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TENSILE FATIGUE ENDURANCE IN UHPC REINFORCED WITH STEEL AND CARBON FIBERS USING ADVANCED MONITORING TECHNIQUES

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Abstract. This study examines the tensile fatigue behavior of Ultra-High Performance Concrete (UHPC) reinforced with steel and carbon fibers under cyclic loading. Three specimen types —unreinforced matrix (BM), steel fiber-reinforced (SF), and carbon fiber-reinforced (CF)— were tested using indirect tensile static and fatigue methods with a modified Brazilian test setup. A hinge-based T-shaped loading mechanism ensured stable crack propagation, while strain monitoring combined localized strain gauges with full-field digital image correlation (DIC) for detailed crack behavior analysis. Results indicate tensile strength enhancements of 40% for CF and nearly 3 times for SF over BM. Crack initiation stresses were 7.5 MPa (BM), 6.8 MPa (CF), and 8.6 MPa (SF), with SF specimens demonstrating superior fatigue resistance, sustaining one order of magnitude more cycles than BM. Conversely, CF specimens showed reduced fatigue life due to fiber brittleness and matrix porosity. These findings highlight the influence of fiber type on the fatigue durability and mechanical performance of UHPC under cyclic loading.

1 INTRODUCTION

Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) has emerged as a transformative construction material, celebrated for its exceptional strength, durability, and resilience. These remarkable properties are attributed to its densely packed matrix, achieved through advanced material design and processing techniques. However, this very density also increases brittleness, necessitating strategies to enhance ductility and energy absorption capacity, particularly for demanding structural applications like bridges, pavements, and high-rise buildings [1,2].

Fiber reinforcement is one such strategy, offering a significant improvement in UHPFRC's tensile performance. Steel fibers (SF) are widely used to enhance tensile strength, toughness, and cracking resistance [3], while carbon fibers (CF), known for their lightweight and high tensile strength, present a promising alternative. Despite these advantages, the long-term performance of UHPFRC under cyclic loading, particularly fatigue behavior, remains critical for ensuring structural reliability and safety [4]. Fatigue behavior, characterized by the material's response to repeated loading cycles, depends on various factors, including fiber type, content, orientation, and environmental conditions [5].

Advanced monitoring techniques, such as Digital Image Correlation (DIC) and X-ray Computed Tomography (CT), have revolutionized the analysis of UHPFRC's microstructural and mechanical behavior. DIC enables full-field surface strain measurement, providing valuable insights into crack initiation and propagation mechanisms [6]. Similarly, X-ray CT facilitates the non-destructive examination of internal structures, including pore networks and fiber distribution, enhancing the understanding of fatigue damage evolution [1,7].

This study aims to investigate the tensile fatigue endurance of UHPFRC reinforced with steel and carbon fibers using DIC monitoring technique. By unraveling the interplay between microstructure, fiber reinforcement, and fatigue damage evolution, this research contributes to the development of more durable and reliable UHPFRC materials for critical infrastructure applications, ensuring long-term structural integrity and safety.

2 SPECIMEN PREPARATION AND EXPERIMENTAL SETUP

2.1 Material

Material proportions are arrayed in Table 1.

Table 1: Material Proportions

Material	Quantity [kg/m^3]
Cement 52.5	540
Silica Fume	210
Slag without limestone	310
Fine Sand	470
Coarse Sand	470
Water	130.69 L
SP Sika 20 HE	44

Ultra-High-Performance Concrete (UHPC) specimens were prepared with a water-to-binder ratio of 0.2, ensuring a densely packed matrix. Three types of specimens were included in this study: the plain base matrix (BM) without any fiber reinforcement, UHPC reinforced with 20 kg/m^3 of 13-mm long steel fibers (SF), and UHPC reinforced with 1.5 kg/m^3 of carbon fibers comprising 80% 3-mm fibers and 20% 0.1-mm fibers (CF). All specimens were cast into 40-mm cubic molds and subjected to a controlled curing process under regulated humidity and temperature conditions for 28 days to achieve consistent hydration and optimal mechanical properties.

2.2 Experimental Setup

A modified Brazilian test was employed to evaluate both static and fatigue performance. The setup utilized a T-shaped loading mechanism with a hinge mounted over it to ensure precise load alignment and minimize eccentric loading (see Figure 1 for details).Tests were conducted using a servohydraulic machine under displacement control to maintain accurate and consistent testing conditions.

2.2.1 Testing Protocol

Static Testing: Static tensile strength was measured by applying a monotonic load until failure. The peak load was recorded and used to determine the tensile strength of the specimens. The load-displacement and stress-strain curves highlighting key load stages during static loading are depicted in Figure 3a.

Fatigue Testing: Fatigue tests were performed at a frequency of 2 Hz, with the peak load set at 85% and the minimum load at 10% of the mean peak load obtained from the static tests. Testing continued until the specimen failed or reached a predefined maximum of 150,000 cycles.

The testing specimens used in this experimental program were cubic with dimensions of 40 mm. Compressive loads were applied at two points using a T-shaped loading device with a hinge mounted on top, specifically designed to minimize load eccentricity. The tests were conducted using a 1 MN servohydraulic universal testing machine (Instron 8801).

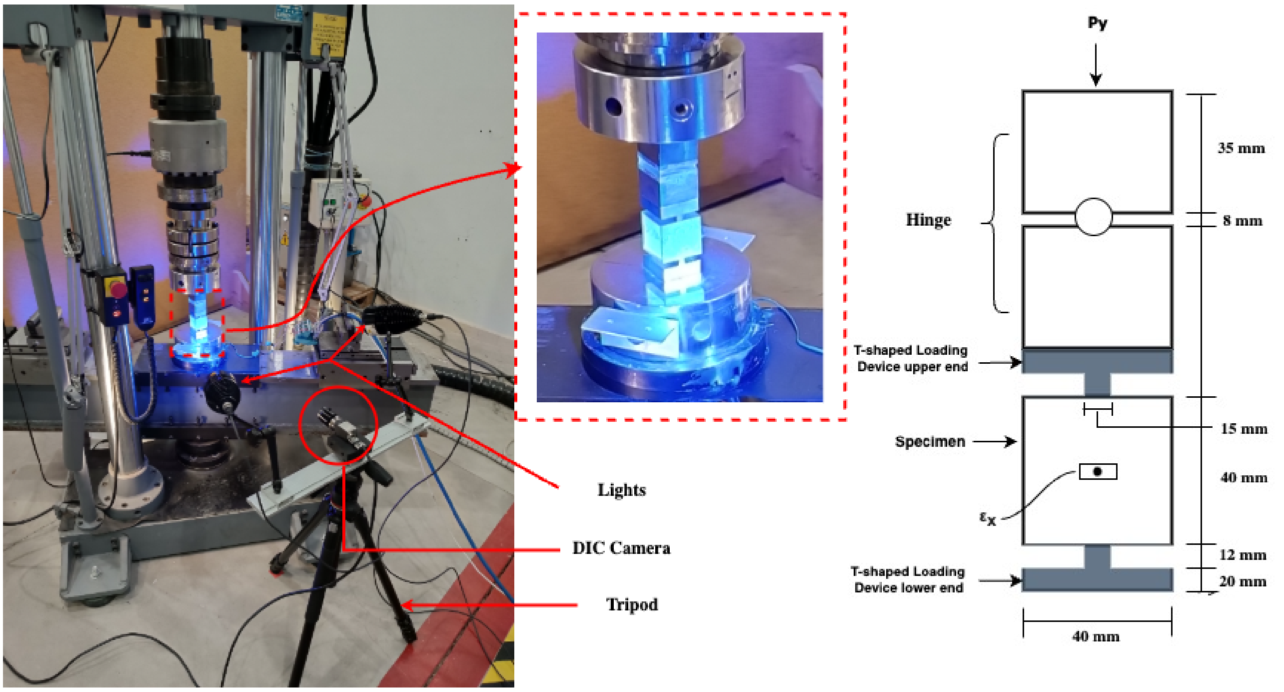

Figure 1: Experimental setup for cyclic loading of cubic specimens using the Modified Brazilian Test and DIC analysis.

2.2.2 Image Acquisition by Digital Image Correlation (DIC)

The 2D Digital Image Correlation (DIC) technique was employed to monitor surface deformations and crack propagation during the tests. A high-resolution speckle pattern of 19×16 pixels was applied to the specimen surface to enable accurate image tracking. A random black-on-white speckle pattern was applied to the specimen surface to enable precise image tracking. The specimens were positioned perpendicular to the camera's axis, with the optical module calibrated for accurate in-plane deformation capture. Camera settings, including focal length, distance, and field of view, were optimized to align with the area of interest, while proper lighting ensured clear image quality. Images were processed using GOM software to compute full-field strain and displacement. The DIC system captured sequential images, and regions of interest were tracked across these images to analyze crack initiation and growth. Post-processing provided visual outputs such as strain maps and displacement vectors, offering valuable insights into the material's response to loading.

3 RESULTS AND DISCUSSION

The static tensile performance of UHPC was evaluated using six specimens for each type: BM (plain matrix), CF (carbon fiber-reinforced), and SF (steel fiber-reinforced). The BM specimens demonstrated a tensile strength of 7.5 MPa. CF specimens increased the strength to 10.2 MPa, a 40% improvement over BM, but with a lower crack initiation stress of 6.8 MPa due to porosity introduced by the carbon fibers. SF specimens outperformed both, with a tensile strength of 19.7 MPa and a crack initiation stress of 8.6 MPa, nearly tripling the base matrix strength and showcasing the superior crack resistance provided by steel fibers.

Under cyclic loading at a frequency of 2 Hz, 12 specimens of each type were tested. BM specimens exhibited a logarithmic mean fatigue life of 3.5, while CF specimens showed a reduced fatigue life of 2.5, likely due to the brittle nature of carbon fibers and porosity introduced in the matrix. SF specimens demonstrated exceptional performance, achieving a mean fa-

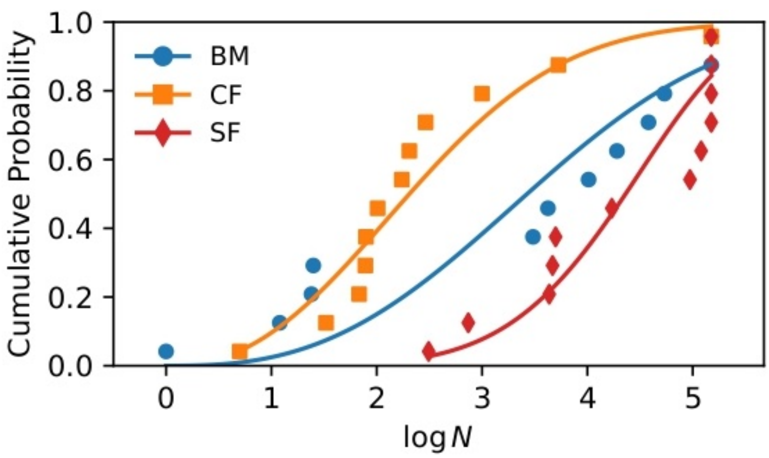

Figure 2: Failure probability distribution of experimental results and fitted Weibull function for each specimen category.

tigue life of 4.5, resisting one order of magnitude more cycles than BM. The failure probability distribution of experimental results is shown in Figure 2.This highlights the benefits of steel fibers in improving fatigue resistance.

Crack Propagation and Monitoring: Strain gauges and Digital Image Correlation (DIC) were employed to monitor crack behavior during fatigue testing. Strain gauges provided localized data, while DIC enabled full-field visualization of crack initiation and growth. CF specimens exhibited rapid crack propagation consistent with their lower fatigue life, whereas SF specimens displayed controlled crack growth, contributing to their superior performance. The load-displacement curves and corresponding DIC strain fields (DIC-1 to DIC-4) illustrating strain localization and crack propagation at key load stages are presented in Figure 3. Displacement maps generated from DIC provided detailed insights into the microcrack development during cyclic loading.

4 CONCLUSIONS

This study demonstrated the significant impact of fiber type on the tensile and fatigue performance of UHPC. Steel fibers enhanced tensile strength and fatigue resistance, tripling the base matrix's strength and resisting one order of magnitude more cycles under cyclic loading, making them ideal for applications requiring high durability and crack resistance. Although carbon fibers improved tensile strength by 40%, their associated porosity negatively affected fatigue life. These findings underscore the importance of fiber selection in optimizing UHPC for structural applications, providing valuable guidance for the design of durable, high-performance materials under cyclic loading conditions.

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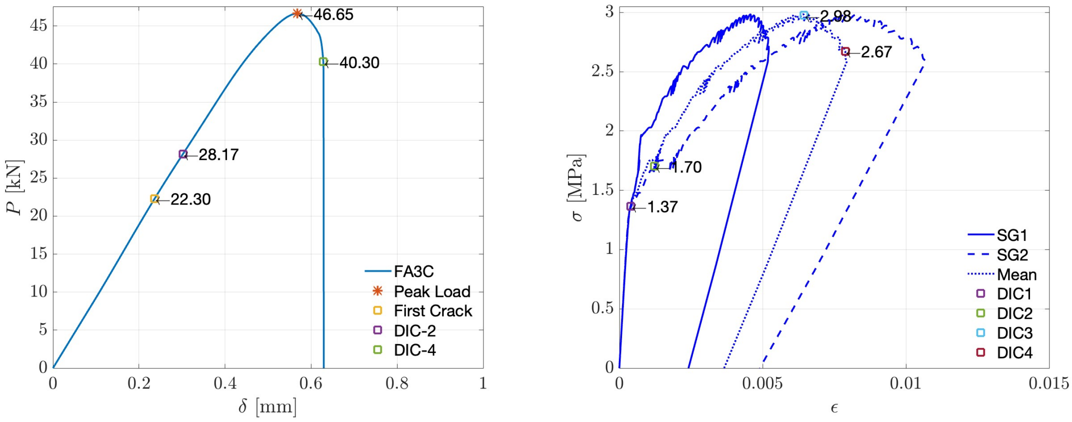
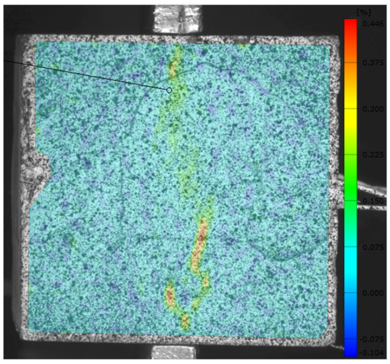
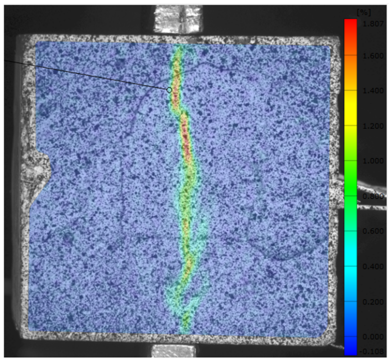


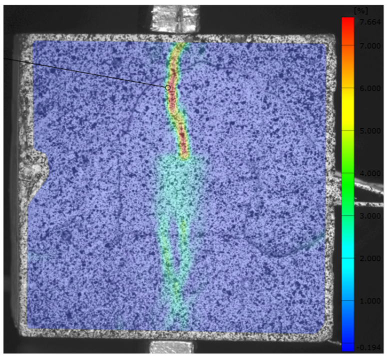
(a) Load-displacement and stress-strain curves for high-strength concrete under static loading, highlighting key load stages.



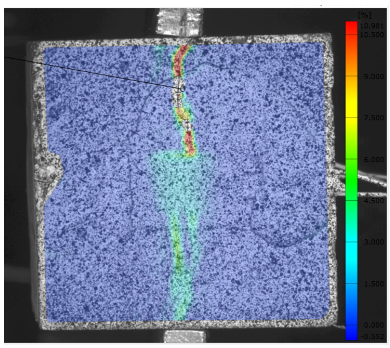
DIC-1



DIC-2



DIC-3/ Peak Load



DIC-4

(b) DIC strain field images (DIC-1 to DIC-4) corresponding to specific load stages, showing strain localization and crack propagation

Figure 3: Load-displacement curves and corresponding DIC strain fields (DIC-1 to DIC-4) showing fracture behavior and strain localization at key load stages.

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