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EXPERIMENTAL INVESTIGATIONS ON HIGH PERFORMANCE FIBER REINFORCED CONCRETE UNDER VARIOUS LOADING

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ABSTRACT

This study experimentally evaluated the shear performance of reinforced concrete (RC) beams strengthened with U-shaped High-Performance Fibre-Reinforced Concrete (HPFRC) under static and fatigue loading. The key parameters were HPFRC jacket thickness and the shear span-to-depth (a/d) ratio of the beams. Under static loading, five beams were tested to assess ultimate shear strength, followed by fatigue testing on identical beams at 30–70% of their ultimate shear strengths at a frequency of 4 Hz. The results showed that HPFRC jacketing effectively enhanced the shear strength of RC beams by 95% to 130% without altering their failure mode. Instead, the strengthened beams displayed pseudo-ductile behavior. However, the shear enhancement decreased with a higher a/d ratio. In fatigue loading tests, all HPFRC systems significantly improved the fatigue life of the beams. Beams with an a/d ratio of 2.0 saw an increase in fatigue life from 75 cycles to a maximum of 951 cycles, while those with an a/d ratio of 3.5 showed an increase from 12,525 cycles to 48,786 cycles. Additionally, a predictive model was developed to estimate the fatigue life of HPFRC/UHPFRC shear-strengthened beams based on maximum fatigue load and ultimate shear strength under static loading conditions.

Keywords: reinforced concrete; beam; HPFRC; fibre-reinforced concrete; shear strengthening; retrofitting; fatigue

1. Introduction

In recent years, reinforced concrete (RC) structures have shown a decline in load-bearing capacity due to increased loading, environmental degradation, and more stringent design standards. This deterioration, coupled with the damage from seismic events, highlights the vulnerability of older structures. For instance, the 7.8 magnitude earthquake in Turkey and Syria in January 2023 led to over

50,000 deaths and 173,000 building collapses, underlining the urgent need for structural strengthening measures. Most RC buildings constructed before the 1970s suffer from deficiencies like insufficient transverse reinforcement, inadequate lap splices, and material degradation, which contribute to their increased vulnerability to shear failures and collapse during earthquakes [1].

Fatigue loading is another critical issue for existing structures, especially for bridges and coastal infrastructure, where repeated cyclic loading can lead to gradual degradation and eventual failure. Studies on masonry and brick arch bridges emphasize the importance of understanding fatigue performance to ensure structural integrity under these conditions. Repeated loading cycles exacerbate deformation and cracking in RC structures, leading to further exposure of embedded steel reinforcement to corrosive environments, which reduces load-bearing capacity and long-term durability. High-Performance Fibre-Reinforced Concrete (HPFRC) and Ultra-High-Performance Fibre-Reinforced Concrete (UHPFRC) are emerging materials for strengthening RC structures due to their dense matrix, low permeability, and high corrosion resistance. UHPFRC exhibits exceptional compressive strength, reaching over 120 MPa, and provides enhanced ductility and stiffness due to its high fibre content. These properties make HPFRC/UHPFRC suitable for strengthening RC beams via jacketing, addressing weaknesses in tensile strength and durability found in ordinary concrete.

Research on the shear and fatigue performance of UHPFRC-strengthened beams is still limited, particularly in the context of fatigue shear behavior. Previous studies have shown UHPFRC's effectiveness in enhancing shear capacity and fatigue life under static and cyclic loading. However, gaps remain in understanding the impact of different shear span ratios and HPFRC/UHPFRC jacket thicknesses on fatigue shear performance. Recent work by Murthy et al. and Wang et al. has shown promising results for fatigue life improvement in flexurally strengthened beams, but comprehensive data on shear behavior remains sparse [2].

This study addresses this research gap by experimentally investigating the shear performance of RC beams strengthened with HPFRC jackets under static and fatigue loading. It examines the effects of shear span ratios (2.0 and 3.5) and HPFRC jacket thicknesses (10 mm and 20 mm) on shear behavior, contributing essential data for understanding HPFRC's potential as a fatigue shear-resistance strengthening method. Additionally, digital image correlation (DIC) techniques are employed to provide detailed insights into deformation and failure mechanisms in strengthened beams. This study represents the first comprehensive analysis of fatigue shear performance in HPFRC/UHPFRC shear-strengthened beams, aiming to advance the use of HPFRC in enhancing critical infrastructure's resilience and durability.

1.1 2. Experimental Programme

1.1. 2.1. Specimen Details

This study examined ten RC beams under three-point bending: five tested under monotonic loading and five under fatigue loading. The monotonic set included three beams with a shear span–depth ratio of 2.0 (Group A) and two with a ratio of 3.5 (Group B). All beams measured 102 mm wide, 203 mm high, and 1677 mm long, with an effective span of 1100 mm.

No transverse reinforcement was used in shear-critical zones to encourage shear failure, while stirrups (8 mm at 140 mm spacing) were placed in shear-sufficient zones. Longitudinal reinforcement consisted of 16 mm and 10 mm rebars. HPFRC jacketing with 1.66% steel fibers was applied in critical zones, enhancing shear capacity by confining diagonal cracks. HPFRC achieved a compressive strength of 106.5 MPa and elastic modulus of 43 GPa.

Concrete compressive strength at 28 days averaged 22 MPa, with yield stresses for longitudinal rebars and stirrups at 538 MPa, 527 MPa, and 340 MPa, respectively. HPFRC jacketing proved effective in enhancing the shear capacity of RC beams [3].

1.1. 2.2. Test Setup

The beams were tested in three-point bending using a 500 kN servohydraulic actuator on a steel reaction frame. Positioned on anchored supports, the beams had constraints to prevent rotation. Vertical displacements were tracked with LVDTs at load points and supports, while DIC technology recorded strain distribution in shear-critical zones.

Static Loading: Conducted at 0.02 mm/s in displacement control, with high-speed camera images captured every 2 seconds for DIC analysis [4].

Fatigue Loading: Cyclic loads applied until failure, with a maximum of 2 million cycles. Fatigue load range was 30–70% of shear resistance, based on Dynamic Amplification Factor (DAF) of 0.4 and 50% of peak load. Testing frequency was 4 Hz to reduce hysteresis and avoid heating. DIC images were recorded every 8 cycles up to 10,000, then every 1000 cycles. DIC analysis used ZEISS software for high-resolution speckle image assessment.

3. Results and Discussion

3.1. Static Tests

Table 1 presents key test results, including peak load (Pmax), displacement at peak load (δmax), strength increase (ΔPmax), ultimate load (80% of Pmax, denoted Pu) and corresponding displacement (δu), shear strength in the critical span (V), shear strength contribution from HPFRC jacketing (VJAC), displacement ductility (μδ), and failure mode. "SH" indicates shear failure.

Displacement ductility (μδ), calculated as δu/δy, reflects deformation capacity, following ASCE/SEI Standard 41-06 guidelines with a bilinear load–deflection approximation. Control beams (A-N and B-N) did not exhibit ductile behaviour, so their μδ was not computed. In Series A (a/d = 2.0), the control beam failed in shear at 51.3 kN and 2.5 mm displacement. HPFRC jacketing increased peak load by 122% for A-10 and 130% for A-20, with thicker jacketing improving load capacity and stiffness, attributed to better fibre distribution and reduced fibre aggregation. In Series B (a/d = 3.5), the 10 mm jacketing (B-10) achieved a 48% increase in peak load. The "bridging effect" of fibres across cracks enhances structural integrity and delays failure onset [5].

Table 1. Summary of monotonic loading test results.

Series	Beam	*fc* (MPa)	*Pmax* (kN)	Δ*Pmax* (%)	*Pu* (kN)	*δmax* (mm)	*δd* (mm)	*V* (kN)	*VJAC* (kN)	V_{JAC}/V (%)	μ_δ	Failure Mode
A	A-N	26.2	52.3	-	41.3	2.52	3.92	35.0 *	-	-	-	SH
	A-10	30.5	103.7	122	91.3	4.95	6.31	77.5 $^{\$}$	42.4	53	1.73	SH
	A-20	27.4	127.8	130	94.7	4.35	6.52	80.3 $^{\$}$	45.5	58	2.05	SH
B	B-N	23.2	39.8	-	30.2	1.41	1.53	16.9 *	-	-	-	SH
	B-10	26.9	75.7	95	60.5	4.33	5.42	32.9 $^{\$}$	17.0	48	2.05	SH

* *VCON*; $^{\$}$ *VRET*.

With the increase in a/d ratio from 2.0 to 3.5, there was a reduction in shear strength (V), strength increase (ΔPmax), and effectiveness of HPFRC reinforcement (VJAC/V). This reduction in reinforcement efficiency occurs because beams with higher a/d ratios transition from a deep to a slender structure, shifting from an arching load transfer to a truss-like action, reducing shear resistance. In Series A (a/d = 2), arching action in deep beams allows the load to transfer directly through the diagonal strut, which diminishes as the a/d ratio rises, weakening the concrete's contribution to shear resistance. A higher shear span also increases the chance of shear damage, weakening the HPFRC jacket's bond and increasing stress concentration near beam ends, accelerating reinforcement failure.

The strain fields captured through Digital Image Correlation (DIC) reveal that HPFRC enhances stress redistribution across critical regions. Strengthened beams showed pseudo-ductile behaviour, sustaining peak loads post-cracking due to the HPFRC's "bridging effect." This effect, with strain-hardening properties, allows gradual load reduction after peak load, beneficial for seismic resilience by enhancing energy dissipation. Strengthened beams' displacement ductility ranged between 1.72 and 2.06, with ductility improving alongside HPFRC jacket thickness and a/d ratio, validating the reinforcement's impact on ductility. At testing end, damage in all beams was localized in the shear-critical region [6]. Control beams displayed typical diagonal tension failure, while HPFRC-reinforced beams exhibited pseudo-ductility with gradual shear detachment and multiple diagonal cracks, particularly visible with 20 mm jackets, which showed enhanced crack development but increased detachment issues. In Series B (a/d = 3.5), B-10 beams failed similarly to controls due to slenderness, limiting HPFRC's capacity for multi-crack distribution and reducing its effect on failure mode alteration [7].

3.2. Fatigue Tests

The fatigue test results, covering each beam's concrete compressive strength on the test day (fc), fatigue life (Nf), total deflection (δ), stiffness degradation (β) at the last cycle, energy dissipation (Ψd) at the last cycle, and the failure mode. Stiffness degradation per cycle (β) is calculated using:

$$\beta = \frac{K_1 - K_n}{K_1} \times 100\%$$

where K_n is the stiffness of each cycle, and K_1 is the stiffness of the first cycle. The stiffness (K) for each cycle is calculated as the ratio of the load range ($P_{max} - P_{min}$) to the corresponding displacement range ($\delta_{max} - \delta_{min}$) [40]. The energy dissipation (Ψ_d) is represented by the area enclosed in the load–displacement curve for each cycle: the difference between the energy absorbed during the load increase phase (Ψ_a) and the energy released during the load decrease phase (Ψ_r) [52]. Furthermore, as previously stated, the fatigue load range encompasses a span of 30% to 70% of P_{peak}. Consequently, based on the outcomes of static testing, the loads applied to each beam are also delineated.

1.2 The fatigue test results indicate that HPFRC jacketing significantly improved the fatigue life and maximum deflection of shear-deficient beams, with both Series A and B beams benefiting. Sample A-10, despite undergoing a higher load than its control, exhibited a 20% increase in cycle count. Increasing the HPFRC jacket thickness from 10 mm to 20 mm in Series A yielded a notable enhancement in fatigue life, attributed to improved fibre distribution, which aligns with static loading results [8-10]. Series B showed that as the a/d ratio rose from 2.0 to 3.5, the fatigue performance of the 10 mm strengthening system also improved, with B-10 demonstrating quadruple the fatigue life of A-10.

1.3 The load–displacement response and stiffness degradation (β) evolved through three stages under fatigue loading:

1.4 1. Initial Stage: Rapid increase in deflection and strain due to initial cracks.

1.5 2. Stable Stage: Slower accumulation of damage and stiffness degradation, lasting until just before failure.

1.6 3. Final Stage: Sharp increase in deflection and stiffness degradation, culminating in failure.

1.7 For Series A, HPFRC jacketing reduced stiffness degradation rates, with β values at failure for A-10 and A-20 recorded at 25.2% and 47.8%, respectively, compared to 56.0% for the control. Beam A-20 experienced premature cracking that partially offset its fatigue performance enhancement. In Series B, higher deflection and stiffness degradation amplitudes were observed, indicating that increasing the a/d ratio slowed damage accumulation during the stable stage, leading to smoother degradation curves and extended fatigue life.

1.8 Energy dissipation (Ψd) followed a similar three-stage trend, where all strengthened beams exhibited higher Ψd than the control, owing to the higher loads. Increased shear span–depth ratios reduced energy loss per cycle, enhancing fatigue resistance. All beams experienced shear failure with a diagonal tension crack forming in the shear span, leading to beam failure after gradual shear capacity reduction. DIC strain analysis showed that HPFRC promoted uniform strain distribution, while thicker HPFRC and increased a/d ratios enhanced ductility, as evidenced by greater vertical strain values [11-12].

1.9 4. Fatigue Life Prediction of the HPFRC Jacketed Beams

Research on predicting the shear strength of HPFRC/UHPFRC jacketed beams is limited, with models focusing mainly on bottom-bonded configurations, which are not applicable to U-shaped jacketing due to the prevention of the crack-induced debonding (ICD) zone. Therefore, a shear design model from the Japan Society of Civil Engineers (JSCE) has been adapted for U-shaped HPFRC reinforcement systems [13]. The shear strength of the strengthened beams (Pref) is calculated as the sum of the shear strength from the concrete (Vc) and the HPFRC jacket (VJAC), with the latter determined by combining contributions from the cementitious matrix and the fibres, following JSCE guidelines.

The S-N relationship for HPFRC-strengthened beams shows that an increase in cyclic stress (S) leads to a decrease in fatigue life (N), consistent with the trend observed in Series A. However, deviations in Series B, particularly for specimen B-10, suggest varying fatigue responses due to different shear span ratios. Further data is needed to refine the S-N relationship and to develop distinct expressions based on shear span ratios [14].

1.10 5. Conclusions

This study evaluated the static and fatigue performance of RC beams strengthened with U-shaped HPFRC jacketing, examining the effects of HPFRC thickness (10 mm and 20 mm) and shear span-to-depth ratio (a/d = 2.0 and 3.5). Key findings include:

- Static Loading: HPFRC increased shear strength by 95% to 130%, with thicker jacketing providing more significant enhancement, especially in deeper beams. Partial detachment occurred, but fibre bridging controlled crack growth.
- Fatigue Loading: HPFRC improved fatigue life, with beams experiencing up to 951 additional cycles for a/d = 2.0 and 48,786 cycles for a/d = 3.5. The failure mode remained diagonal tension, with three phases of deflection, stiffness degradation, and energy dissipation observed.
- Fatigue Life Prediction Model: A predictive model was developed based on fatigue load and static shear strength, though more data is needed for refinement.

HPFRC jacketing proves effective for retrofitting RC structures, enhancing shear capacity and fatigue resistance, making it ideal for improving the longevity and safety of older structures under cyclic and seismic loads.

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