, if sufficient amount of reinforcement is added, will depend on the applied force. However, if cracking is caused by an imposed deformation the force in the member depends on the actual stiffness on the number of cracked formed. However, most codes do not distinguish between these two cases. Furthermore, for structures having both fibre- and bar reinforcement there exist almost no guidelines exists for structural engineers. In this section, the crack spacing of experimentally tested direct tension reinforced specimens have been compared with mean crack spacing models mentioned as per CEB-FIP model 2010 (draft) code [9]. According to CEB-FIP Model code, the crack spacing for stabilized cracking is given by,

$$s_m = \frac{2}{3} \cdot \frac{d_b}{3.6 \rho_e}$$

Where,

$S_m$  = mean crack spacing (mm)

$d_b$  = longitudinal bar diameter (mm)

$\rho_e$  = ratio of the area of reinforcement effectively bonded to the concrete to the cross-sectional area of the effective embedment zone of the concrete.

In Table 6 the crack spacing of experimentally tested direct tension reinforced specimens have been compared with mean crack spacing models mentioned as per CEB-FIP model 2010 (draft) code.

Table: - 6 Crack spacing

Specimen	No of transverse cracks observed	Average crack spacing experimental (mm)	Average crack spacing-CEB-FIP Model 2010,(mm)
NSC1	7	73	104
SFRC1	4	137	104
SFRC2	4	142	104
PFRC1	6	79	104
PFRC2	6	83	104
PFRC3	5	97	104
NSC2	7	69	79
SFRC3	5	109	79
SFRC4	2	223	79
PFRC4	7	72	79
PFRC5	7	78	79
PFRC6	5	105	79

For the entire specimens used in this study, the average crack spacing was calculated using the equation CEB-FIP Model code 2010 (draft) was also shown in Table 6. It may be noted that the theoretical values computed by the aforementioned equation were higher than experimental values. However in the case of SFRC specimen, the equation

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underestimates the crack spacing. It was observed that all the specimens with steel fibres, exhibited increased crack spacing compared to specimens with polyester fibres, which has resulted due to decrease in number of cracks as well as width of crack.

## V. CONCLUSIONS

Based on the results obtained from experimental and analytical works in this study, the following conclusions are made.

- 1) While considering the bar diameters it is clear that, 8 mm bar has less ability to control the sudden local instability at the crack formation, as that of 10 mm bar. Based on the results, the prism specimens containing 10 mm diameter reinforcement bar shows more tension stiffening behaviour than that of specimens containing 8 mm diameter reinforcement bar.
- 2) From load deformation graphs it is clear that, prism specimens containing 10 mm diameter reinforcement bar has more ability to carry axial load than that of specimens containing 8 mm diameter reinforcement bar. Especially in the case of SFRC specimens contains 1% steel fibres.
- 3) The addition of steel fibre and polyester fibres improved the tension stiffening effect considerably and, thus, increased the bond stress of reinforced bars (in both 8 mm and 10 mm reinforced bar ) in fibre reinforced concrete compared to concrete without fibres.
- 4) Load at yielding was 11.18% higher in SFRC2 and 13.2% higher in SFRC4 specimens and 4.19% higher in PFRC3 and 4.24% higher in PFRC6 than that of NSC specimens.
- 5) Specimen with 1% of steel fibre and specimen with 0.3% polyester fibres significantly improved the tension stiffening effect when compared to other fibre reinforced specimens considered in this study.
- 6) Both the steel fibre specimens and specimen containing 0.3% polyester fibres [PFRC6] have large crack spacing considerably, which shows better performance with respect to serviceability criteria.
- 7) Within the limitations of ANSYS FEA model also shows tension stiffening behaviour. FEA model shows tension stiffening effect much less than experimental specimen and much more than bare bar response in axial load carrying condition.

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