

Article

Experimental Study on Bending Behaviors of Ultra-High-Performance Fiber-Reinforced Concrete Hollow-Core Slabs

Liuyiyi Yang ^{1,*}, Quan Shen ^{1,*} , Miao Lu ¹ and Xiaohua Yang ^{1,2}

¹ School of Civil Engineering, Hunan University of Technology, Zhuzhou 412007, China; yangliuyiyi@hut.edu.cn (L.Y.); lumiao126@outlook.com (M.L.); yangxiaohua9988@outlook.com (X.Y.)

² Blackstone Management Consulting Co., Shenzhen 518000, China

* Correspondence: shenquan@hut.edu.cn

Abstract: Ultra-high-performance fiber-reinforced concrete (UHPFRC) has the characteristics of high strength, toughness, and excellent crack resistance. In order to fully utilize the high-strength properties of UHPFRC and reduce the structural weight and construction cost, solid slabs can be fabricated into hollow-core slabs or composite sandwich slabs. In order to further analyze the mechanical properties and mechanism of action of UHPFRC hollow-core slabs, one solid slab and two hollow-core slabs with the same geometric dimensions, reinforcement, and steel fiber volume content are designed in this paper, and their stress performance under a static load was investigated using a four-point bending test. The research results show that the UHPFRC hollow-core slab is anisotropic, and the bending stiffness of the section with parallel, distributed tubes is slightly smaller than that of the solid slab. The addition of steel fibers can greatly limit the development of cracks on a slab surface, so the elastic limit of a UHPFRC hollow slab is higher than that of a conventional concrete hollow slab. The whole bending process is roughly divided into the elastic stage, the elastic–plastic stage, and the plastic stage; the crack development process on the bottom of the slab can be classified into the cracking stage, the stable crack development stage, and the rapid propagation stage. In the elastic stage, the cross-sectional deformation of the UHPFRC hollow-core slab in the bending process still satisfies the assumption of a flat section. A row of parallel, round tubes on the neutral axis has a little effect on the cracking load, bearing capacity, and deformation capacity of the UHPFRC slab. By conducting the comparative analysis of the hollow rate and bearing capacity, when the hollow rate reaches 13.57%, the comprehensive weight of the solid slab is reduced by 13.16%, the cracking moment is slightly reduced, and the ultimate load is only reduced by 8.78%. Under the premise of meeting the bearing capacity, the hollow rate of the UHPFRC hollow-core slab can be appropriately increased to save money and energy.

Keywords: ultra-high-performance fiber-reinforced concrete (UHPFRC); hollow-core slab; steel fiber; mechanical properties; economic performance



Academic Editor: Cedric Payan

Received: 28 January 2025

Revised: 18 February 2025

Accepted: 24 February 2025

Published: 4 March 2025

Citation: Yang, L.; Shen, Q.; Lu, M.; Yang, X. Experimental Study on Bending Behaviors of Ultra-High-Performance Fiber-Reinforced Concrete Hollow-Core Slabs. *Buildings* **2025**, *15*, 812. <https://doi.org/10.3390/buildings15050812>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

With the improvement in science and technology and environmental awareness, people are demanding a better performance from engineering materials, thus promoting the development of concrete with high strength, toughness, and durability. Ultra-high-performance fiber-reinforced concrete (UHPFRC), with its excellent mechanical properties and long-term durability, is gradually being regarded as an ideal construction material for civil engineering [1–6]. In recent years, other researchers have improved the compressive strength and material properties of concrete [7–11]. The incorporation of discontinuous

short fibers has been proved to be an effective way to improve the mechanical properties of concrete materials, especially in terms of toughness, fracture energy, and ductility [12–15], and the incorporation of a suitable amount of micro-staple fibers into concrete has a good effect on inhibiting the formation of cracks and expansion [16–18]. Rezakhani et al. [19] found that corrugated and hook-ended fibers more significantly increased flexural strength compared to that of straight fibers, with the most significant increase at 2% by volume. Multiple studies [20–23] investigated the effect of the dispersion of steel fibers and coarse aggregate on flexural properties through a four-point bending test and found that the addition of coarse aggregate to concrete affects the dispersion of the steel fibers, thus producing a combined effect that both enhances and limits their respective advantages, and cracks may form and develop along the transition zone of the coarse aggregate interface. UHPFRC material exhibits flexural toughness, high compressive and tensile strength, durability, and freeze–thaw resistance [24,25]. Yoo [26] used steel fibers with a volume content of 3% to control the generation of microscopic cracks and inhibit the development of macroscopic fractures. Park [27] found that basalt fibers can increase the yield strength and ultimate strength of beams by about 27% during flexural tests on members. Seong [28] studied the effect of different amounts of fiber on the mechanical properties of concrete members. The results show that the addition of fibers enhanced the early crack resistance of the concrete members. However, He [29] found that a high fiber content or agglomeration during the mixing process would adversely affect strength, complicating the pouring process and increasing the production cost of concrete. Therefore, to achieve the high strength and toughness of UHFRPC, it is necessary to carefully determine its material mix ratio.

Saeed et al. [30] conducted an experimental study on concrete solid slabs; circular hole, hollow-core slabs; and square-hole, hollow-core slabs, respectively, and showed that the load carrying capacity of the circular hole, hollow-core slabs was 12% higher than that of the square hole, hollow-core slabs, and the load carrying capacity of the hollow-core slabs was reduced by 11–25% compared to that of the solid slabs. The deflection value of the solid slabs was lower than those of the two hollow slabs, and the two hollow slabs were 23% lighter than the solid slabs. Gao Sheng [31] studied the ribbed, hollow slab floor of a subway station by using the finite element analysis method and analyzed the influence of different hole ratios on the slab bending moment, shear force, and crack width. The analysis showed that with an increase in the void ratio, the bending moment, the shear force, and the crack width in the slab also increase accordingly. Zhou Chaoyang et al. [32] used the finite element analysis method to verify that the average strain in the transverse tube direction of the hollow slab conforms to the plane section assumption. The research results show that flexural stiffness in the transverse and longitudinal tube directions decreases with the increase in hole diameter and the decrease in hole spacing, and the hole spacing has a greater influence. Yang Xiaohua et al. [33] fabricated a 1/4 scale test model of an unbonded, prestressed, hollow slab–column structure to study the mechanical performance of the hollow slab floor. The results of the structural test and numerical simulation show that the hollow floor slab exhibits orthotropic anisotropy. In the direction parallel to the pipe layout, the continuity of the floor slab is destroyed, and the floor slab is weakened to a large extent; in the direction perpendicular to the pipe layout, despite deformation, the unbonded, prestressed, tubular, hollow slab floor can still be considered as a continuous slab.

Conventional concrete hollow slabs substantially decrease the weight of the slab while preserving structural performance comparable to solid concrete slabs. Nevertheless, structural fractures frequently develop as a result of the material's inadequate crack resistance. These cracks will progressively widen and deepen, thereby compromising the structure's resistance to harmful substances and expediting steel corrosion.

The cost of raw materials for UHPC is increased, the production process is intricate, and the processing is challenging, leading to a much higher overall cost compared to conventional concrete. Economically, conventional concrete structures may not fully utilize the capabilities of UHPC materials. The application of UHPFRC materials to hollow and laminated slabs is an achievable solution.

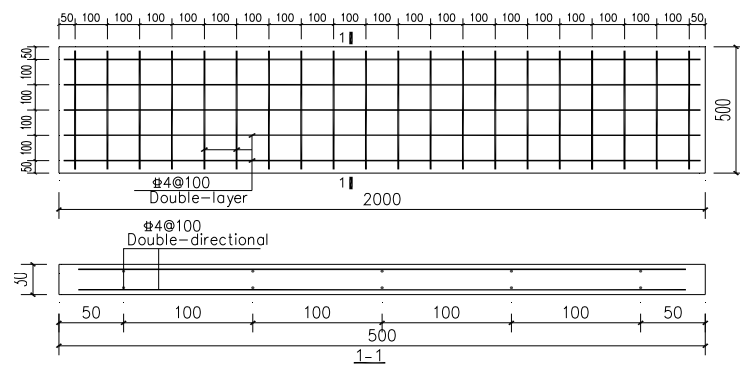
Zou et al. [34–39] used ultra-high-performance concrete (UHPC) circular hollow slabs for bridge decks. According to research conducted on the bending performance of these slabs, UHPC circular hollow bridge platforms exhibit exceptional material efficiency and bending load-bearing capacity. Luo [40], Bu [41], and Zou [42] performed bending experiments on hollow steel-UHPC composite slabs. The findings suggest that the fracture spacing can be effectively reduced by reducing the thickness of the protective layer and increasing the reinforcement ratio. Hollow steel-UHPC composite slabs can diminish the mass of bridge decks and enhance the use of UHPC material. Li's results from the four-point bending test on UHPC composite slabs [43] indicate that the slab exhibits substantial bearing capacity and ductility. The augmentation of shear stirrups significantly mitigates slide in the composite slab and improves its overall mechanical properties. Ding [44] conducted four-point bending tests on UHPC sandwich panels. The findings of the study indicate that the specimens exhibit good flexural performance and crack resistance, with typical bending failure being the mode of failure. No crushing occurs in the compression zone, and only a small number of cracks manifest in the tension zone. In comparison to conventional concrete, the hardness of UHPFRC has been markedly improved and demonstrates greater reliability [45]. The utilization of UHPFRC has increasingly proliferated, prompting the urgent necessity for researchers to address the effective reduction in its building costs [46,47].

However, the current research on UHPFRC hollow slabs remains inadequate. Aligning a series of circular or square holes parallel to the neutral axis of UHPFRC slabs can save material consumption and substantially reduce the weight of the structure. To gain a more comprehensive understanding of the mechanical properties of the structure, this study conducted a flexural performance test of UHPFRC solid slab and hollow-core slabs with the same geometric size and reinforcement. It also analyzed the mechanical properties of UHPFRC hollow-core slabs under bending loads and briefly presented the economic comparison of UHPFRC hollow-core slabs. The objective of this study is to encourage the use of UHPC hollow slabs in practical engineering.

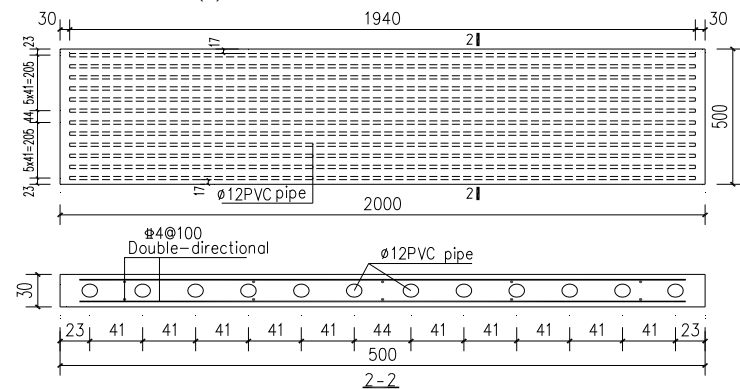
2. Materials and Methods

2.1. Design of the Test Model

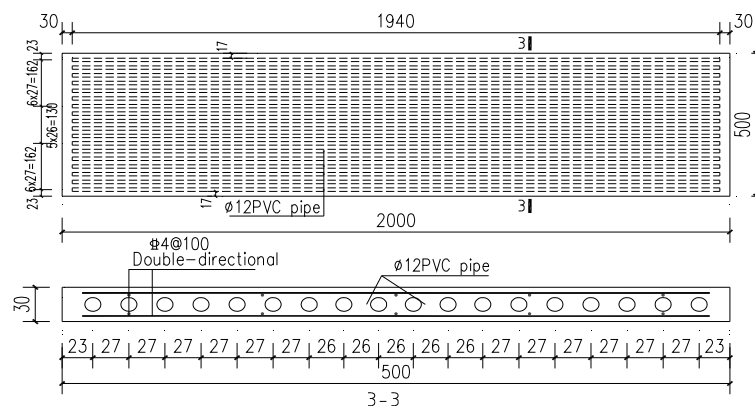
The experimental test model in this experiment was based on the trestle slab from the project. Three UHPFRC test slabs with identical geometric dimensions and reinforcement were fabricated at a 1/4 scale. One was a solid reference test slab (SXB1), and two were hollow slabs containing several PVC circular tubes with a diameter of 12 mm, positioned parallel to the length of the slab along the neutral axis. Hollow slab 1 (KXB1) contained 12 hollow circular tubes with a spacing of 41 mm, whereas the hollow slab 2 (KXB2) contained 18 hollow circular tubes with a spacing of 26 mm to 27 mm. The openings of the hollow circular PVC tubes were sealed and secured to the top and lower distributed reinforcement of the test slab using iron wires. The dimensions of the model slab were 2000 mm in length, 500 mm in width, and 30 mm in thickness. The three test slabs were produced concurrently and cured under identical conditions. The specified concrete strength was C120, and double-layer bidirectional reinforcement $\Phi 4@100$ was implemented. Figure 1 shows the structural dimensions and reinforcement of the test slabs.



(a) Solid slab and reinforcement



(b) Hollow slab 1 and circular tubes



(c) Hollow slab 2 and circular tubes

Figure 1. Dimensions and reinforcement of specimens.

The basic material for constructing the UHPFRC test model was Grade 52.5 cement. The composition ratio of materials is presented in Table 1. Copper-coated steel fibers with a diameter of 0.22 mm and a length of 12 mm were incorporated into the model, with a volume fraction of 2% for the steel fibers. The performance metrics of the selected steel fibers are shown in Table 2. During the fabrication process of each test slab, three groups of cube specimens with an edge length of 100 mm and three groups of prism specimens measuring 100 mm × 100 mm × 300 mm were reserved. The test models were subjected to identical curing conditions. The material properties of UHPFRC that were measured after the curing period are presented in Table 3.

Table 1. UHPFPC dry mix benchmark ratio.

Material	Cement	Silica Fume	Water Reducing Agent	Medium Sand	Water	Steel Fibers
Quality ratio	1	0.21	0.025	1.32	0.23	2% (vol.)

Table 2. Performance parameters of steel fiber.

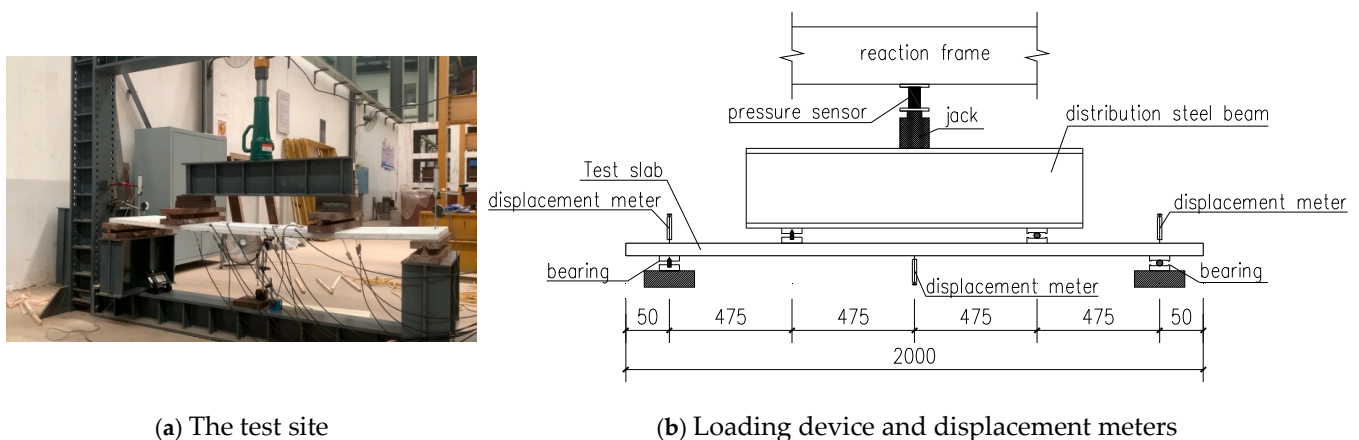
Length of Steel Fibers/mm	Fiber Diameter/mm	Elastic Modulus/GPa	Tensile Strength/MPa
12	0.22	200	380

Table 3. UHPFRC mechanical properties.

Compressive Strength/MPa	Tensile Strength/MPa	Elastic Modulus/GPa	Poisson's Ratio
121.2 ± 5.3	7.8 ± 0.4	44.1 ± 2.1	0.20 ± 0.02

2.2. Loading Device and Loading Method

The ‘Technical Code for Application of Fiber Reinforced Concrete’ (JGJ/T 221-2010) [48] stipulates that a four-point bending static load test was carried out on the UHPFRC test slabs. The two shorter sides of the test slabs were supported on the test bench, with a clear span length of 1900 mm. Loading crossbeams were positioned 475 mm from the simply supported edges at both ends of the slab surface, with a pure bending section length of 950 mm at the midpoint of the span. A 200 kN screw jack was used to load the test model, and a 200 kN load cell was positioned above the screw jack to measure the magnitude of the applied external load. The top end of the load cell was fixed to the reaction frame, while the lower end of the jack's piston rod exerted pressure on a high-stiffness distribution steel beam. The vertical load generated by the jack was uniformly distributed to the two loading steel beams on the test slab surface in order to achieve a uniform line load on the tested slab surface. The loading device is shown in Figure 2.

**Figure 2.** Loading device diagram.

Initially, the theoretical cracking load and ultimate load were calculated and analyzed according to the force conditions of the slab. Prior to commencing the test, the testing device was preloaded to verify its operational status, eliminate any contact gap between

the test slab and the device, and assess the centering of the device. The specimen was initially subjected to loading in three stages, reaching 30% of the theoretical cracking load value, followed by another three stages to 90% of the theoretical cracking load value. After that, the increment in load in each stage was diminished until the specimen cracked. When cracks emerged at the bottom of the test slab, the slab was subjected to a loading of 90% of the theoretical breaking load in five stages. Subsequently, the load value of each stage systematically diminished until the specimen failed. A hold period exceeding four minutes was maintained after each loading stage, during which the cracks were carefully examined to assess their formation and propagation, while test data, including strain and deformation, were recorded.

2.3. Measurement Content and Arrangement of Measuring Points

The main measurement parameters of the flexural test on the UHPFRC hollow slab included the surface stresses at both the top and bottom of the slab, the mid-span deflection, the cracking load, the ultimate load, and the formation and shape of cracks.

Two strain gauges were positioned transversely near the mid-span and loading sites on the top surface of the slab to measure surface strain, with a transverse interval of 260 mm between them. Three strain gauges were affixed transversely at the mid-span of the slab's bottom surface and at the quarter points of the left and right spans. The transverse distance between the strain gauges on the slab's bottom surface was 230 mm. A total of 15 strain gauges were distributed across the entire slab. The specific arrangement is shown in Figure 3.

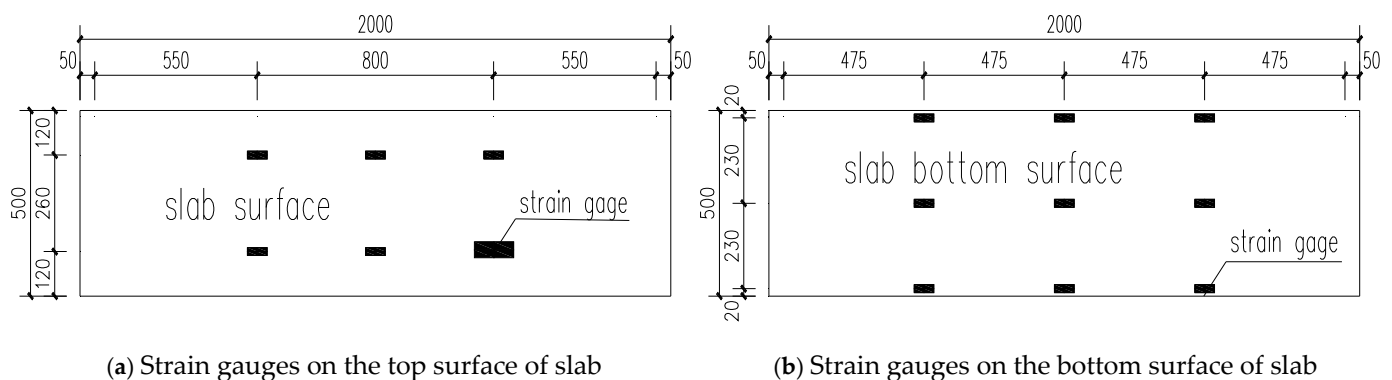


Figure 3. Layout of strain measurement points of specimen slab.

To mitigate the influence of factors like support settlement on the test data, one displacement meter was installed at each of the left and right supports, along with one dial gauge. One displacement meter and one dial gauge were installed at the mid-span position to measure the displacements occurring at the support and mid-span positions of the slab. Figure 2 illustrates the arrangement of the dial gauges and displacement meters. A sophisticated crack monitoring instrument with an accuracy of 0.01 mm was employed to conduct a meticulous examination of the crack width in the test slab.

3. Test Phenomena and Result Analysis

3.1. Test Process and Damage Phenomena

3.1.1. Test Process and Results of the Solid Slab

A UHPFRC solid slab (SXB1) was made as a comparative specimen for this experiment. The damage to the slab exhibited a noticeable elastic–plastic behavior. The whole loading process can be divided into the elastic stage, the elastic–plastic cracking stage, and the plastic crack propagation stage. In the elastic stage, the test model's appearance remained mostly

unchanged, and the recorded strain and displacement data exhibited an approximately linear increase. At a load of 1.76 kN (17.02% of the ultimate load), a faint sound emanated from the test slab, accompanied by the presence of minor discontinuous cracks on the bottom of the slab. The most significant crack emerged in the middle span. The crack width was around 0.049 mm, and the deflection at the midpoint span was 7.305 mm. As loading progressed, the slope of the load–displacement curve changed significantly, indicating that the test slab had transitioned into the elastic–plastic cracking stage. At an external load of 2.52 kN (24.37% of the ultimate load), both the pure bending section and the bending and shear section at the bottom of the slab exhibited obvious cracks, with a gradual change in crack width. The largest crack width remained the first fracture located in the midspan, measuring around 0.073 mm, and the deflection at the midspan was 10.98 mm. As the external load intensified, further hairline-like cracks emerged on the underside of the slab. Upon increasing the load to 4.29 kN (41.49% of the ultimate load), the visible cracks on the underside of the slab totaled 14, with a midspan deflection of 20.32 mm. At a load of 6.85 kN (66.25% of the ultimate load), the slab entered the plastic crack propagation stage, exhibiting two full-length cracks spanning its width. Additional cracks also propagated to both sides sequentially, accompanied by the “rustling” sound caused by the extraction of steel fibers. At this point, the middle span’s deflection value was 37.11 mm, and the crack’s greatest width reached 0.155 mm. When the load value increased to 8.79 kN (85.01% of the ultimate load), many cracks on the underside of the slab propagated across its whole width. The maximum crack width value measured 0.294 mm, and the deflection at the midpoint span was 54.86 mm. Upon reaching a load value of 10.34 kN (ultimate load), the deflection at the midpoint span measured 94.97 mm, resulting in a deflection-to-span ratio of 1/20. The downward bending deformation of the test slab assumed an arc shape, indicating the significant toughness and deformability of the UHPFRC test slab.

3.1.2. Test Process and Results of the Hollow Slabs

To study the flexural performance of UHPFRC hollow slabs involving circular holes, two test models of hollow-core slab with identical reinforcement and geometric dimensions but varying quantities of plastic circular tubes were fabricated. The damage forms of the two UHPFRC hollow-core slabs (KXB1 and KXB2) were fundamentally identical to that of the solid slab (SXB1), exhibiting normal bending failure with ductile damage characteristics. In the elastic stage, the strain and deflection of the two hollow slabs exhibited a linear relationship with the external load. Upon the external load reaching 20% of the ultimate load, a faint sound emanated from the test slab, accompanied by the emergence of fine, discontinuous cracks at the slab’s underside. Upon entering the elastic–plastic cracking stage, each test model’s initial crack width in the middle span was approximately 0.04 mm, and its deflection ranged from 7.99 mm to 9.96 mm. With the rise in load, the slope of the load–displacement curve began to decrease, and micro-cracks became evident in both the pure bending section and the shear bending section. Upon reaching 38.5% of the ultimate load, three further visible cracks appeared at the bottom of the two test slabs, with mid-span deflections measuring 15.81 mm and 20.45 mm, respectively. The load continued to increase, resulting in the emergence of hairline cracks at the bottom of the slabs; with the external load reaching 47% of the ultimate load, the crack widths expanded to 0.08 mm to 0.09 mm, with mid-span deflections measuring 21.05 mm and 24.51 mm, respectively. Upon reaching 53% of the ultimate load, the quantity of cracks at the bottom of each slab escalated to 14, with crack widths ranging from 0.11 mm to 0.16 mm, and the deflection at the mid-span measured 25.29 mm and 28.11 mm, respectively. When each test slab’s external load exceeded 73% of its ultimate load, it reached the plastic crack propagation stage. At this point, cracks at the bottom of the slabs persist, followed by the “rustling”

sound of steel fibers being pulled out. Three cracks went transversely through the bottom of each test model slab, and further cracks rapidly developed and extended to both sides. The maximum width of the crack was approximately 0.164 mm, and the deflections at the mid-span were 37.74 mm and 44.14 mm, respectively. Upon reaching 85% of the ultimate load, the majority of the cracks at the bottom of each slab extended to its edge, with the maximum crack width reaching 0.236 mm, and the mid-span deflections recorded at 48.69 mm and 57.75 mm, respectively. Upon completion of loading, the maximum crack width at the bottom of each slab reached 0.871 mm, and the mid-span deflections reached 76.13 mm and 84.43 mm, respectively. The bending deformation of each test slab is substantial, with a displacement-to-span ratio approaching 1/23, indicating that the UHPFRC hollow test slabs possess comparable toughness and deformation capacity to that of the solid slab.

Table 4 presents a comparison of the cracking moments, ultimate moments, and maximum mid-span deflections of the three test slabs. Figure 4 illustrates the final deformations of the UHPFRC solid slab and hollow slabs.

Table 4. Loading test data of specimen.

Serial Number	Cracking Moment/(kN·m/m)	Ultimate Moment/(kN·m/m)	Maximum Mid-Span Deflection/mm
SXB1	0.84	4.91	94.97
KXB1	0.83	4.35	76.13
KXB2	0.91	4.31	84.43

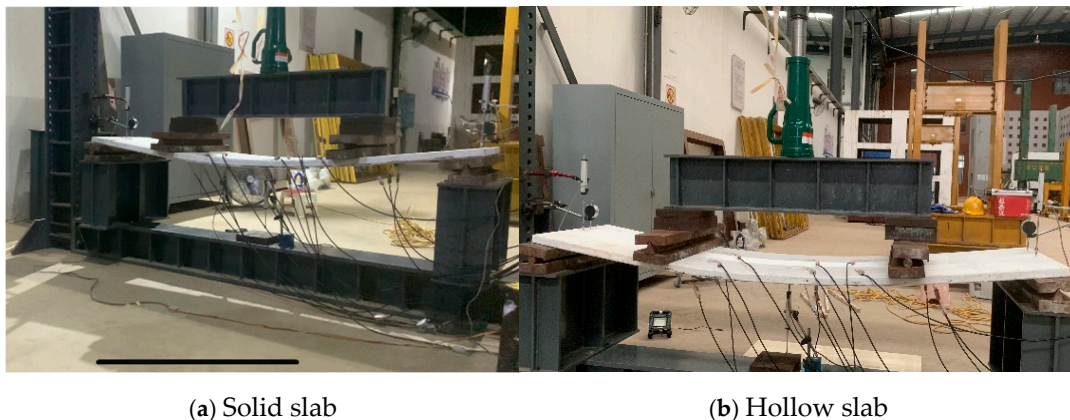


Figure 4. Final deformation of slabs.

Both the solid slab and hollow slab developed using UHPFRC materials exhibited excellent ductility and deformability. The failure of a flexural part constructed from standard reinforced concrete with adequate reinforcing under load was caused by the formation of a primary cracking. Upon the yielding of the steel bars, the concrete at the upper portion of the slab was compromised. The damage pattern of a UHPFRC flexural part was markedly different from that. After tensile cracking at the slab's bottom, numerous more cracks gradually emerged. The augmentation in crack width was not apparent during the early loading stage, and the degradation of stiffness was also gradual. In addition, due to the superior toughness and compressive properties of the UHPFRC material, when the steel reinforcement in the tensile zone finally yielded, the concrete at the upper portion of the slab remained intact.

Supporting the reduction in the self-weight of the structure, the parallel arrangement of multiple hollow circular tubes along the neutral axis had little effect on the load-bearing capacity and deformation capability of the UHPFRC slab. Table 4 demonstrates that the

cracking moments of the hollow-core slabs were largely stable, however the ultimate moments exhibited a modest decrease, averaging a reduction of approximately 11.8% compared to the UHPFRC solid slabs. The average maximum deflection of the hollow-core slab was 80.28 mm, while the maximum deflection of the solid slab was 94.97 mm, indicating a difference of 15.4%.

3.2. Load–Mid-Span Displacement Curve

The concentrated line loads applied to the above four-point flexure test slabs were converted to pure bending section moments, enabling the derivation of comparison curves for pure bending section moments and mid-span deflections by combining the UHPFRC solid slabs with the hollow-core slabs, as shown in Figure 5.

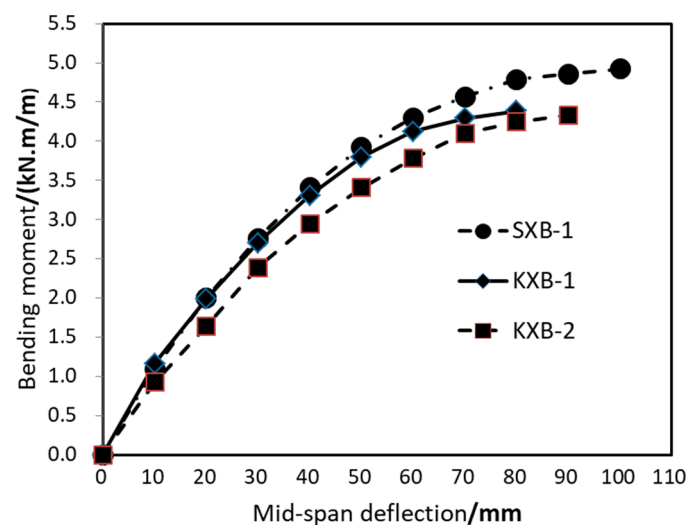


Figure 5. Bending moment–deflection curves.

According to Figure 5, the bending process of UHPFRC slabs could be divided into three phases: the elastic phase, the elastic–plastic cracking phase, and plastic crack propagation phase. In the elastic phase, the moment–mid-span deflection curves of the hollow slab with circular tubes and the solid slab were approximately linear. The bearing capacity of the two was remarkably similar. The moment–displacement curves of KXB1 and SXB1 nearly coincided; the loading-bearing capacity of KXB2, which had additional tubes, was marginally inferior to that of SXB1. Upon entering the elastic–plastic cracking phase, the slope of the moment–mid-span deflection curve altered. The moment–displacement curves of the hollow slab with circular tubes progressively diverged from those of the solid slab. The bearing capacity of the hollow slab became inferior to that of the solid slab, and the bearing capacity of the hollow slab decreased with an increase in the number of hollow circular tubes. Subsequently, the tensile zone of the test model slab’s bottom exhibited visible cracks. The role of the steel fibers as a connector became evident in resisting the tensile stress of the slab. As the quantity of cracks at the slab’s bottom and the depth of these cracks increased, the neutral axis of the bending test slab approached the surface of the slab, thus altering the bending stiffness. The existence of hollow circular tubes along the neutral axis of the slab contributed to a more significant decrease in the bending stiffness of a hollow slab compared to a solid slab. Furthermore, the arrangement of parallel hollow tubes resulted in an increased decrease in the bending stiffness of the slab. Consequently, the reduction in the bearing capacity of a hollow-core slab following cracking was inferior to that of a solid slab.

The UHPFRC hollow-core slab has been shown to be orthotropic. When the parallel hollow tubes were placed on the neutral axis, the bending stiffness of the cross-section

aligned with the parallel tube distribution was slightly inferior to that of solid slab, while the bending stiffness of the cross-section aligned with the vertical tube distribution was significantly lower than that of the solid slab. The existence of steel fibers greatly limited the development of surface cracks to the interior, resulting in a larger elastic limit for the UHPFRC hollow-core slab compared to traditional concrete, while the bending stiffness of the slab remained largely unchanged.

3.3. Crack Development and Distribution

The test results indicated that the slab's pure bending section at the base exhibited the emergence of initial visible cracks along its breadth. Following this, transverse cracks appeared sequentially in both the pure bending section and the shear bending section. With the augmentation of the external load, the number of cracks increased, the intervals between cracks decreased gradually, and the pace of crack propagation accelerated. Eventually, the pure bending section developed two to four major cracks across the slab's bottom surface. The majority of the cracks subsequently extended across the bottom surface of the slab. Figure 6 illustrates the final development of crack patterns of the three tested slabs.

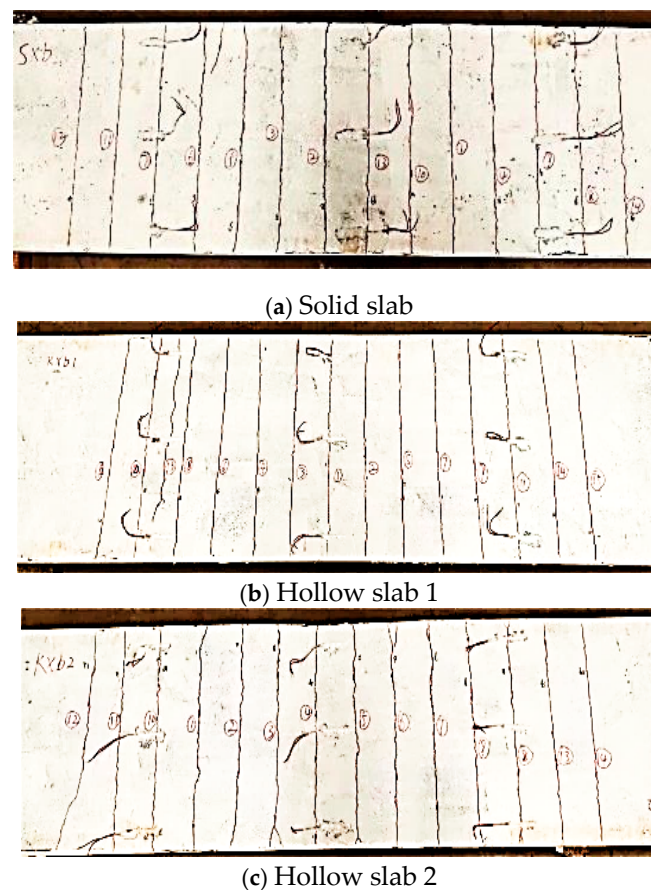


Figure 6. Distribution of cracks across the bottom surface of test slabs.

The crack development process can be divided into the cracking period, the stable development period, and the rapid development period. As can be observed in Figure 6, the cracks at the bottom of test slabs are distributed uniformly and densely. At the bottom of each test slab, Table 5 displays the number of cracks, the maximum crack width values, and the actual measured average values of the intervals of the cracks running through the slabs.

Table 5. Basic data on crack development in each specimen.

Serial Number	Model Number	The Number of Cracks	Average Crack Spacing/mm	Crack Width/mm
1	SXB1	14	102.15	1.16
2	KXB1	15	93.57	0.81
3	KXB2	14	99.34	0.86

With high material strength, UHPFRC was different from typical reinforced concrete. Short steel fibers were randomly distributed in the concrete matrix, and the tensile strength of short steel fiber anchored in the concrete was significantly greater than that of the concrete, which played a role in bridge connection to the concrete. Initially, short steel fibers on the bottom surface of the slab collaborated with concrete to resist external forces. When the surface of the base slab cracked, the surface cracks immediately encountered the random distribution of short steel fibers, so the cracks were constantly suppressed by short steel fibers during the development of the concrete matrix. Cracks continued to deepen, widen, and expand only when short fibers were removed or broken. The bridge connection effect of steel fibers created cracks on the bottom surface of the UHPFRC hollow-core slab that were fine and dense, and the distribution was relatively uniform.

3.4. Surface Strain of UHPFRC Slabs

Figure 7 displays the surface strain curves at the top and bottom of the UHPFRC test model's mid-span slabs as they changed with load.

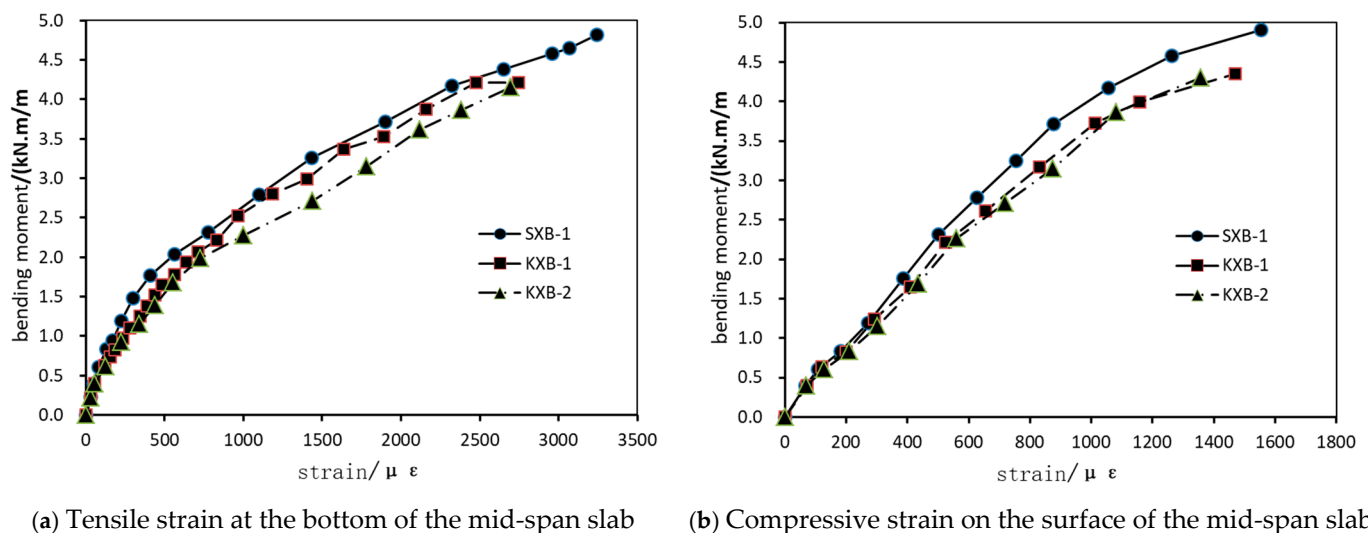
**Figure 7.** Comparison of load–strain curves.

Figure 7 illustrates that prior to the cracking of the UHPFRC test slab, the tensile and compressive strains at both the bottom and surface of the slab were relatively low. The strain curves of the solid slab and the hollow-core slabs almost overlapped, and the load–strain curve exhibited a predominantly linear variation. As noticeable cracks appeared on the bottom of the slab, the slope of the load–strain curve gradually declined, approaching the yield strain. Subsequently, the strain curves of the solid slab and the hollow-core slabs diverged. The strain increase in the hollow-core slab was marginally greater than that of the solid slab, and the hollow-core slab exhibited a larger strain with increasing circular holes. Upon maximization of the external load, the peak compressive strain values for the solid slab and hollow-core slabs were $1555 \mu\epsilon$, $1469 \mu\epsilon$, and $1356 \mu\epsilon$, respectively. However, these values failed to reach the ultimate compressive strain of the UHPFRC

material. This signifies that the steel-fiber concrete in the compression zone of the test slab does not undergo crushing, contrasting with traditional reinforced concrete, which is prone to bending failure in the slab.

The experiment found that placing parallel hollow circular tubes along the span direction on the neutral axis can effectively reduce the self-weight of the slab, with little impact on its load-bearing capacity. During the normal use stage, the deformation characteristics of the circular tube hollow slab were identical to those of the solid slab.

4. Effect of Hollowness on Slab Load Capacity and Economic Comparison

The experimental analysis of UHPFRC solid and hollow slabs demonstrates that the arrangement of hollow circular tubes in the slab influences its bearing capacity. An increased number of hollow tubes embedded in the slab results in a higher void ratio. Table 6 illustrates that the ultimate bearing capacity of the hollow slab decreased with an increase in the number of circular tubes, albeit the decrease was not significant. An augmentation in the quantity of circular tubes could reduce the volume of UHPFRC material used, thus correspondingly reducing the slab structure's self-weight. The void ratio is defined as the area of the hollow circular tubes in any cross-section divided by the total area of the slab, allowing for the assessment of changes in the self-weight and bearing capacity of the slab structure with regard to the void ratio, as shown in Table 6. Figure 8 illustrates the curve of the ultimate moment as it varies with the void ratio.

Table 6. Comparison table of the economy of hollow slabs.

Serial Number	Number	Economic Comparison			Comparison of Bearing Capacity			
		Empty Heart Rate/%	Volume/cm ³	Mass Deviation/%	Cracking Moment/(kN.m/m)	Comparison with Solid Slabs	Ultimate Moment/(kN.m/m)	Comparison with Solid Slabs
1	SXB1	0	30,000.00	1	0.84	1	4.91	1
2	KXB1	9.05%	27,367.10	8.78%	0.83	0.988	4.35	0.886
3	KXB2	13.57%	26,050.64	13.16%	0.91	1.083	4.31	0.878

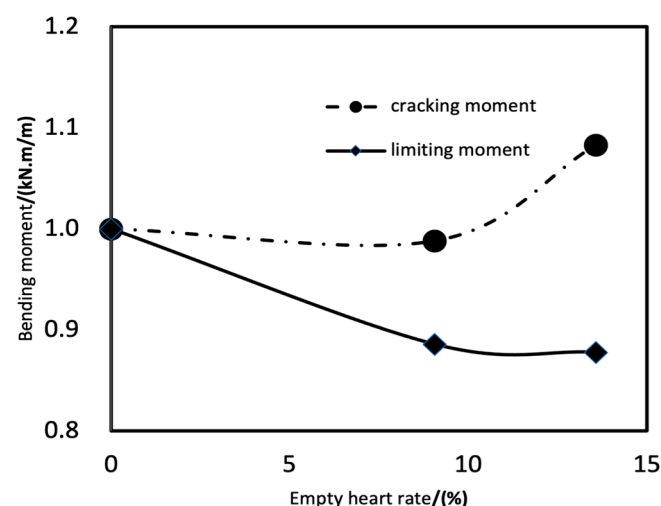


Figure 8. Moment–void ratio variation curve.

Upon creating a row of parallel circular tubes on the central axis, the slab can be regarded as a sandwich slab or an I-shaped cross-section slab. The upper and lower sides of the holes were regarded as the upper and lower flanges of the I-shaped cross-section, respectively supporting the compressive and tensile forces generated during bending, while the region between the circular holes was designated as webs, which transmitted

the shear forces generated during deformation. The presence of holes on the central axis could reduce the self-weight of the slab structure, thereby reducing construction costs while exerting minimal influence on the flexural stiffness of the slab, thus having little effect on the flexural load-bearing capacity of the UHPFRC slab. In Table 6 and Figure 8, when the slab's void ratio was 9.05%, its weight reduced by 8.78%, while the cracking moment reduced by just 1.2%. At a void ratio of 13.57%, the slab's weight decreased by 13.16%, and the cracking moment of the slab experienced a little increase. When the void ratio of the slab remains within a certain limit, the cracking moment of the hollow slab is comparable to that of the solid slab, showing that under identical loading conditions, the hollow slab is more cost-effective than the solid slab. Increasing the holes at the neutral axis position affects the ultimate bearing capacity of the slab, which decreases monotonically with an increase in the void ratio. Compared to the UHPFRC solid slab, the ultimate bending moment decreased by 11.4% with the slab hollowness of 9.05% and by 12.2% with the slab hollowness of 13.57%. KXB2 exhibited a 4.52% increase in hollowness relative to KXB1, and the ultimate bending moment decreased by only 0.8%. The results suggest that while the hollow ratio remains within the specified limit, the ultimate load-bearing capacity of UHPFRC hollow-core slabs gradually decreases as the hollow ratio increases, with the rate of decline also gradually decreasing as the hollow ratio rises. When the void ratio reaches a certain threshold, its effect on the ultimate load-bearing capacity of UHPFRC hollow-core slabs diminishes significantly, resulting in the mid-span moment void ratio curve approaching a horizontal line. This means that the hollow ratio of UHPFRC slabs can be appropriately increased while maintaining load-bearing capacity to achieve economic energy savings.

5. Conclusions

Static four-point bending tests were conducted on three UHPFRC slabs with identical geometric dimensions, reinforcement, and steel fiber content but differing void ratios. This study examined the bearing capacity, crack propagation behavior, and load–displacement curves, along with a basic economic analysis of the UHPFRC slab. The following conclusions were obtained:

1. Both the UHPFRC hollow-core slab and the solid slab exhibit strong load-bearing capacity and obvious elastoplastic characteristics. The incorporation of steel fibers into the concrete matrix can effectively inhibit the formation and propagation of cracks. The entire deformation process can be divided into the elastic stage, the elastic–plastic stage, and the plastic stage. In the elastic stage, the flexural stiffness of the UHPFRC circular hole hollow slab is relatively large, resulting in the load–displacement curves of both the hollow-core slab and the solid slab almost overlapping, approximating a slanted straight line. In the elastic–plastic stage, visible micro-cracks appear at the bottom of the slab, the slope of the load–displacement curve changes, and the load–displacement paths of the hollow-core slab and the solid slab gradually diverge, indicating that the flexural stiffness of the slab decreases as the void ratio increases. Upon entering the plastic stage, the mid-span displacement and the cracks at the bottom of the slab gradually increase as the applied load continues to increase, demonstrating good ductility.
2. When the diameters of the hole and void ratio are within certain limits, the circular holes on the neutral axis hardly affect the cracking moment of the UHPFRC hollow slab, making it comparable to the UHPFRC solid slab with identical geometric dimensions and reinforcement. Placing hollow tubes on the neutral axis affects the ultimate moment of the hollow slab, resulting in a decrease in the ultimate bearing capacity of the hollow-core slab as the slab void ratio increases, with the rate of decrease dimin-

ishing progressively with the slab void ratio. When the void ratio reaches a certain threshold, its influence on the ultimate bearing capacity of the UHPFRC hollow slab diminishes significantly.

3. The progression of crack formation in the UHPFRC slab can be delineated into three distinct phases: the initial cracking phase, the stable crack development phase, and the subsequent rapid crack propagation phase. In the initial phase of cracking, the inhibitory effect of steel fibers on crack initiation and propagation is pronounced. As crack development progresses, the restraining capacity of steel fibers diminishes, progressively being substituted by the reinforcement mechanisms located at the slab's base and surface. The ultimate damage characteristics of UHPFRC slabs contrast with the flexural failure of conventional reinforced concrete slabs with adequate reinforcement, and the steel fiber concrete in the slab's compression zone does not undergo crushing.
4. To reduce the deadweight of the structure and constructing costs, it is possible to reserve the slab hollow ratio and the diameter of the hole on the central axis to some parallel holes, provided that the construction limits and stress conditions are not exceeded. Under identical stress conditions, the cracking moment of the UHPFRC hollow-core slab is comparable to that of the solid slab; nevertheless, its ultimate bearing capacity is slightly inferior to that of the solid slab. It is important to note that an increase in the slab hollow results in a corresponding decrease in the ultimate flexural load capacity of the slab. When the hollow rate reaches a certain threshold, the ultimate load capacity of the UHPFRC slab stabilizes, indicating that under conditions that ensure adequate load-bearing capacity, the hollow ratio of the UHPFRC slab can be appropriately augmented to achieve the objective of economic energy savings.

This experimental study demonstrates that UHPFPC possesses exceptional mechanical properties that surpass those of conventional concrete and that the application of UHPFPC hollow-core slab with circular tubes significantly improves the stiffness, load-bearing capacity, and deformation capacity of the entire slab structure while effectively reducing the self-weight. It is extensively applicable in large-span bridges and large public building structures, offering considerable cost efficiency.

In this paper, the mechanical properties of UHPFRC hollow-core slabs were examined using only three test slabs and a limited number of samples. In a subsequent stage, experimental research will be conducted on hollow-core slabs with varying numbers of roots and hole diameters. The finite element method will be employed to comparatively analyze the various elements affecting the load-bearing capacity of UHPFRC hollow-core slabs. An approximate analytical method consistent with the load-bearing capacity of UHPFRC hollow-core slabs will be developed based on the experimental results and the finite element method analysis. This approach will satisfy the requirements of engineering applications.

Author Contributions: L.Y.: conceptualization, investigation, methodology, data curation, writing—original draft, and writing—review and editing and funding acquisition. Q.S.: formal analysis, data curation, and funding acquisition. M.L.: investigation, project administration, and data curation. X.Y.: supervision, resources, data curation, and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Science Foundation of Hunan Province, China (grant No. 2023JJ50206), and the Natural Science Foundation of Hunan Province, China (grant No. 2023JJ50183).

Data Availability Statement: The data presented in this study are available upon request from the corresponding author. The data are not publicly available due to continuing research.

Conflicts of Interest: Xiaohua Yang was employed by the company Blackstone Management Consulting Co. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Shao, X.; Fan, W.; Huang, Z. Application of Ultra-High-Performance Concrete in engineering structures. *China Civ. Eng. J.* **2021**, *54*, 1–13. (In Chinese)
- Yue, X.; Xiao, J.; Zhen, Q.; Ding, R.; Ren, Y.; Pan, J. Experimental study on mechanical behavior of wet joint in ultra-high-performance concrete decks. *China Civ. Eng. J.* **2023**, *56*, 94–107. (In Chinese)
- Peng, F.; Fang, Z. Calculation approach for flexural capacity of reinforced UHPC beams. *China Civ. Eng. J.* **2021**, *54*, 86–97. (In Chinese)
- Zhang, Y.; Ren, S.; Yuan, S. Domestic based on ultra high performance concrete (UHPC) review of research on connection application of prefabricated buildings. *Build. Struct.* **2023**, *53*, 1020–1024. (In Chinese)
- Akeed, M.H.; Qaidi, S.; Ahmed, H.U.; Faraj, R.H.; Mohammed, A.S.; Emad, W.; Tayeh, B.A.; Azevedo, A.R.G. Ultra-high-performance fiber-reinforced concrete. Part I: Developments, principles, raw materials. *Case Stud. Constr. Mater.* **2022**, *17*, e01290. [[CrossRef](#)]
- Deng, M.; Zhang, Y. Cyclic loading tests of RC columns strengthened with high ductile fiber reinforced concrete jacket. *Constr. Build. Mater.* **2017**, *153*, 986–995. [[CrossRef](#)]
- Fang, B.; Hu, Z.; Shi, T.; Liu, Y.; Wang, X.; Yang, D.; Zhu, K.; Zhao, X.; Zhao, Z. Research progress on the properties and applications of magnesium phosphate cement. *Ceram. Int.* **2023**, *49*, 4001–4016. [[CrossRef](#)]
- He, H.; E, S.; Wen, T.; Yao, J.; Wang, X.; He, C.; Yu, Y. Employing novel N-doped graphene quantum dots to improve chloride binding of cement. *Constr. Build. Mater.* **2023**, *401*, 132944. [[CrossRef](#)]
- Lahalle, H.; Cau Dit Coumes, C.; Mesbah, A.; Lambertin, D.; Cannes, C.; Delpech, S.; Gauffinet, S. Investigation of magnesium phosphate cement hydration in diluted suspension and its retardation by boric acid. *Cem. Concr. Res.* **2016**, *87*, 77–86. [[CrossRef](#)]
- Orouji, M.; Zahrai, S.M.; Najaf, E. Effect of glass powder & polypropylene fibers on compressive and flexural strengths, toughness and ductility of concrete: An environmental approach. *Structures* **2021**, *33*, 4616–4628.
- Won, J.P.; Hong, B.T.; Choi, T.J.; Lee, S.J.; Kang, J.W. Flexural behaviour of amorphous micro-steel fibre-reinforced cement composites. *Compos. Struct.* **2012**, *94*, 1443–1449. [[CrossRef](#)]
- Yoo, D.Y.; Kim, J.J.; Chun, B. Dynamic pullout behavior of half-hooked and twisted steel fibers in ultra high performance concrete containing expansive agents. *Compos. Part B Eng.* **2019**, *167*, 517–532. [[CrossRef](#)]
- Li, J.; Wu, C.; Hao, H.; Liu, Z. Post-blast capacity of ultra-high performance concrete columns. *Eng. Struct.* **2017**, *134*, 289–302. [[CrossRef](#)]
- Shi, T.; Liu, Y.; Hu, Z.; Cen, M.; Zeng, C.; Xu, J.; Zhao, Z. Deformation performance and fracture toughness of carbon nanofiber-modified cement-based materials. *ACI Mater. J.* **2022**, *119*, 119–128.
- Yang, S.; Yang, C.; Huang, M.; Liu, Y.; Jiang, J.; Fan, G. Study on bond performance between FRP bars and seawater coral aggregate concrete. *Constr. Build. Mater.* **2018**, *173*, 272–288. [[CrossRef](#)]
- Zhou, F.; Jiang, H.; Huang, L.; Hu, Y.; Xie, Z.; Zeng, Z.; Liu, M.; Wang, B.; Zhou, X. Early shrinkage modeling of complex internally confined concrete based on capillary tension theory. *Buildings* **2023**, *13*, 2201. [[CrossRef](#)]
- Michaud, D.; Fam, A.; Dagenais, M.A. Development length of sand-coated GFRP bars embedded in Ultra-High performance concrete with very small cover. *Constr. Build. Mater.* **2020**, *270*, 121384. [[CrossRef](#)]
- Faried, A.S.; Mostafa, S.A.; Tayeh, B.A.; Tawfik, T.A. The effect of using nano rice husk ash of different burning degrees on ultra-high-performance concrete properties. *Constr. Build. Mater.* **2021**, *290*, 123279. [[CrossRef](#)]
- Rezakhani, R.; Scott, D.A.; Bousikhane, F.; Pathirage, M.; Moser, R.D.; Green, B.H.; Cusatis, G. Influence of steel fiber size, shape, and strength on the quasi-static properties of ultra-high performance concrete: Experimental investigation and numerical modeling. *Constr. Build. Mater.* **2021**, *296*, 123532. [[CrossRef](#)]
- Abbas, Y.M.; Khan, M.I. Behavioral response of reinforced concrete beams with ultra-ductile fiber-reinforced cementitious composite layers—Experiments, models and reinforcement limits. *J. Build. Eng.* **2023**, *77*, 107475. [[CrossRef](#)]
- Liang, X.; Hu, A.; Yu, J.; Shi, Q. Effect of steel fibers on the flexural response of ultra-high performance concrete. *Acta Mater. Compost. Sin.* **2018**, *35*, 722–731. (In Chinese)
- Shen, C.; Tang, D.; Lyu, Z.; Yang, C.; Yu, L. Distribution of coarse aggregate and steel fibers in ultra-high performance concrete containing coarse aggregate (UHPC-CA) and their effect on the flexural performance. *Constr. Build. Mater.* **2024**, *421*, 135666. [[CrossRef](#)]
- Du, J.; Meng, W.; Khayat, K.; Bao, Y.; Guo, P.; Lyu, Z.; Obeidah, A.; Nassif, H.; Wang, H. New development of ultra-high-performance concrete (UHPC). *Case Stud. Constr. Mater.* **2021**, *224*, 1092220. [[CrossRef](#)]

24. Khan, M.I.; Abbas, Y.M.; Fares, G. Curing-dependent structural behavior of ultra-high-performance hybrid fiber-reinforced concrete beams. *Structures* **2023**, *54*, 1440–1451. [\[CrossRef\]](#)
25. Niu, F.; Liu, Y.; Xue, F.; Sun, H.; Liu, T.; He, H.; Kong, X.; Chen, Y.; Liao, H. Ultra-high performance concrete: A review of its material properties and usage in shield tunnel segment. *Case Stud. Constr. Mater.* **2025**, *22*, e04194. [\[CrossRef\]](#)
26. Yoo, D.Y.; Kim, S.W.; Park, J.J. Comparative flexural behavior of ultra-high-performance concrete reinforced with hybrid straight steel fibers. *Constr. Build. Mater.* **2017**, *132*, 219–229. [\[CrossRef\]](#)
27. Park, J.J.; Yoo, D.Y.; Park, G.J.; Kim, S.W. Feasibility of reducing the fiber content in ultra-high-performance fiber-reinforced concrete under flexure. *Material* **2017**, *10*, 118. [\[CrossRef\]](#)
28. Chin, S.; Youn, H.; Ryu, J.; Sim, K. Polyelectrolyte multilayering of fibers with different polymer combinations and a comparison of its effect on paper strength with a conventional dry strength agent treatment. *Nord. Pulp Pap. Res. J.* **2012**, *27*, 915–922. [\[CrossRef\]](#)
29. He, D.R.; Liao, Q.M.; Hong, L. Hybrid fiber concrete compressive strength test and crack resistance mechanism research. *J. Wuhan Polytech. Univ.* **2010**, *29*, 97–99. (In Chinese)
30. Saeed, S.; Alkhafaji, S.; Al-kaabi, J. The flexural behavior of hollow core concrete slabs with different shape. *J. Appl. Eng. Sci.* **2023**, *21*, 1–7.
31. Gao, S. Research on mechanical characteristics of ribbed hollow slab in metro station. *Spat. Struct.* **2024**, *30*, 70–78. (In Chinese)
32. Zhou, C.; Liu, S.; Ouyang, Z. Determination of flexural stiffness for voided plates with parallel circular-tubes. *Chin. J. Comput. Mech.* **2008**, *25*, 517–520. (In Chinese)
33. Yang, X.; Zhou, C.; Chen, H. Experiment research on bearing behavior of post-tensioned unbounded prestressed concrete hollow flat floor. *Ind. Constr.* **2015**, *45*, 80–84. (In Chinese)
34. Si, X.; Pan, H. Influences of fiber on early crack resistance of concrete. *Bull. Chin. Ceram. Soc.* **2011**, *30*, 1425–1429. (In Chinese)
35. Wu, Z.; Shi, C.; He, W.; Wu, L. Effects of steel fiber content and shape on mechanical properties of ultra high performance concrete. *Constr. Build. Mater.* **2016**, *103*, 8–14. [\[CrossRef\]](#)
36. Yao, Z.; Zhou, J. Study on fracture energy of fiber-reinforced reactive powder concrete. *J. Build. Mater.* **2005**, *8*, 356–360.
37. Abbas, Y.M.; Fares, G.; Khan, M.I. Strength and sensitivity analysis of shear-deficient ultrahigh performance fiber reinforced concrete beams using hybrid neuro-fuzzy approach. *J. Build. Eng.* **2023**, *72*, 106624. [\[CrossRef\]](#)
38. Ashkezari, G.D.; Fotouhi, F.; Razmara, M. Experimental relationships between steel fiber volume fraction and mechanical properties of ultra-high performance fiber-reinforced concrete. *J. Build. Eng.* **2020**, *32*, 101613. [\[CrossRef\]](#)
39. Zou, Y.; Zheng, K.; Zhou, Z.; Zhang, Z.; Guo, J.; Jiang, J. Experimental study on flexural behavior of hollow steel-UHPC composite bridge deck. *Eng. Struct.* **2023**, *274*, 115087. [\[CrossRef\]](#)
40. Luo, J.; Shao, X.; Cao, J.; Xiong, M.; Fan, W. Transverse bending behavior of the steel-UHPC lightweight composite deck: Orthogonal test and analysis. *J. Constr. Steel Res.* **2019**, *162*, 105708. [\[CrossRef\]](#)
41. Bu, Y.; Li, M.; Wei, C.; Cheng, Z.; Cui, C.; Bao, Y. Experimental and analytical studies on flexural behavior of composite bridge decks with orthotropic steel deck and ultra-high-performance concrete (UHPC) slab under negative moment. *Eng. Struct.* **2023**, *274*, 115190. [\[CrossRef\]](#)
42. Zou, Y.; Zhou, H.; Yang, J.; Zhang, Z.; Zheng, K.; Jiang, J. Mechanical behavior of natural bonding interface in hollow steel-UHPC composite bridge deck. *J. Constr. Steel Res.* **2023**, *210*, 108093. [\[CrossRef\]](#)
43. Li, W.; Yan, B.; Yu, J.; Shao, X. Mechanical behavior of UHPC hollow slab under different pouring modes. *J. Railw. Sci. Eng.* **2021**, *18*, 476–484. (In Chinese)
44. Ding, R.; Sun, Y.; Fan, J.; Chen, D. Experimental and theoretical study on flexural behaviour of a new UHPC sandwich slab. *Eng. Struct.* **2022**, *267*, 114673. [\[CrossRef\]](#)
45. Majidi, Y.; Hsu, C.-T.T.; Zarei, M. Finite element analysis of new composite floors having cold-formed steel and concrete slab. *Eng. Struct.* **2024**, *77*, 65–83. [\[CrossRef\]](#)
46. Akhnoukh, A.K.; Xie, H. Welded wire reinforcement versus random steel fibers in precast/prestressed ultra-high performance concrete I-girders. *Constr. Build. Mater.* **2010**, *24*, 2200–2207. [\[CrossRef\]](#)
47. Zhang, Y.; Wei, S.; Sifeng, L.; Chujie, J.; Jianzhong, L. Preparation of C200 green reactive powder concrete and its static–dynamic behaviors. *Cem. Concr. Compos.* **2008**, *30*, 831–838.
48. JGJ/T 221-2010[S]; Ministry of Housing and Urban-Rural Development of the People’s Republic of China, Technical Specification for Application of Fiber Reinforced Concrete. Architecture & Building Press: Beijing, China, 2010. (In Chinese)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.