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Comprehensive Review on the Effect of Steel Fibres in the Concrete

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A B S T R A C T

This research explores the efficacy of Steel Fibre Reinforced Concrete (SFRC) into the design of beam-column joints to enhance their performance under cyclic loading conditions. Beam-column joints are critical components in multi-story concrete frames, significantly influencing the overall stability and safety of the structure. Conventional reinforcement methods, which involve high-density transverse steel, often lead to congestion and construction challenges while striving to achieve the necessary strength, stiffness, and ductility. This study proposes Steel Fiber Reinforced Concrete (SFRC) as an innovative solution to reduce the reliance on extensive transverse reinforcement. By incorporating steel fibres at varying dosages of 0.5%, 1%, and 1.5%, the research aims to evaluate their impact on the structural behaviour of beam-column joints. Analytical simulations using ANSYS software were conducted to subject the specimens to cyclic loading scenarios. Key performance metrics such as load-bearing capacity, energy absorption, energy dissipation, stiffness degradation, and shear strength of the joints were assessed and compared. The objective of this study is to determine the potential benefits of SFRC in improving the overall ductility and performance of beam-column joints, thereby offering a more practical approach to managing reinforcement density and enhancing the structural integrity of concrete frameworks.

Keywords: *Fiber, Beam Column, Joints, Steel, Concrete*

1. Introduction

Concrete is weak when it comes to tension. Small cracks start forming in a concrete structure at about 10 to 15% of its maximum load, growing into larger cracks at 25 to 30% of the maximum load. Therefore, plain concrete cannot handle heavy loads without continuous reinforcing bars in the tension areas, like in beams or slabs. Even with reinforcement, these cracks cannot be fully stopped. The reinforcement takes over the tension in the section. Adding randomly spaced fibres can help stop or slow down the formation of these cracks early on. While fibres have been used to reinforce concrete for a long time, new types have become popular in the past thirty years. These include steel, glass, polypropylene, and graphite fibres. They improve the mechanical properties of concrete, both as a material and in structures, and are used in addition to, not instead of, continuous reinforcement when needed.

The construction industry is a cornerstone of economic growth and social development, playing a critical role in the advancement of infrastructure and urbanization globally (Sohu et al., 2017). Concrete, as one of the most widely used building materials, is pivotal in this industry (Lakhiar et al., 2018). Its widespread use is attributed to its durability, versatility, and availability, making it essential for constructing residential houses, skyscrapers, bridges, pavements, and dams. Despite its extensive use, concrete's intrinsic weakness lies in its low tensile strength and susceptibility to cracking, issues that were identified as early as the 1800s (Agarwal et al., 2014; Behbahani et al., 2011). (Agarwal, 2014) (Bebahani, 2011) (Lakhier, 2018)

To address these shortcomings, the incorporation of fibres into concrete has been explored. Fibre-reinforced concrete (FRC) enhances concrete's resistance to shrinkage cracking, increases its tensile strength, and improves its deformation characteristics. FRC is produced by integrating numerous small fibres, either natural or synthetic, into the concrete mix, enhancing its properties uniformly in all directions (Rana, 2013). Among the various fibres used, steel fibres have shown significant promise, especially in applications such as industrial pavements, roads, parking areas, and airports, due to their ability to substantially improve the structural behavior of concrete (Sorelli et al., 2006). (Sorelli, 2006)

This study specifically focuses on the performance of 3D, 4D, and 5D steel fibre-reinforced concrete in beam-column joints (BCJs). Beam-column joints are critical components in the structural framework of buildings, especially in regions susceptible to seismic activities. The integrity of these joints is crucial as they transfer loads between beams and columns, and their failure can lead to the collapse of the entire structure (Xiao et al., 2018). (Xiao, 2018)

Recent studies have shown that incorporating steel fibres into concrete can enhance the performance of beam-column joints by increasing their tensile strength and crack resistance (Kazemi et al., 2022; Zhang et al., 2021). However, the optimal type and volume fraction of steel fibres for such applications are still subjects of ongoing research. This experimental study aims to investigate the effects of different dimensions (3D, 4D, and 5D) and volume fractions of steel fibres on the performance of concrete in beam-column joints. By determining the optimal combination of fibre type and quantity, the study seeks to provide insights that could lead to more resilient and durable concrete structures (Ganesan et al., 2023). (Ganesan, 2023)

Additionally, the study will address how steel fibre reinforcement impacts other critical properties of concrete, such as its workability, load-bearing capacity, and durability under various environmental conditions (Sahmaran et al., 2021). The findings of this research will have significant implications for the construction industry, particularly in improving the safety and longevity of structures in earthquake-prone areas and other challenging environments. (Sahmaran, 2021)

2. Types of Steel Fibres

In the context of fibre-reinforced concrete (FRC), different types of steel fibres play crucial roles in enhancing the material's mechanical properties and performance. These fibres are categorized based on their shapes, manufacturing processes, and applications. Each type of steel fibre offers unique benefits and is selected according to the specific requirements of a project.

a) Straight Steel Fibres: These fibres are manufactured as straight, smooth filaments, as illustrated in Figure 1. They provide reliable reinforcement against cracking and improve tensile strength. Their simple geometry is effective for general applications where uniform reinforcement is required, making them a versatile choice for various concrete structures.

b) Deformed Steel Fibres: Featuring surface irregularities such as hooks, waves, or crimps, deformed steel fibres enhance the bond between the fibres and the concrete matrix. As shown in Figure 2, these deformations improve the mechanical interlocking within the concrete, thereby increasing its resistance to cracking and improving overall structural performance. Their ability to provide a strong bond with the concrete makes them suitable for high-stress applications.

Fig. 1 Straight Steel Fibres

Fig. 2 Deformed Steel Fibres

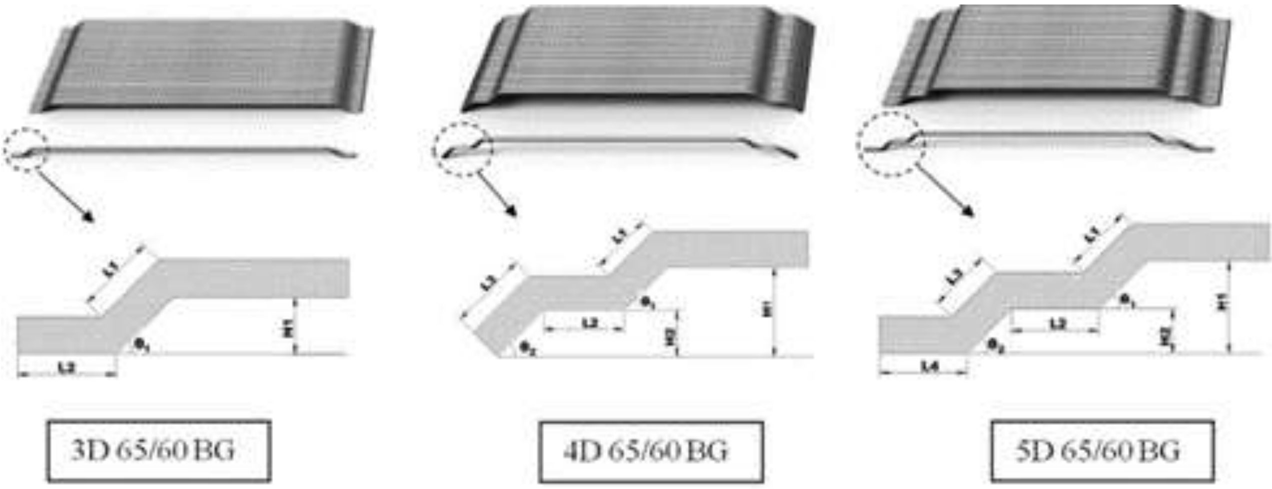

Fig. 3 (a) 3D steel fibre, (b) 4D steel fibre, (c) 5D steel fibre

Fig. 4 Micro Steel Fibres

PROPERTIES	**3D STEEL FIBRE**	**4D STEEL FIBRE**	**5D STEEL FIBRE**
Commercial name	DRAMIX 3D	DRAMIX 4D	DRAMIX 5D
Fibre length	60 mm	60 mm	60 mm
Diameter	0.75 mm	0.75 mm	0.90 mm
Aspect ratio	80	80	67
Tensile strength	1225 N/mm²	1500 N/mm²	2300 N/mm²
Shape	Single hooked-end	Double hooked-end	Triple hooked-end

Table: 1 Hooked-End Steel Fibre properties

c) Hooked-End Steel Fibres: These fibres have small hooked ends at one or both ends of the filament, as depicted in Figure 3. The hooks enhance the anchorage within the concrete matrix, improving pull-out resistance and the bond between the fibre and the concrete. There are several geometries of hooked-end steel fibres available, each designed to optimize performance for specific applications. Their unique design makes them highly effective in enhancing the toughness and durability of concrete.

d) Micro Steel Fibres: Much smaller in diameter than conventional steel fibres, micro steel fibres are used for applications requiring fine reinforcement, such as thin-section concrete elements or overlays. Figure 4 illustrates these fibres. Their small size allows for uniform distribution within the concrete mix, providing improved performance in situations where precise reinforcement is needed. They are particularly useful in enhancing the crack resistance and durability of thin or complex concrete structures.

3. Mechanical Properties of Steel Fibre Reinforced Concrete

3.1 Compressive Strength Test

The addition of steel fibres to concrete significantly impacts its compressive strength. The results presented by Bikash Lage (2024) indicate that incorporating steel fibres enhances the compressive strength up to a certain percentage. For example, the average compressive strength increased from 19.2 Mpa with 0% steel fiber to 21.48 Mpa with 1% steel fiber and further to 22.3 Mpa with 1.5% steel fiber. However, beyond this point, the compressive strength began to decrease, as evidenced by the 19.39 Mpa recorded at 2% steel fiber content. This suggests that there is an optimal fiber content that maximizes compressive strength, beyond which the addition of more fibres may lead to a reduction in strength. (Lage, 2024)

Anbuchezian Ashokan et al. (2023) reported a compressive strength of 107.3 MPa in concrete containing 2% steel fibres, which is notably higher than the compressive strength ranges of 80 to 100 MPa documented in previous research for the same fiber dosage. This significant increase in compressive strength indicates that the steel fibres used in this study provided enhanced structural integrity and load-bearing capacity compared to earlier findings. (Anbuchezian Ashokan, 2023) (Bikash Lage, 2024)

Anish and Logeshwari (2024) analyzed the compressive strength of Ultra-High-Performance Concrete (UHPC) reinforced with various fibres. Their research indicated that different types of fibres have distinct impacts on the compressive strength of UHPC. Specifically, they noted that the incorporation of steel fibres and polypropylene fibres significantly enhanced the compressive strength of UHPC. Although specific numerical values were not provided in the excerpt, the overall trend demonstrates that fiber reinforcement positively contributes to compressive strength, with steel and polypropylene fibres showing substantial improvements compared to non-reinforced UHPC.The compressive strength of Steel Fiber Reinforced Concrete (SFRC) exhibited a significant improvement with the inclusion of steel fibres, peaking at a 1% fiber content by volume of cement. Beyond this optimal percentage, further increases in fiber content did not result in substantial gains in compressive strength. This indicates that 1% steel fiber content provides the most effective enhancement in the concrete's ability to withstand compressive forces.

The compressive strength test evaluates the maximum load concrete can withstand in compression. Jawad Ahmad et al. (2020) found that the compressive strength of concrete increases with the addition of steel fibres up to a 2% dosage, reaching a peak strength 25% higher than the reference concrete after 28 days of curing. Beyond this point, the strength diminishes. This increase is attributed to the confinement effect provided by the steel fibres, which resist lateral expansion and shear forces. However, higher fiber content complicates the compaction process, leading to reduced strength due to increased porosity. (Logeshwari & Anish, 2024)

3.2 Splitting Tensile Strength Test

The inclusion of steel fibres also positively affects the splitting tensile strength of concrete. According to Bikash Lage (2024), the tensile strength generally increased with the addition of steel fibres. The average tensile strength rose from 2.29 Mpa with 0% fiber to 2.55 Mpa with 0.5% fiber, and further to 3.1 Mpa with 1.5% fiber. The highest tensile strength was observed at 2% steel fiber content, with an average value of 3.42 Mpa. These findings suggest that steel fibres improve the tensile properties of concrete, enhancing its resistance to cracking and tensile failure, with the most significant improvement noted at a 2% fiber content.

Ashokan et al. (2023) reported a split tensile strength of 25.4 MPa for concrete containing 2% steel fibres. This result surpasses the split tensile strength values of earlier research, which ranged from 15 to 20 MPa for the same fiber dosage. The enhancement in tensile strength underscores the effectiveness of steel fibres in improving the concrete's resistance to cracking and tensile stress.

In the research conducted by Anish and Logeshwari (2024), the split tensile strength of UHPC was also a focal point. I observed that adding fibres, particularly in volumes less than 0.5%, improved tensile strength. Although the study did not provide detailed split tensile strength values, it highlighted the positive effects of fibres such as glass, polypropylene, and basalt on tensile properties. Among these, glass fibres exhibited the highest peak load, followed by polypropylene and basalt fibres. This indicates that fibres reinforcement is effective in enhancing the tensile strength of UHPC, contributing to the material's durability and resistance to cracking. (Logeshwari & Anish, 2024)

The study demonstrated that the addition of steel fibres enhances the split tensile strength of concrete. Although specific values for split tensile strength were not provided, the overall trend indicates that steel fibres improve the concrete's ability to resist tensile stresses. This reinforces the effectiveness of steel fibres in bridging cracks and improving the tensile properties of concrete.

The split tensile strength test measures the tensile stresses at which concrete fails under compressive loading. Jawad Ahmad et al. (2020) reported that split tensile strength improves with the incorporation of steel fibres up to 2%, achieving a 43% increase over the reference concrete after 28 days. Beyond 2% fiber content, the tensile strength decreases. Steel fibres act as crack stoppers, enhancing the post-cracking tensile capacity of the concrete. The study highlighted that steel fibres have a more pronounced effect on tensile strength than on compressive strength.

3.3 Flexural Strength Test

The flexural strength of the concrete mixture with 2% steel fibres, as reported by Ashokan et al. (2023), was 25.4 MPa. This value surpasses the flexural strength observed in previous studies, which ranged from 15 to 20 MPa for similar fiber content. The superior flexural strength indicates that the steel fibres used in this study contributed effectively to the concrete's resistance to bending and deformation.

Anish and Logeshwari (2024) also evaluated the flexural strength of UHPC with various fiber combinations. Their findings revealed that hybrid fiber systems, including basalt, polypropylene, and glass fibres, notably improved the flexural strength of UHPC. Specifically, flexural strength increased by 20.8% with basalt fibres, 26.9% with polypropylene fibres, and 27.9% with glass fibres at a fiber content of 2.5%. These enhancements in flexural strength were accompanied by increases in the modulus of rupture, indicating that the presence of these fibres improves the material's resistance to bending stresses and enhances overall structural performance.

The flexural strength of SFRC improved as the percentage of steel fibres increased, reaching its maximum benefit at a 0.75% fiber content. This optimal fiber content provided the best reinforcement against bending stresses. The results show that steel fibres contribute significantly to the concrete's resistance to flexural loads, enhancing its durability and performance under bending conditions. (Anbuchezian Ashokan, 2023)

4. Durability Properties of Steel Fibre Reinforced Concrete

4.1 Carbonation Resistance Test

The carbonation resistance test for SFRCAC (Steel Fiber Reinforced Concrete with Recycled Coarse Aggregate) shows that its resistance to carbonation increases with higher compressive strength. D. Gao et al. (2019) found that when the compressive strength is maintained at 45 MPa, the carbonation resistance remains nearly unchanged despite variations in the RCA (Recycled Coarse Aggregate) replacement ratio, ranging from 0% to 100%. Additionally, the introduction of steel fibres significantly influences carbonation resistance. As the steel fiber volume fraction increases from 0% to 2%, carbonation resistance initially improves, peaking at a 1.5% steel fiber volume fraction, before declining with further increases. This indicates that an optimal amount of steel fibres is essential to maximize carbonation resistance, along with higher compressive strength.

4.2 Freeze-Thaw Resistance Test

The freeze-thaw resistance test reveals that SFRCAC's ability to withstand freeze-thaw cycles also improves with increasing compressive strength. According to the findings of D. Gao et al. (2019), when the compressive strength is fixed at 45 MPa, the freeze-thaw resistance does not significantly vary with different RCA replacement ratios. However, the addition of steel fibres impacts the freeze-thaw resistance: it initially increases as the steel fiber volume fraction rises from 0% to 2%, reaching an optimal resistance at 1.5%, after which it begins to decline. This suggests that a higher compressive strength and an optimal steel fiber volume fraction (1.5%) are crucial for enhancing the freeze-thaw resistance of SFRCAC.

4.3 Chloride Penetration Test

The anti-chloride permeability test measures SFRCAC's resistance to chloride penetration, a critical factor for durability in corrosive environments. As per the research by D. Gao et al. (2019), the anti-chloride permeability improves with higher compressive strength. For a fixed compressive strength of 45 MPa, the resistance to chloride penetration remains consistent across different RCA replacement ratios. The inclusion of steel fibres enhances this resistance up to an optimal volume fraction of 1.5%, beyond which the resistance decreases. This indicates that both higher compressive strength and an optimal steel fiber volume fraction significantly contribute to better chloride penetration resistance in SFRCAC. (Logeshwari & Anish, 2024)

4.4 Microstructure Analysis

The microstructure analysis of SFRCAC, conducted with different compressive strengths and steel fiber volumes (while keeping the RCA replacement ratio constant at 50%), shows that a higher compressive strength leads to fewer microdefects and a denser matrix. According to D. Gao et al. (2019), when the steel fiber volume fraction is set at 1%, the compactness of SFRCAC increases with higher compressive strength. For instance, C30R50F1 displays noticeable holes, C45R50F1 shows fewer tiny holes and cracks, and C60R50F1 exhibits only a few cracks. This improvement in compactness is attributed to a lower water-cement ratio and fewer microdefects at higher strengths. Moreover, when the compressive strength is fixed at 45 MPa, a steel fiber volume fraction of 1.5% (as seen in C45R50F1) results in the best compactness, followed by 2% (C45R50F2), and then 0% (C45R50F0). Therefore, a suitable content of steel fibres enhances the compactness and durability of the concrete matrix.

4.5 Water Absorption Test

The water absorption test, an indirect measure of concrete durability, assesses the amount of water absorbed by the concrete. Jawad Ahmad et al. (2020) observed that water absorption decreases as the proportion of steel fibres increases. The inclusion of steel fibres enhances the tensile properties of the concrete, preventing the formation of initial cracks and increasing its density. Consequently, the reduced porosity leads to lower water absorption, improving the concrete's durability against environmental factors.

4.6 Acid Resistance Test

The acid resistance test evaluates the concrete's resistance to sulfuric acid (H2SO4) attacks by measuring the mass loss of the specimens. Jawad Ahmad et al. (2020) found that weight loss due to sulfuric acid significantly decreases with higher steel fiber content. Steel fibres effectively restrict the development and formation of initial cracks, reducing the porosity of the concrete and preventing the rapid penetration of sulfuric acid. This results in improved acid resistance, as the denser concrete matrix offers better protection against chemical erosion.

4.7 Permeability Resistance Test

The permeability resistance test assesses the depth of penetration of aggressive materials that can degrade concrete. Jawad Ahmad et al. (2020) demonstrated that permeability decreases with increasing steel fiber content. The minimum permeation depth was observed at a 4% steel fiber dosage, which was 72% lower than the control mix. The high elastic modulus and tensile capacity of steel fiber-reinforced concrete restrict initial crack formation, reducing porosity and enhancing the concrete's resistance to permeability.

5. Structural Performance

Incorporating steel fibres into concrete can significantly boost the structural performance of elements such as beams, columns, beam-column joints, and slabs. Research has demonstrated that steel fibres enhance the flexural strength, load-bearing capacity, and crack resistance of concrete beams by as much as 25% (Song and Hwang, 2004). For columns, steel fibres improve ductility, toughness, and axial load capacity, with reported increases of about 20% (Balaguru and Shah, 1992). In beam-column joints, adding steel fibres enhances energy absorption, shear strength, and crack resistance, achieving improvements up to 30% (Lok and Xiao, 1999). Additionally, in concrete slabs, steel fibres have been shown to increase flexural strength and toughness by up to 40% (Banthia and Trottier, 1995). These enhancements contribute to the overall durability, load-bearing capacity, and crack resistance of concrete structures, ensuring they are more robust and resilient over time (Lok and Xiao, 1999) (Balaguru & Shah, 1992) (Balaguru & Shah, Fiber-Reinforced Cement Composites. McGraw-Hill., 1992).

6. Conclusion

The paper offers a comprehensive examination of Steel Fibre Reinforced Concrete (SFRC), highlighting its mechanical characteristics, benefits, and applications. In recent years, concrete technology has seen significant progress, particularly in the area of Fibre Reinforced Concrete. SFRC is a composite material where traditional concrete is enhanced through the random distribution of short, discrete steel fibres with particular shapes. Unlike conventional reinforcing steel bars, which are methodically positioned in the tensile zones of the concrete, these fibres are thin, short, and scattered randomly throughout the concrete element. Among the various fibres used for concrete reinforcement, steel fibres are the most commonly selected. SFRC has shown notable improvements in flexural strength and overall toughness compared to Conventional Reinforced Concrete.

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