Experimental Investigation on the Cyclic Flexural Behaviour of Steel Fibre Reinforced Concrete Beams for Seismic Applications

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Abstract - The seismic performance of reinforced concrete (RC) structures largely depends on the ductility, energy dissipation capacity, and stiffness retention of their structural members under cyclic loading. In this context, the present study experimentally investigates the cyclic flexural behaviour of steel fibre reinforced concrete (SFRC) beams with a focus on their suitability for seismic applications. A series of simply supported RC and SFRC beam specimens were cast and tested under reverse cyclic loading using a two-point loading arrangement to simulate earthquake-induced forces. Steel fibres were incorporated at an optimized volume fraction, and the performance of SFRC beams was compared with conventional RC beams. Key response parameters such as load–deflection behaviour, crack development, energy absorption capacity, ductility factor, and stiffness degradation were evaluated from the experimentally obtained hysteresis curves. The results demonstrate that the inclusion of steel fibres significantly delays crack initiation, enhances post-cracking behaviour, and improves the overall ductility of beams under cyclic loading. SFRC beams exhibited substantially higher cumulative energy absorption capacity and superior ductility indices compared to conventional RC beams, indicating improved seismic resistance. Furthermore, steel fibre reinforcement was found to reduce stiffness degradation and control crack propagation through effective crack-bridging action. The experimental findings confirm that steel fibre reinforced concrete beams possess enhanced deformation capacity and energy dissipation characteristics, making them a promising alternative to conventional RC beams in earthquake-resistant structures. The study highlights the potential of steel fibres in improving the seismic performance of flexural members without major changes in conventional reinforcement detailing.

Key Words: *Steel fibre reinforced concrete; Cyclic loading; Flexural behaviour; Seismic performance; Energy absorption; Ductility*

1.INTRODUCTION

Reinforced concrete (RC) remains the most widely used structural material in seismic regions due to its versatility, economy, and ease of construction. However, the brittle nature of conventional concrete and its limited tensile strength often result in poor post-cracking performance, rapid stiffness degradation, and inadequate energy dissipation when structural members are subjected to earthquake-induced cyclic loading. Past seismic events have repeatedly demonstrated that insufficient ductility and energy absorption capacity in flexural members can lead to catastrophic structural failures, emphasizing the need for improved materials and design strategies for earthquake-resistant structures.

Cyclic loading, characterized by repeated load reversals, induces progressive damage in RC members through crack initiation, crack propagation, stiffness degradation, and strength deterioration. The seismic performance of flexural members is therefore governed not only by their ultimate load-carrying capacity but also by their ductility, hysteretic energy dissipation, and crack control capability. Enhancing these parameters is essential for ensuring structural safety and serviceability during and after seismic events.

Steel fibre reinforced concrete (SFRC) has emerged as a promising composite material capable of addressing several limitations of conventional RC. The random distribution of short steel fibres within the concrete matrix enhances tensile resistance, controls crack propagation through fibre bridging, and improves post-cracking behaviour. Unlike conventional reinforcement, steel fibres contribute to load transfer across cracks at micro and macro levels, thereby enhancing ductility and energy absorption under cyclic loading conditions.

Although several studies have reported the benefits of steel fibres under monotonic loading, their effectiveness under reverse cyclic loading representative of seismic actions requires further systematic investigation. In particular, limited experimental data are available on the cyclic flexural behaviour of SFRC beams, focusing on key seismic performance indicators such as hysteretic response, cumulative energy absorption, ductility factor, and stiffness degradation.

In this context, the present study experimentally investigates the cyclic flexural behaviour of steel fibre reinforced concrete beams under simulated seismic loading. The research aims to quantify the improvement in seismic performance achieved through steel fibre inclusion and to assess the suitability of SFRC beams as efficient flexural members for earthquake-resistant structures.

2. LITERATURE REVIEW

2.1 Behaviour of Reinforced Concrete Beams under Cyclic Loading

Extensive research has been conducted on the cyclic behaviour of reinforced concrete (RC) beams to understand their response under earthquake loading. Early experimental studies established that RC beams subjected to reverse cyclic loading exhibit progressive stiffness degradation, strength deterioration, and accumulation of residual deformations due to repeated cracking and yielding of reinforcement (Park and Paulay, 1975; Clough and Penzien, 1993). Subsequent investigations emphasized that ductility and hysteretic energy dissipation are critical parameters governing seismic performance rather than ultimate strength alone.

Several researchers reported that conventional RC beams often suffer from wide crack openings, spalling of concrete cover, and premature failure under cyclic loading, especially in regions of plastic hinging (Priestley et al., 2007). These deficiencies have motivated the exploration of alternative materials and reinforcement strategies aimed at enhancing post-cracking behaviour and deformation capacity.

2.2 Fibre Reinforced Concrete and Flexural Performance

Fibre reinforced concrete (FRC) has been widely studied as an effective material for improving the tensile and post-cracking performance of concrete. Studies on steel fibre reinforced concrete (SFRC) under monotonic loading conditions demonstrated enhanced flexural strength, improved crack control, and increased toughness compared to conventional concrete (ACI 544, 2002; Bentur and Mindess, 2007). The presence of steel fibres was found to bridge cracks, redistribute stresses, and delay crack propagation, leading to improved structural integrity.

Experimental investigations on SFRC beams have shown that fibre inclusion improves load-deflection behaviour and residual strength after cracking (Narayanan and Darwish, 1987; Swamy and Mangat, 1974). These improvements are primarily attributed to fibre pull-out resistance and enhanced bond between fibres and the cement matrix.

2.3 Cyclic and Seismic Behaviour of Fibre Reinforced Concrete Beams

In recent years, attention has shifted toward evaluating the seismic performance of FRC members under cyclic loading. Researchers have reported that SFRC beams exhibit improved hysteretic behaviour, higher energy dissipation, and reduced stiffness degradation when compared to conventional RC beams (Lok and Xiao, 1999; Henager and Doherty, 2001). The fibre bridging mechanism was observed to be particularly effective in controlling crack widening during load reversals.

Some studies highlighted that steel fibres delay the formation of plastic hinges and improve confinement in the compression zone, thereby enhancing ductility (Ganesan et al., 2014). Investigations involving hybrid reinforcement systems combining conventional steel bars and fibres also reported superior cyclic performance and reduced damage accumulation.

However, reported results vary significantly depending on fibre type, volume fraction, aspect ratio, and loading protocol. Moreover, many studies focused primarily on qualitative observations or limited response parameters, without comprehensive evaluation of cumulative energy absorption and stiffness degradation.

2.4 Identified Research Gaps

From the critical review of existing literature, the following gaps are identified:

1. Limited experimental studies focusing exclusively on the cyclic flexural behaviour of SFRC beams under controlled reverse cyclic loading.

2. Insufficient emphasis on quantitative evaluation of seismic performance indicators, such as cumulative energy absorption, ductility factor, and stiffness degradation.

3. Lack of systematic comparison between SFRC beams and conventional RC beams under identical cyclic loading conditions.

4. Limited experimental data supporting the practical applicability of SFRC beams for seismic design, especially using optimized fibre content without altering conventional reinforcement detailing.

2.5 Novelty and Contribution of the Present Study

To address the above research gaps, the present study provides a **comprehensive experimental investigation** on the cyclic flexural behaviour of steel fibre reinforced concrete beams subjected to reverse cyclic loading. Unlike previous studies, this work systematically evaluates key seismic performance parameters—including load–deflection response, hysteretic energy dissipation, cumulative energy absorption, ductility factor, and stiffness degradation—under simulated earthquake loading conditions. The study offers clear experimental evidence on the effectiveness of steel fibres in enhancing seismic performance, thereby contributing valuable insights for the adoption of SFRC beams in earthquake-resistant structural design.

3. MATERIALS AND EXPERIMENTAL PROGRAM

3.1 Materials

3.1.1 Cement

Ordinary Portland Cement (OPC) conforming to relevant Indian Standards was used as the primary binder in all concrete mixes. The cement was fresh, free from lumps, and stored under dry conditions to ensure consistency in strength development.

3.1.2 Aggregates

Locally available natural river sand conforming to grading requirements for fine aggregates was used. Crushed stone coarse aggregates with a nominal maximum size suitable for reinforced concrete beams were adopted. Both fine and coarse aggregates were tested for specific gravity, water absorption, and grading to ensure uniformity across all mixes.

3.1.3 Steel Fibres

Hooked-end steel fibres were used as secondary reinforcement in steel fibre reinforced concrete (SFRC) beams. The fibres were incorporated at an optimized volume fraction of 0.75%, selected based on workability considerations and previous research findings. The fibres were uniformly distributed within the concrete matrix to ensure effective crack-bridging action and enhanced post-cracking behaviour.

Figure 3.1 Round Crimped Steel fibre **Figure 3.2 Mixing of fibres in concrete**

3.1.4 Conventional Reinforcement

High-yield strength deformed steel bars were used as longitudinal reinforcement and stirrups in all beam specimens. Identical reinforcement detailing was adopted for both conventional RC beams and SFRC beams to ensure a fair comparison of flexural performance.

3.1.5 Mixing Water

Potable water free from impurities was used for mixing and curing of concrete.

3.2 Specimen Details

A total of reinforced concrete beam specimens were cast and tested under cyclic loading. The beams had a rectangular cross-section of 100 mm × 150 mm and an overall length of 1500 mm, with an effective span of 1400 mm. The specimens were categorized into two groups:

- Control beams (RC) without fibres
- Steel fibre reinforced concrete beams (SFRC) with 0.75% steel fibres(RCSFC

Each category consisted of identical specimens to ensure repeatability and reliability of results. The reinforcement detailing was designed to promote flexural failure and avoid premature shear failure.

3.3 Casting and Curing of Specimens

Concrete was prepared by hand mixing to achieve a uniform and homogeneous mix. For SFRC specimens, steel fibres were gradually sprinkled into the concrete during mixing to prevent fibre balling and ensure proper dispersion. The fresh concrete was placed into wooden moulds in layers and compacted manually using tamping rods. After casting, the specimens were finished smoothly and left undisturbed for 24 hours.

All beams were demoulded after one day and cured in water for 28 days under controlled laboratory conditions to achieve adequate strength prior to testing.

3.4 Experimental Setup and Loading Protocol

After curing, the beam specimens were tested under reverse cyclic loading using a loading frame of 1000kN capacity. The beams were simply supported over a clear span of 1400 mm and subjected to two-point loading at one-third span locations to induce a constant moment region in the central portion of the beam.

Cyclic loading was applied in a load-controlled manner, with incremental loading and unloading in both forward and reverse directions to simulate seismic effects. For each cycle, load and corresponding mid-span deflection were recorded during both loading and unloading phases using dial gauges. The specimens were subjected to successive load cycles until failure.

Figure 3.3 Experimental setup for flexural members

3.5 Test Measurements and Evaluated Parameters

During testing, the following parameters were recorded and evaluated:

- Load–deflection response
- Crack initiation, propagation, and failure mode
- Hysteretic behaviour under cyclic loading
- Relative and cumulative energy absorption capacity
- Ductility factor
- Stiffness and stiffness degradation

The experimental data obtained from cyclic load–deflection curves were used to assess the seismic performance of SFRC beams in comparison with conventional RC beams.

4. RESULTS AND DISCUSSION

4.1 Load–Deflection Behaviour under Cyclic Loading

The load–deflection response of conventional RC and steel fibre reinforced concrete (SFRC) beams under reverse cyclic loading is presented through the hysteresis curves (Figures corresponding to load–deflection behaviour). The control RC beams exhibited relatively steeper stiffness degradation with increasing load cycles, accompanied by wider crack openings and reduced load-carrying capacity during subsequent cycles. In contrast, SFRC beams demonstrated improved load–deflection characteristics with enhanced deformation capacity and reduced residual deflections.

The inclusion of steel fibres delayed the initiation of first cracking and resulted in a more gradual post-cracking response. SFRC beams sustained higher deflections at comparable load levels, indicating superior ductile behaviour under cyclic loading. The hysteresis loops of SFRC beams were fuller and more stable than those of conventional RC beams, reflecting improved energy dissipation capacity.

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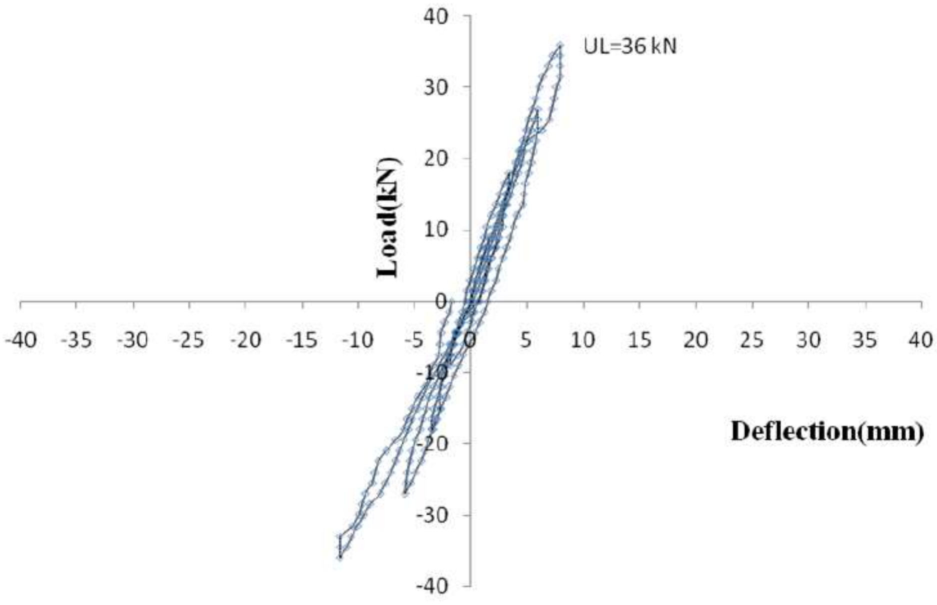

Figure 4.1 Load deflection behaviour of RC

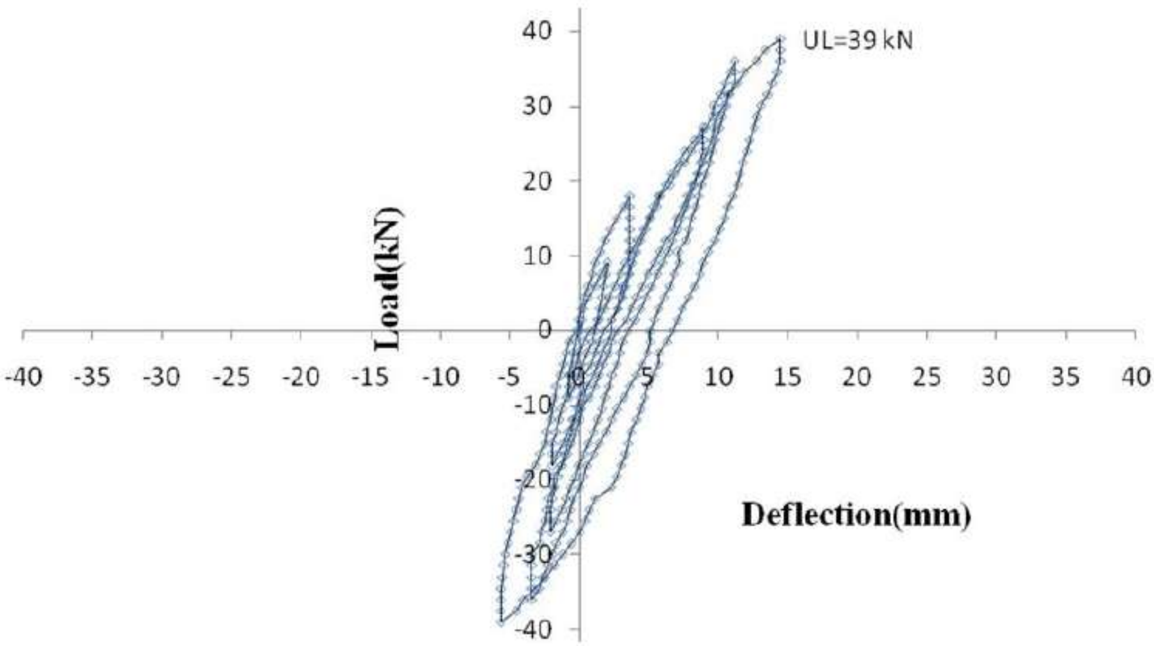

Figure 4.2 Load deflection behaviour of SFRC

4.2 Crack Development and Failure Characteristics

Crack patterns observed during testing revealed significant differences between RC and SFRC beams. Conventional RC beams exhibited fewer but wider cracks concentrated near the maximum moment region, leading to localized damage and earlier stiffness loss. In contrast, SFRC beams developed multiple fine cracks with smaller widths distributed along the flexural zone.

The steel fibres effectively bridged cracks and restrained their propagation during load reversals. This crack-arresting mechanism improved structural integrity and delayed spalling of concrete in the tension zone. Failure in SFRC beams was characterized by gradual degradation rather than sudden collapse, which is a desirable behaviour for seismic-resistant structures. The first crack for the reinforced concrete beam was noted at 12 kN whereas the inclusion of fibres delayed the formation of first crack to 18 kN for steel fibre reinforced concrete beam

4.3 Energy Absorption Capacity

The relative and cumulative energy absorption capacities of the beam specimens, obtained from the areas enclosed by the hysteresis loops (Tables corresponding to energy absorption and Figures showing cumulative energy variation), clearly demonstrate the superior seismic performance of SFRC beams. The cumulative energy absorption of SFRC beams was significantly higher than that of control RC beams.

SFRC beams were able to withstand a greater number of load cycles before failure, indicating enhanced capacity to dissipate seismic energy. The increase in energy absorption is attributed to fibre pull-out resistance and crack-bridging action, which allow the beams to undergo large inelastic deformations while maintaining load-carrying capacity.

Table 4.1 Cumulative Energy Absorption capacity of RC

Cycles	Relative Energy Absorption Capacity (kN-mm)	Cumulative Energy AbsorptionCapacity (kN-mm)
1	15	15
2	38	53
3	89	142
4	331	473

Table 4.2 Cumulative Energy Absorption capacity of SFRC

Cycles	Relative Energy Absorption Capacity (kN-mm)	Cumulative Energy Absorption Capacity (kN-mm)
1	25	25
2	67	92
3	136	228
4	169	397
5	346	743

4.4 Ductility Characteristics

The ductility factors calculated from the load–deflection response (Tables and Figures showing ductility variation) indicate a marked improvement in ductility for SFRC beams. While the ductility factor of conventional RC beams increased moderately with successive cycles, SFRC beams exhibited substantially higher ductility values, particularly in the later cycles.

The cumulative ductility factor of SFRC beams was significantly greater than that of RC beams, confirming the effectiveness of steel fibres in enhancing deformation capacity. Improved ductility ensures better redistribution of stresses and prevents sudden brittle failure, which is critical under seismic loading.

Table 4.3 Cumulative ductility factor for RC

Cycle no	Ductility factor	Cumulative Ductility factor
1	0.90	0.90
2	1.80	2.70
3	3.16	5.86
4	5.36	11.22

Table 4.4 Cumulative ductility factor for RCSF0.75

Cycle no	Ductility factor	Cumulative Ductility factor
1	0.93	0.93
2	1.84	2.77
3	3.60	6.37
4	6.06	12.43
5	7.94	20.37

4.5 Stiffness Degradation Behaviour

Stiffness degradation curves derived from the cyclic load–deflection response (Figures and Tables corresponding to stiffness variation) show that conventional RC beams experienced rapid stiffness loss with increasing cycles. In contrast, SFRC beams retained higher stiffness values throughout the loading history.

The reduced rate of stiffness degradation in SFRC beams can be attributed to improved crack control and enhanced post-cracking resistance provided by steel fibres. Higher residual stiffness contributes to improved serviceability and reduced damage accumulation during seismic events.

Table 4.5 Stiffness degradation for RC

Forward cycle	Stiffness(kN/mm)	Reverse cycle	Stiffness(kN/mm)
1	4.1	1	4.3
2	3.7	2	3.8
3	3.3	3	3.3
4	3.0	4	3.0

Table 4.6 Stiffness degradation for SFRC

Forward cycle	Stiffness(kN/mm)	Reverse cycle	Stiffness(kN/mm)
1	5.0	1	6.4
2	4.7	2	5.5
3	4.2	3	4.7
4	3.8	4	4.0
5	3.2	5	3.4

4.6 Discussion on MODE OF FAILURE & Seismic Performance Enhancement

The experimental results collectively indicate that steel fibre inclusion significantly enhances the seismic performance of flexural members. SFRC beams exhibited improved hysteretic stability, higher energy dissipation, enhanced ductility, and reduced stiffness degradation compared to conventional RC beams. These improvements are particularly beneficial in earthquake-resistant design, where the ability to undergo large cyclic deformations without significant loss of strength is essential.

Figure 4.3 Failure of the RC beam

Figure 4.4 Failure of the SFRC beam

The study confirms that the incorporation of steel fibres at an optimized volume fraction can effectively improve the cyclic flexural performance of RC beams without requiring major modifications to conventional reinforcement detailing, thereby offering a practical and efficient solution for seismic applications.

5. Conclusions

5.1 Key Experimental Findings

Based on the experimental investigation on the cyclic flexural behaviour of steel fibre reinforced concrete beams, the following conclusions are drawn:

- Steel fibre reinforced concrete (SFRC) beams exhibited delayed crack initiation and improved crack distribution compared to conventional reinforced concrete (RC) beams under cyclic loading.
- The load–deflection response of SFRC beams demonstrated enhanced post-cracking behaviour and higher deformation capacity, indicating improved ductility.
- SFRC beams showed significantly higher cumulative energy absorption capacity, reflecting superior ability to dissipate seismic energy.
- The ductility factor and cumulative ductility of SFRC beams were substantially greater than those of conventional RC beams, confirming enhanced inelastic deformation capacity.
- Stiffness degradation in SFRC beams occurred at a slower rate, and higher residual stiffness was retained throughout successive loading cycles.
- The crack-bridging action of steel fibres effectively restrained crack widening and prevented sudden brittle failure, resulting in a more stable hysteretic response.

5.2 Seismic Implications

The experimental results clearly demonstrate that the inclusion of steel fibres significantly improves the cyclic flexural performance of reinforced concrete beams. By enhancing ductility, energy dissipation, and stiffness retention, steel fibres contribute to a more damage-tolerant structural response under simulated earthquake loading. The observed improvements in hysteretic behaviour and crack control indicate that SFRC beams are capable of sustaining larger cyclic deformations with reduced strength degradation, which is a critical requirement for earthquake-resistant structures.

Importantly, the study confirms that these performance enhancements can be achieved using an optimized fibre dosage without altering conventional reinforcement detailing, making SFRC a practical and cost-effective solution for seismic applications. The findings support the potential use of steel fibre reinforced concrete beams as efficient flexural members in seismic zones, contributing to improved structural safety and resilience.

5.3 Future Scope

- The study is limited to a single fibre volume fraction and beam geometry.
- Future research may focus on different fibre contents, hybrid fibre systems, and full-scale beam–column joints.
- Numerical modelling and analytical validation can further extend the applicability of the experimental findings.
- Investigate different reinforcement ratios, shear span-to-depth ratios and axial load levels to develop detailed design recommendations and modification factors for seismic codes when fibres are used.
- Perform long-term durability and corrosion studies (e.g., wet–dry cycles, carbonation, marine exposure) on SSFRC structural elements to quantify service-life extension relative to SFRC and conventional RC.

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