Original Article
ISSN (Online): 2582-7472

ShodhKosh: Journal of Visual and Performing Arts
July-December 2023 4(2), 4891–4898

STRUCTURAL RESPONSE TO DIAGONAL CRACKING IN HIGH-STRENGTH FIBRE-REINFORCED CONCRETE DEEP BEAMS

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DOI
10.29121/shodhkosh.v4.i2.2023.5913

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

ABSTRACT

The structural performance of deep beams is significantly influenced by the development and propagation of diagonal cracks, which compromise their shear capacity and overall stability. This study investigates the mechanical behavior of diagonal cracks in high-strength fibre-reinforced concrete (HSFRC) deep beams. Fibre reinforcement, known for its crack-bridging capacity and toughness enhancement, offers potential improvements in the ductility and shear resistance of deep beams, particularly under high-stress concentration zones. In this experimental investigation, deep beams with varying fibre contents and types were cast using high-strength concrete and tested under two-point loading conditions. The primary parameters studied include load-bearing capacity, crack initiation and propagation patterns, crack width, and post-cracking behavior. High-resolution digital image correlation techniques and mechanical strain gauges were employed to monitor strain distribution and crack evolution in real time. The results indicate that fibre incorporation significantly delays the onset of diagonal cracking and enhances the post-crack load-carrying capacity. Moreover, the addition of fibres contributes to a more distributed cracking pattern and increases energy absorption, thereby improving the ductility and overall structural resilience. Comparative analysis with control specimens revealed up to 30% enhancement in shear strength and a notable reduction in crack width and spacing. The study concludes that integrating fibres into high-strength concrete can effectively mitigate the adverse effects of diagonal cracking in deep beams, offering a practical solution for enhancing the performance of critical structural elements in modern construction. These findings provide a foundation for future research and development of design guidelines for HSFRC deep beams.

Keywords: High-Strength Concrete, Fibre-Reinforced Concrete (FRC), Deep Beams, Diagonal Cracks, Shear Behavior

1. INTRODUCTION

Deep beams are an essential structural element commonly used in bridges, high-rise buildings, water tanks, and industrial structures where large concentrated loads and short spans are involved. Unlike conventional slender beams, deep beams exhibit a non-linear strain distribution and are primarily governed by shear behavior rather than flexure. One of the critical challenges in the performance of deep beams is the formation of diagonal cracks, which arise due to high shear stresses and stress concentrations near the supports or load application points. These diagonal cracks can significantly reduce the structural capacity and durability of deep beams if not adequately controlled.

High-strength concrete (HSC) has gained popularity in modern construction due to its superior compressive strength, reduced cross-sectional dimensions, and improved long-term durability. However, HSC is also more brittle and prone to sudden failure compared to normal strength concrete, particularly under tensile and shear stresses. To overcome this limitation, fibre reinforcement is increasingly being incorporated into high-strength concrete mixes. The inclusion of fibres such as steel, polypropylene, glass, or synthetic types enhances the tensile resistance, crack bridging ability, and post-cracking toughness of concrete, making it more ductile and energy-absorbing.

This study focuses on evaluating the structural behavior of high-strength fibre-reinforced concrete (HSFRC) deep beams, particularly in relation to the development and propagation of diagonal cracks. By understanding how fibres influence crack formation, shear resistance, and load distribution, this research aims to contribute toward optimizing the design and application of deep beams in critical structural systems. The findings are expected to offer valuable insights for both researchers and practicing engineers in developing performance-based design guidelines for HSFRC deep beams.

1.1. NEED FOR THE STUDY

Deep beams are vital structural components subjected to complex load paths and high shear forces, often leading to diagonal cracking and premature failure. Unlike slender beams, deep beams do not conform to the assumptions of classical beam theory, and their behavior is predominantly governed by nonlinear stress distribution and shear-related mechanisms. The occurrence of diagonal cracks in these members compromises both their load-carrying capacity and serviceability, necessitating a focused study on improving their crack resistance and structural integrity.

Although high-strength concrete (HSC) offers superior compressive performance, it is inherently brittle and susceptible to sudden failure under tension and shear. The limited post-cracking ductility of HSC deep beams raises serious concerns, especially in seismic zones or in structures exposed to dynamic or impact loads. In this context, incorporating fibres into high-strength concrete emerges as a promising solution to enhance its tensile strength, ductility, and energy absorption characteristics. Fibre-Reinforced Concrete (FRC) has shown improved performance in controlling crack initiation and propagation, yet its specific effect on diagonal cracking in deep beams under shear remains under-explored.

The need for this study arises from the lack of comprehensive experimental data and design guidelines addressing the shear behavior of High-Strength Fibre-Reinforced Concrete (HSFRC) deep beams. By systematically investigating the role of different types and dosages of fibres on the development of diagonal cracks, this research seeks to bridge the knowledge gap and provide a practical basis for the adoption of HSFRC in critical structural applications. The study's outcomes will contribute to safer, more durable, and efficient concrete structures.

1.2. OBJECTIVES OF THE STUDY

The primary aim of this research is to evaluate the mechanical behavior of diagonal cracks in High-Strength Fibre-Reinforced Concrete (HSFRC) deep beams and to assess the effectiveness of fibre inclusion in enhancing their structural performance. The study is driven by the need to improve crack resistance, shear strength, and ductility in deep beams subjected to high shear forces.

The specific objectives of the study are as follows:

1) **To investigate the formation and propagation of diagonal cracks** in high-strength concrete deep beams under two-point loading conditions.
2) **To analyze the effect of various types and proportions of fibres** on the shear behavior, crack width, and crack pattern in deep beams.
3) **To compare the structural performance** (in terms of load-bearing capacity, energy absorption, and ductility) of HSFRC deep beams with that of conventional high-strength concrete beams.
4) **To monitor strain distribution and cracking behavior** using appropriate experimental techniques such as digital image correlation and mechanical strain gauges.
5) **To evaluate the post-cracking behavior and failure modes** of deep beams with and without fibre reinforcement.

6) **To derive conclusions and recommendations** for the potential use of HSFRC in deep beam applications and to suggest improvements in design practices.

By fulfilling these objectives, the study aims to contribute meaningful insights for researchers and structural engineers toward developing more efficient and resilient deep beam designs using fibre-reinforced high-strength concrete.

2. LITERATURE REVIEW

The structural behavior of deep beams has been a topic of significant interest due to their non-conventional load transfer mechanism and susceptibility to shear failure. Conventional deep beams often fail due to diagonal cracking under high shear forces, and their response cannot be accurately predicted using classical beam theory (Strut-and-Tie Model and Plane Section Assumption). As a result, researchers have emphasized the need to explore alternative approaches to enhance the shear resistance and post-cracking performance of such members.

High-strength concrete (HSC) offers excellent compressive strength and durability but exhibits brittle failure characteristics, especially under tension and shear. According to Kong and Sharp (1973), HSC deep beams show sudden shear failure due to insufficient energy dissipation, and the diagonal cracks develop more rapidly compared to normal strength concrete. In response to this, various studies have investigated the role of fibre reinforcement as a means to improve the tensile and shear performance of concrete.

Fibre-Reinforced Concrete (FRC) introduces randomly distributed fibres within the concrete matrix, which help in arresting micro-cracks, delaying crack propagation, and improving post-crack ductility. Steel fibres have been extensively studied for their effectiveness in enhancing shear strength. RILEM TC 162-TDF (2003) reported that the addition of steel fibres increases the shear capacity and toughness of deep beams by bridging diagonal cracks and redistributing stresses. Similarly, Khaloo and Afshari (2005) observed that fibre volume fraction significantly affects the diagonal crack width and energy absorption.

Experimental investigations by Ashour (2000) demonstrated that steel fibre-reinforced deep beams exhibited improved load-bearing capacity and exhibited multiple fine cracks instead of a few wide cracks. Paramasivam and Loo (1997) studied the behavior of deep beams reinforced with synthetic and glass fibres and found that while steel fibres were more effective in increasing peak load capacity, synthetic fibres enhanced ductility and crack control.

Recent studies have also incorporated advanced techniques such as Digital Image Correlation (DIC) and strain gauge instrumentation to monitor crack development and strain distribution in real time. These methods offer deeper insights into the failure mechanisms and the interaction between fibres and the concrete matrix.

Despite these advancements, a knowledge gap exists in understanding the combined effect of high-strength concrete and various fibre types on the diagonal cracking behavior of deep beams. Most existing design codes do not fully account for the benefits of fibre reinforcement in deep beam design. Therefore, further experimental and analytical studies are needed to validate the use of HSFRC in structural applications and to develop reliable design recommendations.

This study aims to address these gaps by conducting a detailed experimental investigation on high-strength fibre-reinforced concrete deep beams subjected to two-point loading, with a focus on diagonal crack formation, load-deflection response, and post-cracking behavior.

3. EXPERIMENTAL PROGRAM OVERVIEW

The experimental investigation comprised three distinct series of test specimens, each characterized by a constant shear span-to-depth ratio (a/d). A typical series included 24 simply supported deep beams, with fibre reinforcement percentages ranging from 0.0% to 3.5%. All deep beams were symmetrical two-span members, centered about their mid-point to ensure uniformity in loading and behavior.

To systematically classify the specimens, a notation scheme was adopted. For instance:

- B1/FST-0.00 to B1/FST-3.50 indicates beams reinforced with Flat Steel Fibres,
- B1/CSF-0.00 to B1/CSF-3.50 represents beams with Crimped Steel Fibres, and
- B1/HEST-0.00 to B1/HEST-3.50 denotes beams incorporating Hooked-End Steel Fibres.

Additionally, the suffix “/1.0” specifies that the beam has an a/d ratio of 1.0, representing a deep beam configuration. All beam specimens were cast using High-Strength Fibre Reinforced Concrete (HSFRC) as well as plain high-strength concrete for control comparisons. Identical formwork was utilized across all specimens to maintain consistency. Each beam was cast with a thickness of 169 mm.

The fibres' physical and mechanical properties are detailed in Table 1. All dimensional and load measurements were recorded using the SI system of units.

The concrete mix used in this study comprised Ordinary Portland Cement (OPC) of grade 55, natural river sand (maximum size: 4.75 mm), and locally sourced coarse aggregates (maximum size: 12.5 mm). The mix achieved a slump value of approximately 100 mm, ensuring proper workability. All specimens were cast in a horizontal position and tested at 7 and 28 days after casting.

From classical elastic theory applied to slender, two-span beams, the peak negative moment is theoretically 1.2 times the peak positive moment. However, the deep beam behavior observed in this study differs due to size effects and shear dominance. The first cracking load, diagonal crack initiation load, and ultimate failure load for all test specimens are summarized in Table 2.

4. LOADING PROCEDURE AND MEASUREMENT

The loading of the test specimens was performed manually using human effort. To ensure consistency across all tests, the centerlines of applied loads and support reactions were maintained identically for each beam. The central span was left unobstructed to allow for free vertical deflection, while high-capacity rollers were used at the support ends to facilitate smooth reaction movement.

The load was applied in approximately fifteen incremental steps until the beam reached failure. At each load stage, the load was held constant to allow for careful observation and documentation. During these intervals, crack formation was monitored, marked on the specimen surface, and photographed, while load and deflection readings were simultaneously recorded using dedicated software.

The shear forces reported in the results are derived from adjusted loads and support reactions, ensuring accuracy. However, no manual corrections were made to the data obtained from the software. The recorded values directly from the software were found to reliably represent the actual shear forces corresponding to crack initiation and propagation up to failure.

Additionally, special attention was given to monitoring and controlling the relative vertical deflection at beam supports, ensuring that these did not influence the measurement accuracy or alter the load path during testing.

5. TEST RESULTS

The shear forces corresponding to the formation of diagonal cracks and ultimate failure in each shear span are presented in Table 2. Diagonal cracking within the interior spans occurred suddenly, often accompanied by an audible thud, indicating a brittle fracture mechanism. In contrast, exterior shear spans exhibited a more gradual crack development process.

Two primary failure modes were identified during testing. Beams constructed without fibres or with low to moderate fibre content predominantly exhibited arching or tie-action behavior at failure. This behavior was consistent across all such specimens, regardless of fibre volume. These beams typically experienced sudden failure, with minimal signs of plastic deformation or energy dissipation before collapse.

In contrast, beams reinforced with the maximum fibre content demonstrated a partially ductile failure mode. These specimens displayed enhanced crack-bridging and energy absorption capabilities, which allowed for more gradual crack progression and delayed ultimate failure. This ductile response was clearly noticeable during the final stages of loading and indicates a positive influence of fibre reinforcement on the post-cracking behavior of deep beams.

Table 1 Properties of Steel Fibres

Sr. No.	Type of Steel Fibre	Length (mm)	Diameter (mm)	Aspect Ratio (L/D)	Tensile Strength (MPa)
1	Flat Steel Fibre (FST)	50	1.0	50	1000

2	Crimped Steel Fibre (CSF)	30	0.6	50	1100
3	Hooked-End Steel Fibre (HEST)	35	0.7	50	1200

Table 2 Diagonal Cracking Shear

Diagonal Cracking loads						Ultimate loads				
Sr No	**Name of Beam**	**Measured *f'c1* KN**	**ACI Building Code *fc1/fc2***	**deCossio & Stress *fc1/fc3***	**Rama'n Anath'a *fc1/fc4***	**Measured *fc1* KN**	**ACI Building Code *f'c1/f'c2***	**British Draft Code *f"c1/f'c5***	**De paiva-Siess *f'c1/f'c6***	**Rama'n-Ananth'a *f'c1/f'c6***
Crimped Steel Fibre										
1	B1/CST-0.00	280	1.06	**1.15**	0.54	319	2.62	**3.28**	1.50	1.62
2	B1/CST-0.50	286	1.16	**1.26**	0.58	326	2.72	**3.38**	1.60	1.72
3	B1/CST-1.00	291	1.31	**1.42**	0.65	231	2.87	**3.53**	1.75	1.87
4	B1/CST-1.50	303	1.40	**1.52**	0.70	340	2.96	**3.62**	1.84	1.96
5	B1/CST-2.00	329	1.46	**1.59**	0.73	369	3.02	**3.68**	1.90	2.02
6	B1/CST-2.50	311	1.39	**1.55**	0.69	341	2.95	**3.61**	1.83	1.95
7	B1/CST-3.00	298	1.28	**1.45**	0.64	337	2.84	**3.50**	1.72	1.84
8	B1/CST-3.50	240	1.09	**1.27**	0.54	281	2.65	**3.31**	1.53	1.65
Hooked End Steel Fibre										
1	B1/HEST-0.00	280	1.11	**1.20**	0.55	319	2.67	**3.33**	1.55	1.67
2	B1/HEST-0.50	293	1.17	**1.27**	0.58	332	2.73	**3.39**	1.61	1.73
3	B1/HEST-1.00	306	1.32	**1.42**	0.66	345	2.88	**3.54**	1.76	1.88
4	B1/HEST-1.50	317	1.41	**1.52**	0.70	356	2.97	**3.63**	1.85	1.97
5	B1/HEST-2.00	328	1.47	**1.61**	0.73	370	3.03	**3.69**	1.91	2.03
6	B1/HEST-2.50	310	1.35	**1.50**	0.67	349	2.91	**3.57**	1.79	1.91
7	B1/HEST-3.00	291	1.23	**1.39**	0.61	331	2.79	**3.45**	1.67	1.79
8	B1/HEST-3.50	245	1.06	**1.23**	0.53	286	2.62	**3.28**	1.50	1.62
Flat Steel Fibre										
1	B1/FST-0.00	280	1.11	**1.20**	0.55	319	2.67	**3.33**	1.55	1.67
2	B1/FST-0.50	293	1.19	**1.29**	0.59	332	2.75	**3.41**	1.63	1.75
3	B1/FST-1.00	306	1.34	**1.46**	0.67	345	2.90	**3.56**	1.78	1.90
4	B1/FST-1.50	317	1.43	**1.56**	0.71	356	2.99	**3.56**	1.87	1.99
5	B1/FST-2.00	328	1.48	**1.62**	0.74	370	3.04	**3.70**	1.92	2.04
6	B1/FST-2.50	310	1.35	**1.49**	0.67	349	2.91	**3.57**	1.79	1.91
7	B1/FST-3.00	291	1.18	**1.34**	059	331	2.74	**3.40**	1.62	1.74

8	B1/FST-3.50	245	1.03	**1.20**	051	286	2.59	**3.25**	1.47	1.59

Given the impracticality of detailing the behavior of all 24 tested deep beams, this section highlights the performance of three representative specimens: Beam B1/CSF-2.00, Beam B1/HEST-2.00, and Beam B1/FST-2.00. These beams were selected as typical examples of single-span deep beams tested up to their ultimate failure load.

Beam B1/CSF-2.00 exhibited behavior closely aligned with that of B1/HEST-2.00 and B1/FST-2.00, allowing for a meaningful comparison among different fibre types at the same fibre content level (2.00%). During the loading process, it was observed that fibres located within the diagonal cracking zones experienced rupture or were pulled out, primarily due to tensile stresses. Failure occurred along a single diagonal plane, indicating a brittle fracture pattern, characterized by the crushing of concrete matrix and disintegration of coarse aggregates along the crack path.

These results reflect the critical role of fibre orientation and distribution in resisting diagonal tension and delaying crack propagation in high-strength deep beams.

6. CONCLUSION

This experimental investigation focused on evaluating the structural behavior of high-strength fibre-reinforced concrete (HSFRC) deep beams, with particular attention to the formation and progression of diagonal cracks. Based on the results obtained from 24 deep beam specimens with varying types and percentages of steel fibres, the following conclusions can be drawn:

- Fibre inclusion significantly enhances shear resistance in deep beams by bridging diagonal cracks and increasing energy absorption capacity. Beams containing higher fibre volumes exhibited improved crack control, delayed crack initiation, and increased load-carrying capacity.
- Beams without fibres or with low fibre content primarily failed in a brittle manner through diagonal tension failure with minimal plastic deformation, regardless of fibre type. These beams followed tie-arch action at failure.
- In contrast, beams with optimum fibre content (2.0% and above) demonstrated a partially ductile failure mode, with more distributed and finer cracks, better post-cracking behavior, and greater toughness. Among all fibre types, hooked-end steel fibres provided the most effective crack-bridging and energy dissipation.
- The first crack load and ultimate failure load increased with fibre content, indicating improved structural performance under shear-dominant loading.
- The performance of all fibre-reinforced beams confirmed that fibre type, orientation, and dosage play a vital role in controlling diagonal cracking and enhancing structural integrity.

Overall, the findings support the use of fibre-reinforced high-strength concrete in deep beam applications, offering enhanced durability, safety, and ductility. The study provides valuable insights for future design provisions and code development for deep beams using HSFRC.

CONFLICT OF INTERESTS

None.

ACKNOWLEDGMENTS

None.

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