Results in Nonlinear Analysis 7 (2024) No. 3, 226–243
https://doi.org/10.31838/rna/2024.07.03.019
Available online at www.nonlinear-analysis.com

Results in Nonlinear Analysis
ISSN 2636-7556

Peer Reviewed Scientific Journal

The behavior of UHPC deep beam using the hybrid combination of steel and basalt fibers

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Abstract

This research looks at how hybrid fiber reinforcement changes the shear behavior of ultra-high-performance concrete (UHPC), focusing on deep beams that are likely to fail in this way. The research involved casting four groups of deep beams with different fiber fractions and a/d ratios, comparing them with the ultra-high-strength concrete UHSC. Add 1% of basalt fibers to a UHSC specimen, the diagonal shear cracks get 86.66% bigger, and the ultimate shear capacity gets 28.69% bigger. In steel fiber specimens with the same fraction volume, the diagonal shear crack load increased by 98.54%, and the ultimate shear capacity increased by 55.24%. In hybrid fiber ultra-high-performance concrete (UHPC) deep beams, which have the same percentage of fibers (75% basalt fibers and 25% steel fibers), the diagonal shear capacity improves by 97.08%, and the ultimate shear capacity increases by 32.33%. The investigation revealed that altering the proportions of fibers (25% basalt fibers and 75% steel fibers) resulted in a 67.81% enhancement in the load at which diagonal shear cracks occur and a 44.71% increase in the maximum shear load. The optimal development performance may be achieved by utilizing the ideal basalt and steel fibers proportion. These performance improvements are also observed when the shear span ratio a/d changes from 1.8 to 1.0. Hybrid beams also displayed more significant ductility gains than single-fiber designs. The study focuses on understanding the impact of hybrid fiber reinforcement on shear behavior and enhancing UHPC deep beam shear strength and ductility, potentially leading to a new construction era by optimizing hybrid fiber use.

Key words and phrases: hybrid fibers, basalt fibers, steel fibers, deep beam, mid-span deflection, diagonal cracks, ultimate shear capacity.

Mathematics Subject Classification (2010): 18D30.

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Received October 7, 2024; Accepted November 23, 2024; Online December 30, 2024

Introduction

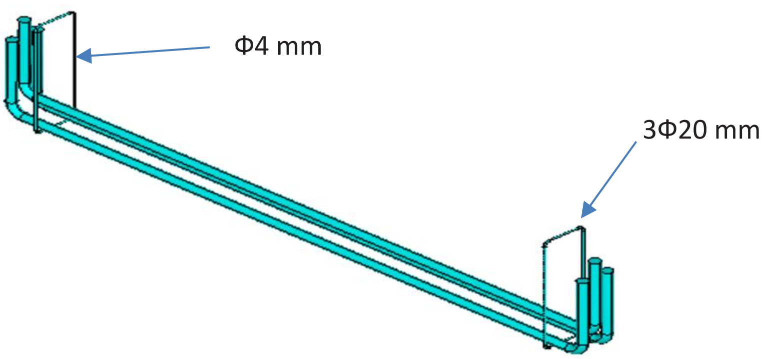
In 2012, Zaman, Solanki, and Chin [1] conducted a study on the structural qualities of concrete. They focused on two types of concrete: normal-strength concrete (NSC) and high-strength concrete (HSC). These types of concrete are often used in construction because they are water-resistant and have plenty of available resources, as emphasized by Solanki and Zaman. Ultra High-Performance Concrete (UHPC) has been used for decades to strengthen materials by incorporating fibers. Its composition and geometry increase tensile strength and energy absorption, making its structural design intricate. UHPC uses reactive powder concrete principles to enhance uniformity and minimize defects [2, 3]. Karim and Shafei (2022) [4] explored various fiber types, including natural fibers and synthetic fibers, to enhance the strength and tensile strength of UHPC, highlighting their potential benefits. Bywalskiet al. and Yan et al. have shown that the inclusion of glass fibers in UHPC panels benefits their quality. These fibers improve the material's flexibility and mechanical strength, and the specific kind and quantity of fibers substantially impact these attributes [5, 6]. Amran's study [7] on UHPC matrices emphasizes the possibility of integrating organic fibers, such as carbon, into the substance. This integration can improve the material's tensile strength, ductility, and deformation behavior. UHPC provides improved longevity and capacity to withstand pressure, boosting overall stability and reducing the likelihood of shrinking. Fiber reinforcement enhances the reaction of the material after breaking, exhibiting the capacity to undergo several cracks under normal loads, thereby improving stability and quality. Abadel's research [8] highlights the superior corrosion resistance of Basalt fibers, which are stabilized oxide-based, compared to steel fibers and conventional steel reinforcement. These fibers maintain resistance even under mechanical stresses, with minimal cracking and spalling compared to steel fiber samples [9, 10]. Basalt fibers can be dispersed within a matrix higher than steel fibers in concrete, improving the composite material's mechanical properties while using less fiber overall [11]. The growing use of basalt reinforcement is attributed to sustainable sourcing and energy reduction in manufacturing, with life cycle assessments showing lower carbon footprints than synthetic polymer fibers or steel production [12, 13]. To enhance pullout resistance, various steel fiber geometries, such as straight, hooked, spiral, and crimped configurations, have been commercially developed to avoid the issues of balling during mixing when the aspect ratio increases more than 60. Meanwhile, the basalt fibers, which have a very high aspect ratio, provide a very high surface area to contact with the matrix, preventing debonding. The ACI Committee [14] has created several steel fiber shapes to enhance pullout resistance and prevent clumping when mixed, with an aspect ratio greater than 60. Zheng and Ramirez emphasize the significant surface area of basalt fibers, which effectively inhibit debonding because of their elevated aspect ratio [9, 15]. Šavija and van Zijl [16] researcheda hybrid fiber system combining steel and aluminum, zinc-coated glass, and hybrid steel-polypropylene fibers. Their study emphasizes the synergistic interaction between these materials, which can improve crack control and distribution in UHPC, ultimately enhancing its structural integrity.Hybrid fiber systems are a promising approach to enhance the performance of concrete by incorporating diverse types of fibers. These systems combine the best feature of more used fibers within the UHPC matrix, leading to better performance than concretes containing onlysingle- fibers. The dispersion and alignment of various fiber geometries within the matrix contribute to more consistent crack bridging and multiple cracking [17–21]. Al-Shaarbaf and Hamood [22] are investigating the capabilities of UHPC in enhancing the performance of deep beams by using a combination of different reinforcing fibers. Experimental approaches like digital image correlation and finite element modeling are recommended for mapping the formation and advancement of cracks in hybrid mixtures. These techniques may also provide valuable insights into improving the interaction between fibers at a microstructural level.This study aims to analyze and describe the behavior of UHPC deep beams reinforced with a combination of steel and basalt fibers. It will investigate the impact of modifying the hybrid fiber ratio on the mechanical strengths of the composite and its shear load-deformation response. The primary goal is to evaluate the effects of steel fiber specimens with single and hybrid fibers on the behavior of the UHPC deep beam, examine the impact of these fibers on the UHPC matrix to withstand generated stresses, determine the optimal volume fraction of basalts and hybrid fibers, and compare extracted results by examining the crack pattern in UHPC deep beams reinforced by hybrid fibers:fibers and basalt.

Experimental work

Test specimens

An analysis was performed on a simply supported deep beam constructed from Ultra-High Performance Concrete (UHPC) to examine their response and behavior under shear forces. The deep beams were reinforced using steel fibers; basalt chopped fibers separately, and a combination of basalt and steel fibers. Then, they were compared to UHSC as the control specimen and compared with samples with steel fiber specimens. The variables considered were variables such as volume of fraction and shear span to effective depth ratio a/d. A total of 55 cylindrical specimens of UHPC and Ultra-High Strength Concrete (UHSC) were manufactured, in addition to 22 prisms and 44 cubes,to conduct compression tests, as shown in Figure 1. The UHPC deep beams were designed to comply with ACI 19 requirements [23]. They have identical cross-sections, with a web width of 100 mm and a total height of 300 mm. The beams have a length of 1200 mm and a clear span of 1050 mm. Additionally, they maintain a consistent longitudinal reinforcement ratio, as illustrated in Figure 2. The research objective was

Figure 1: All produced UHPC deep beams.



Figur 2: Steel reinforcement detail of all tested specimens.

to guarantee shear failure in UHPC deep beams. The deep beams were categorized into four classes as follows:

1. The first group had a single deep beam specimen that lacked fibers labeled as UHSC.
2. The second set had five deep beams with varying amounts of steel fibers.
3. The third set had five deep beams, each containing varying percentages of basalt, equivalent to the fraction volume utilized in steel fiber deep beams.
4. The fourth group, hybrid specimens, consisted of two kinds of fibers in the concrete deep beam specimensin differentvolumes of fraction, basalt and steel fibers, as shown in Table 1.

The deep beams were strengthened using three bars with a diameter of 20 mm each and a consistent reinforcement ratio of 0.0355%. Transverse shear reinforcement was implemented by using 4 mm bars and closed stirrups positioned at the supports. Figure 2, depicts the reinforcement configuration and specific specifications about the shape and dimensions of the deep beams.

Materials used in the mixtures of UHPC

Steel fibers

The study employed microsteel fibers from HONGTU Steel Fiber Product Company, coated with a copper film to achieve a glossy appearance. The utilization of these fibers is prevalent in UHPC and RPC owing to their exceptional tensile strength and enhanced concrete characteristics. The products conform to the ASTM A820/A820M-11 standards, and their characteristics are outlined in Table 6, as illustrated in Figure 3,b.

Table 1: Coding and variables used for deep beam specimens

		Fiber content								
		Steel fibers				Basalt fibers				
		Volume of fraction V_f %				The volume of fraction V_f%				
Group	Deep beam code	0.25	0.50	0.75	1.00	0.25	0.50	0.75	1.00	a/d ratio
1	D0–1.8									1.8
2	D 0.50S–1.8	■	■							1.8
	D0.75S–1.8	■	■	■						1.8
	D1.00S–1.8	■	■	■	■					1.8
	D1.00S–1.4	■	■	■	■					1.4
	D1.00S–1.0	■	■	■	■					1.0
3	D 0.50B–1.8					■	■			1.8
	D0.75B–1.8					■	■	■		1.8
	D1.00 B–1.8					■	■	■	■	1.8
	D1.00 B–1.4					■	■	■	■	1.4
	D1.00 B–1.0					■	■	■	■	1.0
4	D 0.25B-0.75S-1.8	■	■	■		■				1.8
	D 0.50B-0.50S-1.8	■				■	■			1.8
	D 0.75B-0.25S-1.8	■	■			■	■	■		1.8
	D 0.50B-0.50S-1.4	■	■			■	■			1.4
	D 0.50B-0.50S-1.0	■	■			■	■			1.0

■ Basalts Fibers, ■ Steel Fibers, □ no fibers

Table 2: Specimen's mixtures physical properties

Mix ID	Fiber type	Vf%	Fc MPa	Ft MPa	Flexural strength Frf, MPa	Elastic modulus Es
M0	fibers	0.00	103.4	8.0	15.0	34.6
M0.5 S	steel	0.50	112.5	10..0	17.3	37.6
M0.75S	steel	0.75	126.9	13.0	19.7	41.2
M1.00S	steel	1.00	137.2	15.2	21.0	45.5
M0.50B	basalt	0.50	148.8	7.3	14.4	41.4
M0.75B	basalt	0.75	156.4	8.5	16.4	44.2
Mb1.0B	basalt	1.00	145.4	8.2	17.0	41.4
M0.25B-0.75S	hybrid	1.00	137.9	12.7	19.3	38.3
M0.50B-0.50S	hybrid	1.00	141.4	10.0	16.7	39.9
M0.75B-0.25S	hybrid	1.00	133.3	9.5	17.1	41.1

Basalt fibers

Basalt fibers are organic fibers characterized by exceptional durability, tensile strength, and resistance to corrosion, moisture, and chemical substances. The fibers are derived from basalt rocks formed during prehistoric volcanic eruptions and are produced by melting basalt stones in furnaces without chemical additives. Basalt fibers can enhance strength, minimize micro-cracks, and improve the resistance of concrete to frost and water. When comparing basalt and steel fibers in reinforced concrete, it is observed that adding three kilograms of basalt fibers per cubic meter of concrete can result in a 29% increase in flexural strength. On the other hand, adding 25–45 kilograms of steel fibers can lead to a 12–17% increase in flexural strength. To prevent the formation of lumps, it is advisable to refrain from adding fibers towards the end of the mixing process (Figure 3A).

Composition of UHPC Mixture

The study investigates the composition of UHPC, a blend of fine and ultra-fine materials, and its strength and w/em ratio. It tests 15 trial mixtures, focusing on compressive and tensile strength and interior composition homogeneity. The binder makes up 50% of the total content and significantly impacts strength. The optimal dosage of silica fume to cement is 3.69%. Sand acts as a restraining agent, minimizing empty spaces and alleviating self-induced contraction. The optimal cement-to-sand ratio is between 1.0 and 1.1, with a sand content of 1.076%, as illustrated in Table 4. The study also uses three different proportions of basalt fibers.

Test setup and instruments

The AL Shatra Technical Institute laboratory employed a hydraulic loading system with a capacity of 1000 kN to conduct tests on deep UHPC beams. An LVDT was strategically positioned to measure deflection, while high-resolution cameras documented crack behavior and progression. Data logger devices were connected to load cells positioned beneath support structures and subjected to two-point loads, as shown in Figure 3. The study examined the tensile strength of UHPC deep beams by monitoring the test outcomes using webcams, guaranteeing precise measurements of compressive, split tensile, modulus of elasticity, and bending strength.The experiment employed four roller supports with a load-bearing capacity of 1000 kN, designed for the load-transfer and load-receiving devices. A load cell with a maximum capacity of 500 kN was placed under the support structure. The final two rollers were combined to enhance the performance of the load transfer devices. Load cells were measured, and the applied load on each side was compared with the received load at the base of the

Table 3: Steel and basalt fiber characteristics

Properties	Steel fiber	Basalt fiber
shape	Round and straight	Short filament that has been chopped up
Material	The low proportion of carbon steel wire, covered copper	Basalt
Radius, mm	0.1	0.008 – 0.009
Length, mm	12	12
Tensile strength, MPa	2850	2400 - 4800
The fiber density, kg/m³	7810	2825
Aspect ratio	60	--

Provided by the manufacturer catalog note

Table 4: Chosen UHPC mix proportions

Ordinary Portland cement (ASTM). kg/m³	Condensed silica fume(s). kg/m³	Quartz s and kg/m³	Water kg/m³	Viscocrete Hi-Tech Sika 1316 kg/m³
975	225	1050	196	36

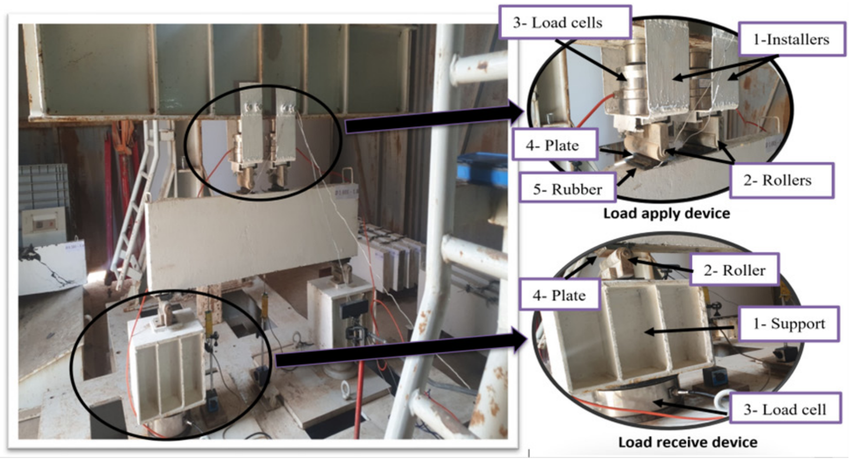


Figure 3: The test setup and instruments.

supports. A hydraulic pressure device suspended the support from its horizontal steel beams.It connects all the measurement instruments to the PC.

Results and Discussions

The deep beam characteristics and crack pattern

The study examines crack patterns in UHPC deep beams, revealing the significant impact of fiber reinforcements on structural strength. The analysis of crack orientation, intensity, and propagation helps optimize fiber reinforcement strategies for future UHPC designs. The study reveals that basalt fibers exhibit brittle failure, highlighting the importance of fiber reinforcement in controlling failure mechanisms and improving UHPC beams' shear capacity [24]. The addition of steel fibers to UHPC deep beams results in several changes in the observed cracks in the tested specimens. The load-midspan deflection measurements at different loading stages demonstrate that cracks in steel

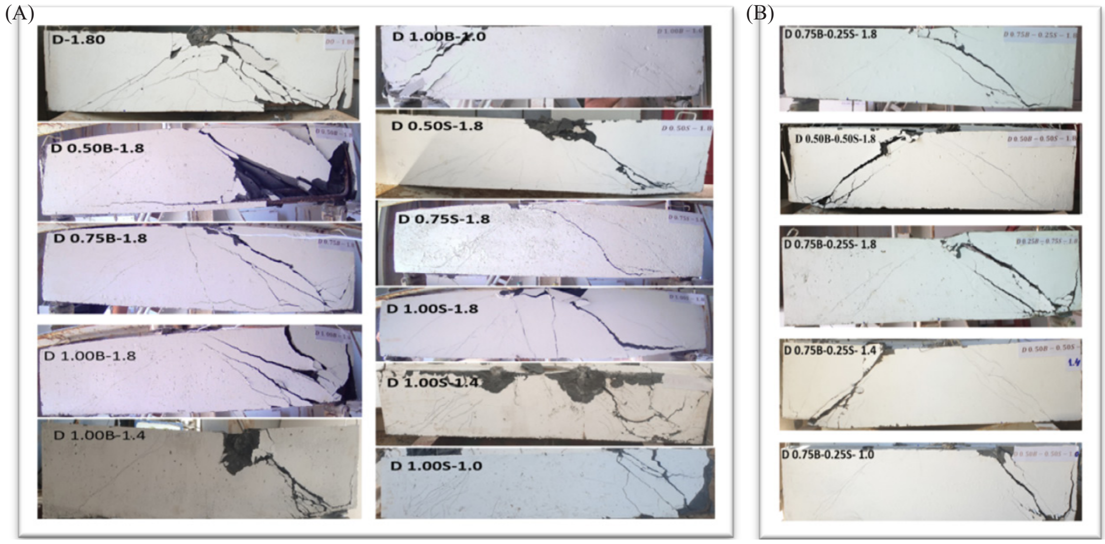


Figure 4: Crack pattern of the single and hybrid fibers UHPC deep beam.

fiber-reinforced specimens exhibit considerably greater width and length in comparison to cracks in basalt specimens [12, 24]. Hybrid fiber reinforcement can improve structural performance by combining the characteristics of different fiber types. Steel fiber-reinforced specimens display higher cracks, which are more easily detectable and spread over a larger surface area. Increasing the proportion of basalt fibers in hybrid specimens delays the occurrence of first and diagonal cracks, leading to a load-deflection curve that approaches the vertical axis of the load value. Hybrid fiber-reinforced UHPC deep beams show more beneficial performance than UHPC reinforced exclusively with single fibers. This enhances durability, ductility, and overall performance, increasing shear capacity and ductility. Figure 4 illustrates the Crack pattern of the single and hybrid fibers UHPC deep beam.

The impact Volume of the fraction

The effect of volume of fraction on the behavior of the steel fiber-reinforced ultra-high performance concretedeep beams

Increasing the volume fraction of steel fibers from 0.0% to 0.5% and 1.0% led to increasing mid-span deflection at diagonal shear crack by 5.18%, 12.95, and 67.36% while at the ultimate load increase by 45.34%, 61.12%, and 78.57%, respectively, over the deflection of non-fibrous UHSC deep beam, as shown in Figure 5. It could be seen that, at the first loading stage, the deflection for the same load decreased as the volume fraction of steel fibers increased. This behavior could be attributed to the role of steel fibers in raising the tensile strength and modulus of elasticity, which increased with the volume fraction of steel fibers. At ultimate loads, the deflection was increased considerably as the volume fraction of steel fibers increased. This behavior could explain that fibers' action started after the initiation of cracking. The fibers acted on connecting the counterpart sides along the cracks to enhance the stiffness of the beam. Thus, the specimen acquired further resistance to the deflection progression and retarding the expansion of cracking. That would retard the increase of deflection with increasing fiber content. Hence, the beam could resist greater loads and deflection before failure. The ductility ratio increased in the presence of steel fibers, as shown in Table 5. The ductility ratio increased by 38.46, 42.98, and 6.78% when steel fiber content was increased by 0.5, 0.75, and 1.0%, respectively, over that of non-fibrous UHSC deep beam.

In terms of diagonal shear cracks, steel fibers enhanced the ability to resist the diagonal shear cracks appearance in the tested UHPC deep beam by 50.88.49, 52.21, and 68.80% over the non-fibrous UHSC deep beam upon using steel fibers at 0.5, 1.0, and 1.5%, respectively. That could be explained as more energy was required to propagate the cracks since most of these cracks were intersected by the

Table 5: The impact of steel fiber volume fractions on mid-span deflection, diagonal cracking load, and ultimate load while maintaining a constant a/d.

Deep beem	Vf %	a/d	V_{di} kN	δ_{di} mm	$\delta_{di}/\delta_{di\,D0}$ %	φ	V_u kN	δ_u mm	$\delta_u/\delta_{u\,D0}$%	V_{di}/V_{diD0} %	Net rise V_{di}/V_{diD0}%	$V_u/V_{u\,D0}$ %	Net rise V_u/V_{uD0} %
D0–1.8	0.00	1.80	137.00	1.93	0.00	2.21	279.00	4.27	0.00	100.00	0.00	100.00	0.00
D 0.5S–1.8	0.50	1.80	162.00	2.03	5.18	3.06	334.33	6.21	45.34	118.25	18.25	119.83	19.83
D0.75S–1.8	0.75	1.80	206.00	2.18	12.95	3.16	375.23	6.88	61.12	150.36	50.36	134.49	34.49
D1.0S–1.8	1.00	1.80	272.00	3.23	67.36	2.36	433.12	7.63	78.57	198.54	98.54	155.24	55.24

Table 6: The impact of basalt fiber volume fractions on mid-span deflection, diagonal cracking load, ultimate load, and load increase percentages while maintaining a constant a/d ratio

Deep beem	Vf %	a/d	V_{di} kN	δ_{di} mm	$\delta_{di}/\delta_{di\,D0}$%	φ	V_u kN	δ_u mm	$\delta_u/\delta_{u\,D0}$ %	V_{di}/V_{diDo} %	Net rise V_{di}/V_{diD0}%	$V_u/V_{u\,D0}$ %	Net rise V_u/V_{uD0} %
D0–1.8	0.00	1.80	137.00	1.93	0.00	2.21	279.00	4.27	0.00	100.00	0.00	100.00	0.00
D 0.5B–1.8	0.50	1.80	203.00	2.16	11.92	2.24	311.43	4.83	13.11	148.18	48.18	111.62	11.62
D0.75B–1.8	0.75	1.80	233.00	3.12	61.66	1.71	362.93	5.33	24.82	170.07	70.07	130.08	30.08
D1.0B–1.8	1.00	1.80	256.00	3.38	75.13	1.42	359.05	4.81	12.64	186.86	86.86	128.69	28.69

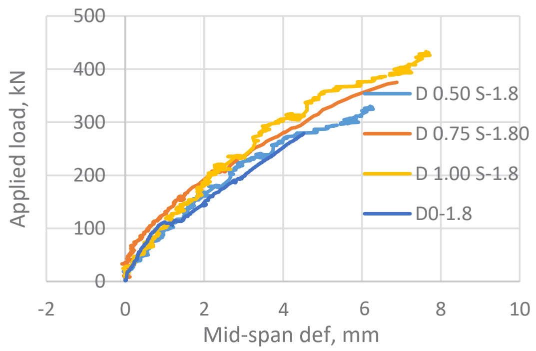


Figure 5: Load-deflection curve of the UHPC deep beam reinforced by steel fibers compared with the non-fiberous UHSC deep beam.

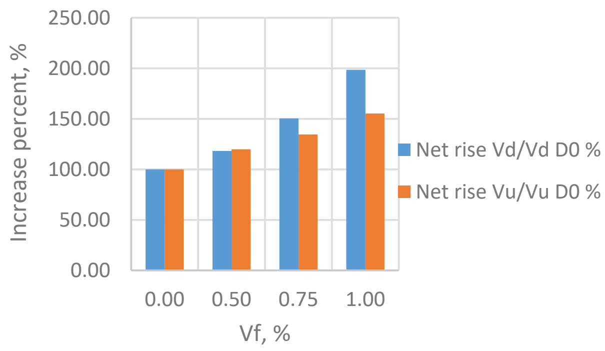


Figure 6: Rise percent in diagonal shear crack and ultimate shear cracks capacity of UHPC deep beams having steel fibers compared with non-fibrous UHSC deep beam with the non-fiberous UHSC deep beam.

steel fibers, which were oriented in different directions. Therefore, energy was required to overcome the bonding forces between fibers and the attached concrete. Referring to the load-deflection diagrams in Figure 5, The diagram demonstrates that the final recorded deflections increase with an increase in steel fiber content. The initial lines are nearly identical before cracking, but slight changes occur due to the UHPC nature. At higher loads, the deflection decreases as the Vf increases, attributed to steel fibers' contribution to tensile strength and elastic modulus.

The effect of volume of fraction on the behavior of the basalt fiber-reinforced ultra-high performance concretedeep beams

Table 6 illustrates the variation in load as the mid-span deflection changes for UHPC deep beams reinforced with basalt fibers compared to the D0-1.8. The deflection at the diagonal shear crack increased by 11.92%, 61.66%, and 75.13% when the basalt fiber content increased from 0.5% to 1.0%. Similarly, the deflection increased by 13.11%, 24.82%, and 12.62% at the ultimate shear load. Adding a precisely measured 1.0% volume fraction of basalt fibers results in a 28.69% increase in the ultimate shear capacity. However, this increase is slightly lower than the recorded value of 0.75%, corresponding to a 30.08% increase. Utilizing basalt fibers at concentrations of 0.5%, 0.75%, and 1.0% leads to a moderate enhancement in the ultimate shear capacity, thereby substantially improving the capacity to resist diagonal shear cracking. The utilization of basalt fibers at the specified proportions resulted in a respective increase of 111.62%, 130.08%, and 128.19% in the ultimate shear capacity. The diagonal shear capacity increased by 48.18%, 70.07%, and 86.86% compared to the D0-1.8, as present in Figure 8.

The influence of basalt fibers on the ductility ratio by using 0.5, 0.75, and 1.0% volume of fraction led to reduce the ductility ratio by 1.06, -22.78, and -35.68%, respectively, compared to non-fibrous UHSC deep beam.

The slight differences in the amount of basalt fiber used in each mixture were still apparent in their different maximum load capacities, as indicated by the small deviations between the curves. The graph illustrates the correlation between the test beams' applied load and the mid-span deflection. As shown in the figure, once the initial diagonal shear cracking load is exceeded, the load-deflection curves for all basalt fiber mixes do not show a tendency to move horizontally. Instead of observing a leveling reduction in the load capacity followed by a gradual decline, the beams underwent a sudden and rapid fracture marked by brittleness once the maximum load was reached, as shown in Figure 7.

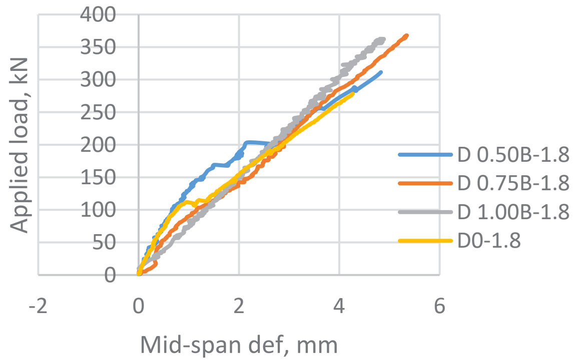


Figure 7: Load-deflection relationship of UHPC deep beams having basalt fibers compared with non-fibrous UHSC deep beam

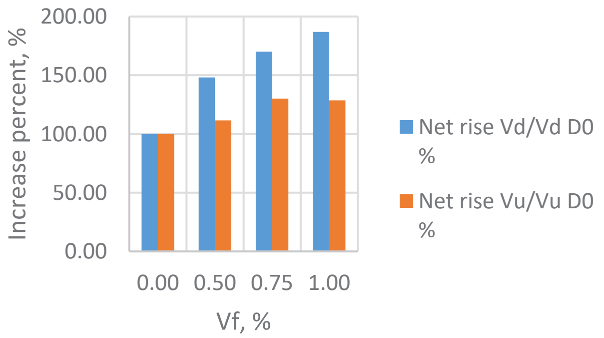


Figure 8: Rise percent in diagonal shear crack and ultimate shear cracks capacity of UHPC deep beams having basalt fibers compared with non-fibrous UHSC deep beam

The effect of volume of fraction on the behavior of the Hybrid fiber-reinforced ultra-high performance concrete HFR-UHPC deep beams

Table 7 presents the extracted results, which indicate the significant influence of the fibers in the matrix. The study explores the use of hybrid fibers in UHPC to enhance diagonal shear and ultimate shear load performance, comparing the structural characteristics of UHPC to a control sample, UHSC (D0-1.8), as depicted in Figure 9. The use of hybrid fibers in UHPC specimens significantly improves their performance, with improvements in diagonal shear and ultimate shear load depending on the rate of basalt or steel used within the matrix. Basalt fibers enhance load-carrying capacity during initial loading, while steel fibers enhance maximum load-bearing capacity and resistance to failure. Figure 10 unambiguously demonstrates the load-midspan deflection behavior for the 3% hybrid fibers, denoted as a, b, and c.Adding 0.25%, 0.50%, or 0.75% of basalt fibers to hybrid specimens, which were already reinforced with 1%, significantly delays the initiation of diagonal fractures. The diagonal shear crack experiences growth rates of 67.81%, 81.75%, and 97.08%, respectively. The shear capacity values in the corresponding records were 44.71%, 25.81%, and 32.33%. Consequently, the beams acquired additional energy from the increased basalt volume in the matrix, resulting in enhanced performance in diagonal shear cracking compared to steel fibers. The steel fibers exhibited a higher level of improvement in their maximum shear capacity when compared to the basalt fibers.

The study's ductility calculation demonstrates a strong correlation between the ductility and the percentage of basalt fibers in the matrix. The recorded percentages for the hybrid specimens, with

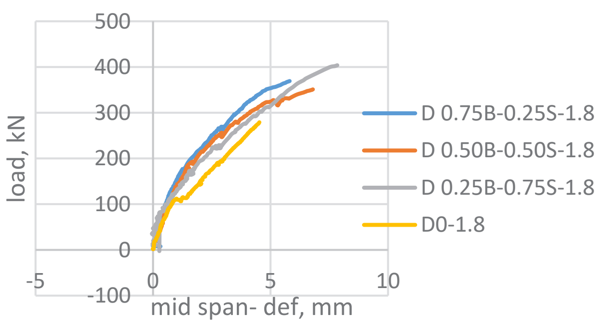


Figure 9: Load-deflection relationship of UHPC deep beams having hubrid fibers compared with non-fibrous UHSC deep beam

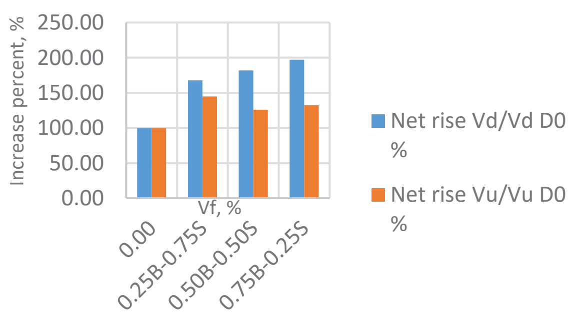
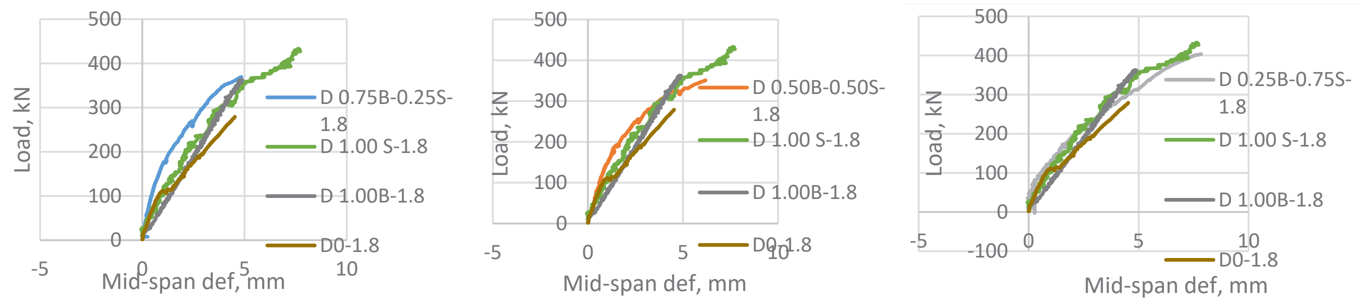


Figure 10: Rise percent in diagonal shear crack and ultimate shear cracks capacity of UHPC deep beams having hybrid fibers compared with non-fibrous UHSC deep beam



(A) Hybrid fiber involve 0.75 basalts to 0.25 steel fibers

(B) Hybrid fiber involve 0.50 basalt to 0.50 steel fibers

(C) Hybrid fiber involve 0.25 basalt to 0.75 steel fibers

Figure 11: Compare the load-deflection curve of the UHPC deep beam reinforced by 1% hybrid fibers and 1% single fibers comparedto the non-fibrous UHSC deep beam

basalt fiber concentrations of 0.25, 0.5, and 0.75, are 23.98%, 10.84%, and 9.5%, respectively. The introduction of more basalt fibers alongside the steel fibers will decrease the ductility of the specimens, as the basalt fibers exhibited a notable enhancement in diagonal shear load capacity and vice versa. Figures 11, A, B, and C illustrate a positive correlation between the curve's distance from the vertical axis and the percentage of basalt fibers utilized in the matrix. Hence, the load-mid-span deflection can accurately represent the specimens' ductility.

The impact of shear span ratio a/d

a/d Ratio of Steel Fibers UHPC deep beams

Figure 12 shows the impact of the shear span-to-depth (a/d) ratio on the mid-span deflection of deep beams made of ultra-high-performance concrete (UHPC) reinforced with steel fibers. The study reveals that deflection increases as the a/d ratio increases, with the highest load capacity observed in the D 1.00 S-1.0 configuration. This is due to the transition from a shear-dominated to a flexural-dominated response as the a/d ratio increases.The longer shear span results in higher bending moment due to increased moment arm for a given shear force, leading to higher flexural stresses and more significant mid-span deflections. Higher ratios strengthen flexural effects, leading to more deflection and less load-bearing capacity.A comparison between UHPC deep beams containing steel fibers and control deep beams with an a/d ratio of 1.8 (D1.0S-1.8) is presented in Figure 13. The crack capacity and ultimate shear crack capacity significantly increased with a decrease in the a/d ratio, as shown in the bar chart, Figure 15.By reducing the a/d ratio to 1.40, the diagonal shear crack capacity increases by approximately 150%, and the ultimate shear crack capacity increases to approximately 175%. This indicates a significant enhancement in the ability of the beams to resist shear forces, implying that adjusting the amount of fibers in the UHPC mix can greatly improve the structural effectiveness of the beams.At a/d 1.00, the ratio of the net increase in diagonal shear crack capacity is approximately 175%, while the ultimate shear crack capacity ratio increases significantly to about 225%. The results show that hybrid fibers play a crucial role in greatly improving the shear resistance of UHPC deep beams.In conclusion, Table 8 demonstrates how the shear span ratio can enhance the shear crack resistance of UHPC deep beams. The results indicate that precise adjustments to the a/d ratio can result in substantial improvements in structural performance, providing valuable knowledge for the design and use of UHPC in construction.

a/d Ratio of Basalt Fibers UHPC deep beams

Figure 14 illustrates the relationship between load and mid-span deflection in UHPC deep beams with 1.0% basalt fiber content.The study tested the beams at different a/d ratios to understand the

Table 7: The impact of hybrid fiber volume fractions on mid-span deflection, diagonal cracking load, ultimate load, and load increase percentages while maintaining a constant a/d

Deep beem	Vf %	a/d	V_{di} kN	δ_{di} *mm*	$\delta_{di}/\delta_{di\,D0}$ %	φ	φ / φ_{Do} %	V_u kN	δ_u *mm*	$\delta_u/\delta_{u\,D0}$ %	V_{di}/V_{diD0} %	Net rise V_{di}/V_{diD0} %	$V_u/V_{u\,D0}$ %	Net rise V_u/V_{uD0} %
D0–1.8	0.00	1.80	137	1.93	0.00	2.21	0.00	279.00	4.27	0.00	100.00	0.00	100.00	0.00
D 0.25B-0.75 S-1.8	0.25B-0.75S	1.80	229	2.86	48.19	2.74	23.98	403.75	7.83	83.37	167.81	67.81	144.71	44.71
D 0.50B-0.50 S-1.8	0.50B-0.50S	1.80	249	2.78	44.04	2.45	10.84	351.00	6.80	59.25	181.75	81.75	125.81	25.81
D 0.75B-0.25 S-1.8	0.75B-0.25S	1.80	270	2.64	36.79	2.20	9.95	369.21	5.81	36.11	197.08	97.08	132.33	32.33

Table 8: Mid-span deflection, diagonal shear crack, ultimate shear capacity, and percent increasing of deep beams with steel fibers at variable a/d ratio

Deep beem	Vf %	a/d	V_{di} kN	δ_{di} *mm*	$\delta_{di}/\delta_{di\,(D1.0S-1.8)}$ %	φ	V_u kN	δ_u *mm*	$\delta_u/\delta_{u\,(D1.0S-1.8)}$ %	$V_{di}/V_{di(D1.0S-1.8)}$ %	Net rise $V_{di}/V_{di(D1.0S-1.8)}$ %	$V_u/V_{u(D1.0S-1.8)}$ %	Net rise Vu/ $V_{u(D1.0S-1.8)}$ %
D1.0S–1.8	1.00 S	1.80	272	3.23	0.00	2.36	433.12	7.62	0.00	100.00	0.00	100.00	0.00
D1.0S–1.4	1.00 S	1.40	334	1.92	-28.17	1.95	605.46	3.36	-40.68	122.79	22.79	163.36	63.36
D1.0S–1.0	1.00 S	1.00	384	2.01	-37.77	2.03	799.02	3.87	-46.46	141.18	41.18	234.52	134.52

Table 9: Mid-span deflection, diagonal shear crack, ultimate shear capacity, and percent increase in deep beams with basalt fiber content at variable a/d ratio

Deep beem	Vf %	a/d	V_{di} kN	δ_{di} *mm*	$\delta_{di}/\delta_{di\,(D1.0B-1.8)}$ %	φ	V_u kN	δ_u *mm*	$\delta_u/\delta_{u\,(D1.0B-1.8)}$ %	$V_{di}/V_{di(D1.0B-1.8)}$ %	Net rise $V_{di}/V_{di(D1.0B-1.8)}$ %	$V_u/V_{u\,(D1.0B-1.8)}$ %	Net rise $V_u/V_{u(D1.0B-1.8)}$ %
D1.0B–1.8	1.00B	1.80	256	3.38	0.00	1.42	359.05	4.81	0.00	100.00	0.00	100.00	0.00
D1.0B–1.4	1.00B	1.40	383	2.79	-17.46	1.57	562.13	4.39	-8.82	149.61	49.61	156.56	56.56
D1.0B–1.0	1.00B	1.00	466	2.11	-37.57	1.53	728.62	3.22	-33.09	182.03	82.03	202.93	102.93

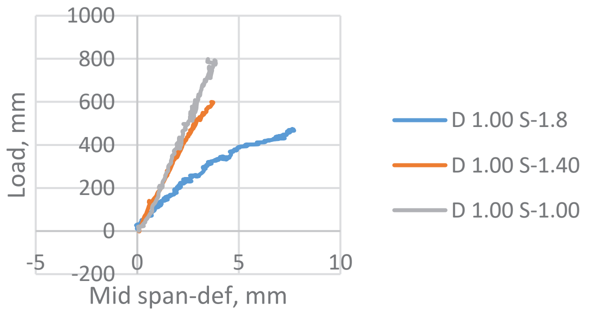


Figure 12: Load-deflection behavior of steel fiber-reinforced ultra-high performance concrete (UHPC) deep beams with different (a/d) variations.

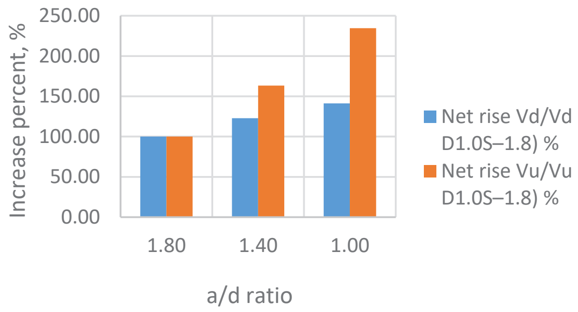


Figure 13: Rise percent in diagonal shear crack and shear cracks capacity of UHPC deep beams having hybrid fibers compared with D1.0S–1.8

impact of the a/d ratio on deflection.When using basalt fibers, the deflection at the ultimate load decreases as the a/d ratio decreases. The deep beams were tested at a/d values of 1.0, 1.4, and 1.8, resulting in 3.22, 4.39, and 4.81 mm deflections, respectively. This behavior was similar to using steel fibers. Otherwise, the basalt specimens' recorded value is less than that of steel fibers. The same goes for steel fibers. Table 12 shows that basalt specimens' ductility ratios are more closed. Otherwise, all values are less than the achieved values of specimens reinforced by steel fibers. With the same a/d ratios of 1.0, 1.4, and 1.8, the ductility was 1.53, 1.57, and 1.42.The tabulated data reveals that the a/d ratio significantly influences the structural performance of basalt fiber-reinforced UHPC deep beams. The deep beam configurations have better shear resistance and capacity, as shown by the fact that they have lower midspan deflections under ultimate load, better control of shear cracks, and higher ultimate shear capacities. The values of "Net rise Vd/Vd (D1.0B-1.8)%" and "Net rise Vu/Vu (D1.0B-1.8)%" in Figure 15 indicate the degree to which the a/d improves the Vdi and the Vu. Nevertheless, the Vdi net rise exhibits the most significant enhancement in the net increase of the Vu in comparison to the D1.0B-1.8 deep beam with a/d = 1.8. These measurements tell us a lot about how changing the a/d and using basalt fiber reinforcement can change the shear performance of UHPC deep beams. All the test results taken from the basalt fiber specimens show improvement over the values of the steel fiber specimens. The only exception is the diagonal shear crack load, which is higher than the steel specimens. Table 12 presents the essential research findings on the structural performance of deep beams constructed with ultra-high-performance concrete (UHPC) reinforced with basalt fibers.

a/d Ratio of Hybrid Fibers HFR-UHPC deep beams

Figure 16 shows the deflection responses of deep beam specimens made of hybrid fiber-reinforced ultra-high performance concrete (HFR-UHPC) under monotonic loading. The study analyzes the impact of the shear span-to-depth ratio (a/d) on these responses. The load-deformation behavior of these composites provides insights into their nonlinear structural performance. When the a/d ratio decreases from 1.8 to 1.4 and then to 1.0, the deflection response changes. Deep beam specimens with lower a/d ratios show a more linear and brittle behavior after cracking, with a steeper ascending branch and decreased ultimate midspan deflection. This is due to the improved contribution of the tie-and-strut mechanism in deep beams with shorter shear spans.Figure 19 demonstrates the percentage increase in the diagonal shear cracking load (V_{di}) and ultimate shear capacity (V_u) of the HFR-UHPC deep beams compared to a reference specimen (D 0.50B-0.50S-1.8), supporting the previous observation. Increasing the fiber volume fraction (a/d) from 1.0% to 1.4% and 1.8% leads to a significant improvement in the net increase of $Vdi/Vdi_{(D\ 0.50B\text{-}0.50S\text{-}1.8)}$ and $Vu/Vu_{(D\ 0.50B\text{-}0.50S\text{-}1.8)}$, reaching approximately 157% and 200% respectively, for the a/d = 1.0 deep beam configuration. The significant enhancement in shear performance can be credited to the combined crack-bridging and toughening mechanisms

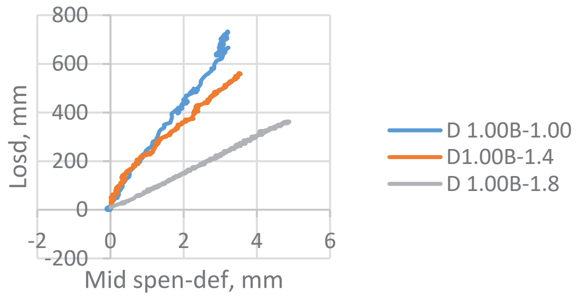


Figure 14: Load-deflection behavior of steel fiber-reinforced UHPC deep beams with different (a/d) variations.

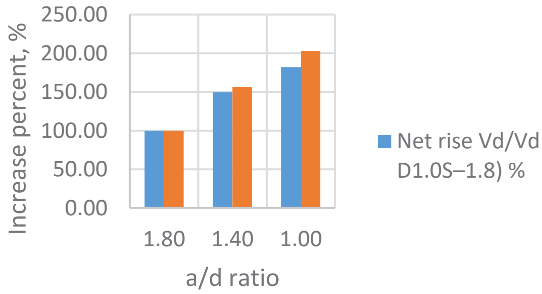


Figure 15: Rise percent in diagonal shear crack and ultimate cracks capacity of UHPC deep beams having basalt fibers compared with D1.0B–1.8

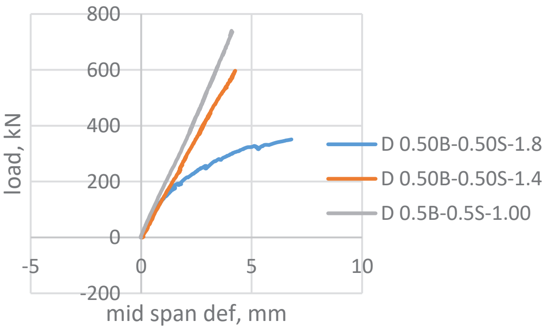


Figure 16: Load-deflection behavior of hybrid fiber-reinforced ultra-high performance concrete (UHPC) deep beams with different (a/d) variations.

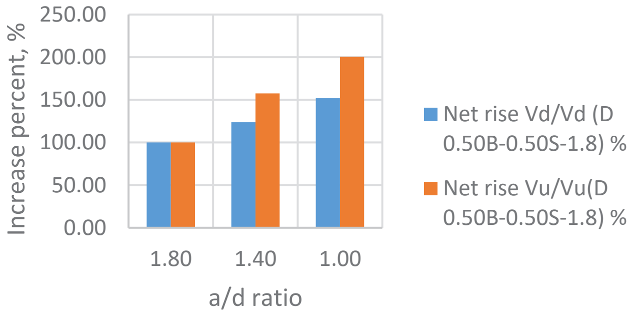
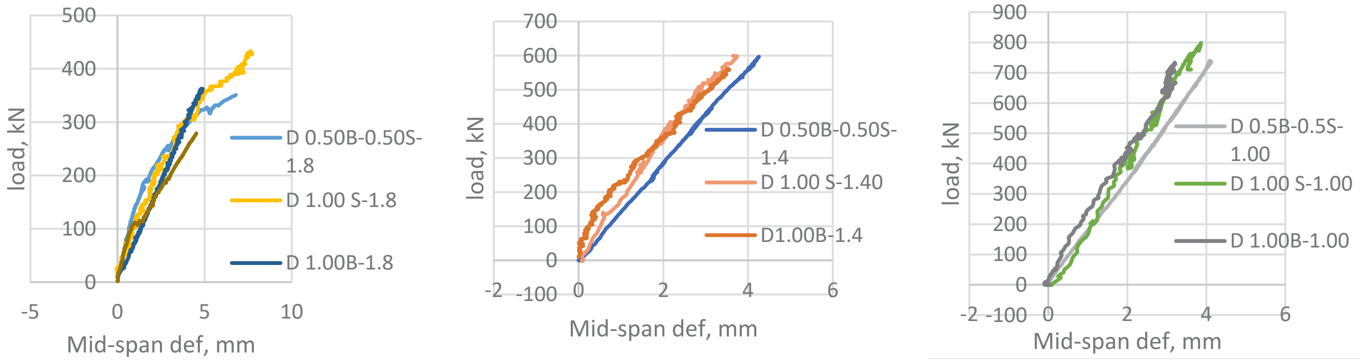


Figure 17: Rize percent in diagonal shear crack and ultimate shear cracks capacity of UHPC deep beams having hybrid fibers compared with D1.0S–1.8

caused by the hybrid reinforcement system of basalt and steel fibers. This system effectively reinforces the compressive struts and ties within the truss-like load transfer mechanism of the deep beam. Figures 17 provide a comprehensive understanding of the structural behavior of HFR-UHPC deep beam elements, enabling informed decisions about the best design and use of high-performance concrete systems. The load-mid span deflection curve of the hybrid UHPC deep beam reinforced with 0.5% basalt fibers and 0.5% steel fibers shows that basalt fibers play a significant role, delaying first cracks and raising diagonal shear load by 23% and 51% compared to specimens with a/d ratio 1.8.

Figure 18 A,B,C illustrates the load-mid span deflection curve of UHPC deep beams with 1% single fibers, steel or basalt, and hybrid fibers. The study reveals that a decrease in the shear span ratio reduces mid-span deflection and results in a more linear behavior. Basalt fibers increase shear diagonal crack load, while steel fibers increase ultimate shear capacity.

The study explores the mechanical response of a hybrid deep beam specimen made of steel and basalt fibers. The angular orientation of the specimen is modulated by the (a/d) ratio, requiring it to withstand increased stresses to achieve the required strain within the tensile reinforcement. As the tensile tie experiences elevated stresses, microcracks propagate within the surrounding ultra-high performance concrete (UHPC) matrix. These cracks progress from the central zone surrounding the tensile reinforcement toward the beam supports, resulting in diagonal cracking and widening until the specimen reaches its failure condition.The study reveals that the diagonal cracking load increases significantly as the a/d ratio decreases from 1.8 to 1.0, leading to increased arch action and excellent shear resistance before critical diagonal cracks. This reduction in midspan deflection indicates increased brittleness in deeper beam specimens. Hybrid fiber reinforcement has shown significant



(A) Behavior of single and hybrid fiber in UHPC with a (a/d) of 1.8

(B) Behavior of single and hybrid fiber in UHPC with a (a/d) of 1.4

(C) Behavior of single and hybrid fiber in UHPC with a (a/d) of 1.0

Figure 18: Compare the load- mid span deflection of single and hybrid fibers UHPC deep beams with volume of fraction 1% and the variable a/d ratio

efficacy in enhancing structural performance, with a specimen with an a/d ratio of 1.8 experiencing a 100% increase in net shear capacity and a 23% increase in ultimate shear strength. The study also found that ductility decreases from 2.58 for the specimen with an a/d ratio of 1.8 to 1.74 for the specimen with an a/d ratio of 1.0. Table 10 summarizes the salient experimental observations and provides key extracted results for the hybrid deep beam specimen.

The effects of the steel fibers and basalt fiber inside the matrix on the behavior of the load-mid span deflection curve

The load-deflection curves of ultra-high-performance fiber-reinforced concrete (UHPFRC) deep beams incorporating steel fibers exhibit variations that are contingent upon the specific characteristics of the fibers used, such as the type, volume fraction, a/d ratio, and application parameters [25]. The mid-span deflection plot versus the applied load shows that steel fibers have a more significant initial curvature than basalt fibers, meaning there are more microcracks in the matrix [26]. Steel fibers control crack width less than basalt fibers due to debonding, which facilitates microcrack propagation in the matrix, as illustrated in Figure 21. Cracking initiates at a specific load, increasing deflection and causing a nonlinear load-deflection curve. Steel fibers' discrete and discontinuous structure reduces their effectiveness in mitigating localized stress concentrations near cracks.Conversely, The load-deflection curve of deep beams reinforced with basalt fibers follows a linear pattern. The behavior of the basalt fibers on the load-deflection curve is clear and consistent. The load-deflection graph exhibits an upward trend across the entire loading range due to the high aspect ratio of basalt fibers, which form a uniform and extensive network within a UHPC matrix [27]. This uniform network is superior to steel fibers because it resists pullout forces and effectively prevents debonding. Furthermore, once initiated, it effectively stops the propagation of microcracks.Basalt fibers reduce crack formation and control crack width, while steel fibers enhance deep beam ductility and elongation capacity. Steel fibers have a 60 aspect ratio, but debonding is common under high loads, especially when applying loads [28].

Conclusion

The findings of this study can be indicated by the following:

- The addition of steel fibers to the UHPC deep beam greatly improves various properties, exceeding the performance of specimens reinforced with basalt fibers.

Table 10: Mid span deflection, diagonal shear crack, and ultimate shear capacity and percent increasing of deep beams with hybrid fibers content at variable a/d ratio

Deep beem	Vf %	a/d	$2V_{di}$ kN	δ_{di} mm	δ_{di}/δ_{di} $_{(0.50B\text{-}0.50S\text{-}1.8)}$ %	φ	$2V_u$ kN	δ_u mm	δ_u/δ_u $_{(0.50B\text{-}0.50S\text{-}1.8)}$ %	$V_{di}/V_{di(D\ 0.50B\text{-}0.50\ S\text{-}1.8}$ %	Net rise $V_{di}/V_{di(0.50B\text{-}0.50S\text{-}1.8)}$ %	$V_u/V_{u(D\ 0.50B\text{-}0.50\ S\text{-}1.8)}$ %	Net rise $V_u/V_{uD\ (0.50B\text{-}0.50S\text{-}1.8)}$ %
D 0.50B-0.50 S-1.8	0.50B-0.50S	1.80	270	2.64	0.00	2.58	369.21	6.80	0.00	100.00	0.00	100	0.00
D 0.50B-0.50 S-1.4	0.50B-0.50S	1.40	334	2.33	-11.74	1.78	581.68	4.15	-38.97	123.70	23.70	157.55	57.55
D 0.50B-0.50 S-1.0	0.50B-0.50S	1.00	410	2.35	-10.98	1.74	739.86	4.09	-39.85	151.85	51.85	200.39	100.39

- The incorporation of basalt fiber improves the performance of the matrix, especially during the initial stages of loading, by delaying the formation first crack and diagonal shear crack. The ideal basalt volume for a fraction is 0.75%, based on data indicating that a range of 0.6 to 1.0% provides the best performance.
- The inclusion of fibers in the matrix of the UHPC deep beam significantly improves its performance by favorably impacting the modulus of elasticity and tensile strength. This enhancement is especially advantageous for the compression zone (strut) of the UHPC deep beam being tested, as it effectively mitigates the formation of diagonal fractures that may result in the failure of the deep beam.
- The study analyzed the cracking behavior of UHPC reinforced by basalt fibers, revealing that while the fibers reduced crack propagation, they didn't prevent catastrophic failure under intense stress. The specimen was more likely to propagate before additional cracks developed, indicating the need for further strengthening or composite optimization to improve the material system's shear toughness.
- Basalt fibers have a high aspect ratio, providing a greater surface area for interaction with the concrete matrix and high pullout resistance. This high aspect ratio prevents debonding in basalt fiber-reinforced matrix. It delays microcrack formation and propagation until the fibers reach their maximum tensile stress threshold, ensuring a more durable and tensile-resistant matrix.
- The hybrid UHPC deep beam specimens use a combination of basalt and steel fibers, with the steel fibers having a higher modulus of elasticity and the basalt fibers absorbing stresses during early loading stages. The combination prevents crack formation and maintains the concrete's integrity, enhancing load-bearing and shear performance, and is a key factor in the improved structural behavior observed in these specimens.
- The hybrid specimen test's stiffness is primarily influenced by basalt fibers, resulting in minimal elongation and no debonding. Despite the same volume fraction and shear span ratio, all tested deep beams showed lower mid-span deflection under the same shear load.
- Once inclined shear cracks form at higher loads, typically indicated by a change in curve gradient, the mid-span deflection of steel fiber beams increases more rapidly with additional loading. This nonlinear profile indicates degrading shear performance as cracks propagate. Steel fibers are less effective at mitigating localized stress concentrations that drive crack growth in the shear span.
- The presence of basalt fiber in the hybrid matrix maintains a linear load-deflection relationship even after diagonal shear cracks, as the dense network distributes stresses more homogeneously, allowing for high crack control width.
- The hybrid UHPC specimens showed a single diagonal shear crack after failure, unlike basalt fiber specimens which broke into smaller pieces. This was due to intact basalt fibers in the hybrid matrix, which resisted cracking under stress below the maximum tensile capacity of the filaments.

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