GADL

Journal of Computers, Mechanical and Management

Journal homepage: www.jcmm.co.in

JCMM Journal of Computers, Mechanical and Management

Volume 1 Issue 1

Finite Element Modelling and Analysis of Fiber Reinforced Concrete Under Tensile and Flexural Loading

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Abstract

Concrete is a material exhibiting high compressive strength but about tenfold lower tensile strength. Its brittle property also prohibits the transmission of stresses after cracking. Thus, steel, polymer, polypropylene, glass, carbon, and other fibers are added to concrete to form fiber-reinforced concretes (FRC), having enhanced mechanical properties. The utilization of fiber-reinforced concrete is widespread. Identifying the mechanical properties of fiber-reinforced cement composites under dynamic loading, establishing relationships between their composition, structure, and properties, justifying the correct mathematical model, and determining its parameters are challenging. Utilizing finite elemental modeling and analysis to comprehend the mechanical characteristics of the FRC addition to concrete bricks has shown considerable benefit. In the present study, polypropylene microfibers are included in fiber-reinforced concrete composites, and their performance is compared to that of unreinforced concrete bricks. Under FEA analysis, three-point bending and uniaxial tensile tests were conducted. The results indicate that using fiber reinforcements increases the tensile strength and endurance of the brick.

Keywords: Concrete; Composite; Polymer; Mechanical Strength; ANSYS

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1 Introduction

Concrete is a material with high compressive strength but has about tenfold lower tensile strength. In addition, it exhibits a brittle characteristic and prohibits the transmission of stresses after cracking. It is feasible to incorporate fibers into the concrete mixture to prevent brittle failure and increase mechanical qualities, producing fiber-reinforced concrete (FRC), a cementitious composite material with a distributed reinforcement in the form of fibers, steel, polymers, glass, carbon, and others [1]. AC1 116R, cement and concrete terminology, defines FRC as concrete having scattered, randomly oriented fibers. More than 30 years have elapsed since the present age of FRC research and development began [2].

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Received: 28 August 2022; **Accepted:** 17 September 2022; **Published:** 30 October 2022

DOI: 10.57159/gadl.jcmm.1.1.23004.

Many scholarly articles have recently focused on creating new cement matrix compositions and using modified multicomponent fibers in concrete compositions for static and dynamic loads [3]. Identifying the mechanical properties of fiber-reinforced cement composites under dynamic loading, establishing relationships between their composition, structure, and properties, justifying the correct mathematical model, and determining its parameters are challenging. If this problem can be resolved, the efficiency of building structures operating under dynamic loads can be increased, i.e., from an economic standpoint, due to a reduction in material consumption and the accurate findings of analytical and numerical approaches [4]. Polypropylene fibers (PPF) are a type of polymer fiber composed of straight or distorted fragments of extruded, orientated, and cut polymer material. PPF was previously referred to as Stealth. These micro reinforcement fibers are homopolymer polypropylene graded monofilament fibers made entirely from virgin polypropylene. PPF does not contain any reprocessed Olefin components. The raw material for polypropylene is monomeric C3H6, an entire hydrocarbon compound [5]. PPF microfibers are shorter than 30 mm and do not serve a load-bearing function, but they do overcome plastic shrinkage and prevent the creation of concrete fractures. As a result, they strengthen the element's durability and extend its life [6]. Yew et al. [7] examined the performance of concrete reinforced with different polypropylene fibers. Concrete's tensile and flexural strength and its modulus of elasticity improved using polypropylene fibers. Moreover, adding a 0.5 % volume fraction of polypropylene fibers reduced the slump by 95.8 %. Deb et al. [8] proved an improvement in the ductility of the concrete with the inclusion of the PPF. Cracks are detrimental to concrete's mechanical and durability properties because they propagate under the influence of loads and allow aggressive agents to enter the surrounding environment. Polypropylene fiber in concrete acts as a crack arrestor and alters the fresh and hardened properties due to improper packing and dispersion, negatively impacting concrete [9]. The addition of PPF enhances the mechanical property of the concrete as it bridges the macro and micro-cracks present in the concrete and inhibits the further propagation of stress-induced failure [10]. However, excessive PPF content in concrete mixtures increases abrasion and freeze-thaw resistance and reduces volume expansions caused by sulfate attack and alkaline silica reaction (ASR) [11].

Thus it becomes necessary to use the optimum amount of PPF in concrete. Using soft techniques like ANSYS and ABAQUS simulation and modeling has been a preferred approach over the conventional destructive testing by several researchers in recent times to determine the property enhancement and optimize the PPF content in the concrete [12–14]. Understanding the positive impact of PPF addition in concrete and using the ANSYS simulation and modeling techniques, the present study aims at determining the optimum PPF content in the concrete while improving its mechanical properties, viz., bending and uniaxial tensile strength.

2 Materials and Methods

Concrete variants with compressive strength classification B25 were examined. These concretes were designed in ANSYS workbench in line with ASTM regulations. Polypropylene microfiber was considered while modeling the fiber-reinforced concrete for discrete concrete reinforcement. The modeled variants were based on the quantities of microfibers, which were 0, 3, 5 and 7 kg/m^2. The concrete damage plasticity model was created to explain how concrete behaves mechanically when subjected to uniaxial, biaxial and volumetric stress conditions with negligible lateral compression [4, 15, 16]. To model irreversible deformations in concrete, the mechanical behavior of the material is based on isotropic elastic damage in conjunction with isotropic plastic behavior for bending and tension. The assumption that the orientation of the microfibers in concrete is chaotic makes this technique appropriate, and because the content is so huge, the models may be made to assume that the concrete hardens in the same way in all possible directions. The method mentioned above not only permits the use of the model under simple or cyclic static loads or dynamic loads but also considers concrete reinforcement with individual rods, meshes, or scattered reinforcement. The scattered concrete reinforcement in the model is chosen based on the energy needed for the formation and full opening of a crack.

Young's modulus, Poisson's ratio, ultimate uniaxial tension strength, ultimate uniaxial compression strength, diagram of concrete deformations in the axes "force versus CMOD" from bending test, Dilation angle measured in the p–q plane at high confining pressure, default values concerning the ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress, flow potential eccentricity and coefficient of the shape of plastic surface flow were the variables used to configure the parameters of the accumulated damage concrete damage plasticity model. These parameters' values were chosen in accordance with tests, regulatory document specifications, numerical modeling, and recommendations made in scientific and technical documents [4, 17–20]. Based on the findings of a concrete test under bending, a method for creating a diagram of the severe deformation of concrete under uniaxial strain is used. It entails establishing the model parameters of concrete's plastic behavior on the findings of a numerical experiment. As a flow chart, Figure 1 depicts the order of parameter selection for the damaged concrete plasticity model.

The numerical model has dimensions of 400 × 100 × 150 mm for each model, with a notch 2 mm wide and 25 mm deep on the bottom side of the brick for the three-point bending test utilizing the crack mouth opening displacement (CMOD) method. The numerical model for concrete that is prone to bending is composed of a concrete beam, two supporting bars, and a loading bar. Figure 2(a), Figure 2(b), Figure 2(c) and Figure 2(d) represent the variants of B25 concretes modeled in the present study. Similarly, models of uniaxial test blocks made of B25 concrete variants with dimensions of 150 × 150 × 550 mm and a notch in the middle of the brick measuring 100 × 100 × 60 mm are created. The models created in this manner with ANSYS Workbench are shown in Figure 3(a), Figure 3(b), Figure 3(c), and Figure 3(d). The models are changed into FEM models by adding the mesh. The model's mesh thickness varies from 7mm to 15mm. These variances give the deformation values extra depth. Figure 4(a) and Figure 4(b) show examples of the meshing that was produced for the three-point bending and tensile model, respectively.

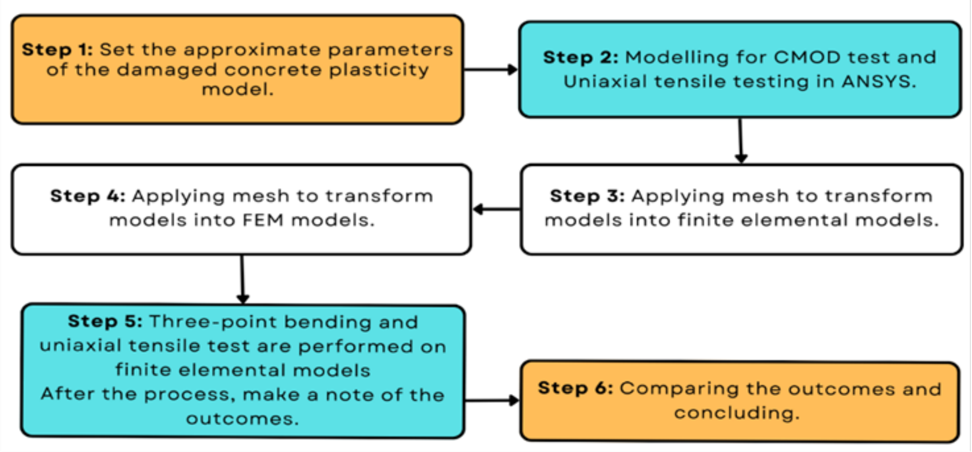


Figure 1: Flow chart of the selection sequence concerning damaged concrete plasticity model parameters

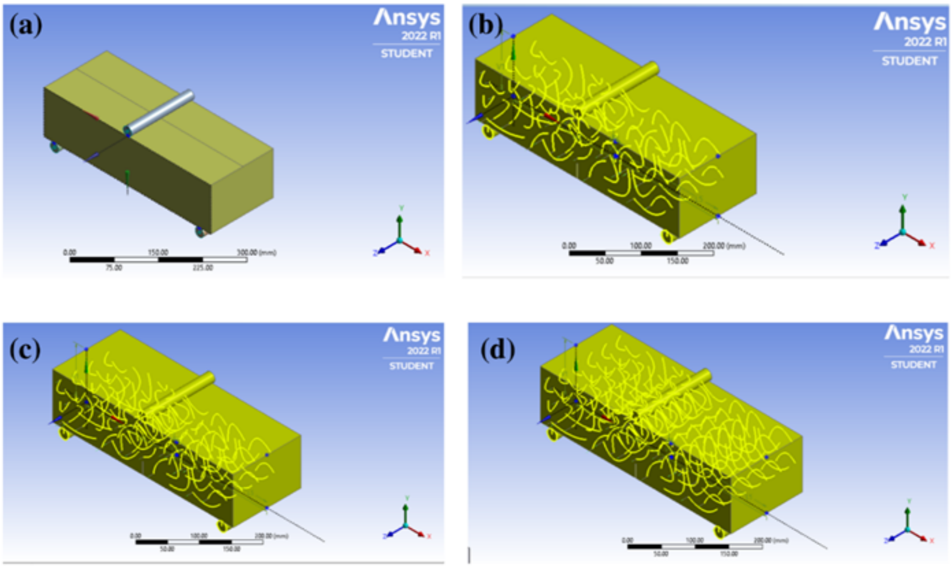


Figure 2: Models for three-point bending test utilizing crack mouth opening displacement (CMOD) method of B25 concrete with: **(a)** 0 % **(b)** 3 %, **(c)** 5 % and **(d)** 7 % by weight of polypropylene microfibers.

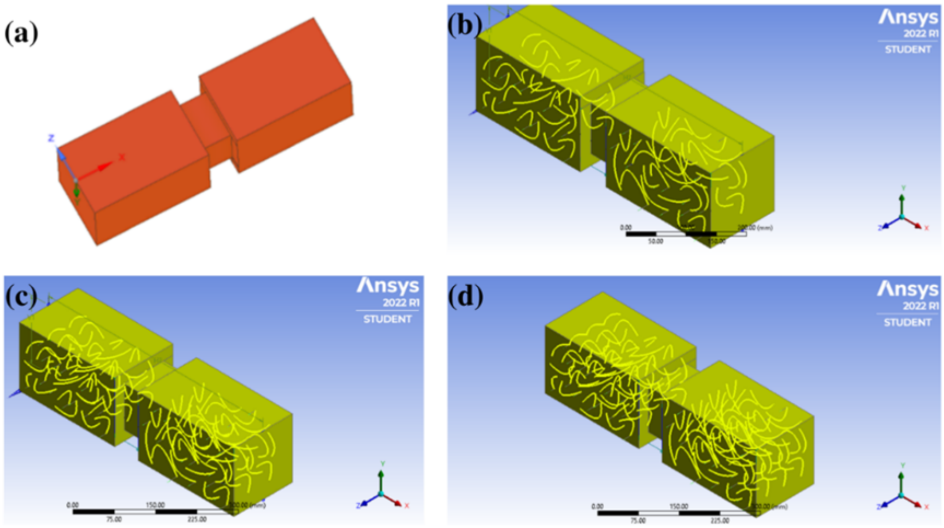


Figure 3: Models for uniaxial test utilizing crack mouth opening displacement (CMOD) method of B25 concrete with: **(a)** 0 % **(b)** 3 %, **(c)** 5 % and **(d)** 7 % by weight of polypropylene microfibers.

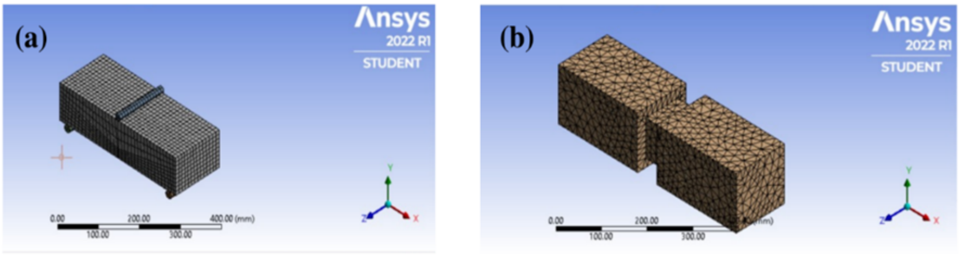


Figure 4: Meshed models sample for: **(a)** three-point bending and **(b)** uniaxial test using ANSYS workbench.

3 Results and Discussion

The results obtained through the FEM analysis for three-point bending after subjecting the designed variants of B25 concrete to 1 kN are represented in Figure 5(a), Figure 5(b), Figure 5(c) and Figure 5(d). The results obtained for the uniaxial tensile loading using FEM analysis after subjecting the designed variants of B25 concrete in Figure 6(a), Figure 6(b), Figure 6(c) and Figure 6(d).

Table 1 and Table 2 detail the result obtained from the three-point bending and uniaxial tensile loading test analysis. The findings above show that reinforced concrete has a stronger uniaxial tensile strength than non-reinforced concrete, which increases brick durability. The toughness and uniaxial tensile stress of the material also increase with increasing polypropylene microfiber content.

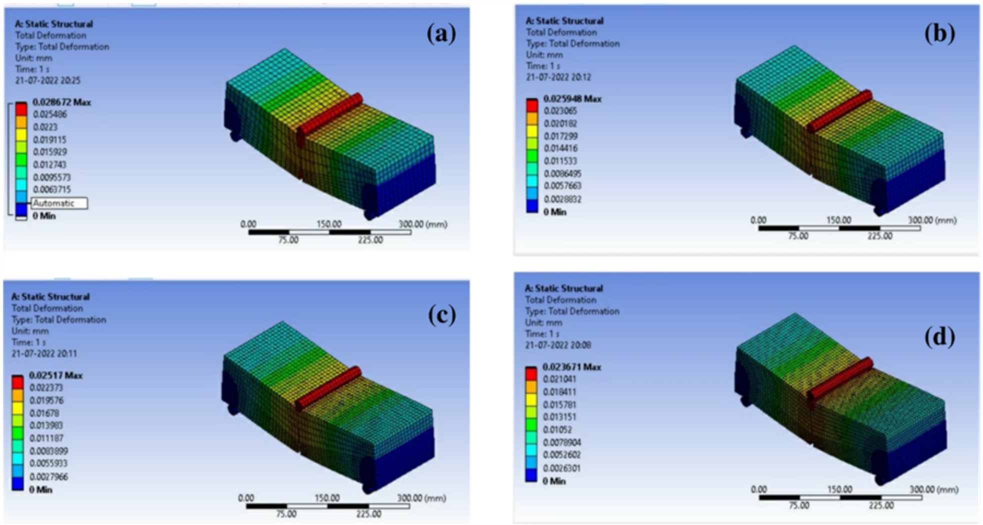
Table 1: Three-point bending deformation in B25 concrete variants.

Sl.	Force applied (N)	Three-point bending deformation (mm)			
		0% fiber	3% fiber	5% fiber	7% fiber
1	1000	0.029	0.026	0.025	0.024
2	2000	0.058	0.051	0.050	0.048
3	3000	0.083	0.075	0.071	0.067
4	4000	0.117	0.104	0.100	0.095
5	5000	0.145	0.130	0.125	0.117
6	6000	0.170	0.155	0.144	0.143
7	7000	0.194	0.176	0.172	0.158
8	8000	0.224	0.198	0.192	0.182
9	9000	0.240	0.213	.207	.202

Table 2: Tensile deformation in B25 concrete variants.

Sl.	Tensile rupture crack opening (mm)	Uniaxial tensile strength (MPa)			
		0% fiber	3% fiber	5% fiber	7% fiber
1	0.10	31.10	37.80	39.90	40.36
2	0.15	46.47	75.60	79.90	80.80
3	0.20	62.33	113.40	119.85	121.18
4	0.25	78.18	151.24	159.80	161.57

The results thus obtained are in direct agreement with similar work done earlier [21–23], wherein the researchers noticed a reduction in crack growth and an improvement in durability with the increased fiber reinforcement in concrete concerning tensile strength, impact strength and also the chloride binding. The three-point bending deformation was reduced by an average of 10, 14 and 18 % with the inclusion of 3, 5 and 7 % by weight of the microfibers in the B25 concrete. The uniaxial strength improved by an average of 65, 74 and 76 % with the inclusion of 3, 5 and 7n% by weight of microfibers in the B25 concretes.

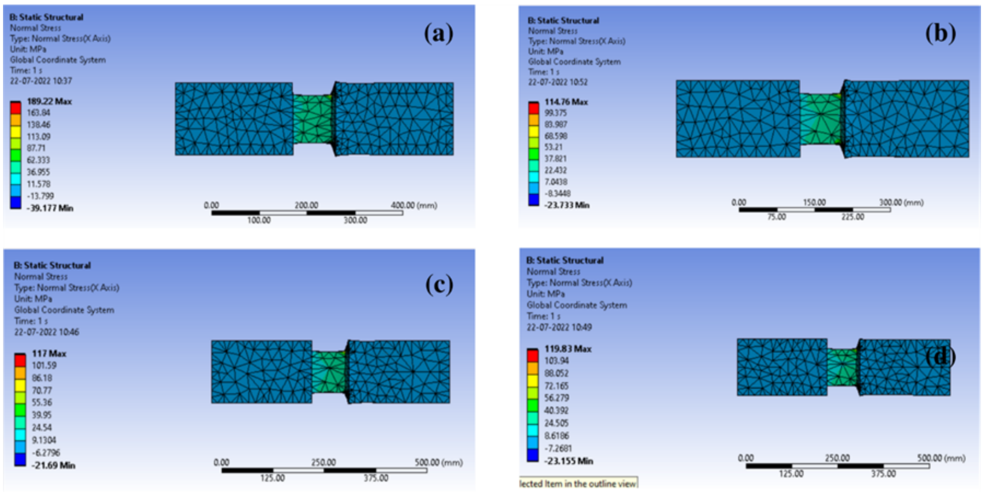

(a)
A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1 s
21-07-2022 20:25

(b)
A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1 s
21-07-2022 20:12

(c)
A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1 s
21-07-2022 20:11

(d)
A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1 s
21-07-2022 20:08

Figure 5: Three-point bending analysis models of B25 concrete with: (a) 0 % (b) 3 %, (c) 5 % and (d) 7 % by weight of polypropylene microfibers.


(a)
B: Static Structural
Normal Stress
Type: Normal Stress(X Axis)
Unit: MPa
Global Coordinate System
Time: 1 s
22-07-2022 10:37

(b)
B: Static Structural
Normal Stress
Type: Normal Stress(X Axis)
Unit: MPa
Global Coordinate System
Time: 1 s
22-07-2022 10:52

(c)
B: Static Structural
Normal Stress
Type: Normal Stress(X Axis)
Unit: MPa
Global Coordinate System
Time: 1 s
22-07-2022 10:46

(d)
B: Static Structural
Normal Stress
Type: Normal Stress(X Axis)
Unit: MPa
Global Coordinate System
Time: 1 s
22-07-2022 10:49

Figure 6: Uniaxial tensile test analysis models of B25 concrete with: (a) 0 % (b) 3 %, (c) 5 % and (d) 7 % by weight of polypropylene microfibers.

4 Conclusion

The work focused on developing and analyzing B25 concrete models using the ANSYS workbench. Four variants were analyzed having the variation of polypropylene content in the material. The study indicated increased durability concerning the reduction in the three-point bending deformation and increased uniaxial strength with the increased microfiber content in the B25 concretes.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding Declaration

This research did not receive any grants from governmental, private, or nonprofit funding bodies.

Author Contribution

V. Srikanth: Data curation, Writing–Original draft preparation, Methodology, Investigation, Software, Validation; **Suhas Kowshik**: Conceptualization, Supervision, Validation, Writing- Reviewing and Editing; **Dhanraj Narasimha**: Conceptualization, Writing-Reviewing and Editing; **Santosh Patil**: Methodology; **Kaustubh Samanth**: Validation; Udit Rathee: Software.

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