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Study on the Influence of 3D, 4D, and 5D Steel Fibre Reinforced Concrete in Beam-Column Joints

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A B S T R A C T

This study explores the use of 3D, 4D, and 5D steel fiber-reinforced concrete (SFRC) to improve the structural performance of beam-column joints under cyclic loading. Beam-column joints, essential components of multi-story frames, often face challenges such as reinforcement congestion and construction difficulties. By incorporating steel fibers at dosages of 0.5%, 1%, and 1.5%, this research evaluates the impact on strength, ductility, and energy absorption through experimental testing and ANSYS-based numerical analysis. Results demonstrate that SFRC significantly enhances load-bearing capacity, energy dissipation, stiffness, and shear strength, suggesting its potential to improve structural integrity while reducing traditional reinforcement requirements.

Keywords: Steel Fiber Reinforced Concrete, 3D Fibers, 4D Fibers, 5D Fibers, Beam-Column Joint, Cyclic Loading, ANSYS Analysis

1. Introduction

Concrete is strong in compression but weak in tension, leading to early cracking. Traditional steel reinforcement improves tensile strength but cannot fully prevent cracks. Adding fibers helps bridge cracks, enhancing strength and flexibility.

Fiber-reinforced concrete (FRC) consists of cement, aggregates, and randomly distributed fibers like steel, glass, or polypropylene. Steel fibers, preferred for their strength and bonding ability, typically range from 0.25% to 2% by volume. Unlike steel bars, fibers improve toughness, durability, and crack resistance, making FRC ideal for bridges, pavements, and earthquake-resistant structures.

This study examines 3D, 4D, and 5D steel fibers, which have hooked-end designs for better anchorage. Their impact on beam-column joints under cyclic loading is analyzed to determine the best fiber type and dosage for improved structural performance.

1.1 Fiber-Reinforced Concrete:

Fiber-reinforced concrete (FRC) enhances conventional concrete by improving tensile strength, reducing crack width, and increasing ductility. Fibers are short, randomly distributed, and help resist impact and tension. Steel fiber-reinforced concrete (SFRC) is the most common type, using straight, deformed, or hooked-end fibers for better bonding. While SFRC does not significantly boost compressive strength, it greatly improves toughness, shear resistance, and energy absorption, enhancing overall durability.

1.2 Types of Steel Fibers

Straight Steel Fibers: These fibers are smooth and straight, providing uniform reinforcement. They are suitable for general applications where simple crack control is required.

Deformed Steel Fibers: Featuring surface irregularities like crimps or waves, these fibers improve mechanical interlocking with the concrete matrix, enhancing overall performance.

Hooked-End Steel Fibers: Designed with hooks at the ends, these fibers provide superior anchorage within the concrete, improving pull-out resistance and post-crack behavior. The 3D, 4D, and 5D fibers used in this study have varying degrees of bends and hooks to optimize performance.

Micro Steel Fibers: These fine fibers are ideal for applications requiring precise reinforcement, such as overlays and thin-section elements. They enhance crack resistance and durability in complex structures.

2. Literature Review

The influence of steel fibers on the mechanical and durability properties of concrete has been extensively studied. Key findings from previous research are summarized below:

Lage, B. (2024) investigated the impact of varying steel fiber content on the compressive strength of concrete. The study demonstrated that adding steel fibers up to 1.5% by volume significantly improved compressive strength, with values increasing from 19.2 MPa (0% fibers) to 22.3 MPa. Beyond this optimal dosage, a decrease in strength to 19.39 MPa was observed at 2% fiber content, indicating that excessive fiber content can negatively affect strength due to potential issues like poor compaction.

Anbuchezian, A., Ashokan, A., Rajendran, S., & Dhairiyasamy, R. (2023) focused on enhancing the structural integrity and load-bearing capacity of concrete using 2% steel fibers. The study reported an exceptional compressive strength of 107.3 MPa, far surpassing the typical range of 80-100 MPa for similar mixes. This improvement highlights the critical role of steel fibers in enhancing mechanical properties and making concrete more resilient under applied loads, particularly in demanding structural applications.

Anish, A., & Logeshwari, L. (2024) analyzed the effect of different fiber types on the compressive strength of ultra-high-performance concrete (UHPC). The inclusion of steel and polypropylene fibers was found to substantially enhance compressive strength compared to non-reinforced UHPC. The findings emphasize the importance of selecting appropriate fiber types to optimize performance in high-strength concrete applications.

Ahmad, J., et al. (2020) studied the compressive strength of concrete with steel fiber reinforcement, observing a peak strength increase of 25% at a fiber dosage of 2%. Beyond this point, reduced strength was attributed to compaction challenges and increased porosity. This study underscores the need to balance fiber content to maximize strength without compromising workability or homogeneity.

Ashokan, A., et al. (2023) evaluated the tensile strength of concrete reinforced with 2% steel fibers, reporting a split tensile strength of 25.4 MPa, significantly higher than the 15-20 MPa range observed in earlier studies. This notable improvement demonstrates the effectiveness of steel fibers in mitigating cracking and enhancing tensile stress resistance, thereby improving concrete's durability and longevity.

Anish, S., & Logeshwari, V. (2024) explored the impact of various fiber reinforcements on the mechanical properties of UHPC. The study found that fibers such as glass, polypropylene, and basalt significantly improved tensile strength, with glass fibers showing the highest load capacity. These findings indicate that the choice of fibers can profoundly affect the performance and durability of UHPC in structural applications.

Jawad Ahmad, J., et al. (2020) examined the split tensile strength of concrete reinforced with steel fibers. The study recorded a 43% increase in tensile strength at a 2% fiber content. Beyond this dosage, a decline was noted, consistent with earlier findings. The study highlighted steel fibers' role as effective crack stoppers, enhancing post-cracking behavior and tensile capacity.All figures should be numbered with Arabic numerals (1,2,3,….). Every figure should have a caption. All photographs, schemas, graphs and diagrams are to be referred to as figures. Line drawings should be good quality scans or true electronic output. Low-quality scans are not acceptable. Figures must be embedded into the text and not supplied separately. In MS word input the figures must be properly coded. Lettering and symbols should be clearly defined either in the caption or in a legend provided as part of the figure. Figures should be placed at the top or bottom of a page wherever possible, as close as possible to the first reference to them in the paper.

3. Materials Used

3.1 Cement

Cement used in this investigation was DALMIA OPC GRADE 53 conforming to BIS: 12269-1989. The specific gravity of cement was 2.7. Initial and final setting time for the was 35 minutes and 560 minutes.

3.2 Course and Fine Aggregate

Aggregates are inert mineral material used as filler in concrete, which occupies 70% to 85 % volume. Sand passing through 4.75mm IS sieve conforming to grading zone III of IS 383:1970 was used. Its specific gravity is 2.6. Locally available stone aggregate of size 20 mm passing and retained in 19 mm, was used and the specific gravity and fineness modulus for the same are 2.7 and 2.53 as per IS: 2386- 1968 Part III. Both the Aggregates compiled with the requirements of IS 383-1970.

3.3 3D, 4D, and 5D Steel Fibers

In this experimental study, 3D, 4D, and 5D steel fibers from the Dramix brand were employed. These fibers are crafted from copper-coated bright wires and come with distinct specifications. As their names suggest, these fibers have hooked ends, with the number of bends in the hooks increasing from 3D to 5D. This design feature significantly enhances their anchorage within concrete, influenced by the shape of the hooks. The bends and hooks play a crucial role in the fibers' anchoring performance during multi-axial tension, which, in turn, enhances the ductility of the concrete. Combined with the elongation characteristics of steel, these features are fundamental to the performance of Dramix-type steel fibers.

Fig 1 3D, 4D & 5D STEEL FIBERS

Fiber Type	Commercial Name	Fiber Length (mm)	Diameter (mm)	Aspect Ratio	Tensile Strength (N/mm^2)	Young's Modulus (N/mm^2)	Deformation
3D Fibers	DRAMIX 3D	60	0.75	80	1225	210	Hooked end
4D Fibers	DRAMIX 4D	60	0.9	65	1500	210	Hooked end
5D Fibers	DRAMIX 5D	60	0.9	65	2300	200	Hooked end

Table 1 Specifications of Steel Fibers Used

3.4 Super Plasticizer

Super plasticizers are high-range water reducers used to lower the water-cement ratio while maintaining workability. In this study, CONPLAST SP430, a polycarboxylate-based superplasticizer meeting IS 9103:1999 standards, was used, enabling water reduction up to 25%.

3.5 Water

Potable water which is available in laboratory is used for casting of specimen and as well as curing of specimen as per IS 456-2000.

3.6 Percentage Variation of Fibers in Mix

The proportions of fibers used in concrete mix percentage of 3D, 4D, and 5D steel fibers at volume contents of 0.25%, 0.5%, 0.75%, and 1%.volume fractions are added. Table 2 shows the details of the tested specimen designation.

Type of Steel Fiber	% Steel Fiber	Specimen Designation
0%	0%	Conv
3D	0.25%	3D1
3D	0.5%	3D2
3D	0.75%	3D3
3D	1.0%	3D4
4D	0.25%	4D1
4D	0.5%	4D2
4D	0.75%	4D3
4D	1.0%	4D4
5D	0.25%	5D1
5D	0.5%	5D2
5D	0.75%	5D3
5D	1.0%	5D4

Table 2 Specimen Designation

3.7 Concrete Mix Design for M30 Concrete (IS 10262:2009)

Stipulation for mix proportioning

S.No	Content	Mix Proportion
1	Grade destination	M30
2	Type of cement	OPC 53 Grade
3	Maximum nominal size of aggregate	20mm
4	Minimum cement content	$300kg/m^3$
5	Workability	75mm
6	Exposure condition	Severe
7	Method of concrete placing	Normal
8	Degree of supervision	Good
9	Type of aggregate	Crushed angular aggregate
10	Maximum cement content	$450kg/m^3$

Table 3 Stipulation for mix proportioning

3.8 Specimen Details:

- **Bars/Stirrups:** 8 mm dia @ 150 mm c/c
- **Dimensions:** Beam: 150 mm x 150 mm x 1425 mm, Column: 150 mm x 150 mm x 1425 mm

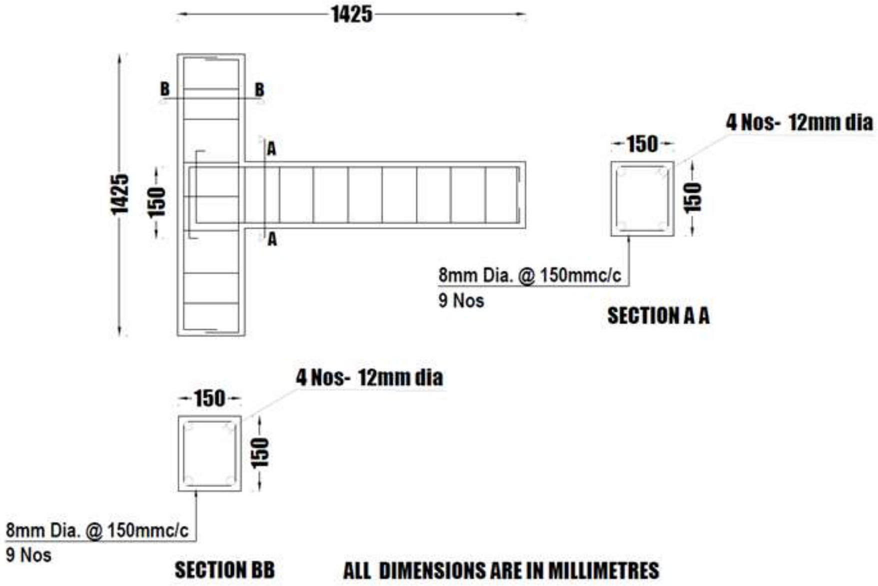


Fig. 2 Reinforcement Details

4. Numerical Analysis

4.1 Engineering Data:

The materials for the model are selected, including steel (Fe500) and concrete (M30 grade). The concrete mixes used are Conventional, 3D3, 4D3, and 5D3, based on their compressive strength. The reinforcement details are shown in **Figure 3.**

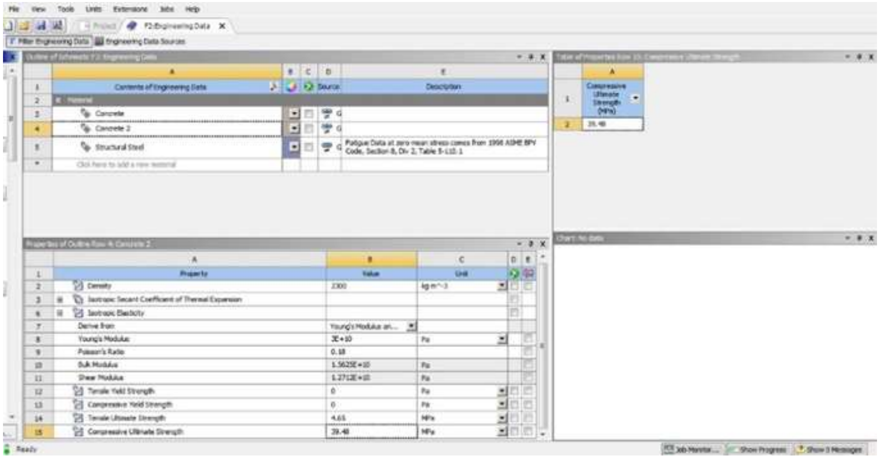


Figure 3 : ANSYS Material Property

4.2 Geometry Creation:

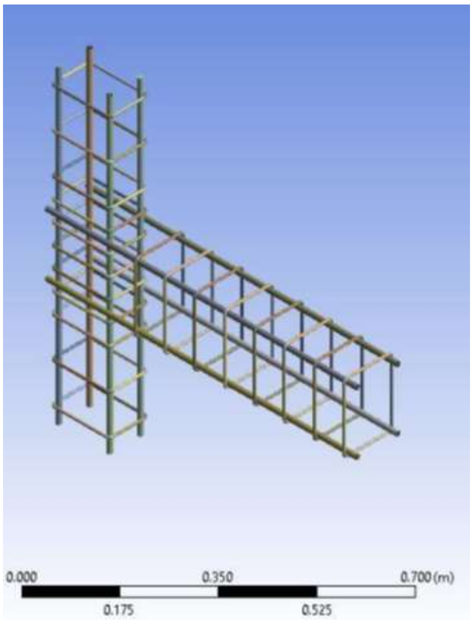
The beam's dimensions and bar diameters are defined. Separate models are created for concrete and steel, assigning appropriate material properties to each.

4.3 Finite Element Model Setup:

After defining the geometry, material properties are assigned, and a mesh is generated to solve the model using the finite element method, ensuring accurate results.

4.4 Support and Loading Conditions:

A point load is applied at the free end of the beam. After applying the load, the model is solved, and the failure mode is determined.



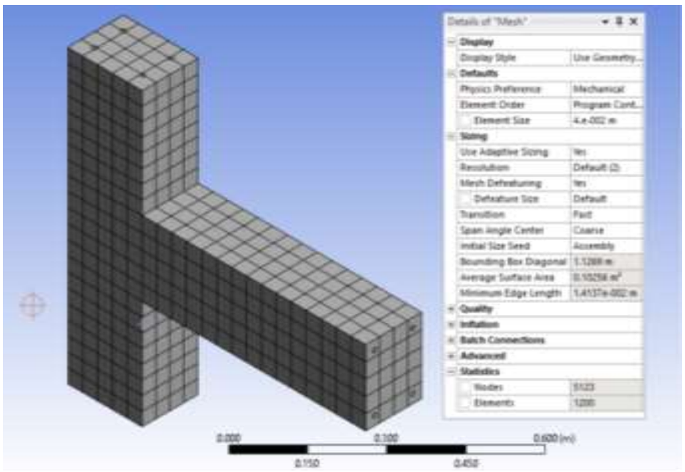


Figure 4 Geometry of Beam in Design Modeler

Figure 5 Mesh in Mechanical Mode

4.5 Providing the Support and Loading condition :

The RC beam Column were applied point load at the free end of the Beam. After the application of load the model is solved for the required results and the failure mode of the model is obtained.

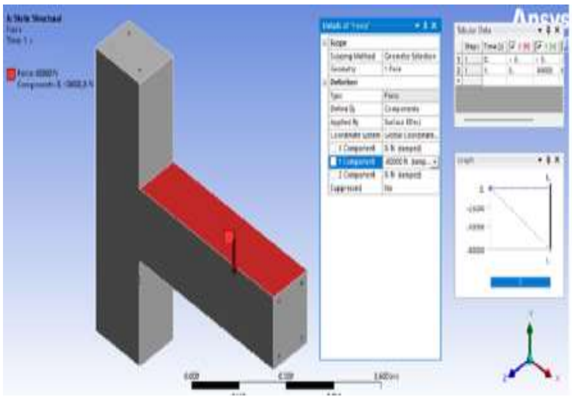


Figure 6 : Loading Configuration

4.6 Load Vs Deflection Envelope Curves

The analytical investigation of the ultimate load capacities of beam-column joint models reveals significant insights into the structural performance and integrity of reinforced concrete joints under applied loads. The study encompasses a control specimen (CC) and three variants incorporating mixed steel fibers (3D3, 4D3, and 5D3).

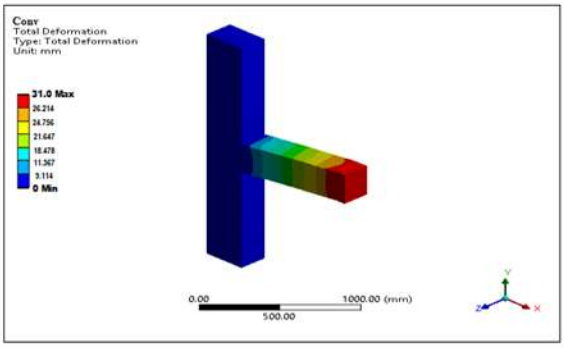


Figure 7 Deformation Diagram– CONV Model

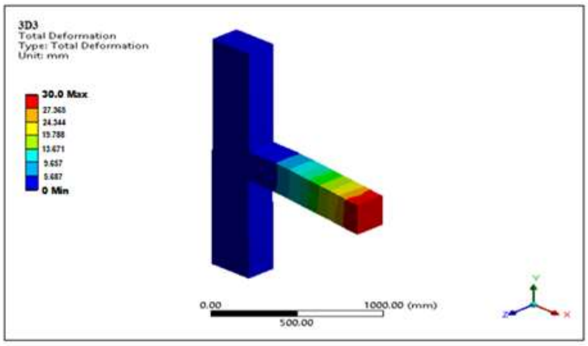


Figure 8 Deformation Diagram– 3D3

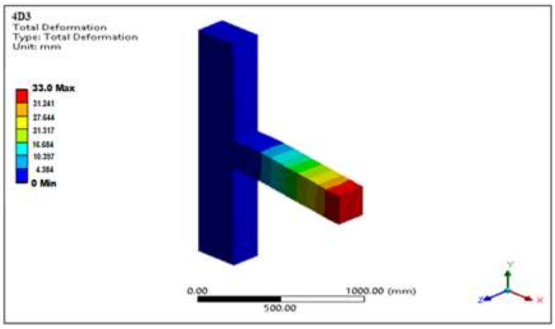


Figure 9 Deformation Diagram– 4D3

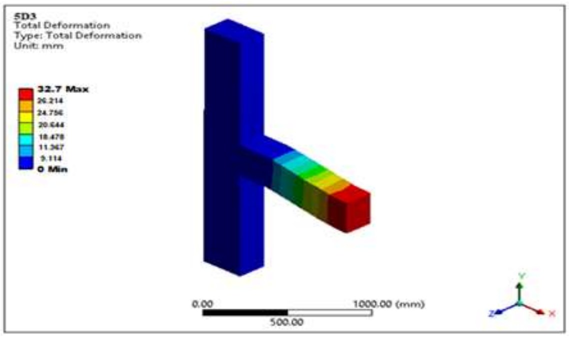


Figure 10 Deformation Diagram– 5D3

Model	Ultimate load (kN)	% Increase	Deflection (mm)
CC	27.93	-	31
3D3	29.43	5.36	30
4D3	31.30	12.05	33
5D3	33.34	19.38	32.7

Table 4 : Analytical Results of Ultimate Load of Models

Deflection is a critical parameter in evaluating the load-carrying capacity of reinforced concrete beam-column joints, as it directly relates to the structural integrity and performance under applied loads. Table 7.1 presents the analytical results detailing the load-carrying capacities of various reinforced concrete beam-column joint specimens, including the control specimen (CC) and those enhanced with 3D3, 4D3, and 5D3 mixed steel fibers. The findings indicate that the ultimate load-carrying capacity of the beam-column joints with steel fibers significantly exceeds that of the control specimen. Specifically, the ultimate loads recorded were 27.93 kN for the control specimen (CC), 29.43 kN for the 3D3 mix (a 5.36% increase), 31.30 kN for the 4D3 mix (a 12.05% increase), and 33.34 kN for the 5D3 mix (a 19.38% increase). This improvement is attributed to the enhanced structural characteristics provided by the incorporation of steel fibers, which contribute to better load distribution and resistance to cracking.

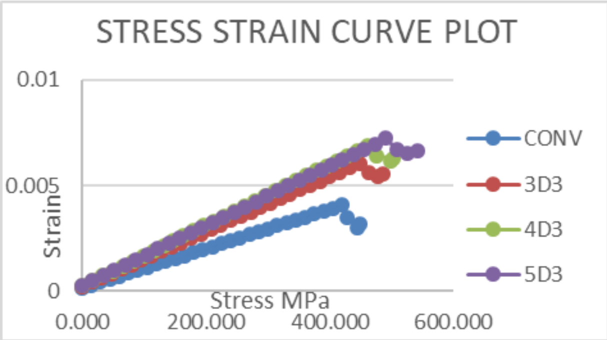


Figure 11 Stress Strain curve Plot – Analytical Results

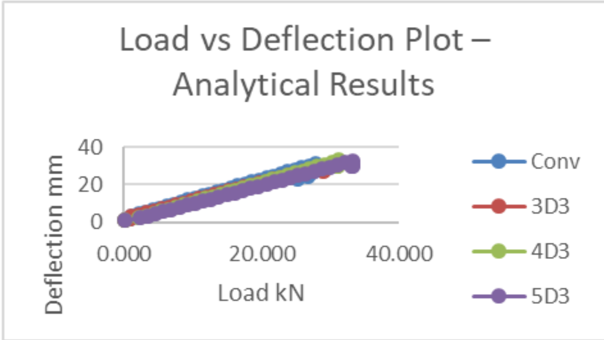


Figure 12 Load vs Deflection Plot – Analytical Results

The data demonstrates that while the specimen enhanced with 5D3 mixed steel fibers exhibited the highest ultimate load capacity, achieving an impressive 19.38% increase compared to the control specimen, the deflection values remained relatively low, with only minor variations across the tested mixes (31 mm for CC, 30 mm for 3D3, 33 mm for 4D3, and 32.7 mm for 5D3). This notable enhancement in load-carrying capacity suggests that the use of mixed steel fibers not only improves the overall strength of the beam-column joints but also enhances their ability to sustain higher loads with minimal deflection. The findings underscore the efficacy of incorporating advanced materials into concrete structures, highlighting their potential for improving performance and extending the service life of reinforced concrete systems in various applications.

4.7 Energy Dissipation Capacity

As a measure of the dissipated energy of the specimens, the area under the load-displacement curves for all cycles was computed and referred to as the energy that could be dissipated by the specimens before losing stability. In evaluating earthquake resistance, the energy dissipation capacity of a structure is traditionally associated with the shape of the load-displacement hysteretic loops. Table 7.2 shows the analytical results of the energy dissipation capacity of the models. It was observed that the maximum energy dissipation capacities of the specimens, including 3D3, 4D3, and 5D3, increased by 5.36%, 11.94%, and 19.32%, respectively, when compared with the control specimen (CC). Notably, the energy dissipation capacity of the reinforced concrete beam-column joint with 5D3 mixed steel fibers exhibited the highest increase of 19.32% compared to the control specimen, highlighting the enhanced performance and stability of this model under load conditions.

Model	Ultimate load (kN)	% Increase
CC	27.93	-
3D3	29.43	5.36
4D3	31.30	11.94
5D3	33.34	19.32

Table 5 : Analytical Results of Energy Dissipation Capacity

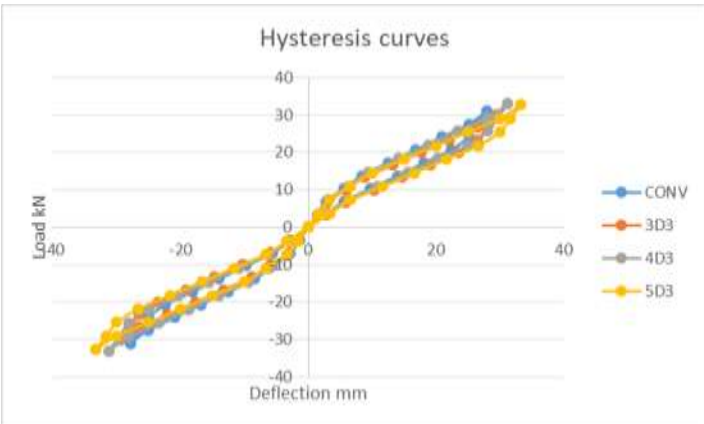


Figure 13 Hysteresis curves – Analytical Results

5 Experimental Analysis

The influence of steel fibers on the mechanical and durability properties of concrete has been extensively studied. Key findings from previous research are The experimental analysis was conducted on four joint specimens, which included one conventional concrete joint and three steel fiber-reinforced concrete (SFRC) joints. These specimens were tested using a loading frame with a capacity of 30 tons to simulate the real-world loading conditions they would experience in structural applications. A constant axial load of 180 kN, representing approximately 40% of the axial capacity of the column, was applied to the specimens. This load served two purposes: it held the specimens in place on the loading frame and simulated the column axial load typically experienced by such structures.

To further simulate real-world loading conditions, a hydraulic jack with a capacity of 32 kN was used to apply a load at the beam end, 50 mm from the tip of the beam. A proving ring with a capacity of 25 kN was employed to measure the applied load accurately. Deflection at the beam tip was measured using a Linear Variable Differential Transformer (LVDT), which was positioned just above the point of load application to capture the beam's deflection as it deformed under load.

The testing procedure involved positive cyclic loading, where the load was incremented in 2 kN steps during each cycle under load control. Within each cycle, the load was varied by 0.5 kN, and deflection was measured for each increment. The load was applied, unloaded, and then reloaded to the next increment, continuing this process for each subsequent load cycle. This cyclic loading pattern effectively simulated real-world conditions in which concrete structures experience repeated loading and unloading over time, such as during seismic events or other dynamic load situations. The experiment was designed to evaluate the behavior of the different joint specimens under cyclic loading, focusing on their deflection response.

Figure 14 : Experimental Setup

The ultimate load values are given in table 4. The results indicate that the specimen with 3D, 4D, and 5D steel fibers showed better ductile properties than conventional concrete. Specifically, the first crack load and ultimate load increased significantly as the fiber content increased. For example, the specimen with 5D3 steel fiber showed an increase of about 14.98% in the first crack load (from 9.81 kN to 11.28 kN), and a substantial increase of approximately 37.5% in the ultimate load (from 23.51 kN to 32.37 kN). During the loading cycle, as the specimen is unloaded, the crack tip becomes blunt. When reloaded, more energy is required to propagate the crack or to change the direction of propagation from the blunt tip. This increase in energy requirement contributes to the higher ultimate load observed in these specimens.

Mix id	Appearance of First Crack (kN)	Ultimate Load (kN)	Maximum Deformation (mm)
CC	9.81	23.51	29
3D3	10.29	26.48	32
4D3	10.79	29.43	36
5D3	11.28	32.37	42

Table 6 Experimental Test Results

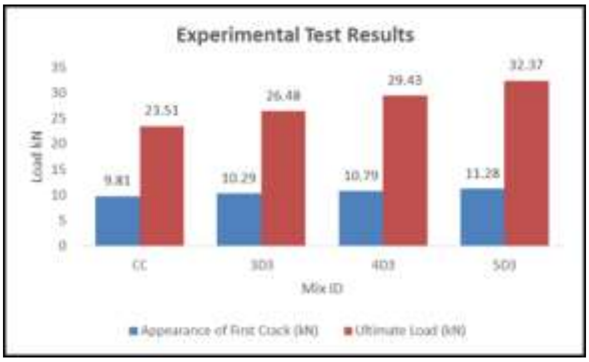


Figure 15 : Experimental Test Results

The results show that the load-carrying capacity of the joints increased with increasing fiber content. Among the specimens, the 5D3 mix showed the maximum values in both ultimate load and deformation, which suggests that this particular fiber content offers the highest performance in terms of load resistance and deformation behavior. This increase in load capacity and deformation suggests that incorporating steel fibers into the concrete improves its overall structural performance. As the fiber content increases, both the first crack load and ultimate load improve, indicating enhanced ductility and load resistance.

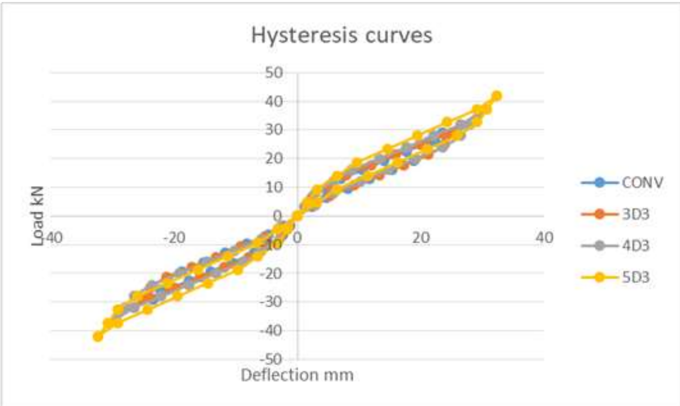


Figure 16 Hysteresis curves – Experimental Results

In all specimens, cracks initially appeared near the joint after reaching the first crack load. As the loading increased, the cracks propagated upwards along the beam, and the initial cracks began to widen. In the steel fiber-reinforced concrete specimens, a large number of closely spaced, finer cracks appeared, and the width of these cracks was smaller compared to those in the conventional concrete specimens. This indicates improved crack control and less pronounced cracking in the fiber-reinforced mixes. The ultimate load and corresponding deflection of specimens increased as the fiber content increased, highlighting the positive influence of steel fibers on the structural behavior of the concrete.

Figure 17 Crack pattern of Specimen

The typical failure patterns of conventional and fiber-reinforced beam-column joints are shown in Figure 10. These patterns provide visual confirmation of the enhanced performance and failure mechanisms in the steel fiber-reinforced concrete specimens, which exhibited more controlled and gradual failure modes compared to conventional concrete.

Lage, B. (2024) investigated the impact of varying steel fiber content on the compressive strength of concrete. The study demonstrated that adding steel fibers up to 1.5% by volume significantly improved compressive strength, with values increasing from 19.2 MPa (0% fibers) to 22.3 MPa. Beyond this optimal dosage, a decrease in strength to 19.39 MPa was observed at 2% fiber content, indicating that excessive fiber content can negatively affect strength due to potential issues like poor compaction.

6 Comparison of Experimental Results with Analytical Results

In this section, we compare the results obtained from the experimental testing of reinforced concrete beam-column joints with those from the Finite Element Analysis (FEA) using ANSYS Workbench. This comparison serves to validate the accuracy and reliability of the analytical results, providing confidence in the use of the ANSYS model for predicting the structural behavior of beam-column joints under load.

Mix id	**Ultimate Load (kN) (Ansys)**	**Ultimate Load (kN) (Experimental)**	**Maximum Deformation (mm) Ansys**	**Maximum Deformation (mm) Experimental**
CC	27.93	23.51	31	29
3D3	29.43	26.48	30	32
4D3	31.30	29.43	33	36
5D3	33.34	32.37	32.7	42

Table 7 Experimental & Ansys Test Results

6.1 Ultimate Load Comparison:

The ultimate load values from both ANSYS and experimental tests are very close for all specimens (CC, 3D3, 4D3, and 5D3), confirming that the ANSYS model accurately predicts the load-carrying capacity of the specimens. For the control specimen (CC), the ultimate load is 27.93 kN in the experimental test, and 23.51 kN in ANSYS. The addition of steel fibers increases the ultimate load, with the 5D3 mix showing a 2.97 kN (8.99%) increase compared to the control specimen, and 19.38% increase over the 3D3 mix.

6.2 Maximum Deformation (Deflection):

Deflection values from ANSYS and experimental results are also close. For the control specimen, the deflection is 31 mm in ANSYS and 29 mm experimentally. For the 5D3 mix, the deflection is 32.7 mm in ANSYS and 42 mm experimentally. The discrepancy in deflection for the 5D3 mix might be due to differences in boundary conditions or material modeling between the experimental setup and the ANSYS model.

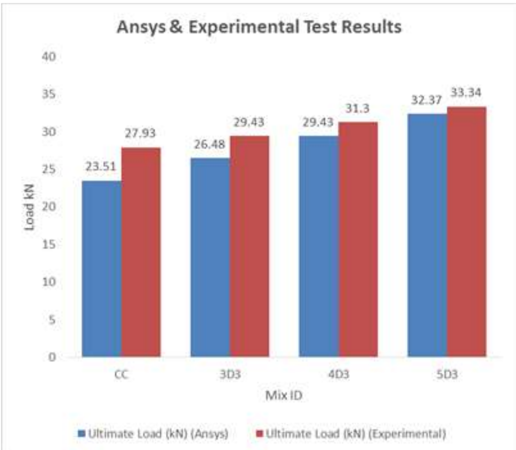


Figure 18 Ultimate Load - Analytical & Experimental Test Comparision

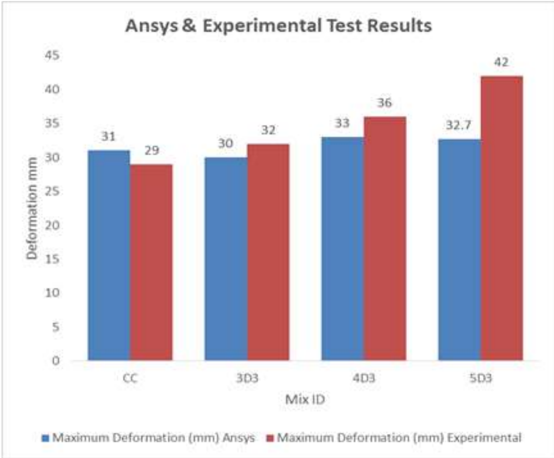


Figure 12 Deformation - Analytical & Experimental Test Comparison

6.3 Load-Deflection Curves:

The load-deflection curves from both ANSYS and experimental tests show similar trends. As the fiber content increases, both load-carrying capacity and deflection increase, indicating that steel fibers enhance the strength and flexibility of the joints.

The comparison between experimental and ANSYS analytical results demonstrates that the Finite Element Method (FEM) in ANSYS accurately predicts the structural behavior of reinforced concrete beam-column joints under cyclic loading. The close agreement between the two sets of results shows that the FEM model is a reliable tool for analyzing the performance of steel fiber-reinforced concrete (SFRC) structures. The addition of steel fibers (3D3, 4D3, and 5D3) improves the ultimate load capacity, deflection, and energy dissipation capacity of the joints, making them more resistant to cracking and deformation under applied loads.

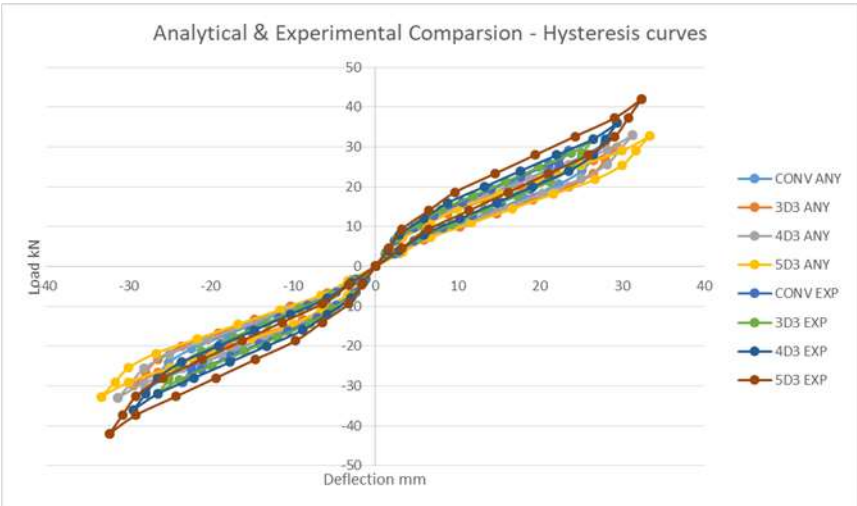


Figure 13 Hysteresis curves - Analytical & Experimental Test Comparison

The results highlight the benefits of incorporating steel fibers into concrete, particularly for applications requiring enhanced strength and durability, such as in seismic-prone regions or in structures subjected to cyclic loading. The findings also support the continued use of advanced modeling techniques like ANSYS for the design and optimization of reinforced concrete structures.

7. Conclusion

The study clearly demonstrates that the inclusion of steel fibers, particularly 5D fibers, significantly improves the mechanical properties and durability of concrete. The enhanced compressive, tensile, and flexural strengths make fiber-reinforced concrete (SFRC) highly suitable for applications requiring superior strength and toughness. Moreover, SFRC performs better in aggressive environments, showing improved resistance to sulphate attacks, saltwater exposure, and carbonation, which makes it more durable over time.

The research also highlights the value of using steel fibers in seismic-resistant designs. The enhanced energy dissipation and load-carrying capacity of fiber-reinforced beam-column joints make them more resilient to dynamic loading conditions, such as those experienced during earthquakes. The results support the use of steel fiber reinforcement in reinforced concrete structures, especially in areas prone to high seismic activity or aggressive environmental conditions.

In conclusion, the study confirms that steel fiber reinforcement, especially using higher-dimensional fibers like 5D, significantly enhances the performance of concrete in both mechanical and durability aspects. Future work should focus on optimizing fiber types, concentrations, and mix designs to further enhance the benefits of SFRC, with a particular focus on real-world applications and long-term durability.

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