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Structural Performance of Reinforced Concrete Beams with Steel Fibres as Secondary Reinforcement: Experimental and Pre-peak Numerical Modelling

Hadjer Belkadi [1,*], Abdelkrim Bourzam [2], Messaoud Saidani [3]

1 Laboratory of Built Environment Research, University of Sciences and Technology. Houari Boumediene (USTHB). Faculty of Civil Engineering. BP 32. El Alia. Bab Ezzouar. Algiers. 16111. Algeria
2 Ecole Nationale Polytechnique (ENP), Algiers, LMGCE/ENP & LBE/USTHB Research laboratories 10, Rue des Frères OUDEK, El Harrach 16200, Algiers, Algeria.
3 Faculty of Engineering. Environment and Computing. School of Energy. Construction and Environment. Coventry University. Priory Street. Coventry CV1 5FB. United Kingdom
* Corresponding Author: hbelkadi@usthb.dz

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Abstract. This research consists of an experimental and a numerical investigation into improving the structural performance of reinforced concrete (RC) beams by incorporating hooked-end steel fibres. Experimentally, steel fibres were added to the concrete matrix of 80 mm × 180 mm × 1500 mm RC beams with fibre contents of 0%, 0.5%, and 1%, without replacing traditional reinforcement bars. Each beam underwent a four-point flexural test using a hydraulic press under static loading to evaluate the influence of fibres on flexural behaviour. The numerical analysis aimed to model the macro-scale flexural behaviour of RC beams using a 3D finite element approach in ABAQUS. Challenges in modelling steel fibres include their discrete nature and computational demands due to intricate meshing and convergence issues. The Simplified Concrete Damaged Plasticity Model was used to characterize the compressive and tensile behaviours of plain and steel fibre reinforced concretes. Nonlinear finite element analysis was performed to predict pre-peak load versus mid-span deflection and crack propagation. The model, which does not explicitly simulate steel fibres, was validated against experimental data, showing strong agreement and confirming its effectiveness in capturing the flexural behaviour of steel fibre reinforced concrete beams. Experiments Results showed that steel fibres enhance the flexural performance. Beams with steel fibres exhibited higher first crack loads, ultimate loads, flexural strengths, and toughness. Additionally, the fibres increased crack numbers, reduced crack spacing and length, and improved post-cracking behaviour. The simulation results were subsequently validated against experimental data. The results of the numerical finite element analysis were in good agreement with those of the experiments.

Key words: Reinforced Concrete beams, Secondary Reinforcement, Flexural behaviour, steel fibres, FEM modelling, crack patterns.

1. Introduction

Reinforced concrete structural system may be subjected to static or dynamic loading during its life. Reinforced concrete beam is a structural element designed to carry bending loads. Its compression section must be designed to resist buckling and crushing while the tension section must be able to adequately resist tension. The behaviour of this structural element is influenced by the properties of concrete. The brittle behaviour of concrete can be enhanced for more ductility when adding steel fibres. The increase in ductility allows concrete to resist cracking and crack propagation which improves its flexural strength. deflection capacity and its cracking behaviour (Altun, Haktanir, and Ari 2007; Arunakanthi, Chaitanya, and Jagarapu 2020). The experimental results obtained by (Campione and Mangiavillano 2008) show that the combination of RC beams with correct percentage of fibres for structural purposes allows the achievement of better performances compared to those of conventionally reinforced beams even with the effect of shear-moment interaction.

Over the last years, new techniques and methods have been developed which aim to improve the mechanical performance of plain concrete, the incorporation of metal fibres into a concrete matrix improves its tensile and the flexural behaviours. The mechanical properties of steel fibre reinforced concrete (SFRC) with medium fibre content suggest the use of such material for many structural applications, with and without conventional reinforcement. Examples include industrial paving, repair of drainage pipes, projection under the vault in tunnels, construction of entirely fibre reinforced concrete pavements, motorway pavements or road pavements aeronautical car parks. The prospect of using steel fibre reinforced concrete is suitable for structures when they are subjected to loads over the serviceability limit state in bending and shear. particularly when exposed to impact or dynamic forces (Rizzuti and Bencardino 2014). Whatever their shape, the addition of steel fibres to a fresh concrete mixture increases the compressive strength. The flexural and tensile strengths of the concrete column improve its stress-strain relationship behaviour (Hadi 2009). (Zhang et al. 2020). Also, it reduces the risk of buckling of longitudinal bars. increases the dissipated energy and improves the displacement ductility of columns (Germano, Tiberti, and Plizzari 2016). According to Aylie et al. results (Aylie, Antonius, and Okiyarta 2015). The injection of steel fibres in flexural elements does not result in a substantial increase in the ultimate moment potential when the element is designed as an under reinforced beam. The concrete's flexural strength is significantly improved by the insertion of fibres. (Behbahani et al. 2018) work shown that RC beams incorporating 1% of hooked-end steel fibres present a considerable increase in first cracking strength flexural strength, stiffness and ductility compared to classic RC beams. Also, has more effects on the RC beams made from the concrete with higher compressive strength compared to the concrete with lower compressive strength due to the better bonding between the fibres and the concrete matrix. The effect of steel fibre incorporation on the compressive strength of concrete has shown some divergence. The compressive behaviour is mildly influenced by the inclusion of fibres. with an increase (Altun, Haktanir, and Ari 2007; Zhang et al. 2020; Behbahani et al. 2018) . or a slight decrease (Saidani, Saraireh, and Gerges 2016; Neves and Fernandes de Almeida 2005) in compressive strength compared to the plain concrete due to the proportion of steel fibres. While the use of steel fibres in concrete enhances its toughness and strain at peak stress, a decrease in elastic modulus may be observed (Neves and Fernandes de Almeida 2005). Bencardino et al (Bencardino et al. 2008) found that the increase of fibre content improves the post-peak behaviour while there is no significant effect on the compressive strength.

This study investigates the structural behavior of reinforced concrete beams incorporating hooked-end steel fibres as secondary reinforcement, with volume fractions of 0%, 0.5%, and 1% randomly distributed within the concrete matrix. Experimentally, the impact of these fibres was assessed on compressive strength, flexural strength, deflection, tensile strain, and energy absorption capacity (toughness). While experiments provided critical insights, they are time-consuming and costly, highlighting the importance of complementary numerical modeling. To simulate the pre-peak flexural behavior of the beams, a numerical analysis was conducted using ABAQUS. The compressive and tensile behaviours of plain and fibre-reinforced concretes were characterized using the Simplified Concrete Damaged Plasticity Model (Hafezolghorani et al. 2017). The numerical results were validated against experimental data, providing reliable predictions of the pre-peak flexural performance of reinforced concrete beams.

2. Experimental investigation

2.1. Materials and Methods

2.1.1 Preparation of the specimens

Concrete cubes with dimensions of 100 mm × 100 mm × 100 mm were cast for each mix design in steel molds, utilizing a vibrating table to ensure proper compaction. All cubes were subsequently cured in water at a controlled temperature ranging between 19 °C and 21 °C until the designated test day, in accordance with the British Standards (British Standard 2000; BS 1993; 2009). In addition, six beams, featuring the specified geometry and reinforcement

configurations as depicted in Figure 1, were cast and subjected to four-point bending tests. The beams have a cross-section of b = 80 mm, d = 180 mm and span L = 1500 mm and were reinforced with 10 mm longitudinal deformed bars (Figure 1), stirrups steps of 100 mm were also adopted. The six (06) beams were de-moulded after one day and cured for 28 days in the laboratory. The beam specimens' characteristics are summarized in Table 3.
In this study, the volume fraction of steel fibres is varied up to 1% to maintain the good workability of concrete. Proportions of all ingredients cited before and the specimens' characteristics are summarized in Table 1. The slump test results have shown a slight decrease for steel fibre concrete compared to plain concrete. The steel fibres used in this experimental study are summarized in Table 2. The steel reinforcement used was the same for all the tested beams. The geometry, loading boundary conditions and arrangement of longitudinal and transversal reinforcement are shown in Figure 1. The geometrical ratio of longitudinal steel at mid-span (Figure 1) is $\rho = \frac{A_s}{b.d} = 1.09\%$, where, A_s is the area of the longitudinal steel reinforcement, b is the width of the beam's cross-section, and d is the effective depth of the beam.

Table 1. Concrete mix quantities for 1 m³

Material	Mix 1 (PC)	Mix 2 (SFC1)	Mix 3 (SFC2)
Ordinary Portland Cement 52.5 (kg)	350	350	350
Sand 0.075-5mm (kg)	790	790	790
uncrushed gravel 5-14 mm (kg)	947.17	947.17	947.17
W/C	0.5	045	0.43
Super plasticizer FOSROC AURACAST 200 (%C)	0.63	2.21	3.15
Hooked-end steel fibre content f (%)	0.0	0.5	1.0
Slump (mm)	170	160	158

Table 2. Steel fibre's Characteristics.

Steel fibre type	Length (mm)	Diameter (mm)	Aspect ratio	Cross section	Tensile strength (MPa)
Hooked-end	60	1.0	60	Circular	1900

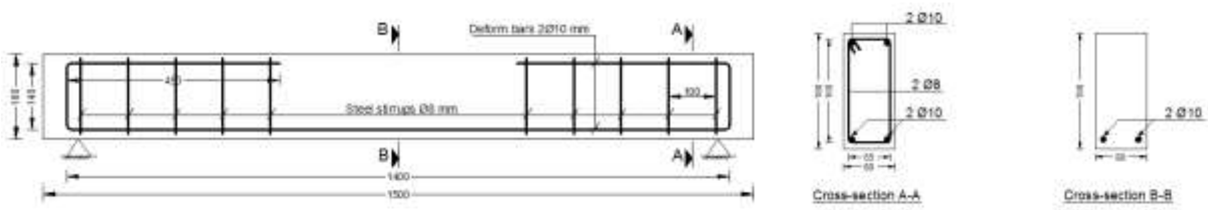


Fig 1. Beam's geometry and reinforcement

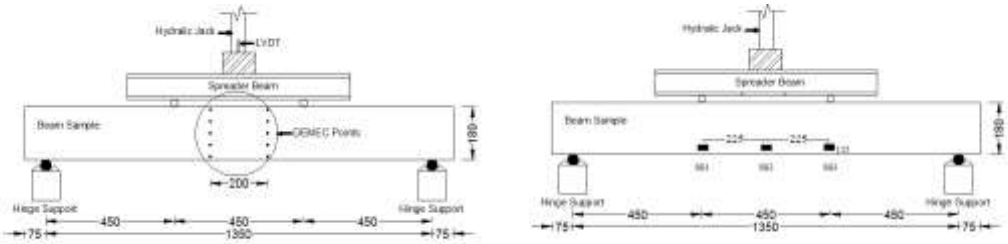
Table 3. Specimens' characteristics

Specimen ID	Mix design	Fibre content (%)
B-RPC-S1 (Control beam)	Mix 1 (PC)	0
B-RPC-S2 (Control beam)		0
B-RSFC1-S1	Mix 2 (SFC1)	0.5
B-RSFC1-S2		0.5
B-RSFC2-S1	Mix 3 (SFC2)	1
B-RSFC2-S2		1

2.1.2. Experimental setup

The cube specimens were tested under compression load by compression machine Avery-Denison, of 2000 kN max capacity. The actuator speed was set at 0.6 kN/s. The testing method of compressive strength is comparable to (BS 2009). The beams were tested using a servocontrolled hydraulic actuator of ±100 kN of max capacity. The experimental tests of the beams were carried out under a vertical actuator where the speed loading was set at 0.2 kN/s.

The beams were simply supported with an effective span of 1350 mm. Two-point loads equally spaced at 225 mm from each side of the centre of the beam as shown in Figure 3 were applied to obtain a pure flexion at the middle third position of the beam. The displacement value records were obtained using a Linear Variable Differential transformer (LVDT) installed at the top at mid-span of the beam. For the strain records a DEMEC gauge was used in different positions spaced to each other by 200 mm horizontally and 40 mm in the vertical direction as shown in Figures 2 and 3. To confirm the accuracy and reliability of the results obtained by the DEMEC gauge in the tensile zone, three strain gauges of gauge length 20 mm were fixed at a distance of 25 mm from the extreme tension face of the beam.



(a) (b)

Fig2. Schematic representation of the 4-point bending test: (a) location of the LVDT and the DEMEC measuring points (b) the strain gauge's locations

(a) (b)

Fig 3. Photograph of (a) the Steel loading frame and (b) the Strain gauges on concrete surface of the beam

Numerical procedures

3.1. Material modelling

In this study, the beam specimen was modelled by the finite element method using the ABAQUS finite element code. The predictions of the proposed FEA model are validated against the experimental results. The discretized beam is modelled as a three-dimensional deformable solid body. The FEM analysis was carried out assigning the same dimensions and material properties of the tested beams, as shown in Figure 4.

Fig 4. Developed solid model

3.2. Methodology

The Concrete Damage Plasticity (CDP) is the most comprehensive continuum model that was used to define concrete behaviour in this analysis' reinforced concrete beam simulation. The CDP model is based on two concrete failure mechanisms and applies to concrete that is subjected to monotonic loading for many types of structures (such as beams. trusses. shells. and solids). Compressive crushing and tensile cracking are two different types of crushing. The compressive and tensile plain and steel fibre reinforced concretes behaviours are characterized based on the Simplified Concrete Damaged Plasticity Model (Hafezolghorani et al. 2017).

Before defining the value of damaged concrete in ABAQUS, four constitutive parameters are required to define the yield surface. Default values are accepted for the plasticity damaged parameters (dilation angle, eccentricity, fb0/fc0, kc, viscosity parameter).

In this investigation, default values for stiffness recovery parameters are used for both PC and SFC. As a result, the compressive stiffness recovery factor equal 1 is used to assume that compressive stiffness is fully recovered upon crack closure as the load changes from tension to compression, while the tensile stiffness recovery factor equal 0 is used to assume that tensile stiffness is not recovered as the load changes from compression to tension once concrete crushing begins. The behaviour of bars and concrete cracking was assumed to be independent.

Uniaxial Compressive Behaviour

In this study, Kent and Park model is used to characterize the uniaxial compressive behaviour. However, the present study employed the Kent and Park parabolic constitutive model for unconfined concrete (Figure 5).

Uniaxial Tensile Behaviour

In tension phase, concrete had many constitutive models. (Lubliner et al. 1989) model are used in the present study (Figure 6).

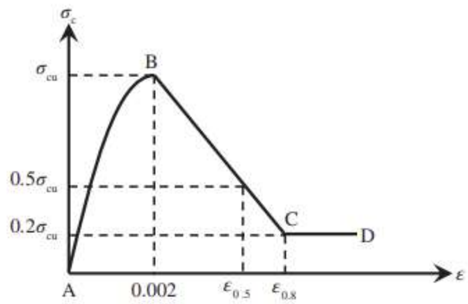


Fig 5. Kent and Park model for confined and unconfined concrete.

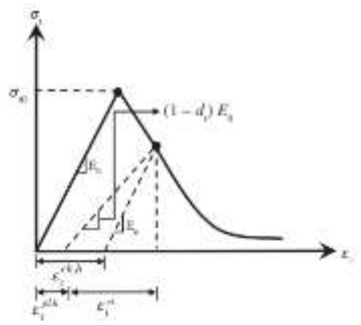


Fig 6. Response of concrete to a uniaxial loading condition in tension

According to the aforementioned damage plasticity formulation derived, the values of PC, SFC1 and SFC2 were presented within tables 4, 5 and 6 respectively. The steel material behaviour inputs are illustrated in Table 7.

3.3. FE model elements

To obtain accurate results the FE model elements were assigned so that two different materials could share the same node with each other. The elements used in this study are C3D8R for both concrete and steel plates, T3D2 for Longitudinal steel reinforcement and stirrups. To assess the influence of mesh sensitivity, a series of models with various element sizes were analyzed. Based on these comparisons, a mesh size of 25 mm was identified as the most suitable for accurately modeling the beam, including the concrete, longitudinal reinforcement, and transverse reinforcement.

Table 4. Material properties for plain concrete with SCDP model

Concrete elasticity		Plasticity Parameters	
Young's Modulus	28900 MPa	Dilation angle	31
		Eccentricity	0.1
Poisson's Ratio	0.2	fb0/fc0	1.16
		kc	0.667
		Viscosity Parameter	0
Concrete Compressive Behaviour		Concrete Compression Damage	
Yield Stress (MPa)	Inelastic Strain	Damage Parameter	Inelastic Strain
17.3	0	0	0
20	0.0001520	0	0.0001520
25	0.0003177	0	0.0003177
34	0.0008236	0	0.0008236
25	0.0019523	0.26	0.0019523
20.5	0.0025524	0.39	0.0025524
15	0.0028910	0.55	0.0028910
12.4	0.0031647	0.63	0.0031647
6.8	0.0035535	0.80	0.0035535
Concrete Tensile Behaviour		Concrete Tensile Damage	
Yield Stress (MPa)	Inelastic Strain	Damage Parameter	Inelastic Strain
3.4	0	0	0
0.034	0.00117647	0.99	0.00117647

Table 5. Material properties for steel fibre reinforced concrete (SFC1) with SCDP model.

Concrete elasticity		Plasticity Parameters	
Young's Modulus	29065 MPa	Dilation angle	31
		Eccentricity	0.1
Poisson's Ratio	0.2	fb0/fc0	1.16
		kc	0.667
		Viscosity Parameter	0
Concrete Compressive Behaviour		Concrete Compression Damage	
Yield Stress (MPa)	Inelastic Strain	Damage Parameter	Inelastic Strain
18	0	0	0
21.9	0.0000906	0	0.0000906
25.6	0.0003020	0	0.0003020
34.4	0.0008166	0	0.0008166
28.6	0.0018334	0.17	0.0018334
24.2	0.0024292	0.29	0.0024292
15.8	0.0028664	0.54	0.0028664
11.6	0.0031947	0.66	0.0031947
6.88	0.0035521	0.80	0.0035521
Concrete Tensile Behaviour		Concrete Tensile Damage	
Yield Stress (MPa)	Inelastic Strain	Damage Parameter	Inelastic Strain
3.44	0	0	0
0.0344	0.0011835	0.99	0.0011835

Table 6. Material properties for steel fibre reinforced concrete (SFC2) with SCDP model.

Concrete elasticity		Plasticity Parameters	
Young's Modulus	30808 MPa	Dilation angle	31
		Eccentricity	0.1
Poisson's Ratio	0.2	fb0/fc0	1.16
		kc	0.667
		Viscosity Parameter	0
Concrete Compressive Behaviour		Concrete Compression Damage	
Yield Stress (MPa)	Inelastic Strain	Damage Parameter	Inelastic Strain
19.5	0	0	0
24.2	0.0000603	0	0.0000603
31	0.0002242	0	0.0002242
36.6	0.0008270	0	0.0008270
30	0.0018879	0.18	0.0018879
23.5	0.0024434	0.35	0.0024434
16.8	0.0029326	0.54	0.0029326
10.15	0.0033749	0.72	0.0033749
7.32	0.0035542	0.80	0.0035542
Concrete Tensile Behaviour		Concrete Tensile Damage	
Yield Stress (MPa)	Inelastic Strain	Damage Parameter	Inelastic Strain
3.66	0	0	0
0.0366	0,0011879	0.99	0,0011879

Table 7. Steel material behaviour definition input for beam model.

Material behaviour	Type	Parameter	Beam model
Elastic	Isotropic	Young's Modulus	210000 MPa
		Poisson's Ration	0.3

3. Results and discussion

4.1. Experimental Results

4.1.1. Compressive strength

The specimen's compressive strength values were determined. The obtained results are shown in Figure 7. The compression test results for the three mix designs presented in Figure 7 show a slight increase in the average compressive strength with an increase in fibre volume ratio. Adding 0.5% of steel fibres to concrete doesn't show any improvement in the compressive strength as opposed to the 1% volume fraction, which shows an increase of 7% compared to plain concrete.

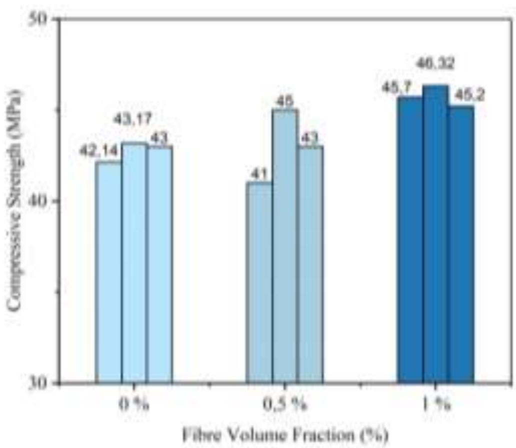


Fig 7. Effect of steel fibres on the average compressive strength of concrete

The results of compressive strength in the literature appear in disagreement. Compressive strength did not show a clear improvement due to the addition of steel fibres. The results of Altun et al (Altun, Haktanir, and Ari 2007) show for steel fibre dosages (30 and 60 Kg/m3), a decrease of 6% and 15% for concrete classes C20 and C30 respectively. The decrease is due to the presence of fibres that can create voids inside the concrete specimens. It can be concluded that the variation in the compression test results is due to the variation of content and orientation of fibres in the specimens.

4.1.2. Flexural behaviour

Load-deflection behaviour

The load-deflection curves, flexural strength, flexural toughness, and pre-peak deflection at the same load level of the different reinforced concrete beams under a four-point bending load are plotted in Figure 8. Figure 8 (a) shows the superposition of the tested beams load-deflection curves. The load-strain curves showed remarkably similar shapes regardless of the steel fibre volume fraction; this indicates that the increase in fibre content doesn't affect the overall behaviour of the tested beams. The results summarized in Figure 8(a) show that incorporating hooked-end steel fibres in traditionally reinforced concrete beams improves the ultimate load, and their values are increased as fibre fraction increases. The ultimate loads recorded for RPC, RSFC1 and RSFC2 beams are 53 KN, 58.05 KN and 60 KN respectively with a corresponding displacement of 10.34 mm. 9.63 mm and 9.55 mm. The random addition of 1% of steel fibres to RC beams shows an ultimate load of 1.13 times more than conventional RC beams. (Pradeep Kumar and Shahul Hameed 2022) Results demonstrated that adding the same amount of crimped steel fibres shows an ultimate load of 1.45 times more than the conventionally reinforced beams.

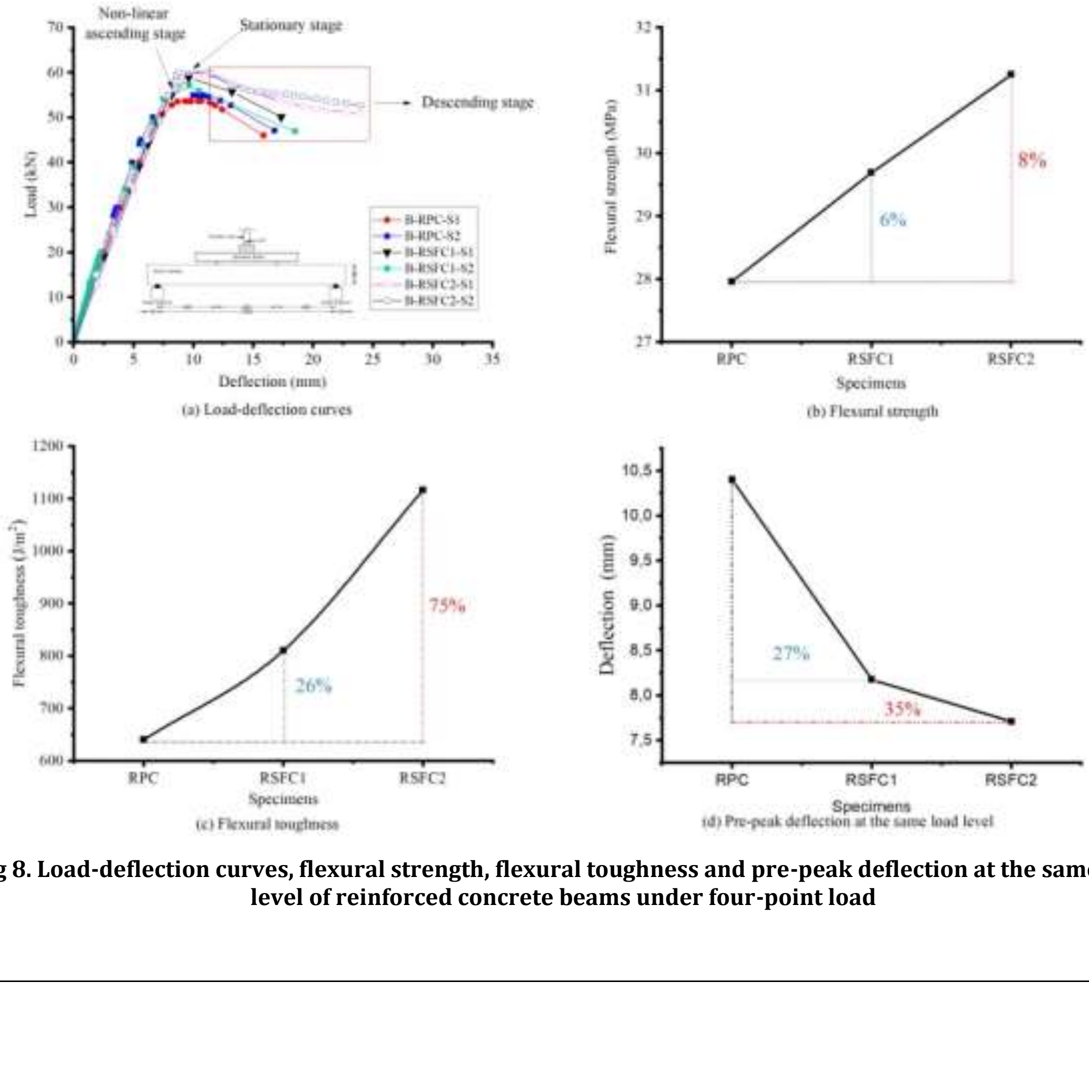


Fig 8. Load-deflection curves, flexural strength, flexural toughness and pre-peak deflection at the same load level of reinforced concrete beams under four-point load

At the same load level, beams containing 0.5% and 1% of steel fibres exhibit lower deflection values than the control beams; the deflection decreases by 28% and 32% when incorporating 0.5% and 1% of steel fibres, respectively. The presence of moderate percentages of steel fibres minimized the deflection, which increases the traditional reinforced beams' stiffness. The improved cracking behaviour increases the initial stiffness and maintains it throughout loading. For reinforced concrete beams with 1% of hooked-end steel fibres both non-linear ascending and stationary stages before peak load are obvious. During the stationary stage of the load-deflection curve, the SFRC2 show a strain-hardening characteristic.

The corresponding beams show ductile behaviour at failure compared to the RPC beams. However, the descending stage on the load-deflection curve gets longer as the steel fibre content increases, consistent with findings of previous studies (Aylie, Antonius, and Okiyarta 2015), (Sakthivel and Vijay Aravind 2020), (Yoo and Moon 2018). The Addition of hooked-end steel fibres in traditional RC beams has slightly improved the first cracking load from 10 kN to 15 kN for the RPC and RSFC beams, respectively.

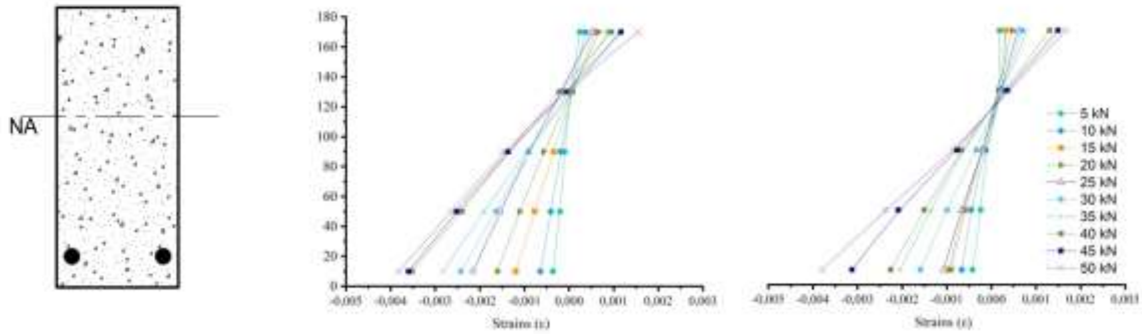
It can be seen from Figure 8 (b) that flexural strengths are improved by 6% and 8% when adding 0.5% and 1% of hooked-end steel fibres, respectively. Figure 8 (c) shows an improvement in the flexural toughness of RSFC1 and RSFC2 beams by 25% and 74%, respectively compared to RPC beams (Pradeep Kumar and Shahul Hameed 2022) results showed that the energy absorption capacity of SFRC beam is 1.52 times more than the conventional RC beam. The improvement of the flexural toughness for both RSFC beams is mainly related to the increase of the peak load and the enhancement of the sewing capacity of hooked-end steel fibres after cracking. The results are consistent with (Sakthivel and Vijay Aravind 2020) findings, reporting that using steel fibres as a secondary reinforcement to RC beams with different contents improves their ductility, flexural strength and toughness. According to (Campione and Mangiavillano 2008) results, 1% of hooked-end steel fibres improved the performance of conventional RC beams. (Yoo and Moon 2018) also reported that incorporating hooked-end steel fibres to RC beams at low reinforcement ratios is beneficial for decreasing deflection at the serviceability limit state, which presents a loss in ductility. The fact that the flexural parameters of RC beams depend on the type of steel fibre, stiffness, and reinforcement bar ratio can help to explain the discrepancies in the results.

Load-strain behaviour

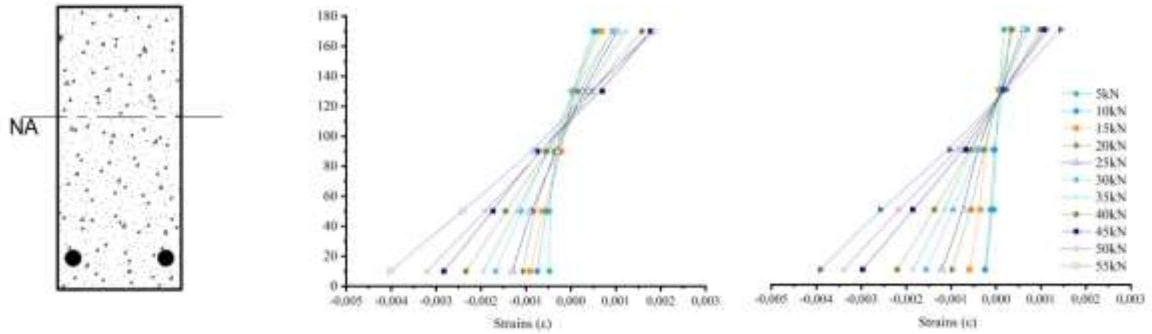
From the data collected through demec gauges reading, the strain distribution over the depth of the cross-section has been investigated and drawn. The strain is measured at the five strain measuring points on the concrete surface of the beam. Figure 9 shows that the different curves for each specimen are close to one another until the loading reaches 25kN, 30kN and 40kN for the RPC, RSFC1 and RSFC2 beams; beyond this load value, the curves diverge. The presence of steel fibres delays the appearance and opening of cracks, which increases the deformation capacity of the RC beams. The neutral axis is located in the compressed zone of the mid-span section of the beam. The position of the neutral axis depends mainly on the presence of the reinforcement bars in the tensioned zone. Whereas, it doesn't seem affected by steel fibres.

Figure 9 also indicates that the strain values increase as the load increases. The strain curves show an increase in tension as opposed to compression. The random addition of the steel fibres has slightly increased the ultimate tensile strains, which reach 3.7‰, 3.9 ‰ and 4‰ for RPC, RSFC1 and RSFC2 beams respectively. There is no improvement in compressive strains. The fact that the steel fibre effect only manifests in traction helps to explain this. In fact, under the same loading level, the tensile strains of the cross-section of RSFC beams show similar or lower values than the RPC beams; this can be explained by the delayed propagation of cracks resulting from the presence of steel fibres.

RPC



RSRC 1



RSRC 2

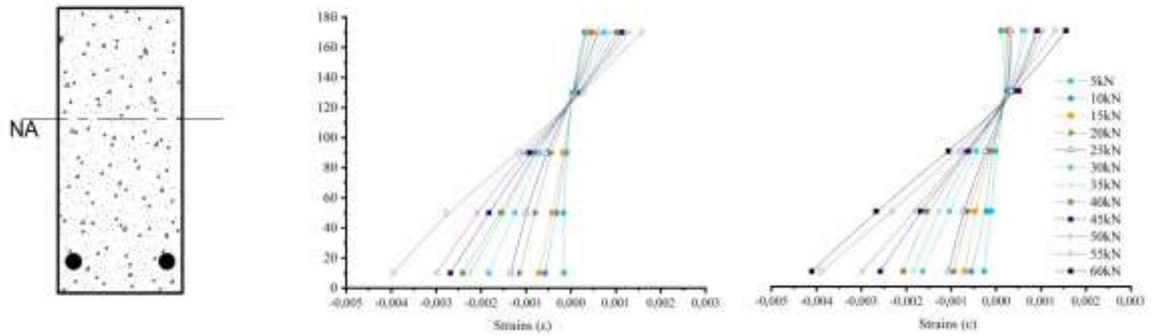


Fig 9. Strain on depth of the beam

4.2. Numerical vs. Experimental Results

The numerical modelling approach was employed to simulate the behaviour of the system and compare it with the experimental results. Through this method, mathematical equations governing the physical phenomena were solved using computational techniques. The model incorporated various parameters such as material properties, boundary conditions, and load scenarios, replicating the conditions of the experimental setup as closely as possible.

A load versus deflection curve was plotted to compare the ultimate load-carrying capacity of the three beam models with the experiments data. The comparison between the numerical and experimental results is presented in Figures 10. The data reveal a strong concordance between the two datasets, thereby providing full validation of the Beam FE model through a rigorous comparison with empirical results obtained from the experiments. Figure 6, which is particularly compelling, eloquently depicts the relationship between load and deformation, encompassing both the experimental data and the projections from the FEM analysis for the three beam samples examined. This comparative analysis clearly demonstrates the remarkable alignment between the predictions of the finite element model and the empirical findings, thereby affirming the model's exceptional capacity to accurately represent the experimental results.

The figures 10 also shows the impact of hooked-end steel fibres on the load-deflection behaviour of steel fibre reinforced concrete (SFRC) beams. As illustrated, the presence of 0.5% and 1% of steel fibres results in an increased peak load, demonstrating the materials enhanced load-carrying capacity. Simultaneously, a noticeable reduction in deflection is observed, particularly at higher loads. The fibres help control crack development, distributing stresses more uniformly and preventing sudden failure. This figure effectively highlights the beneficial role of fibres in improving both strength and ductility, offering a clear visual representation of the structural advantages provided by steel fibre reinforcement.

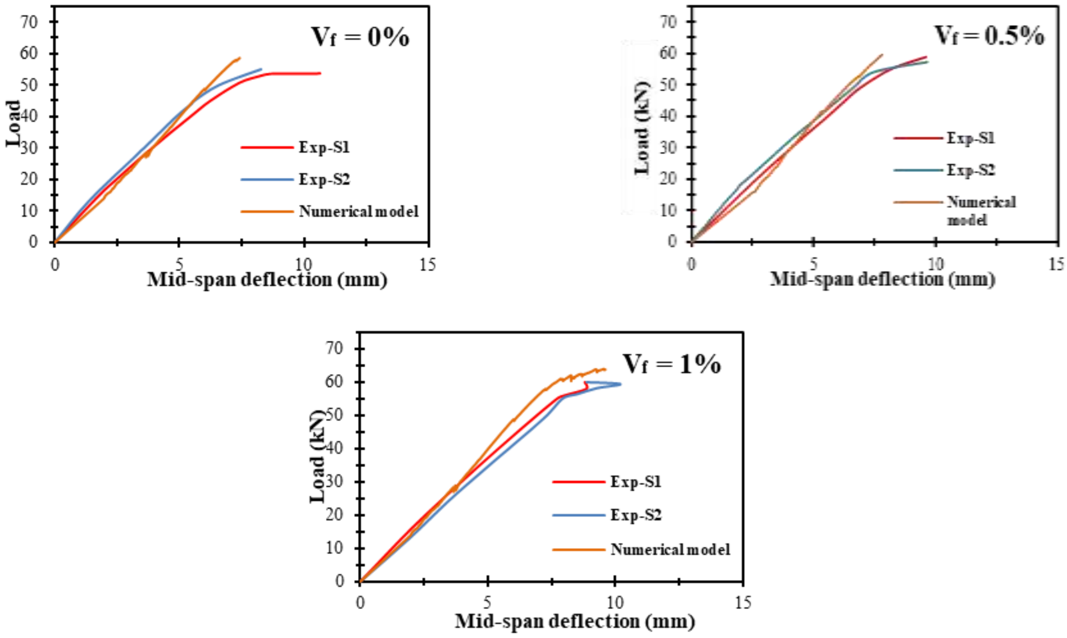


Fig10. Comparison between experimental and numerical results

The comparison of the peak-load between experiments and simulations is illustrated in tables 8 and 9. The relative errors obtained from the model's predictions are all within 10%, indicating a strong agreement between the predicted and actual values. This level of accuracy demonstrates that the model is reliable in capturing the behaviour of the system under study, with deviations that fall within an acceptable range. Such low relative error values further validate the robustness of the model and its ability to generalize well, making it a suitable tool for predicting the mechanical behaviour under bending test in steel fibre reinforced concrete (SFRC) beams.

Table 8. comparison of peak-load between tests and simulations values

No.	0%-S1	0%-S2	0.5%-S1	0.5%-S2	1%-S1	1%-S2
Absolute error (kN)	4.88	3.57	0.67	2.29	3.79	
Relative error (%)	8.32 %	6.09 %	1.14%	3.91%	6.47%	

Table 9. comparison of mid-span deflection at the peak-load between tests and simulations values

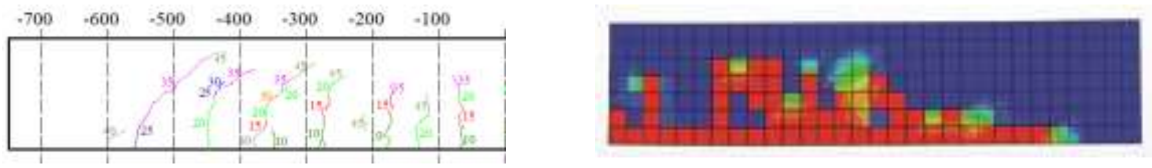
No.	0%-S1	0%-S2	0.5%-S1	0.5%-S2	1%-S1	1%-S2
Absolute error (kN)	-2.38	-0.68	1.41	1.45	0.80	0.73
Relative error (%)	-20.58%	-8.21%	-14.67%	-15.02%	8.36%	7.58%

The results shown in Table 9 indicate a significant deviation between the simulation and experimental values of mid-span deflections of RC beams. This discrepancy suggests that the model may not fully capture all the complex factors influencing the behaviour of steel fibre reinforced concrete (SFRC) beams under loading. The results of RC beams containing 1% of steel fibres indicate a good agreement between the simulation and experimental values.

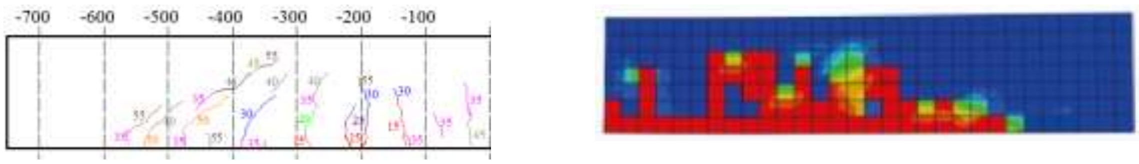
4.3. Evolution of cracks

The evolution of cracks in reinforced concrete (RC) beams is a critical aspect of their structural performance. Cracks in RC beams are generally inevitable due to the nature of concrete. Understanding the crack evolution process is crucial for assessing the beam's durability, safety, and serviceability.

Figure 11 shows a comparison between cracks patterns obtained from the experiments and the finite element analysis for the RC beams containing 0%, 0.5% and 1%, respectively.



(a)



(b)

(c)

Fig 11. Pre-failure cracks patterns on the beams; (a) 0%, (b) 0.5%, (c) 1%

The comparison between experimental and numerical results for crack patterns in reinforced concrete (RC) beams is shown in Figure 11. Experimentally, cracks initiate in the tensile zone and propagate irregularly, influenced by imperfections in the material, load application, and environmental conditions. Shear and flexural cracks develop with increasing load, often showing non-uniform spacing and widths. Numerical simulations, on the other hand, predict crack formation in similar regions but tend to display more uniform crack patterns due to idealized assumptions about material homogeneity and boundary conditions. While simulations can accurately model crack initiation and propagation, they may underestimate localized imperfections and fail to fully capture the variability seen in experimental results.

As illustrated in Figure 11, the presence of steel fibres in concrete significantly influences the crack behaviour by decreasing crack lengths and increasing the number of cracks. Comparing to 0.5%, the inclusion of 1% of hooked-end steel fibres leads to a noticeable reduction in crack lengths while simultaneously increasing the number of cracks formed. The steel fibres improve the tensile strength and ductility of the concrete, allowing it to better absorb stresses and resist cracking. As a result, instead of a few large, uncontrolled cracks developing, the concrete exhibits a greater number of smaller, tightly spaced cracks. This distributed cracking behaviour enhances the overall durability of the concrete, as the fibres bridge these cracks and prevent their growth, ultimately reducing the risk of sudden failure. Additionally, the improved crack distribution contributes to the concrete's resistance to shrinkage and environmental degradation, making it a more robust material for various applications.

4. Conclusions

This article main purpose is to simulate the mechanical behaviour of RSFC beams with modest percentages of hooked-end steel fibres under static loading with no fibre simulation. The conclusions drawn from this study are as follows:

- The addition of 1% of hooked-end steel fibres shows an increase in compressive strength of concrete of 7% compared to plain concrete.
- The ultimate load carrying capacity is 1.09 and 1.13 times that of conventional RC beams for RC beams containing 0.5% and 1% of steel fibres, respectively.
- The flexural toughness is 1.25 and 1.74 times higher than conventional RC beams for RC beams containing 0.5% and 1% of steel fibres, respectively. Using 1% steel fibres as a secondary reinforcement significantly improves the post-peak behaviour and ensures significant ductility compared to plain reinforced concrete.
- The use of Simplified Concrete Damaged Plasticity Model proved able to predict the behaviour of the RC beams containing different volume fraction of steel fibres at both the material and structural levels. The predicted ultimate loads and mid-span deflection at the pre-peak phase were roughly similar to the experimental work.
- The use of SCDP model demonstrates an appreciable degree of accuracy in predicting peak-load without the need to simulate the steel fibres. By leveraging simplified assumptions and focusing on the overall behaviour of the composite material, the model effectively captures the essential mechanical properties and load response. This approach not only streamlines the modelling process but also reduces computational complexity, enabling efficient analysis while still providing reliable predictions. The absolute and relative errors values indicate that the model retains its predictive capability, thereby validating its efficacy in applications where detailed fibre modelling may not be feasible.
- The use of the SCDP model presents some discrepancies in the deflection values, as the predicted deflection tends to deviate from the experimental results. These inconsistencies could stem from the model's inability to accurately capture certain key factors, such as the random distribution of steel fibres, their bonding with the concrete, or the nonlinear material properties under loading.
- The use of the SCDP model demonstrated excellent accuracy in simulating crack patterns within (RC) and (SFRC) beams. The crack behaviour closely aligned with experimental observations, reflecting the model's ability to capture key structural responses under load.

This investigation aims to incorporate hooked-end steel fibres throughout conventional RC beams as a secondary reinforcement. From the obtained results it may be concluded that adding a moderate percentage of hooked-end steel fibres in conventional RC beams presents several advantages such as an improved failure mechanism as showcased by the ductile post-peak behaviour, increased bearing capacity allowing for longer beam spans and a preserved stiffness achieved by the reduction of larger cracks and the decrease of crack propagation ensuring longer structural serviceability.

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