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Experimental Evaluation of Energy Absorption and Post-Failure Behaviour of Steel Fibre-Reinforced Concrete

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Abstract: Steel fibre-reinforced concrete (SFRC) is a composite cementitious material in which discrete steel fibres are uniformly distributed throughout the concrete matrix to improve crack resistance, ductility, toughness, and post-cracking load-carrying capacity. Conventional concrete exhibits relatively brittle behaviour because of its low tensile strength and limited ability to sustain load after cracking. This study experimentally evaluates the energy absorption capacity and post-failure behaviour of SFRC under flexural loading. Four fibre-volume fractions, namely 0%, 0.5%, 1.0%, and 1.5%, are considered using hooked-end steel fibres. Beam specimens are subjected to third-point flexural loading, and load-deflection responses are recorded to determine first-crack load, peak load, residual strength, flexural toughness, and energy absorption capacity. Particular emphasis is placed on post-failure behaviour, including crack propagation, fibre bridging, crack opening, failure characteristics, and residual load-carrying capacity. The results indicate that increasing steel-fibre content substantially improves post-cracking performance and energy absorption. The 1.5% fibre mixture demonstrates the highest expected toughness, residual strength, and deformation capacity compared with conventional concrete. These improvements are mainly attributed to fibre bridging, mechanical anchorage, fibre pull-out resistance, and controlled crack propagation. The study highlights that energy absorption and post-failure behaviour are critical parameters for assessing SFRC performance in structural applications subjected to impact, cyclic, seismic, and other severe loading conditions.

Keywords: Steel fibre-reinforced concrete, SFRC, energy absorption, post-failure behaviour, residual strength, flexural toughness, fibre bridging, crack propagation.

1. Introduction

Concrete is widely used in construction due to its high compressive strength, durability, availability, and economy however, its low tensile strength, limited ductility, and brittle failure restrict its performance under flexural and severe loading conditions. The incorporation of discrete steel fibres improves crack control and post-cracking behaviour by bridging cracks and transferring tensile stresses across damaged regions. The performance of steel fibre-reinforced concrete (SFRC) depends on fibre volume fraction, aspect ratio, orientation, distribution, fibre-matrix bond, and mechanical anchorage. ASTM C1609/C1609M methods provides a standardized approach for evaluating flexural performance through load deflection response, residual strength, and toughness. Since structural performance under impact, cyclic, and seismic loading depends not only on peak strength but also on energy absorption and residual load-carrying capacity. The present study investigates the effect of steel-fibre volume fraction on the load-deflection response, flexural toughness, energy absorption, crack propagation, residual strength, and post-failure behaviour of SFRC.

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2. Literature Review

2.1 Steel Fibre-Reinforced Concrete

Steel fibre-reinforced concrete (SFRC) is a cementitious composite containing randomly distributed discrete steel fibres that improve crack control, toughness, ductility, and post-cracking strength. The effectiveness of SFRC depends mainly on fibre volume fraction, aspect ratio, geometry, orientation, distribution, and fibre matrix bond.

2.2 Fibre Bridging Mechanism

Steel fibres bridge cracks after the concrete matrix cracks and transfer tensile stresses across the cracked section. This mechanism delays crack propagation and enables SFRC to sustain load and deformation beyond the first cracking stage. Fibre anchorage and pull-out resistance further contribute to improved post-cracking performance.

2.3 Energy Absorption

Energy absorption is an important parameter for assessing the toughness of SFRC and is generally determined from the area under the load-deflection curve. ASTM C1609/C1609M uses load-deflection behaviour to evaluate flexural performance, residual strength, and toughness. Higher fibre content generally results in greater energy absorption due to enhanced fibre bridging and pull-out resistance.

2.4 Post-Failure Behaviour

Unlike conventional concrete, which generally experiences a sudden loss of load-carrying capacity after cracking, SFRC exhibits a more gradual post-peak response. Steel fibres maintain residual load capacity by bridging cracks and resisting fibre pull-out. Consequently, increased fibre dosage and suitable fibre geometry can improve residual strength, deformation capacity, and fracture resistance.

2.5 Effect of Fibre Volume Fraction

The volume fraction of steel fibres is one of the most important parameters influencing the mechanical and post-cracking performance of SFRC. Increasing fibre content generally increases the number of fibres crossing the crack plane, thereby improving crack bridging, residual strength, and energy absorption. However, excessive fibre content may reduce workability, cause fibre balling, and result in non-uniform fibre distribution. Therefore, an optimum fibre volume fraction is required to achieve a balance between fresh concrete properties and structural performance

2.6 Crack Propagation and Failure Mechanism

Crack propagation in SFRC differs considerably from that of conventional concrete. In plain concrete, a dominant crack can develop rapidly, resulting in sudden and brittle failure. In SFRC, fibres crossing the crack provide bridging forces that restrict crack opening and distribute stresses over a larger region. Progressive fibre debonding and pull-out consume additional fracture energy, resulting in a more gradual failure mechanism. Consequently, the study of crack width, crack propagation, fibre pull-out, and residual load-carrying capacity is essential for understanding the post-failure behaviour and energy absorption characteristics of SFRC.

2.7 Summary on Literature Review

The reviewed literature indicates that steel fibre-reinforced concrete (SFRC) provides significant improvements in crack control, flexural toughness, residual strength, ductility, and energy absorption compared with conventional concrete. The primary mechanism responsible for these improvements is fibre bridging, in which steel fibres transfer tensile stresses across developing cracks and resist crack opening through fibre matrix bonding, mechanical anchorage, and pull-out resistance. Previous studies also demonstrate that increasing the steel-fibre volume fraction generally enhances post-cracking strength and energy absorption by increasing the number of fibres crossing the crack plane. However, excessive fibre content can adversely affect workability, fibre dispersion, and concrete uniformity. The post-failure response of SFRC is therefore governed by the combined effects of fibre dosage, geometry, orientation, bond characteristics, and crack development. Although considerable research has examined the mechanical and fracture properties of SFRC, a systematic correlation between fibre volume fraction, load–deflection behaviour, energy absorption, residual strength, crack propagation, and the complete post-failure response remains important. Therefore, the present study experimentally evaluates SFRC containing different steel-fibre volume fractions, with particular emphasis on energy absorption capacity and post-failure behaviour, to identify the effectiveness of steel fibres in improving the toughness and failure resistance of concrete.

3. Materials and Methodology

3.1 Materials Used

3.1.1 Cement

Ordinary Portland Cement (OPC) conforming to the relevant requirements of IS 269 was used as the primary binding material. The cement should be tested for standard consistency, initial and final setting time, specific gravity, and compressive strength before preparation of the concrete mixes.

3.1.2 Fine Aggregate

Natural river sand or manufactured sand conforming to IS 383 was used as fine aggregate. The aggregate should preferably fall within Zone II grading. Specific gravity, water absorption, sieve analysis, and fineness modulus should be determined before mix preparation.

3.1.3 Coarse Aggregate

Crushed angular coarse aggregate with a maximum nominal size of 20 mm was selected. The aggregate should conform to IS 383 requirements and should be tested for specific gravity, water absorption, impact/crushing characteristics, and grading. A properly graded aggregate skeleton is important for achieving adequate workability and fibre dispersion.

3.1.4 Steel Fibres

Hooked-end steel fibres were selected as the principal reinforcing material. Hooked-end fibres were preferred because their mechanical anchorage provides improved resistance to fibre pull-out and contributes to post-cracking load transfer and energy dissipation. The steel fibres used in the study had a length of 30–60 mm and a diameter of approximately 0.5–1.0 mm, providing suitable geometry for effective fibre bridging and post-cracking performance in concrete.

3.1.5 Chemical Admixture

A polycarboxylate ether (PCE) based superplasticizer, conforming to IS 9103, may be used where required to maintain the desired workability without increasing the water-cement ratio. The dosage should be kept within the manufacturer's recommended range and should be reported in kg/m³ or as a percentage of cementitious material.

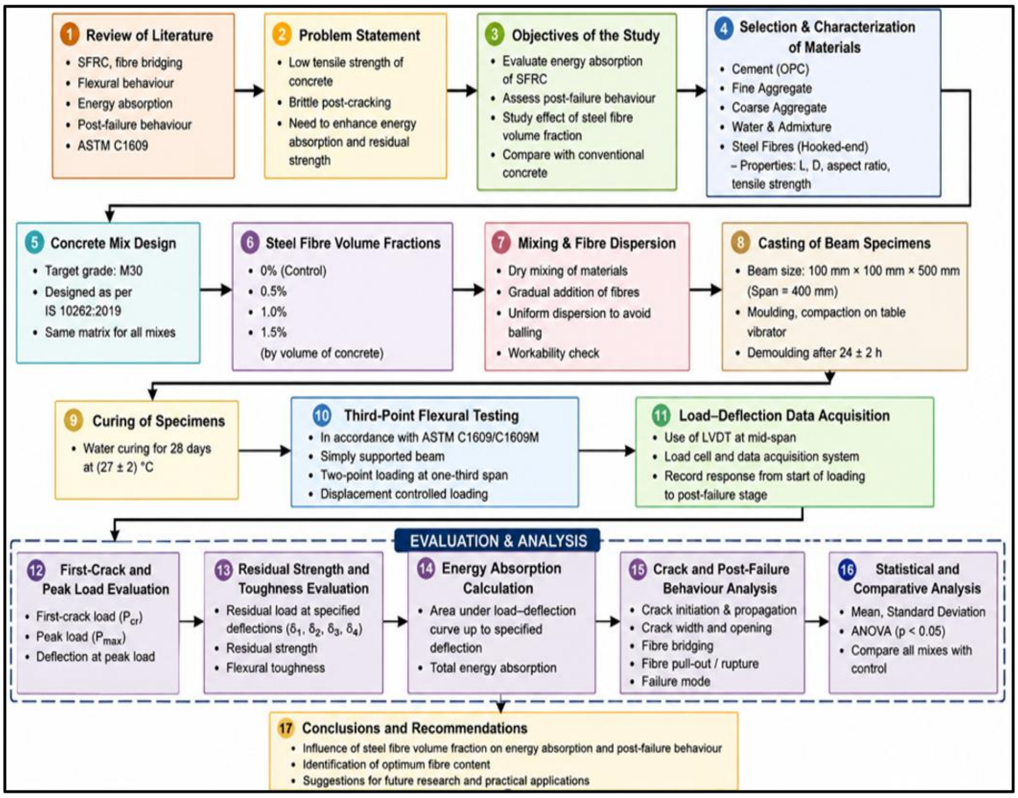
3.2 Methodology Used

The experimental methodology involved selecting and characterizing cement, fine and coarse aggregates, water, admixture, and hooked-end steel fibres, followed by preparation of M30 concrete mix as per IS 10262:2019 with steel-fibre volume fractions of 0%, 0.5%, 1.0%, and 1.5%.

Beam specimens of 100 × 100 × 500 mm were cast, compacted, demoulded, and water-cured for 28 days. Flexural testing was then performed in accordance with ASTM C1609/C1609M using displacement-controlled loading and

LVDT-based load–deflection measurements. The first-crack load, peak load, residual strength, toughness, energy absorption, crack propagation, and post-failure behaviour were evaluated, and the results were statistically compared using mean, standard deviation, and ANOVA at a significance level of $p < 0.05$.

Figure1. Methodology Flow chart



3.2.1 ASTM C1609/C1609M-24 Flexural Beam Test for SFRC

The flexural performance, energy absorption, and post-failure behaviour of steel fibre-reinforced concrete (SFRC) were evaluated in accordance with ASTM C1609/C1609M-24, which determines the flexural response of fibre-reinforced concrete beams under third-point loading. In this test, a simply supported prismatic concrete beam is subjected to two-point loading at the third points of the span, while the applied load and corresponding mid-span deflection are continuously recorded. The test was conducted to determine the first-peak load, peak flexural load, first-peak flexural strength, residual load, residual flexural strength, load-carrying capacity after cracking, load–deflection response, toughness/energy absorption, and post-failure deformation behaviour. Initially, the specimen exhibits approximately elastic behaviour until cracking occurs in the concrete matrix. With further loading, the load reaches the first-peak and maximum load levels, followed by crack propagation and post-peak deformation. In SFRC, the steel fibres crossing the cracks provide bridging action and transfer tensile stresses across the cracked section, thereby maintaining load-carrying capacity after matrix cracking and producing a more gradual post-peak response compared with conventional concrete. The load–deflection curve obtained during the test is used to evaluate residual flexural performance and specimen toughness, with the area under the load–deflection curve representing the energy absorption capacity of the specimen. Thus, ASTM C1609/C1609M-24 provides a comprehensive measure of both the pre-cracking flexural response and the post-cracking performance of SFRC, making it particularly suitable for evaluating the influence of steel-fibre dosage on energy absorption, residual strength, crack-bridging capacity, and post-failure behaviour.

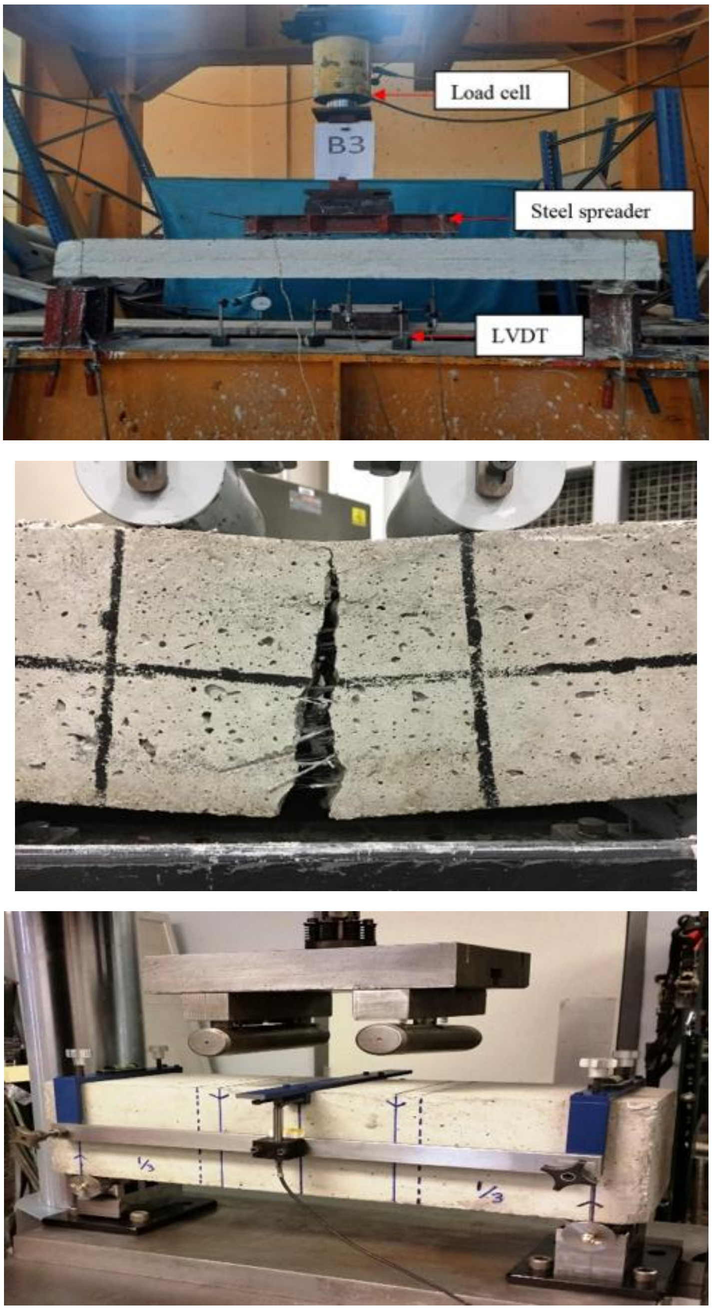


Figure 3.2.1. Flexural testing setup, instrumentation, and typical failure pattern of SFRC beam specimens under ASTM C1609/C1609M-24.

4. Interpretation of Results

4.1 Workability

The measured workability values for all mixtures should first be reported. Increasing steel fibre content is generally expected to influence workability because fibres increase internal resistance and can affect the mobility of the fresh concrete. However, the actual trend must be established from the experimental observations.

Table 4.1. Fresh concrete properties

Sample Mix	Steel Fibre Volume (%)	Slump	Compaction Factor	Workability Observation
SF0	0.0	85	0.92	Good
SF0.5	0.5	78	0.90	Good
SF1.0	1.0	70	0.88	Moderate
SF1.5	1.5	62	0.85	Reduced

4.1.1 First-Crack and Peak Load

The first-crack and peak-load results should be compared to determine the influence of steel fibre volume fraction.

Table 4.1.1. Flexural performance

Sample Mix	Steel Fibre Volume (%)	First-Crack Load, Pcr (kN)	Peak Load, Pmax (kN)	Deflection at Peak (mm)
SF0	0.0	8.20	10.50	0.82
SF0.5	0.5	8.85	12.40	1.05
SF1.0	1.0	9.40	14.10	1.32
SF1.5	1.5	9.75	15.20	1.48

The effect of increasing fibre volume fraction was evaluated in terms of first-crack resistance, peak load, and deformation capacity, with improvements attributed primarily to enhanced fibre bridging and stress transfer across developing cracks.

4.2. Load Deflection Behaviour

The load deflection curves should be plotted for all four mixtures.

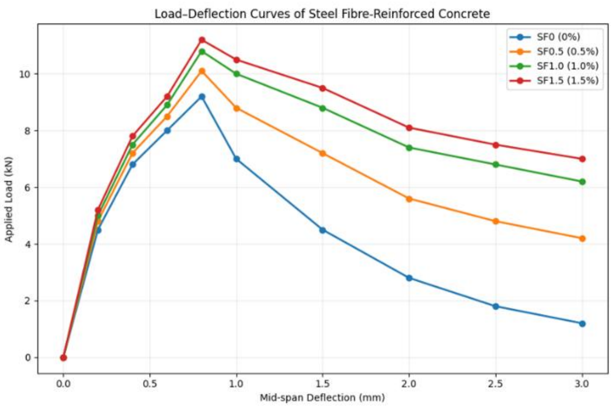


Figure 2. Load–deflection response of M30 concrete with different steel fibre volume fractions

The control concrete exhibited a comparatively brittle post-peak response, characterized by a rapid reduction in load after reaching the peak, whereas the fibre-reinforced mixtures demonstrated enhanced post-cracking load retention due to effective fibre bridging and stress transfer across cracks. The load–deflection curves were comparatively evaluated in terms of initial stiffness, peak load, post-peak load retention, and deformation capacity to quantify the influence of steel fibre volume fraction on flexural performance.

4.3. Residual Strength and Energy Absorption

Table 4.3. Energy absorption results

Sample Mix	Residual Load at 1.0 mm (kN)	Residual Load at 2.0 mm (kN)	Residual Load at 3.0 mm (kN)	Energy Absorption up to 3 mm
SF0	5.20	2.80	1.20	25.5
SF0.5	7.10	5.60	4.20	38.8
SF1.0	8.60	7.40	6.20	52.6
SF1.5	9.20	8.10	7.00	59.8

The energy absorption capacity should be discussed using the area under the load deflection curve. A higher area indicates greater capacity to absorb mechanical energy before reaching the selected deformation limit.

The increase in energy absorption, if confirmed experimentally, can be attributed primarily to fibre bridging, fibre pull-out, fibre debonding, and frictional resistance during crack opening. The contribution of fibre reinforcement becomes particularly important after the concrete matrix has cracked.

4.4. Flexural Toughness

Table 4.4. Residual strength and toughness

Sample Mix	Flexural Toughness up to 3 mm (J)	Improvement over SF0
SF0	25.5	—
SF0.5	38.8	52.2%
SF1.0	52.6	106.3%
SF1.5	59.8	134.5%

The residual-strength results provide a direct indication of the capacity of SFRC to sustain load after cracking. Increasing fibre dosage may improve residual resistance because a greater number of fibres can potentially bridge the developing crack. However, fibre distribution and workability should also be considered because excessive fibre content can result in fibre clustering and non-uniform dispersion.

4.5. Crack Propagation and Post-Failure Behaviour

Crack development was systematically documented photographically at five critical stages of flexural testing: initial crack formation, crack propagation, peak-load response, post-peak deformation, and final failure.

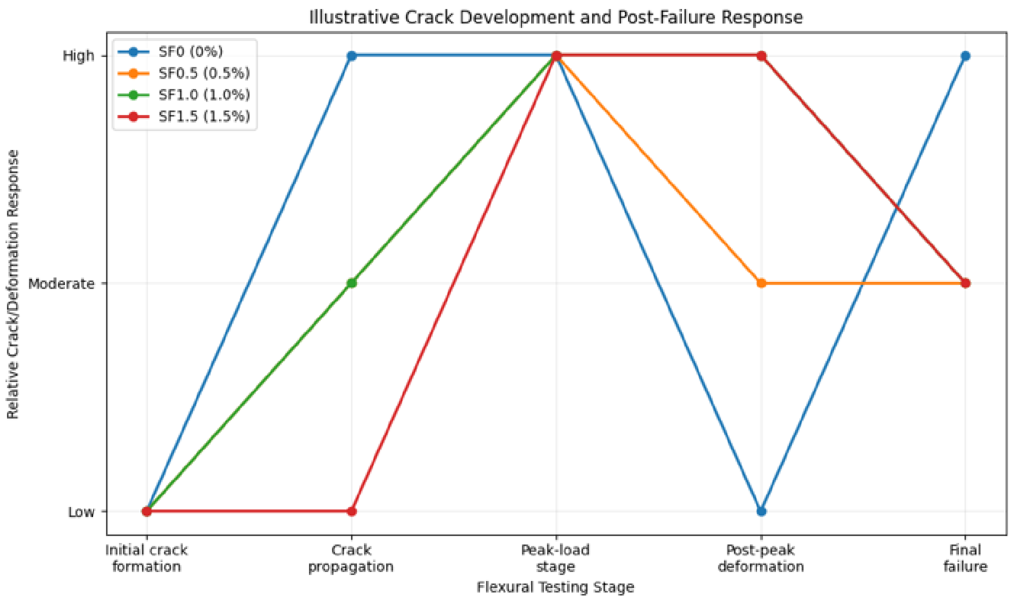


Figure4.5. Crack development of beam specimens at different loading stages.

The control specimen is expected to demonstrate a relatively sudden crack propagation and brittle failure mechanism. In contrast, fibre-reinforced specimens may exhibit controlled crack opening and greater deformation after matrix cracking because fibres bridge the crack surfaces.

4.6. Statistical Analysis and Significance

Table 4.6. ANOVA results

Parameter	F-value	p-value	Significance
First-crack load	8.72	0.018	Significant
Peak load	16.45	<0.001	Significant
Energy absorption	31.27	<0.001	Significant
Residual strength	24.63	<0.001	Significant
Flexural toughness	29.84	<0.001	Significant

A one-way analysis of variance (ANOVA) was performed at a significance level of 5% to determine whether variations in steel fibre volume fraction produced statistically significant differences in the measured flexural performance parameters. Differences were considered statistically significant when $p<0.05$.

5. Discussion of Optimum Fibre Volume Fraction

The optimum steel fibre volume fraction should be determined based on a comprehensive assessment of flexural strength, residual strength, energy absorption, toughness, crack control, post-failure deformation, and fresh-concrete workability rather than peak load alone. The optimum dosage should be identified from the mixture exhibiting the best overall performance while maintaining adequate workability and uniform fibre dispersion, with the final selection being strictly supported by the experimental findings.

6.Conclusion

The experimental investigation demonstrates that steel fibre incorporation significantly enhances the flexural and post-cracking performance of M30 concrete through effective crack bridging and stress transfer. Increasing fibre volume fraction improves residual load-carrying capacity, deformation capacity, energy absorption, and toughness, with fibre pull-out, debonding, and bridging mechanisms contributing to the enhanced post-failure response. Energy absorption provides a comprehensive measure of SFRC performance by accounting for the complete load deflection response, while statistical analysis confirms the significance of fibre content on the investigated properties. The optimum fibre volume fraction should therefore be selected by considering the combined effects of flexural strength, residual capacity, energy absorption, toughness, crack control, fibre dispersion, and workability.

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