Enhancement of the Shear Capacity of RC Deep Beams with Ultra-High Performance Fiber-reinforced Concrete

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ABSTRACT

This research investigates the shear behavior of Reinforced Concrete (RC) deep beams strengthened with Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC). For this purpose, eight RC deep beams were fabricated and tested for failure. One beam served as a control beam (un-strengthened), while the remaining seven deep beams were strengthened utilizing various strengthening schemes. This experimental study primarily focused on the thickness of the UHPFRC layer, Steel Fiber (SF) volume fraction, and strengthening schemes (jacketing, bilateral layers, and strips exclusively in the shear zone). The experimental findings demonstrated that UHPFRC significantly enhanced the shear capacity, toughness, and stiffness of the RC deep beams. The performance of the strengthened beams exhibited improvements in ultimate shear strength, stiffness, and toughness of about 43.6%, 102.2%, and 171.3%, respectively, higher than that of the un-strengthened deep beam. UHPFRC U-jacketing is a highly effective method for strengthening the RC deep beams. Incorporating SF into the UHPFRC mixture improved the shear properties of the strengthened specimens and delayed fracture propagation. Finally, the shear capacity of the strengthened specimens was compared to the values predicted by the analytical approaches presented in earlier research.

Keywords-deep beams; shear behavior; strengthening; ultra-high-performance fiber reinforced concrete

I. INTRODUCTION

Deep beams are RC beams defined by a shear span-to-depth ratio of less than 2 when simply standing [1]. As described in [2], these beams are loaded on the one side and supported on the opposite side, allowing the formation of compression struts between the applied loads and the supports. The strengthening of existing structures is increasingly becoming a primary goal of construction projects. Shear strengthening is required in several situations, such as when there is an increase in service loads, errors in the initial design, and insufficient shear reinforcement. The use of externally bonded techniques, such as UHPFRC, offers a highly effective solution in these circumstances. UHPFRC consists of a cement content with an impressive range of 700 Kg/m^3 to 1000 Kg/m^3, a significant amount of SF [3], a low water content, fine sand, and a high content of micro silica. UHPFRC is defined as concrete with a minimum specified compressive strength of 120 MPa, according to [4]. Similarly, authors in [5] classify mixtures as UHPFRC when their compressive strength exceeds 100 MPa. Due to its exceptional strength and energy absorption capacity, UHPFRC is capable of withstanding impact and explosive loads [6]. This occurs due to the fiber effect, which induces strain hardening. Moreover, the high compactness and density of the UHPFRC matrix contribute to its outstanding physical performance, including durability attributes, such as low permeability and excellent corrosion resistance. These properties enable the material to effectively prevent the penetration of dangerous chemicals, thereby enhancing its durability [7, 8]. The distinctive properties of UHPFRC make it particularly well-suited for enhancing and restoring concrete structures. Conversely, achieving reduced production costs remains a significant issue for the UHPFRC technology [9, 10]. Several researchers performed experimental investigations on the flexural behavior of RC beams strengthened with UHPFRC [11-13]. Authors in [14] performed an experimental study on the flexural behavior of damaged RC beams strengthened with UHPC layers. The strengthened beams exhibited significant improvements in both the cracking resistance and flexural capacity. Authors in [15] conducted an experimental study on the strengthening of damaged RC columns using 30 mm UHPFRC jacketing, and the results demonstrated an enhancement in the load capacity and stiffness of the columns. The literature review indicates a scarcity of studies focusing on the shear behavior of RC deep beams strengthened with UHPFRC under concentrated loads, with certain variables remaining inadequately examined. So, in this context, eight RC deep beams were fabricated and tested to investigate the shear behavior of RC deep beams strengthened with UHPFRC and subjected to two-point concentrated loads. Several variables were evaluated, including the thickness of the UHPFRC layer (20 mm, 30 mm, and 40 mm), the SF content (0%, 0.5%, and 1.5%), and strengthening schemes (jacketing, bilateral layers, and strips in the shear zone only).

II. EXPERIMENTAL PROGRAM

A. Material Properties

1) Normal Concrete

The normal concrete mix proportions were based on the guidelines provided in [16]. As detailed in Table I, the mix was prepared using ordinary Portland cement (CEM I 52.5) and fresh water. Basalt, with a particle size of 16 mm, was used as the coarse aggregate, having a Specific Gravity (SG) of 2.66 and a Fineness Modulus (FM) of 2.56. Sand, which served as the fine aggregate, had an SG of 2.51 and an FM of 2.44. The properties of both the coarse and fine aggregates were evaluated according to [17, 18]. After 28 days of curing, the average compressive strength of a normal concrete cylinder was found to be 28 MPa, as reported in [19].

2) Steel Reinforcement

High-grade steel (grade 40/60) has been used for bars with diameters of 12 mm and 16 mm, while mild steel (grade 28/40) has been utilized for bars with diameters of 6 mm. The properties of the used steel have been experimentally determined according to [20].

3) Ultra-High-Performance Fiber-Reinforced Concrete

In [21], the UHPFRC mixture was made using standard ingredients, including ordinary Portland cement (CEM I 52.5) with a particle size of 19.8 μm and an SG of 3.15. Silica fume, with particles measuring 0.15 μm and an SG of 2.2, was used alongside the cement as a cementitious material. Fine sand (SG 2.51, FM 2.34) and quartz powder (particle size up to 150 μm, SG 2.25, FM 2.14) were combined as aggregates to create a dense UHPFRC mixture. Sika Viscocrete-3425, a superplasticizer with an SG of 1.08, was incorporated to reduce the water content and achieve the desired viscosity for a consistent steel fiber distribution, as confirmed in [22]. The steel fibers used in the mixture were high-strength hooked fibers, each measuring 35 mm in length and 1 mm in diameter, with a tensile strength of 1100 MPa. The proportions of the UHPFRC mixture, derived from several trial mixtures, are presented in Table II, while Table III shows the compressive and tensile strengths of the mix.

TABLE I. PROPORTIONS OF NORMAL CONCRETE MIX (kg/m^3)

Cement	Coarse aggregate	Fine aggregate	Water
400	1160	625	186

TABLE II. PROPORTIONS OF UHPFRC MIX BY WEIGHT (kg/m^3)

Mix #	M1	M2	M3
Cement	900	900	900
Silica fume	220	220	220
Sand	825	815	800
Quartz powder	220	215	210
Super-plasticizers	40	40	40
water	175	178	181
SF content	0 (0%)	39 (0.5%)	117 (1.5%)

TABLE III. COMPRESSIVE AND TENSILE STRENGTH OF UHPFRC

Mix #	Compressive strength (MPa)	Tensile strength (MPa)
M1	120.4	7.6
M2	129.8	10.1
M3	135.7	11.3

B. Test Specimens

Eight RC deep beams with a rectangular cross-section measuring 120 mm × 400 mm, a total length of 1200 mm, and a clear span of 1000 mm were tested. The tested beams had 360 mm of effective depth and 350 mm of shear span. The corresponding shear span to depth ratio (a/d) was equal to 0.96. The examined deep beams were fortified with three Φ16 bars as tension reinforcement and two Φ12 bars as compression reinforcement, respectively. The beams were vertically reinforced with double-legged steel stirrups of a 6 mm diameter at 150 mm intervals, and two stirrups with a conventional diameter of 6 mm were installed horizontally. The clear cover for both the top and bottom reinforcement is 20 mm. Figure 1 illustrates the configuration, dimensions, and reinforcement details of the control RC deep beam. As portrayed in Table IV, several variables were considered in the design, including the thickness of the UHPFRC layers, the SF content, and the strengthening schemes. The UHPFRC layer thicknesses are 20 mm, 30 mm, and 40 mm. The SF content varies at 0%, 0.5%, and 1.5%. The strengthening schemes tested include full U-shaped jacketing, complete bilateral layers, and bilateral strips applied only within the shear zone. The geometry of the strengthened RC deep beams is depicted in Figure 2.

TABLE IV. CONFIGURATION OF TEST SPECIMENS

Specimens #	SF content	UHPFRC Layer thickness (mm)	Strengthening Scheme	Strengthening length
B0	-	-	-	-
B1	0	30	U-Jacketing	Total length (L)
B2	0.5%	30	U-Jacketing	Total length (L)
B3	1.5%	30	U-Jacketing	Total length (L)
B4	1.5%	20	U-Jacketing	Total length (L)
B5	1.5%	40	U-Jacketing	Total length (L)
B6	1.5%	40	Bilateral layers	Total length (L)
B7	1.5%	40	Bilateral strips	Shear zone only

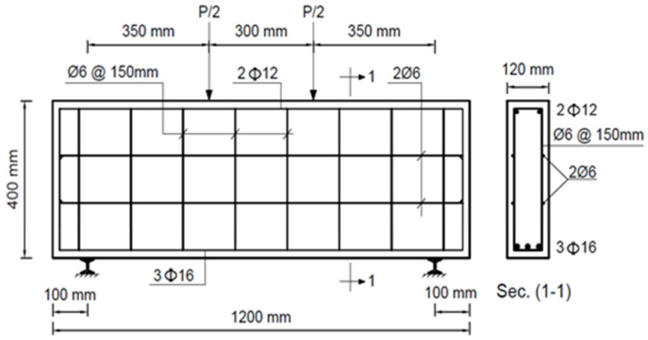

Fig. 1. Dimensions and reinforcement details of the specimen.

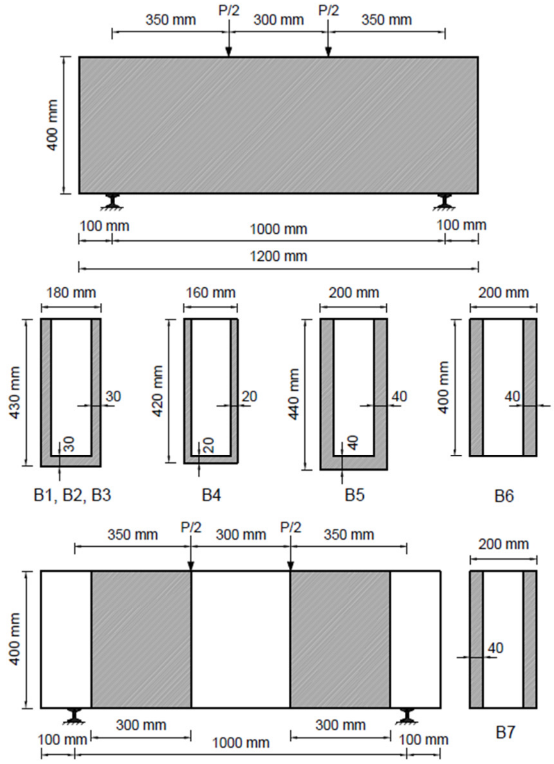

Fig. 2. Strengthening schemes of test specimens.

C. Strengthening Procedure of the Test Specimens

The deep beam specimens have been enhanced by adding a UHPFRC mixture to the rough surface. The technique involves chipping the surface of the beam specimens to provide adhesion between the beam surface and the UHPFRC. Holes with a diameter of 12 mm and a depth of 50 mm were subsequently drilled at specified positions, situated 50 mm from both the upper and lower surfaces of the beam. The requisite holes have been cleared with an air blower to remove all debris particles. Subsequently, the necessary kemapoxy 165 was mixed and applied to the holes [23]. Shear connectors with a 10 mm diameter have been inserted into the holes and held in place until the epoxy resin has cured, as illustrated in Figure 3. Following the preparation of the beam surface according to the required standard, the kemapoxy 104 adhesive was used for bonding. A UHPFRC layer attached to the existing concrete, was prepared and applied to the rough sides of the beam [24].

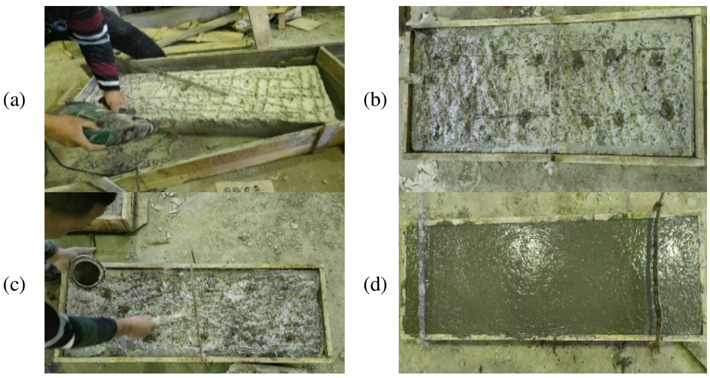

Fig. 3. RC beam strengthening processes. (a) Roughing beam's surface, (b) installing shear connectors, (c) adding adhesive material, (d) casting UHPFRC mix.

D. Test Set Up

The beam specimens were tested under a four-point loading configuration until failure using a hydraulic machine with a z capacity of 700 kN and a displacement control rate of 0.25 mm/min. The central deflection of the tested beams was measured by employing a single Linear Variable Differential Transducer (LVDT) positioned at the midpoint of the beam specimens. The underwent beams were tested 28 days after the casting of the UHPFRC layers. Figure 4 presents the test setup of the deep beam specimen.

Fig. 4. Test setup of the deep beam specimens.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Cracking Pattern and Mode of Failure

Figure 5 presents photographic representations of the crack patterns for all examined specimens. Two failure types have been observed in the experimental program. The first mode of failure is a typical shear failure, with diagonal cracks running from the two loading points to the supports. This type of failure was seen in the RC deep beams (B0 to B6). In these specimens, there was no debonding between the surfaces of the deep beams and the UHPFRC layers due to roughing the surface and using shear connectors. For the control specimen (B0), the first crack load appeared at 238.5 kN (61.3% of the ultimate load), while strengthening the deep beam (B1) with UHPC (0% SF) delayed the appearance of the first crack load to 293.4 kN (67.4% of the ultimate load). Incorporating steel fibers into the UHPFRC mixture enhanced the load capacity and delayed the appearance of the first crack load in the strengthened deep beams (B2 to B7). The first crack load for the strengthened deep beam (B2) with 0.5% SF in the UHPFRC mixture was 345.0 kN, 74.5% of the ultimate load. For the strengthened deep beams (B3, B4, B5, and B6) with 1.5% SF in the UHPFRC mixture, the first crack loads have been recorded at 395.5 kN, 376.5 kN, 423.5 kN, and 402.5 kN, which is between 75% and 78% of the ultimate load. The second mode of failure was observed in the RC deep beam (B7), which was strengthened only with UHPFRC strips at the shear zone. A conventional shear failure mode occurred in the RC deep beam, accompanied by concrete crushing at the support, and the first crack load was recorded at 398 kN (77.3% of the ultimate load). In this specimen, debonding occurred between the surfaces of the RC deep beams and the UHPFRC strip.

B. Load Versus Mid-Span Displacement Curves

Figure 6 depicts the load versus the central displacement curves for the tested deep beams. It was observed that the strengthened deep beams showed significantly stiffer responses and were more ductile than the un-strengthened deep beams. The casting method utilizing UHPFRC jackets proved to be more effective than those employing bilateral layers or strips only in the shear zone. All specimens exhibited nearly identical behavior in the uncracked phase. However, the post-cracking behavior demonstrated notable differences. The slope of the load versus the central displacement curve for all strengthened deep beams exceeds that of the control deep beam in the post-cracking stage due to the enhancement of the UHPFRC elastic modulus. The addition of SF to the UHPFRC mixture resulted in the strengthened deep beams exhibiting greater ductility compared to the un-strengthened beams. As presented in Table V, when compared to the control deep beam, the ductility of the strengthened specimens B1 (0% SF), B2 (0.5% SF), and B3 (1.5% SF) has been increased by 24.5%, 44%, and 58.7%, respectively. The thickness of the UHPFRC jacket had a notable impact on the ductility of the strengthened specimens. Specifically, the ductility of the specimens B4, B3, and B5 improved by 28.3%, 58.7%, and 115.2%, respectively. In contrast, specimens B6 and B7, which were strengthened with bilateral layers and strips in the shear zone only, showed a modest increase in ductility, with improvements of 46.2% and 26.1%, respectively.

TABLE V. EXPERIMENTAL RESULTS OF TEST SPECIMENS

Specimen #	First crack		Ultimate		Initial Stiffness (kN/mm)	Toughness (kN.mm)	Ductility
	V_{cr} (kN)	Δ_{Cr} (mm)	V_u (kN)	Δ_u (mm)			
B0	238.5	4.25	389.3	6.75	41.2	1156.2	1.84
B1	293.4	4.50	435.4	7.25	63.4	1694.0	2.29
B2	345.0	4.75	462.8	7.75	71.2	2047.1	2.65
B3	395.5	5.25	524.1	8.25	78.7	2633.1	2.92
B4	376.5	5.15	490.5	7.50	59.7	1848.3	2.36
B5	423.5	4.50	559.1	9.00	83.3	3136.2	3.96
B6	402.5	5.00	535.4	8.00	66.7	2303.6	2.69
B7	398.0	5.50	514.8	8.50	53.6	2129.8	2.32

C. Ultimate Shear Capacity

Table V displays the ultimate shear capacity (V_u) of the tested specimens. The results indicated that UHPFRC is an efficacious method for enhancing the Vu of RC deep beams. Increasing the SF content of the strengthened concrete deep beams B1 (0% SF), B2 (0.5% SF), and B3 (1.5% SF) with UHPFRC jackets of 30 mm thickness, led to strength enhancements of 11.8%, 18.9%, and 34.6%, respectively. This is due to the SF functioning as a connector among the different elements of the UHPFRC matrix, enhancing its performance [25, 26]. The increase of the V_u in the strengthened deep beams is directly proportional to the thickness of the UHPFRC jacket. The use of UHPFRC U-jackets with layer thicknesses of 20 mm, 30 mm, and 40 mm, containing 1.5% SF for the specimens B4, B3, and B5, respectively, led to enhancements in the Vu of the strengthened deep beams by 26%, 34.6%, and 43.6%, respectively. The enhancement in the deep beam strength is due to the increased thickness of the UHPFRC jacketing, leading to greater cross-sectional dimensions and superior mechanical properties of the UHPFRC, attributable to the inclusion of SF. The findings indicated that the strengthening schemes applied to the test specimens B5, B6, and B7 affected the Vu of the deep beams. The specimen B5, including a UHPFRC U-jacket, showed a 43.6% enhancement in the V_u of the deep beam, whereas the specimen B6 with bilateral layers had a 37.5% improvement in the deep beam shear strength. The specimen B7 with bilateral strips in the shear zone demonstrated an increase of 32.2% [27].

D. Stiffness

Stiffness is the measure of a deep beam's resistance to elastic deformation under applied force. Table V depicts the initial stiffness of the test specimens. Increasing the SF content enhances the stiffness of the strengthened deep beams. The initial stiffness of strengthened beams B1 (0% SF), B2 (0.5% SF), and B3 (1.5% SF) led to an increase in the deep beam stiffness of 53.9%, 72.8%, and 90.6%, respectively. The increase in the stiffness of the strengthened deep beams correlates directly with the thickness of the UHPFRC jacket. Increasing the thickness of the UHPFRC jacket to 20 mm, 30 mm, and 40 mm, with an SF content of 1.5% for the specimens B4, B3, and B5, respectively, led to an improvement in the deep beam stiffness of 44.8%, 90.6%, and 102.2%. The findings indicated that the strengthening methods applied to the test specimens B5, B6, and B7 affected the stiffness of the deep beams. Specimen B5 featuring an HUPFRC jacket had a 102.2% increase in deep beam stiffness, while specimen B6 with laminates on both sides showed a 61.9% increase in deep beam stiffness. The specimen B7 strengthened with strips in the shear zone demonstrated an increase of 30.1%.

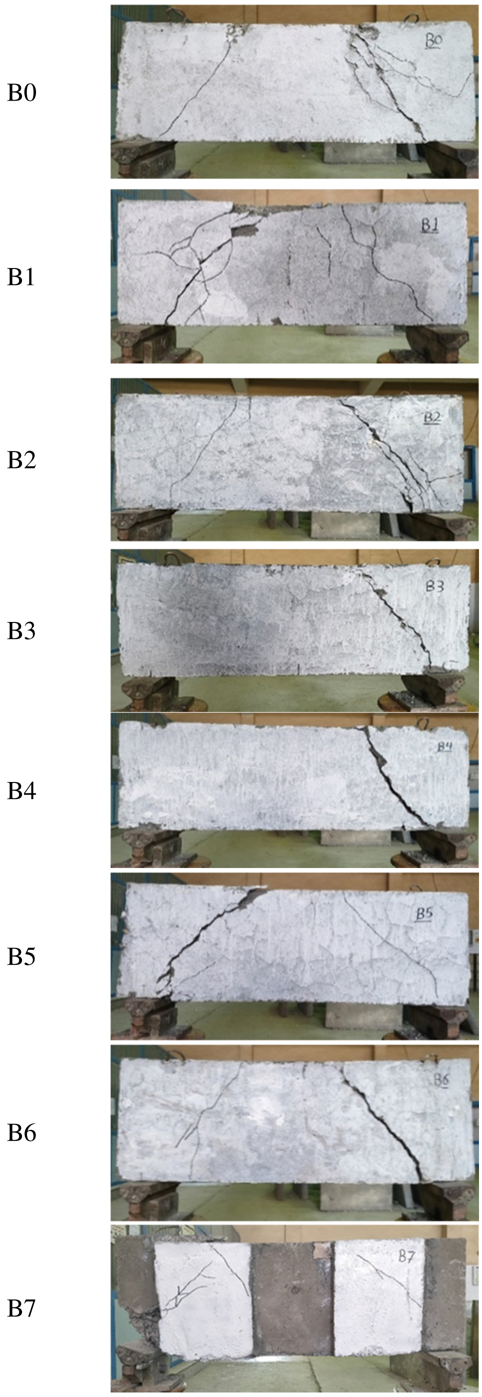

Fig. 5. Failure modes and cracking patterns of the tested deep beam specimens.

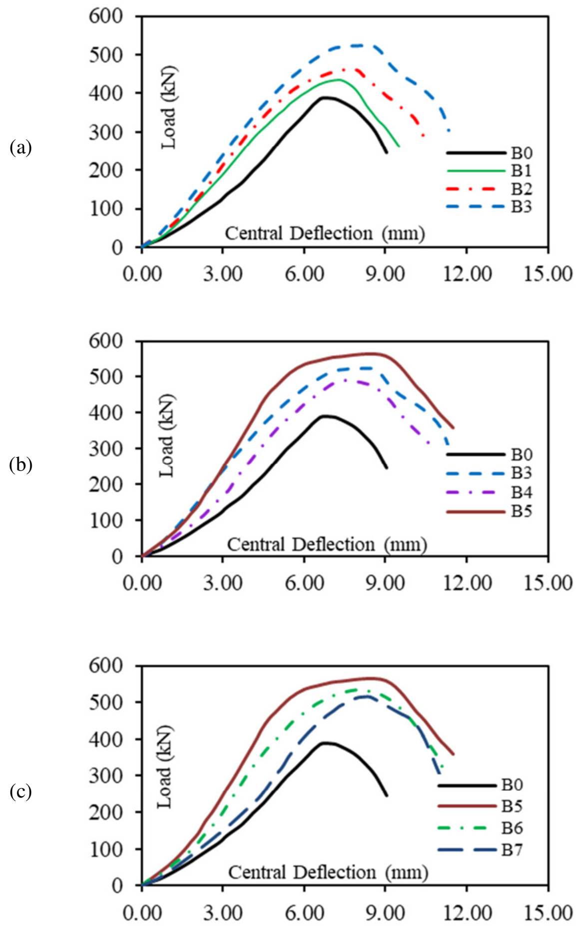

Fig. 6. Load versus central displacement curves of the tested beams: (a) effect of SF content,(b) effect of thickness of UHPFRC jacket, (c) effect of strengthening scheme.

E. Toughness

Toughness is the area under the load versus the mid-displacement curve until the maximum load is reached. It refers to a deep beam's ability to assimilate energy without failure. The results presented in Table V demonstrated that increasing the SF content from 0% to 1.5% in B1, B2, and B3 specimens directly enhanced their shear capacity and ductility. As a result, the toughness increased by 46.5%, 77.1%, and 127.7%, respectively. Increasing the thickness of the UHPFRC jackets by 20 mm, 30 mm, and 40 mm in B4, B3, and B5, respectively, increased the shear capacity and ductility, which in turn increased the toughness by 59.6%, 127.7%, and 171.2%, respectively. Specimen B6, strengthened by bilateral UHPFRC layers, exhibited a 99.2% increase in toughness, surpassing the 84.2% increase in toughness recorded by specimen B7, which was strengthened by bilateral strips in the shear only.

IV. ANALYTICAL APPROACH

A. Proposed Shear Approach of Ultra-High-Performance Fiber-Reinforced Concrete Beams

Three approaches have been used to estimate the shear capacity of the UHPFRC beams. The first approach consisted (1) and (2) [28], the second of (3)-(5) [29], and the third of (6)-(8) [30]:

$$V_{UHPFRC} = F \times \tau \times b_{uh} \times d_{uh} \quad (1)$$

$$F = \frac{V_{sf} \times l_f}{d_f} \quad (2)$$

where F represents the fiber typology, which is determined by the volume content of the steel fibers V_{sf}, the fiber length l_f (mm), and the fiber diameter d_f (mm), and τ denotes the average bond strength of the fibers, which is derived from experiments conducted on a single fiber pullout, with a recommended value of 10 MPa.

$$V_u = V_c + V_s \quad (3)$$

$$V_c = 0.17\sqrt{f'c}\, b_d \quad (4)$$

$$V_s = \frac{A_{sv}\, f_{yv}\, d}{s} \quad (5)$$

where Vu is the addition of the contributions of the concrete Vc and the transverse reinforcement Vs.

$$V_{uh} = V_{uhd} + V_{fd} \quad (6)$$

$$V_{uhd} = 0.18\, \varphi b \sqrt{f'cuh}\; b_{uh} d_{uh} \quad (7)$$

$$V_{fd} = \varphi b \left(\frac{f_{vd}}{\tan(\beta)}\right) b_{uh}\, z \quad (8)$$

where V_{uhd} is the shear capacity provided by the UHPFRC cement matrix, which depends on the member reduction factor (φ_b) with a recommended value of 0.8, and the shear capacity provided by SF V_{fd}. This depends on the tensile strength of UHPFRC f_{vd}, the angle of the diagonal crack surface to the member axis ($\beta = 45^o$), and the distance from the resultant of the compressive strength to the tensile steel centroid (z), which generally equals to ($\frac{d_{uh}}{1.15}$).

B. Comparison between Experimental and Analytical Approach

The estimated values of the shear capacity of the strengthened specimens were compared with the experimental results, as illustrated in Table VI. The first approach came up with an overall average and coefficient of variation of 1% and 19.3%, respectively [28]. It was noticed that this approach could be applied to estimate the shear capacity of the strengthened beams with UHPFRC jacketing and bilateral layers. It was observed that the ACI 318-19 code [29] underestimated the shear capacity values for the strengthened specimens. This occurred because higher safety factors are recommended for the shear capacity to be estimated owing to the limited tests and structural data [31]. On the contrary, the JSCE code [30], overestimated them. Both the ACI and JCSE codes gave a satisfactory match with the UHPC beams with no fiber volume (B1).

TABLE VI. COMPARISON BETWEEN EXPERIMENTAL AND ANALYTICAL RESULTS

Sample #	**$V_{uh,Exp}$* (kN)**	**$V_{uh,}$ predicted (kN)**			**$V_{uh,Exp}$ / $V_{uh,predicted}$**		
		[28]	**ACI**	**JCSE**	**Hussein**	**ACI**	**JCSE**
B1	46.1	-	43.1	36.4	-	1.07	1.26
B2	73.5	56.4	50.1	226.3	1.30	1.46	0.32
B3	134.8	135.4	51.6	239.7	1.00	2.61	0.56
B4	101.2	90.3	35.6	159.8	1.12	2.85	0.63
B5	169.8	180.6	68.4	319.6	0.94	2.48	0.53
B6	146.1	168	63.4	297.3	0.87	2.30	0.46
B7	125.5	168	63.4	297.3	0.75	1.98	0.36
Average					1.00	2.11	0.59
Standard deviation					0.19	0.64	0.32
Coefficient of variation (%)					19.3	30.6	53.5

*Increasing the shear capacity of strengthened beams

V. CONCLUSIONS

Strengthening Reinforced Concrete (RC) deep beams with Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) has yielded valuable insights into its effectiveness as a retrofitting method. The structural benefits and durability of this approach can be better understood by examining the performance improvements. Based on the analysis of the test data collected in this study, the following conclusions can be drawn:

- The UHPFRC strengthening procedure effectively enhances the shear behavior of strengthened deep beams. Using the UHPFRC U-jackets as a strengthening scheme improved the test specimens' ultimate shear capacity (V_u), stiffness, ductility, and toughness. The increase in the V_u due to the UHPFRC U-jacketing is directly proportional to the UHPFRC layer thickness and Steel Fiber (SF) content.
- The thickness of the UHPFRC layer significantly improved the structural behavior of the strengthened deep beams. Compared to the unstrengthened beams, the strengthened beams exhibited an increase in V_u of approximately 43.6% and in stiffness of 102.2%. Additionally, increasing the UHPFRC layer thickness helped to distribute stresses more effectively across the deep beams, reducing the stress concentration and delaying the failure mechanisms.
- The SF content in UHPFRC significantly improved its tensile behavior, allowing it to resist cracking more effectively. This is especially critical in deep beams, which are prone to shear failure. The reduced crack widths and better crack control contribute to an increase in stiffness and durability. The beams strengthened with a 1.5% SF content in the UHPFRC layer had a V_u and ductility higher than those without SF by about 22.8% and 34.2%, respectively.
- In predicting the V_u of the strengthened deep beams using analytical methods, it was found that the first analytical approach, found in [28], provided more accurate predictions than the ACI-318 and JSCE codes. This approach is more precise because it accounts for the interactions between the steel fibers and the matrix. In contrast, the ACI-318 code recommends higher safety factors for the shear capacity to be estimated due to limited test data and structural information, while the JSCE code tended to overestimate the shear capacity values [32].

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