Experimental Investigation of Crack Propagation, Ductility, and Failure Mechanisms of Ultra-High-Performance Fiber Reinforced Concrete Girders

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How to Cite this Article:

Bhardwaj, M. (2026). Experimental Investigation of Crack Propagation, Ductility, and Failure Mechanisms of Ultra-High-Performance Fiber Reinforced Concrete Girders. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(6). https://doi.org/10.55041/ijcope.v2i6.329

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Abstract: Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC) has emerged as an advanced construction material offering superior strength, durability, and crack resistance compared with conventional concrete. This study experimentally investigates the influence of steel fiber volume fraction on crack propagation, ductility, load-carrying capacity, and failure mechanisms of reinforced UHPFRC girders subjected to four-point bending. Four girder specimens containing different steel fiber contents were tested under identical loading conditions. Experimental observations included crack initiation, crack density, load–deflection response, strain development, energy absorption capacity, and ultimate failure behavior. Results indicated that increasing fiber dosage significantly delayed crack initiation, reduced crack widths, enhanced multiple-cracking behavior, and improved post-cracking load resistance. The girder containing 2.0% steel fibers exhibited the highest ductility index and energy absorption capacity while maintaining favorable workability. Failure mode gradually shifted from brittle flexural cracking in low-fiber specimens to ductile fiber pull-out and concrete crushing in high-fiber specimens. The findings demonstrate that steel fibers play a critical role in improving structural performance and durability of UHPFRC girders, making them suitable for bridge and infrastructure applications.

Keywords: UHPFRC, crack propagation, ductility, steel fibers, bridge girders, failure mechanisms.

1. Introduction

The construction industry is continuously seeking advanced materials capable of meeting the growing demands for strength, durability, sustainability, and long-term structural performance. Conventional reinforced concrete has been extensively used in bridges, buildings, and transportation infrastructure because of its versatility and cost-effectiveness. However, its inherent limitations, including low tensile strength, brittle failure behavior, and susceptibility to cracking, often lead to premature deterioration and increased maintenance requirements. Cracks formed under service and ultimate loading conditions facilitate the ingress of water, chlorides, sulfates, and other aggressive agents, accelerating reinforcement corrosion and reducing the service life of structures (Neville, 2011; Mehta & Monteiro, 2014). Consequently, significant research efforts have focused on developing high-performance cementitious materials capable of overcoming these deficiencies.

Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC) has emerged as one of the most promising innovations in concrete technology. UHPFRC is characterized by an optimized particle packing system, very low water-to-binder ratio, incorporation of supplementary cementitious materials such as silica fume, and the addition of high-strength steel fibers. These features result in a highly dense and homogeneous microstructure with compressive strengths typically exceeding 120 MPa, enhanced tensile resistance, exceptional durability, and superior crack-control capabilities (Richard & Cheyrezy, 1995; Graybeal, 2006). Unlike conventional concrete, which often exhibits sudden brittle failure after crack formation, UHPFRC demonstrates strain-hardening behavior and multiple microcracking due to the crack-bridging action of steel fibers. This unique behavior significantly improves structural safety, energy absorption capacity, and post-cracking performance (Naaman & Wille, 2012).

Among the various structural applications of UHPFRC, bridge girders represent one of the most critical elements because they serve as primary load-carrying members subjected to significant flexural stresses. The structural performance of girders is strongly influenced by crack initiation, crack propagation, ductility development, and ultimate failure mechanisms. Steel fibers play a vital role in controlling crack growth, enhancing stress redistribution, and improving post-cracking load resistance. Numerous studies have reported that steel fiber reinforcement can substantially reduce crack widths, increase ductility, and improve the overall structural behavior of UHPFRC members under flexural loading (Wille et al., 2011; Yoo & Banthia, 2016). However, despite considerable advancements in material characterization, the interaction between crack propagation, ductility, and failure mechanisms in full-scale UHPFRC girders remains insufficiently understood.

Previous investigations have primarily focused on compressive strength, tensile strength, and durability properties of UHPFRC, while comparatively limited attention has been given to crack development patterns, energy absorption characteristics, and failure progression at the structural member level. Furthermore, there is no clear consensus regarding the optimum steel fiber dosage required to maximize structural efficiency while maintaining adequate workability and uniform fiber distribution (Fehling et al., 2014). A comprehensive understanding of how steel fiber content influences crack propagation behavior, ductility performance, and ultimate failure mechanisms is therefore essential for developing reliable design methodologies and promoting the wider implementation of UHPFRC in bridge engineering.

In this context, the present study experimentally investigates the effect of varying steel fiber volume fractions on the structural performance of reinforced UHPFRC girders subjected to four-point bending. Particular emphasis is placed on evaluating crack initiation, crack propagation characteristics, load–deflection behavior, ductility development, energy absorption capacity, and failure mechanisms. The findings are expected to provide valuable insights into the behavior of UHPFRC girders and contribute to the development of safer, more durable, and more efficient infrastructure systems.

2. Materials and Methods

2.1 Materials

Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC) mixtures were prepared using Ordinary Portland Cement (OPC) Grade 53, silica fume, quartz sand, polycarboxylate ether (PCE)-based superplasticizer, potable water, and high-strength steel fibers. These materials were selected to achieve a dense microstructure, high compressive strength, superior tensile resistance, and enhanced durability. OPC Grade 53 served as the primary binder, providing the necessary hydration products and strength development required for high-performance concrete applications. Silica fume was incorporated as a supplementary cementitious material to improve particle packing density and promote pozzolanic reactions, resulting in a refined microstructure and reduced permeability (Richard & Cheyrezy, 1995). Quartz sand with a particle size ranging from 0.15 to 0.60 mm was used as the fine aggregate to ensure optimum packing density and homogeneity within the matrix.

A polycarboxylate ether-based superplasticizer was employed to maintain adequate workability at a very low water-to-binder ratio, which is essential for achieving the ultra-high-strength characteristics of UHPFRC

(Aïtcin, 2000). High-strength straight steel fibers with tensile strengths between 2000 and 3000 MPa were incorporated to enhance tensile performance, crack resistance, ductility, and post-cracking behavior through fiber-bridging mechanisms (Yoo & Banthia, 2016). The typical properties of the constituent materials used in the study are summarized in Table 1.

Table 1. Typical Properties of UHPFRC Constituents

Material	Property	Typical Value
OPC 53 Grade	Compressive Strength	53–65 MPa
Silica Fume	SiO_2 Content	90–98%
Quartz Sand	Particle Size	0.15–0.60 mm
Steel Fibers	Tensile Strength	2000–3000 MPa
Superplasticizer	Solid Content	30–40%
UHPFRC	Compressive Strength	120–200 MPa

As shown in Table 1, the selected materials provide the fundamental characteristics required for producing UHPFRC, including high strength, enhanced crack resistance, improved durability, and superior structural performance. The combination of silica fume, fine quartz sand, and steel fibers contributes to the development of a compact matrix capable of resisting crack propagation and sustaining significant post-cracking deformation.

2.2 Experimental Program

The experimental program was designed to investigate the influence of steel fiber volume fraction on the crack propagation behavior, ductility characteristics, and failure mechanisms of reinforced UHPFRC girders subjected to flexural loading. Four girder specimens were fabricated with steel fiber contents of 0%, 1%, 2%, and 3% by volume. All specimens were designed with identical geometric dimensions, reinforcement layouts, curing conditions, and testing procedures to ensure that the observed variations in structural behavior could be attributed solely to differences in fiber dosage.

The details of the experimental matrix are presented in Table 2. Specimen G-0 served as the control girder without fiber reinforcement, whereas specimens G-1, G-2, and G-3 contained progressively increasing steel fiber contents. The selected fiber dosages were based on previous studies that identified fiber volume fractions between 1% and 3% as effective for improving the mechanical and structural performance of UHPFRC members (Fehling et al., 2014; Wille et al., 2011).

Table 2. Experimental Matrix

Specimen	Fiber Content (%)	Span (mm)	Loading Type
G-0	0.0	2000	Four-point bending
G-1	1.0	2000	Four-point bending
G-2	2.0	2000	Four-point bending
G-3	3.0	2000	Four-point bending

All girders were tested under a four-point bending configuration, which provides a constant moment region between the loading points and enables detailed observation of crack initiation and propagation behavior. The experimental setup adopted in the present investigation is illustrated in Figure 1. The specimens were simply supported at both ends and subjected to monotonic loading through two symmetrically positioned concentrated loads. This loading arrangement ensured uniform bending stresses within the central region of the girder and facilitated the evaluation of flexural behavior and failure mechanisms.

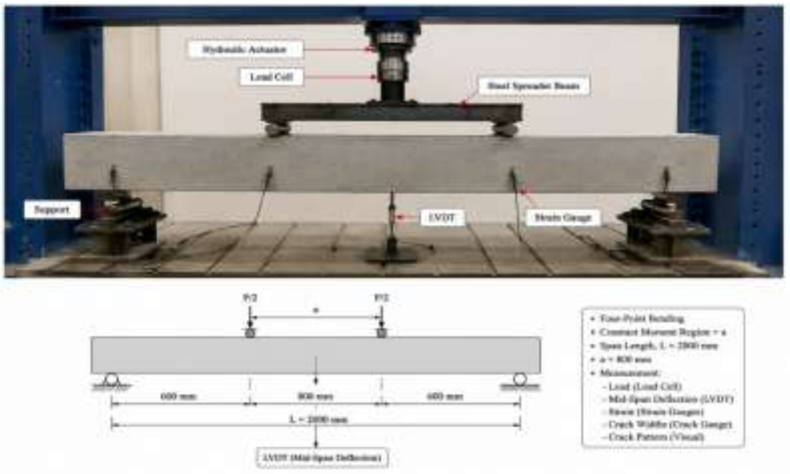

Figure 1. Experimental Setup for Four-Point Bending Test

During testing, load, mid-span deflection, strain, crack width, and crack propagation characteristics were continuously monitored using calibrated instrumentation. Load cells were used to record the applied load, while Linear Variable Differential Transformers (LVDTs) measured mid-span deflections. Electrical resistance strain gauges were installed at critical locations to evaluate strain development in both the concrete and reinforcement. Crack initiation, crack density, crack spacing, and crack width evolution were visually monitored and recorded throughout the loading process. The collected data were subsequently used to evaluate load-carrying capacity, ductility performance, energy absorption characteristics, crack propagation mechanisms, and ultimate failure modes of the tested UHPFRC girders, thereby providing a comprehensive assessment of the structural influence of steel fiber reinforcement.

3. Results and Discussion

3.1 Load-Carrying Capacity

The load-carrying capacity of the UHPFRC girders was significantly influenced by the incorporation of steel fibers. The experimental results presented in Table 3 indicate a progressive increase in both first-crack load and ultimate load with increasing fiber content. The control specimen (G-0), without steel fibers, exhibited a first-crack load of 52 kN and an ultimate load of 118 kN. In contrast, the fiber-reinforced specimens demonstrated considerably higher resistance to crack initiation and ultimate failure. The specimen containing 2.0% steel fibers (G-2) achieved a first-crack load of 84 kN and an ultimate load of 168 kN, representing increases of approximately 61.5% and 42.4%, respectively, compared with the control girder. Similarly, specimen G-3 exhibited the highest ultimate load of 172 kN; however, the improvement beyond 2% fiber dosage was relatively marginal.

The enhancement in load-carrying capacity can be attributed to the crack-bridging action of steel fibers, which delayed crack formation and facilitated stress transfer across cracked sections. As loading progressed, the fibers continued to resist crack widening and contributed to post-cracking strength retention, thereby improving structural performance. Similar observations have been reported by Wille et al. (2011) and Yoo and Banthia (2016), who concluded that steel fibers substantially enhance flexural strength and post-cracking resistance through effective stress redistribution mechanisms.

Table 3. Structural Performance of Tested Girders

Specimen	First Crack Load (kN)	Ultimate Load (kN)	Max Deflection (mm)
G-0	52	118	10.4
G-1	68	142	15.6
G-2	84	168	21.8
G-3	88	172	22.5

The maximum mid-span deflection also increased significantly with fiber dosage, indicating improved deformation capacity and ductility. The G-2 and G-3 specimens exhibited approximately twice the deflection capacity of the control specimen, demonstrating the ability of steel fibers to sustain large deformations prior to failure.

3.2 Crack Propagation Behavior

Crack propagation patterns varied considerably among the tested specimens and were strongly dependent on steel fiber content. The control specimen exhibited rapid crack localization characterized by the formation of a few dominant flexural cracks that widened quickly with increasing load. Once the tensile capacity of the concrete matrix was exceeded, crack propagation occurred abruptly, leading to stiffness degradation and eventual brittle failure.

In contrast, the steel fiber-reinforced girders displayed significantly different crack development behavior. As illustrated in Figure 2, specimens containing steel fibers developed numerous fine cracks distributed throughout the constant moment region rather than a few dominant cracks. This multiple-cracking phenomenon resulted from the crack-bridging mechanism of steel fibers, which transferred tensile stresses across crack surfaces and prevented immediate crack localization. Consequently, crack spacing decreased while crack density increased, producing a more uniform stress distribution throughout the girder.

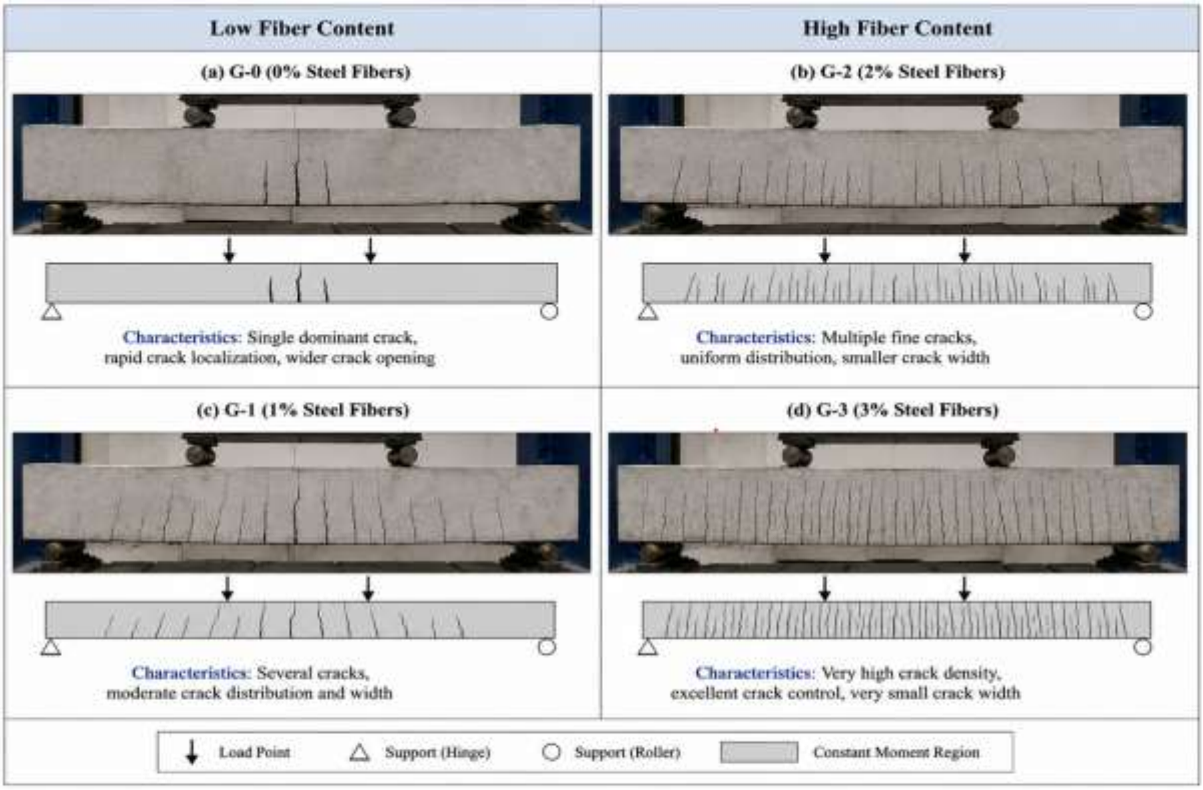

Figure 2. Typical Crack Development Pattern

The effectiveness of crack control improved progressively with increasing fiber content. The G-2 and G-3 specimens exhibited the highest crack densities and the smallest crack widths throughout the loading process. These findings are consistent with previous studies reporting that steel fibers delay crack propagation, reduce crack widths, and improve structural durability by limiting the ingress of moisture and aggressive agents (Naaman & Wille, 2012; Kang et al., 2017). The distributed cracking pattern observed in fiber-reinforced girders also contributed to enhanced energy dissipation and ductile structural behavior.

3.3 Ductility and Energy Absorption

The ductility characteristics of the tested girders were evaluated using the ductility index and energy absorption capacity. The results summarized in Table 4 clearly demonstrate the beneficial influence of steel fibers on deformation capacity and toughness. The control specimen exhibited a ductility index of only 2.1, indicating limited post-yield deformation capability. However, the ductility index increased progressively with fiber content, reaching 4.2 and 4.3 for specimens G-2 and G-3, respectively.

The enhanced ductility can be attributed to the ability of steel fibers to bridge cracks and maintain load transfer after matrix cracking. Instead of experiencing sudden failure, fiber-reinforced girders underwent gradual stiffness degradation accompanied by distributed cracking and fiber pull-out. This behavior enabled the specimens to sustain significant deformation before ultimate collapse. Similar trends have been reported by Fehling et al. (2014), who observed substantial improvements in deformation capacity and post-cracking toughness with increasing fiber volume fractions.

Table 4. Ductility and Energy Absorption Performance

Specimen	Ductility Index	Energy Absorption (kN-mm)	Failure Mode
G-0	2.1	820	Brittle flexural
G-1	3.0	1260	Flexural
G-2	4.2	1890	Ductile flexural
G-3	4.3	1925	Fiber pull-out + crushing

The energy absorption capacity increased substantially from 820 kN-mm for G-0 to 1890 kN-mm and 1925 kN-mm for G-2 and G-3, respectively. This improvement is primarily associated with fiber debonding and pull-out mechanisms, which consume considerable energy during crack propagation. Although G-3 exhibited the highest energy absorption, the difference compared with G-2 was relatively small, indicating that a fiber content of approximately 2% provides an optimal balance between structural performance and practical workability considerations.

3.4 Failure Mechanisms

The failure mechanisms observed during testing evolved significantly with increasing steel fiber content. The control specimen failed through a brittle flexural mechanism characterized by rapid crack widening, loss of stiffness, and sudden collapse after the formation of a dominant crack. The absence of fibers limited stress redistribution and prevented the development of substantial post-cracking resistance.

Fiber-reinforced girders exhibited considerably more ductile failure behavior. Initially, multiple flexural cracks formed within the constant moment region and gradually propagated upward with increasing load. The steel fibers effectively bridged the crack surfaces, delaying crack coalescence and preventing premature localization. As loading continued, fiber debonding and pull-out mechanisms became increasingly dominant, allowing the girders to maintain load-carrying capacity despite extensive cracking. Ultimate failure occurred through a combination of concrete crushing in the compression zone and progressive fiber pull-out in the tension zone.

The transition from brittle flexural failure in G-0 to ductile flexural and fiber pull-out failure in G-2 and G-3 demonstrates the significant role of steel fibers in enhancing structural safety and damage tolerance. The gradual failure progression provided visible warning signs before collapse, thereby increasing reliability and reducing the risk of catastrophic structural failure. These findings corroborate previous investigations by Graybeal (2006) and Yoo and Banthia (2016), which reported that steel fiber reinforcement transforms the failure behavior of UHPFRC members from brittle to highly ductile.

4. Conclusions

This study investigated the influence of steel fiber volume fraction on the structural behavior of reinforced Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC) girders subjected to flexural loading. The results demonstrated that the incorporation of steel fibers significantly improved the load-carrying capacity, crack resistance, ductility, and overall structural performance of the girders. Increasing fiber content delayed crack initiation, enhanced post-cracking behavior, and enabled more efficient stress redistribution throughout the structural member. The fiber-bridging action effectively controlled crack growth and prevented rapid crack localization, resulting in improved serviceability and durability.

The crack propagation analysis revealed that steel fiber reinforcement transformed the cracking behavior from a few dominant cracks to a distributed multiple-cracking pattern. This mechanism reduced crack widths, increased crack density, and improved structural integrity under increasing load levels. The enhanced crack control characteristics are particularly beneficial for bridge girders and other infrastructure components exposed to severe loading and environmental conditions.

Steel fibers also contributed substantially to ductility enhancement and energy absorption capacity. Fiber-reinforced girders exhibited greater deformation capacity and maintained load resistance even after matrix cracking. The energy dissipation associated with fiber debonding and pull-out mechanisms significantly increased toughness and delayed ultimate failure. Consequently, the structural response became more gradual and predictable, providing increased warning prior to collapse and improving overall safety.

Failure mode observations indicated a clear transition from brittle flexural failure in the control specimen to ductile behavior in fiber-reinforced girders. The presence of steel fibers delayed crack coalescence, promoted progressive damage development, and reduced the likelihood of sudden catastrophic failure. Among the investigated fiber dosages, a steel fiber content of approximately 2.0% provided the most favorable balance between strength enhancement, crack control, ductility, energy absorption, and practical workability. Overall, the findings confirm the significant potential of UHPFRC with steel fiber reinforcement for advanced bridge and infrastructure applications requiring superior durability, resilience, and structural reliability.

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