

Article

Shear Behavior of Non-Stirrup Ultra-High-Performance Concrete Beams: Contribution of Steel Fibers and UHPC

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Abstract: The shear stirrups and bend-up reinforcement in ultra-high-performance concrete (UHPC) beams could potentially be excluded due to the superior mechanical properties of UHPC. This paper reports the new findings of an experimental research into the factors that influence the shear behavior of non-stirrup UHPC beams. Fourteen beams were tested in shear, comprising twelve non-stirrup UHPC beams and two normal concrete (NC) beams reinforced with stirrups. The test variables included the steel fiber volume content (2.0%, 1.5%, and 0%), the shear span-to-effective-depth ratio (1.2, 1.8, 2.0, and 3.1), beam width (150 mm and 200 mm), and beam height (300 mm, 350 mm, and 400 mm). The results demonstrated that the steel fiber volume content had a significant influence on the shear behavior of the non-stirrup UHPC beams. The failure modes of the beams without steel fibers were typically brittle, whereas those reinforced with steel fibers exhibited ductile failure. The shear resistance of the beams could be significantly enhanced by the addition of steel fibers in the concrete mix. Furthermore, the post-cracking load-bearing performance of the beams could also be markedly improved by the addition of steel fibers. In addition, the shear span-to-effective-depth ratio had a considerable impact on the failure mode and the ultimate shear strength of the tested beams. The contribution of steel fibers to the shear capacity of the UHPC beams was observed to increase as the shear span-to-effective-depth ratio increased. The French standard formulae tended to overestimate the contribution of steel fibers, and the calculation results were found to be more accurate for UHPC beams with a moderate shear span-to-effective-depth ratio (around 2.0). Moreover, the French standard formulae demonstrated greater accuracy at a larger beam height for calculating the contribution of UHPC matrix.

Keywords: shear behavior; ultra-high-performance concrete (UHPC); non-stirrup UHPC beams; steel fiber volume content; shear span-to-effective-depth



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1. Introduction

As an innovative engineering material, UHPC, comprising of cement, silicon fume, fine aggregates, steel fibers, and admixtures, demonstrates enormous prospects for the manufacture of lightweight and durable structural systems with excellent workability and structural performance. This is due to its superior mechanical properties, including compressive strength (>150 MPa) and tensile strength (>7 MPa), as well as excellent post-cracking performance [1–6]. Nowadays, UHPC has been extensively employed in practical engineering, particularly in the domain of bridge engineering [7–10]. In 1997, the first UHPC pedestrian bridge, Sherbrooke Quebec Bridge, was built in Buchanan County in Canada. In 2010, the world's first UHPC highway arch bridge, Wild Bridgem was built in Austria [7]. In 2023, the first steel–UHPC composite truss pedestrian bridge was completed in China [11]. Additionally, a considerable body of research has been

conducted on the utilisation of UHPC in the construction of bridges, encompassing a range of topics, including segmental bridges [12,13], connections [14,15], joints [16–19], and steel–UHPC composite structures [20–24]. The exceptional corrosion resistance of fiber-reinforced polymer (FRP) bars makes them an excellent alternative for reinforcement in practical engineering projects, particularly in environments with harsh conditions. The combination of FRP bars with UHPC provides an effective solution to the issues of cracking and durability in reinforced concrete structures exposed to corrosive environments [25]. Imjai et al. [26] experimentally demonstrated that the shear performance of high-content recycled aggregate concrete beams reinforced with FRP bars and steel fibers was comparable to or even exceeded those of normal concrete beams. Moreover, a number of studies have been conducted on the utilisation of FRP bars, including investigations into the serviceability behavior of FRP-reinforced slatted slabs [27,28] and the bond performance of FRP bars to UHPC [25,29].

The novel UHPC material facilitates not only innovation and the optimisation of structures, but also gives rise to elevated costs. To maximise the superiority of the novel UHPC material, structural innovations to cut down construction costs are urgent. Given the incorporation of steel fibers, the tensile strength of UHPC has greatly improved. The utilisation of UHPC with variable volume content of steel fibers had been demonstrated to be an effective alternative to replace stirrups and bent-up reinforcements [30,31]. Consequently, the time and labour required for the assembly of stirrups and bent-up reinforcements were diminished, thereby significantly enhancing construction efficiency. Furthermore, the exclusion of the stirrups could enhance the fluidity of UHPC, which in turn leads to a notable improvement in mechanical properties, providing a novel method with which to facilitate the application of UHPC. In 2019, the first prestressed UHPC pedestrian bridge in China was constructed by Zhonglu Dura International Engineering Co, Ltd. in Huangpu, Guangzhou. This innovative structure reduced its self-weight by approximately half in comparison to conventional concrete beams, and greatly cut down the construction cost.

Shear performance is of critical importance in structural design [32,33]. The stirrups and bent-up reinforcements constitute the primary contribution to the shear capacity of the beams [33]. The removal of stirrups and bent-up reinforcements may result in a notable reduction in the shear capacity of the beams [34,35]. It is still uncertain whether steel fibers in UHPC can provide adequate shear capacity with the same capacity as stirrups. Qi et al. [36] demonstrated that non-stirrup UHPC beams with a steel fiber volume content of 2.0% exhibited comparable shear capacity to normal concrete beams reinforced with stirrups. However, it is important to note that a non-stirrup UHPC beam with a steel fiber volume content of less than 0.5% was unable to withstand the same shear load as a normal concrete beam [37]. Amin et al. [38] experimentally found that the shear capacity of the members could be effectively improved by increasing the steel fiber volume content. Nevertheless, as the volume content of steel fiber exceeded a certain extent, the enhancements in shear capacity could diminish [39]. It was demonstrated that the mechanical properties and durability of UHPC were not impacted by the incorporation of high dosages of steel fibers. An elevated stress concentration of steel fibers could result in fiber coalescence, which could create weak points and consequently compromise the efficiency of the fibers [40,41]. Furthermore, it is evident that the price of UHPC material rises considerably with the increase in the volume content of steel fiber. Consequently, a 2% volume content of steel fiber was recommended for an economical and workable UHPC mixture design [42,43]. The incorporation of steel fibers was also found to significantly enhance the post-cracking performance, resulting in an excellent ductility of UHPC beams [44]. The above results demonstrate that the volume content of steel fiber has a considerable influence on the shear behavior of non-stirrup UHPC beams. It is therefore essential to conduct further tests in determining the effect of steel fiber volume content.

Additionally, there are many parameters that influence the shear behavior of non-stirrup UHPC beams, including the shear span-to-effective-depth, prestressing level, types of steel fibers, fiber orientation and the shape of cross-section [44–48]. Zhang et al. [44]

carried out three-point bending tests to investigate the shear behavior of non-stirrup UHPC beams under larger shear span-to-effective-depth ratios (2.8). The test results discovered that the volume content of steel fibers had a more pronounced effect on the shear behavior of non-stirrup UHPC beams under larger shear span-to-effective-depth ratios (2.8). The French standard formulae demonstrated greater accuracy for UHPC beams with larger shear span-to-effective depth ratios. Li et al. [45] designed six non-stirrup UHPC beams with different shear span-to-effective-depth ratios. The findings demonstrated that the shear span-to-effective-depth ratio had a marked influence on the crack pattern and failure mode of the non-stirrup UHPC beams. Feng et al. [46] experimentally demonstrated that the prestressing level had a significant effect on the elastic phase and post-cracking phase in terms of the shear stress and deflection response. Moreover, it was found that applying higher prestressing could effectively enhance the ultimate shear strength of non-stirrup UHPC beams. Jiang et al. [47] tested seven externally prestressed UHPC segmental beams. The test results showed that the cracking and shear strength could be effectively improved by increasing the steel fiber volume content. Voo et al. [48] experimentally demonstrated that the types of steel fibers in the concrete had a minimal effect on the cracking load, but could significantly impact the rate of crack propagation and the failure loads. Baby et al. [49] tested the effect of steel fiber orientation on the shear behavior of UHPC beams. The test results demonstrated that the orientation of steel fibers had a marked impact on the shear strength of UHPC beams. Lee et al. [50] demonstrated that non-stirrup UHPC I-girders exhibited excellent ductility and remarkable post-cracking performance. The digital image correlation (DIC) non-contact strain testing system is an effective measurement system which can monitor shear deformation. Mészöly et al. [51] conducted a series of bending tests utilising the DIC system to investigate the shear behavior of UHPC beams. The test variables included the steel fiber volume content and the degrees of shear reinforcement. The test results revealed a notable discrepancy in the crack development of stirrup-reinforced UHPC beams and fiber-reinforced UHPC beams. At the earlier stage of loading, only a few cracks were observed in the fiber-reinforced UHPC beams. In contrast, the stirrup-reinforced UHPC beams had developed significant cracks. At the final stage of loading, the cracks in the fiber-reinforced UHPC beams were much denser than those in the stirrup-reinforced UHPC beams.

Despite a substantial amount of research focusing on the shear behavior of non-stirrup UHPC beams, due to the significant uncertainties in the shear failure mechanism, a great number of shear tests with a wider range of parameters remains need to be conducted for evaluating the shear safety of non-stirrup UHPC beams. The purpose of this study is to provide a comprehensive evaluation of the shear behavior, failure modes, and shear strength of non-stirrup UHPC beams, considering the effect of different factors (e.g., steel fiber volume content, shear span-to-effective-depth, beam width, and beam height). Specially, the shear contribution of steel fibers and UHPC were deeply investigated and analyzed. A digital image correlation (DIC) non-contact strain testing system was employed to capture the deformations and development of shear cracks. The test results were compared with the calculated values obtained from the French standard formulae [52], the PCI formulae [53], and Xu's formulae [54].

2. Research Significance

Ultra-high-performance concrete (UHPC) is regarded as one of the most promising construction materials, and has been used extensively around the globe. The superior mechanical properties of UHPC permit the potential removal of the stirrups in beams, thus enhancing construction efficiency and reducing costs. However, due to the great uncertainties involved in shear failure mechanism, a great number of shear tests with a wider range of parameters are necessary for evaluating the shear safety of non-stirrup UHPC beams. This study reveals that the shear mechanism of non-stirrup UHPC beams, focused especially on the shear contributions of steel fibers and UHPC, which was the critical issue in accurately estimating the shear resistance for non-stirrup UHPC beams,

providing experimental reference for practical engineering. Furthermore, it serves to validate the applicability of relevant shear design codes for non-stirrup UHPC beams.

3. Experimental Programs

3.1. Specimens and Test Matrix

In this study, two batches of tested beams were designed and fabricated to investigate the effects of shear span-to-effective-depth ratio (λ), steel fiber volume content, and beam height on the shear behavior of non-stirrup UHPC beams. The dimensions and the layouts of the tested beams are illustrated in Figure 1. In the first batch, there were six non-stirrup UHPC beams (B1–B6) with three different beam lengths (l) of 800 mm, 1100 mm, and 1700 mm, respectively. The shear span-to-effective-depth ratios (λ) for these beams were 1.2, 1.8, and 3.1, respectively, where λ was calculated by $\lambda = a/d$, with a and d representing the length of the shear span and effective depth of the beam, respectively. Furthermore, the first batch of beams possessed a rectangular cross-section with a beam width (b) of 150 mm and beam height (h) of 300 mm in dimension. In the second batch, there were six non-stirrup UHPC beams and two stirrup-reinforced normal concrete (NC) beams, with a total length of 1800 mm and a λ of 2.0. The cross-section was rectangular with a beam width (b) of 200 mm, and two beam heights (h) of 350 mm and 400 mm. Double layers of longitudinal reinforcements were placed at the bottom of the tested beams. Two kinds of ribbed reinforcements with the diameter of 25 mm and 32 mm were chosen in this study. The yield strength (f_y) of 25 mm and 32 mm diameter ribbed reinforcements were 425.2 MPa and 418.7 MPa, respectively. The NC beams were reinforced with double-leg stirrups comprising 8 mm diameter ribbed reinforcements with a yielding strength of 415.0 MPa, spaced at 100 mm intervals. The concrete clear cover thickness of the beams with a width of 150 mm and 200 mm was 10 mm and 20 mm, respectively. The arrangement of the rebar is also illustrated in Figure 1.

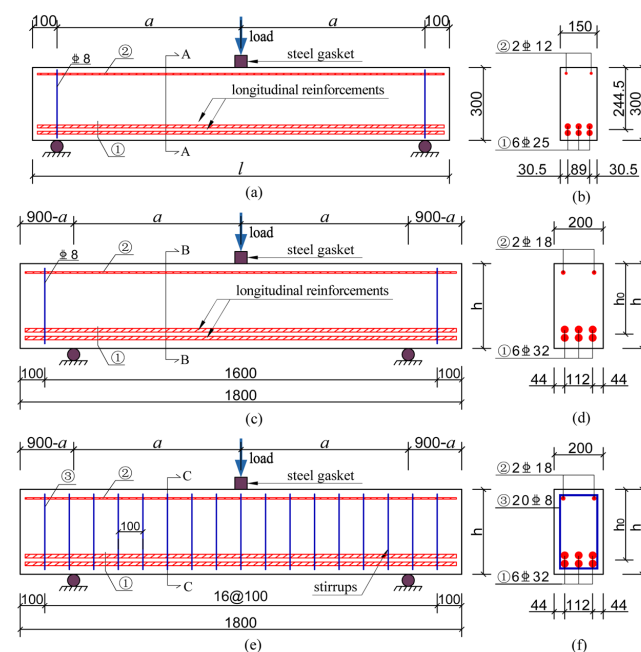


Figure 1. Dimensions and layouts of tested beams (unit: mm). (a) Non-stirrup UHPC beams in the first batch (B1–B6); (b) section A-A; (c) non-stirrup UHPC beams in the second batch (B7–B12); (d) section B-B; (e) stirrup-reinforced NC beams in the second batch (B13–B14); and (f) section C-C. Note: 6C25 indicates six HRB400 ribbed reinforcements with a 25 mm diameter; 2C12 indicates two HRB400 ribbed reinforcements with an 12 mm diameter; 6C32 indicates six HRB400 ribbed reinforcements with a 32 mm diameter; 2C18 indicates two HRB400 ribbed reinforcements with an 18 mm diameter; 20C8 indicates twenty HRB400 double-leg stirrups ribbed reinforcements with an 8 mm diameter.

Table 1 shows the details of the variable specimens. The specimen nomenclatures are referred to as U-W*-H*-V*-* and C-W*-H*-V*-* , which reflect the variables of concrete type, beam width, beam height, volume content of steel fiber, and shear span-to-effective-depth (λ), respectively. The symbols U and C represent ultra-high-performance concrete and normal concrete, respectively. W denotes the beam width, with W150 and W200 indicating beam widths of 150 mm and 200 mm, respectively. H denotes the beam height, with H30, H35, and H40 indicating beam heights of 300 mm, 350 mm, and 400 mm, respectively. V represents the volume content of steel fiber, with V2.0, V1.5, and V0 indicating the volume content of steel fiber at 2.0%, 1.5%, and 0%, respectively. The numbers 1.2, 1.8, 2.0, and 3.1 represent the shear span-to-effective-depth (λ). For example, “U-W150-H30-V2.0-1.2” represents a UHPC beam with a beam width of 200 mm, a beam height of 300 mm, a steel fiber volume content of 2.0%, and a shear span-to-effective-depth ratio of 1:2.

Table 1. Specimen nomenclature and experimental parameters.

NO.	Specimen Nomenclature	Concrete Type	b/(mm)	h/(mm)	Volume Content of Steel Fiber	d/(mm)	a/(mm)	λ	l/(mm)	Stirrup Ratio
B1	U-W150-H30-V2.0-1.2	UHPC	150	300	2.0%	244.5	293.4	1.2	800	0%
B2	U-W150-H30-V2.0-1.8	UHPC	150	300	2.0%	244.5	440.1	1.8	1100	0%
B3	U-W150-H30-V2.0-3.1	UHPC	150	300	2.0%	244.5	758.0	3.1	1700	0%
B4	U-W150-H30-V0-1.2	UHPC	150	300	0%	244.5	293.4	1.2	800	0%
B5	U-W150-H30-V0-1.8	UHPC	150	300	0%	244.5	440.1	1.8	1100	0%
B6	U-W150-H30-V0-3.1	UHPC	150	300	0%	244.5	758.0	3.1	1700	0%
B7	U-W200-H35-V2.0-2.0	UHPC	200	350	2.0%	291.0	582.0	2.0	1800	0%
B8	U-W200-H35-V1.5-2.0	UHPC	200	350	1.5%	291.0	582.0	2.0	1800	0%
B9	U-W200-H35-V0-2.0	UHPC	200	350	0%	291.0	582.0	2.0	1800	0%
B10	U-W200-H40-V2.0-2.0	UHPC	200	400	2.0%	341.0	682.0	2.0	1800	0%
B11	U-W200-H40-V1.5-2.0	UHPC	200	400	1.5%	341.0	682.0	2.0	1800	0%
B12	U-W200-H40-V0-2.0	UHPC	200	400	0%	341.0	682.0	2.0	1800	0%
B13	C-W200-H35-V0-2.0	C40	200	350	0%	291.0	582.0	2.0	1800	0.584%
B14	C-W200-H40-V0-2.0	C40	200	400	0%	341.0	682.0	2.0	1800	0.599%

Note: B1–B6 are the beams in the first batch, B7–B14 are the beams in the second batch.

3.2. Mix Design and Beam Fabrication

The UHPC mixture utilized in this study was supplied by Zhonglu Dura International Engineering Co. Ltd. This was an identical mixture as that from the factory, employed by Feng et al. [46]. Table 2 displays the mixture’s constituents, which primarily comprised cement, silica fume, quartz powder, quartz sand, steel fiber, water reducer, and tap water. The steel fibers were straight, with a length of 20.0 mm, a diameter of 0.2 mm, and a reported tensile strength of 2950 MPa, given by the supplier. Three UHPC mixtures with different steel fiber volume contents of 0%, 1.5%, and 2.0% were adopted in this study. Typically, the UHPC mixture used a steel fiber content of 2.0% by volume. To determine the structural behaviors exhibited by UHPC beams with varying steel fiber volume contents, less steel fiber was used in the UHPC mixture, which helped in reducing material costs. The normal concrete mixture (C40) used in this study was supplied by Guangdong Shengwei Concrete Co., Ltd. in Guangzhou China. Its primary constituent included cement, fly ash, mineral powder, sand, stone, tape water and water reducer, as listed in Table 3. To ensure the fluidity of concrete, fine aggregates were used instead of coarse aggregates.

The production of wooden formwork, installation of strain gauges, steel bar tying and pouring work for the NC beam were all completed in the Structural Laboratory of Guangdong University of Technology. The pouring work for the UHPC beam was completed in the plant of Zhonglu Dura International Engineering Co., Ltd.

Table 2. Mix proportions of UHPC.

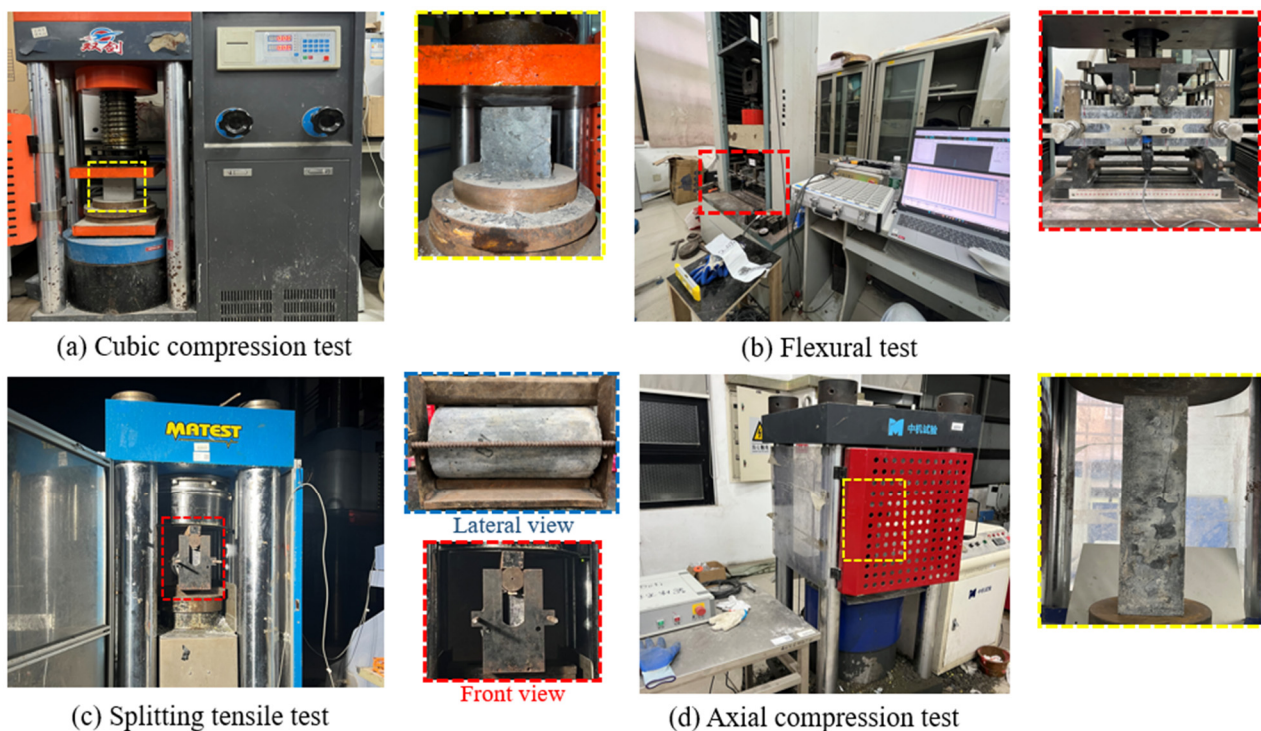
Property (kg/m ³)	Cement	Silica Fume	Quartz Powder	Quartz Sand	Steel Fiber	Water	Water Reducer
UHPC 2.0%	868	181	102	941	161	153	46
UHPC 1.5%	868	181	102	941	121	153	46
UHPC 0%	868	181	102	941	/	153	46

Table 3. Mix proportions of C40.

Property (kg/m ³)	Cement	Fly Ash	Mineral Powder	Sand	Stone	Water	Water Reducer
C40	280	65	61	688	1099	158	8

3.3. Material Characterization

The mechanical properties of UHPC were tested, including cubic compressive strength, axial compressive strength, splitting tensile strength, and flexural tensile strength. For the cube compression test, the $100 \times 100 \times 100 \text{ mm}^3$ cube was adopted to evaluate the ultimate compressive strength. For the axial compression test, the axial compressive strength f_c was determined from a $100 \times 100 \times 300 \text{ mm}^3$ prism according to Xu's formula [54]. For evaluation of the splitting tensile test, a $\phi 150 \text{ mm} \times 300 \text{ mm}$ cylinder was adopted. The cubic compression test, axial compression test, and splitting tensile test were conducted following the relevant provisions of ASTM C496 [55] as well as China's specifications GB/T50448–2015 [56] and JGT472–2015 [57]. For the flexural test, the specimen size ($100 \times 100 \times 400 \text{ mm}^3$ prism) and test method recommended by the French Standard NF P18-470 [58] were employed. The experimental setups of the material property tests are shown in Figure 2.

**Figure 2.** Experimental setup of mechanical property tests for UHPC and NC.

According to French Standard NF P18-470 [58], the tested result for post-cracking strength is calculated by:

$$\sigma_{f1} = \frac{1}{w^*} \int_0^{w^*} \sigma_f(w) dw \quad (1)$$

The post-cracking strength, taking into account the influence of the fiber orientation factor (K), is determined through the following calculation:

$$\sigma_{f2} = \frac{\sigma_{f1}}{K} \quad (2)$$

The post-cracking strength for the design is calculated using the following formula:

$$\sigma_{f3} = \frac{\sigma_{f1}}{K\gamma_{cf}} \quad (3)$$

where the post-cracking stress $\sigma_f(w)$ is determined based on the crack opening w . The study chose a maximum crack width (w^*) of 0.3 mm, a fiber orientation factor of 1.25 (K), and a partial safety factor (γ_{cf}) of 1.3, in accordance with the recommended values set forth in the French standard NF P 18-470 [58].

In accordance with the PCI report [53], the post-cracking residual strength f_{rr} is regarded as the initial peak cracking value, which is calculated using the following equation:

$$f_{rr} = 0.375f_{fu} \quad (4)$$

where f_{fu} is flexural tensile strength.

Table 4 provides the test results regarding the characteristics of the UHPC and C40 materials. It should be noted that the elastic modulus (E_c) of the UHPC refers to the study of Feng et al. [46]. The E_c of C40 is assumed as 34,500 MPa. The PCI report for ductility in the flexural test specifies that the residual strength at a deflection of ($L/300 = 1.33$ mm) must be a minimum of 90% of the cracking strength while, at ($L/150 = 2.67$ mm), it must be a minimum of 75% of the cracking strength [53]. Figure 3 displays the load-deflection curves obtained from the flexural test. The results demonstrate that the residual strengths of UHPC with steel fiber volume contents of 2.0% and 1.5% were markedly superior to the cracking strength at deflections of $L/300$ and $L/150$, respectively. Therefore, it can be demonstrated that the UHPC used in this study meets the ductility requirement in the PCI report.

Table 4. Basic mechanical properties of materials.

Concrete Type	Volume Content of Steel Fiber	f_{cu} (MPa)	f_c (MPa)	f_t (MPa)	σ_{f1} (MPa)	σ_{f2} (MPa)	σ_{f3} (MPa)	f_{fu} (MPa)	f_{rr} (MPa)	E_c (MPa)
UHPC-T1-0	0%	126.1	106.3	/	3.10	2.48	1.94	10.7	4.0	40,518
UHPC-T1-2.0	2.0%	158.8	142.0	/	8.94	7.15	5.50	28.1	10.5	42,780
UHPC-T2-0	0%	113.8	90.9	5.46	3.10	2.48	1.94	9.6	3.6	40,518
UHPC-T2-1.5	1.5%	155.0	139.1	10.33	5.62	5.00	3.46	30.3	11.4	42,500
UHPC-T2-2.0	2.0%	160.3	148.5	13.85	8.94	7.15	5.50	42.3	15.9	42,780
C40	0%	31.7	/	/	/	/	/	/	/	34,500

Notes: “UHPC-T1-0” indicates the UHPC mixture of the first batch with the volume content of steel fiber at 0%, and T1 and T2 represent the first batch and the second batch, respectively; f_{cu} = Cubic compressive strength; f_c = Axial compressive strength; f_t = Splitting tensile strength; σ_{f1} = Tested post-cracking strength; σ_{f2} = Post-cracking strength considering a fiber orientation factor (k) of 1.25; σ_{f3} = Post-cracking strength for design; f_{fu} = Flexural tensile strength; f_{rr} = Post-cracking residual strength. σ_{f1} , σ_{f2} , σ_{f3} , with inferred value according to f_{fu} .

The mechanical property tests on the stirrups and longitudinal reinforcements were conducted in accordance with the provision of China’s specifications GB/T50448–2015 [56]. The results of the tests are presented in Table 5. It is assumed that the elastic modulus of the rebar (E_s) is 2.0×10^5 MPa. The tested process is shown in Figure 4.

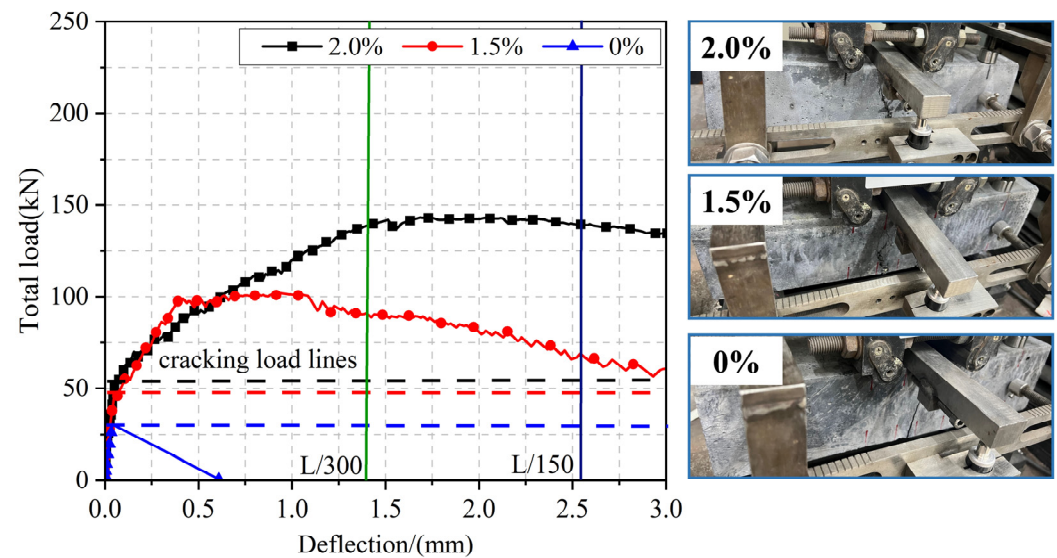


Figure 3. Load-deflection curves and crack patterns of flexural tests. Note: 2.0%, 1.5%, and 0% indicate a steel fiber volume content of 2.0%, 1.5%, and 0%, respectively. The letter “L” indicates the length of the prisms. “L/300” and “L/150” are denoted by the green and dark blue line, respectively.

Table 5. Mechanical properties of rebars.

Specimen	Reinforcing Steel Type	Diameter (mm)	Yield Strength (MPa)	Ultimate Strength (MPa)
Stirrup	HRB400	8	415	623
Longitudinal reinforcement	HRB400	25	425	611
Longitudinal reinforcement	HRB400	32	419	624

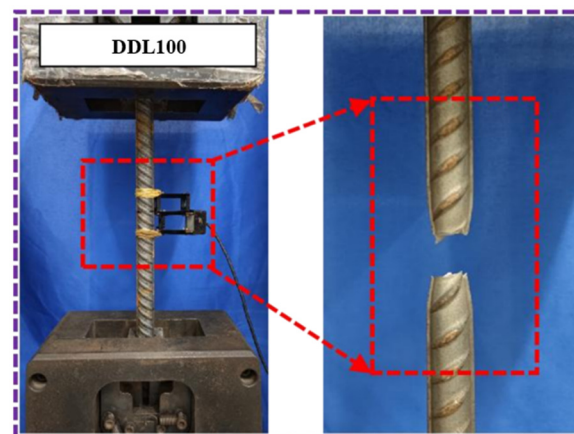


Figure 4. Experimental setup of mechanical property tests for rebar.

3.4. Test Setup and Instrumentation

The specimens were tested in the Structural Laboratory of Guangdong University of Technology. Figure 5 displays the photos of the experimental setup for all tested beams. Each specimen was loaded in a three-point bending configuration to evaluate the shear behavior of non-stirrup UHPC beams. All of the specimens were tested under a vertical concentrated load applied by an electro-hydraulic servo machine capable of a maximum force of 10,000 kN. Each tested beam was supported by two roller supports. Deflections of the beams at the mid-span were monitored by a single Linear Variable Differential Transducer (LVDT). Figure 6a–c displays the strain gauge layout of the tested beams. The

strain rosettes were evenly spaced along the line extending from the loading point to the supports. Each strain rosette consisted of three strain gauges, arranged at 0° , 45° , and 90° , respectively, for the measurement of principal strains. The strains in the longitudinal reinforcements and stirrups were quantified by means of the strain gauges affixed to the rebar. To guarantee precise measurements, the rebars were meticulously sanded smooth at the designated gauge location prior to the affixation of the strain gauges. Additionally, waterproof adhesive and anti-collision blocks were employed to safeguard the strain gauges. The longitudinal reinforcements were numbered 1–3 and 4–6 from the south to the north side of the double layer reinforcements, as illustrated in Figure 7a,b. The letters “N” and “S” indicate the northern and southern sides, respectively. The strain gauges affixed to the longitudinal reinforcements were labeled W_1 – W_6 , M_1 – M_6 , and E_1 – E_6 , respectively, from the western side to the eastern side. The letters “W”, “M” and “E” represent the western, middle and eastern sides, respectively.

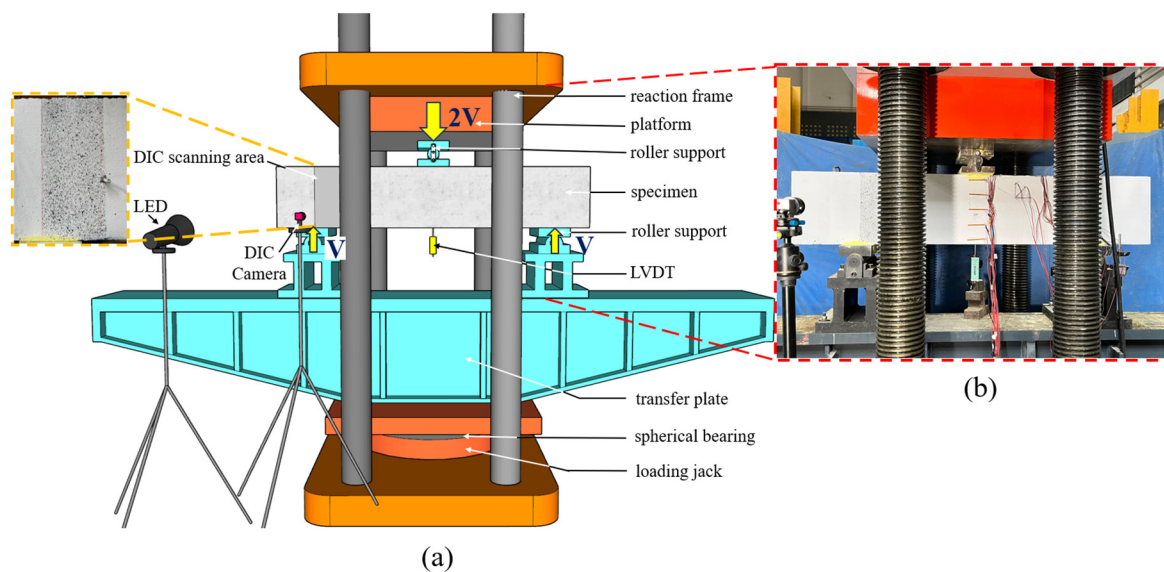


Figure 5. Diagram and photos of experimental setup. (a) Diagram of experimental setup; and (b) photo of experimental setup.

In the second batch beams, a digital image correlation (DIC) non-contact strain testing system was used to capture the deformations and development of shear cracks subsequent to their formation (see Figure 5). The DIC system consisted of a data acquisition system and a black and white 4-megapixel charge coupled device (CCD) camera, which was employed to capture and process the images. The CCD camera was positioned at the same height as the center of the area under evaluation. The surface images are being recorded at one-second intervals. Accurate DIC measurements require sufficient contrast. To achieve this, random speckle patterns were applied by using black and white spray paint (see Figure 5a). Prior to the test, a caliper was employed for calibration.

In all tests, the load was applied by the electro-hydraulic servo machine in 50 kN increments until the first shear diagonal crack was identified. Subsequently, the loading process was modified to displacement control, with a jack displacement rate of 0.1 mm/min. The test was terminated when the load was reduced to 60% of the maximum load after peaks.

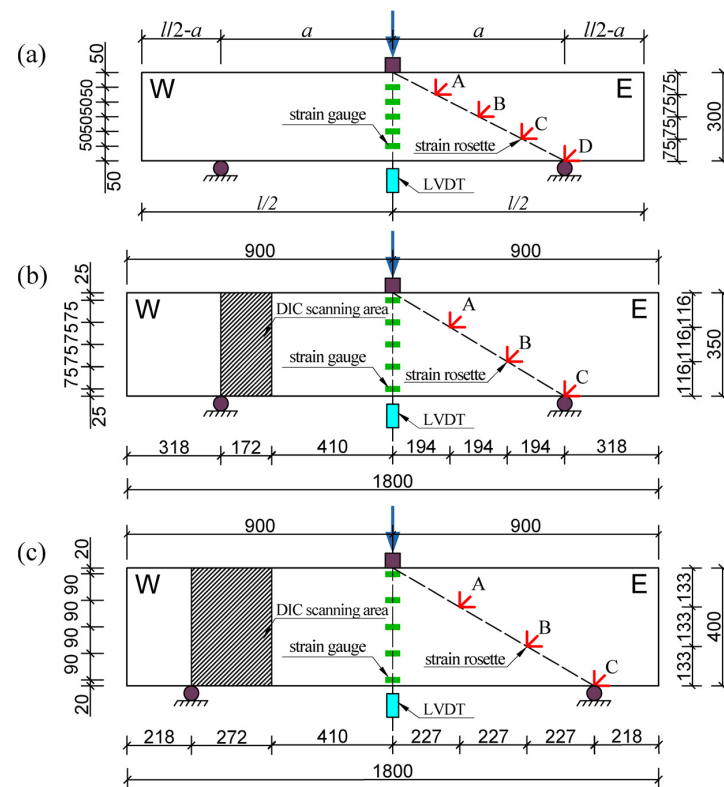


Figure 6. Layout of external measuring points. (a) External measuring points of the 300-mm-high tested beams; (b) external measuring points of the 350-mm-high tested beams; and (c) external measuring points of the 400-mm-high tested beams.

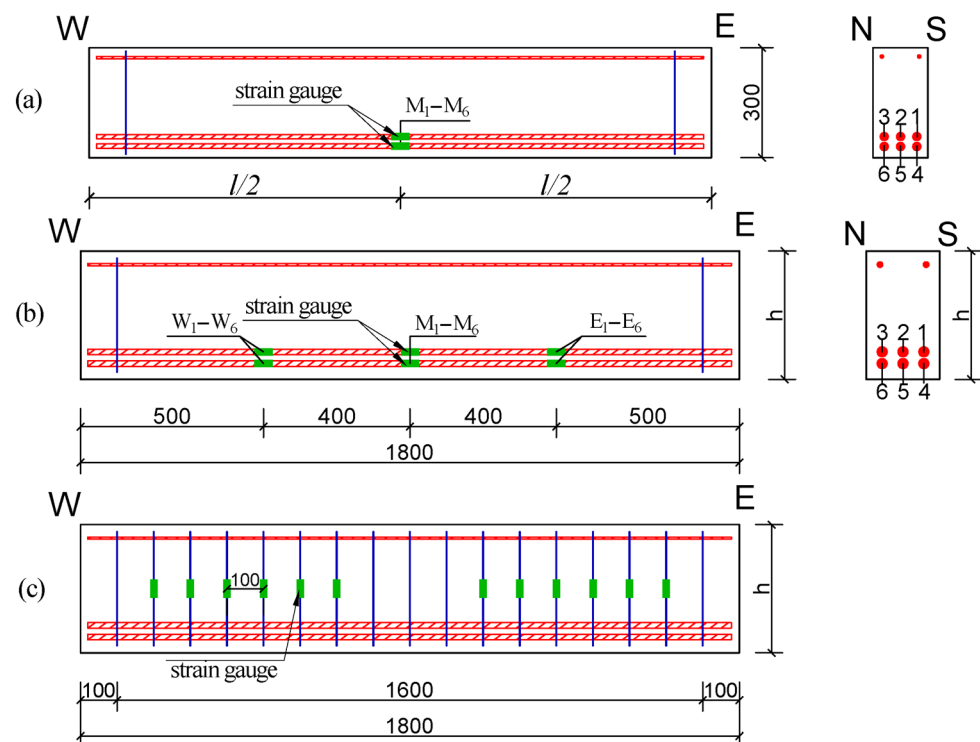


Figure 7. Layout of strain gauge. (a) Strain gauges of the longitudinal reinforcements for the first batch tested beams; (b) strain gauges of the longitudinal reinforcements for the second batch tested beams; and (c) strain gauges of the stirrups for the second batch tested beams.

4. Experimental Results and Discussion

4.1. Crack Patterns and Failure Modes

The cracking patterns and failure modes observed in the tested beams are illustrated in Figure 8. The critical cracks were visually represented by thick black lines and the areas of severe concrete damage were expressed as black bold areas. The type of failure mode observed was dependent on the location of critical cracks. If the critical cracks emerge in the mid-span, flexural failure will occur, while if the critical cracks emerge in the shear-bending section, shear failure will occur.

As seen in Figure 8e, beam B3 experienced flexural failure, so the failure mode of beam B3 is not taken into consideration for shear analysis. For the other tested beams, typical shear failure occurred, which could be divided into three different types, including diagonal tension failure (DT), shear compression failure (SC), and diagonal compression failure (DC).

Beams B1, B2, B7, B8, B10, and B11 exhibited typical patterns of shear compression failure. At the start of loading, flexural cracks appeared at the bottom of the middle of the beams. When the load increased to a level between 23% and 45% of the peak load, diagonal cracks were observed. As the load kept increasing, new diagonal cracks kept emerging, and finally, a critical diagonal crack developed. When the ultimate load was reached, the concrete in the vicinity of the loading point was crushed.

For beams B5, B6, and B12, as the load increased, once the diagonal cracks emerged in the shear span, the crack width increased rapidly and soon became critical diagonal cracks. Subsequently, the two beams abruptly lost their load-bearing capacity and fractured into two pieces, exhibiting flat failure surfaces and no concrete crushing. Consequently, the failure mode of beams B5, B6, and B12 can be identified as diagonal tension failure.

For beams B4, B9, B13, and B14, few cracks were observed at the beginning of loading. As the load approached approximately 40% of the ultimate load, a series of parallel diagonal cracks emerged, dividing the web of the beams into multiple inclined compression columns. As the ultimate load was reached, the beams suddenly failed. Consequently, the failure mode of beams B4, B9, B13 and B14 can be identified as diagonal compression failure.

The above results demonstrate that the incorporation of steel fibers has a significant impact on the cracking patterns and failure modes, which could markedly enhance the ductility of the beams and prevent them from brittle failure. In the previous study conducted by Zhang et al. [44], all of the non-stirrup UHPC beams with 1.5% or 2.0% steel fiber volume content exhibited shear compression failure, whereas the beams with 0% steel fiber volume content exhibited diagonal compression failure. Their findings further demonstrate the significant effect of the incorporation of steel fibers on the cracking patterns and failure modes. Furthermore, it was discovered that the shear span-to-effective-depth ratio exerts a considerable influence on the cracking patterns and failure modes. When the shear span-to-effective-depth ratio is small, the beams generally exhibit diagonal compression failure, whereas high ratios result in diagonal tension failure. In addition, the beam height was also found to exert an influence on the cracking patterns and failure modes. Specifically, when the beam height is relatively smaller, the formation of cracks in the beam is denser, resulting in the occurrence of diagonal compression failure.

The experimental results for all tested beams are summarized in Table 6.

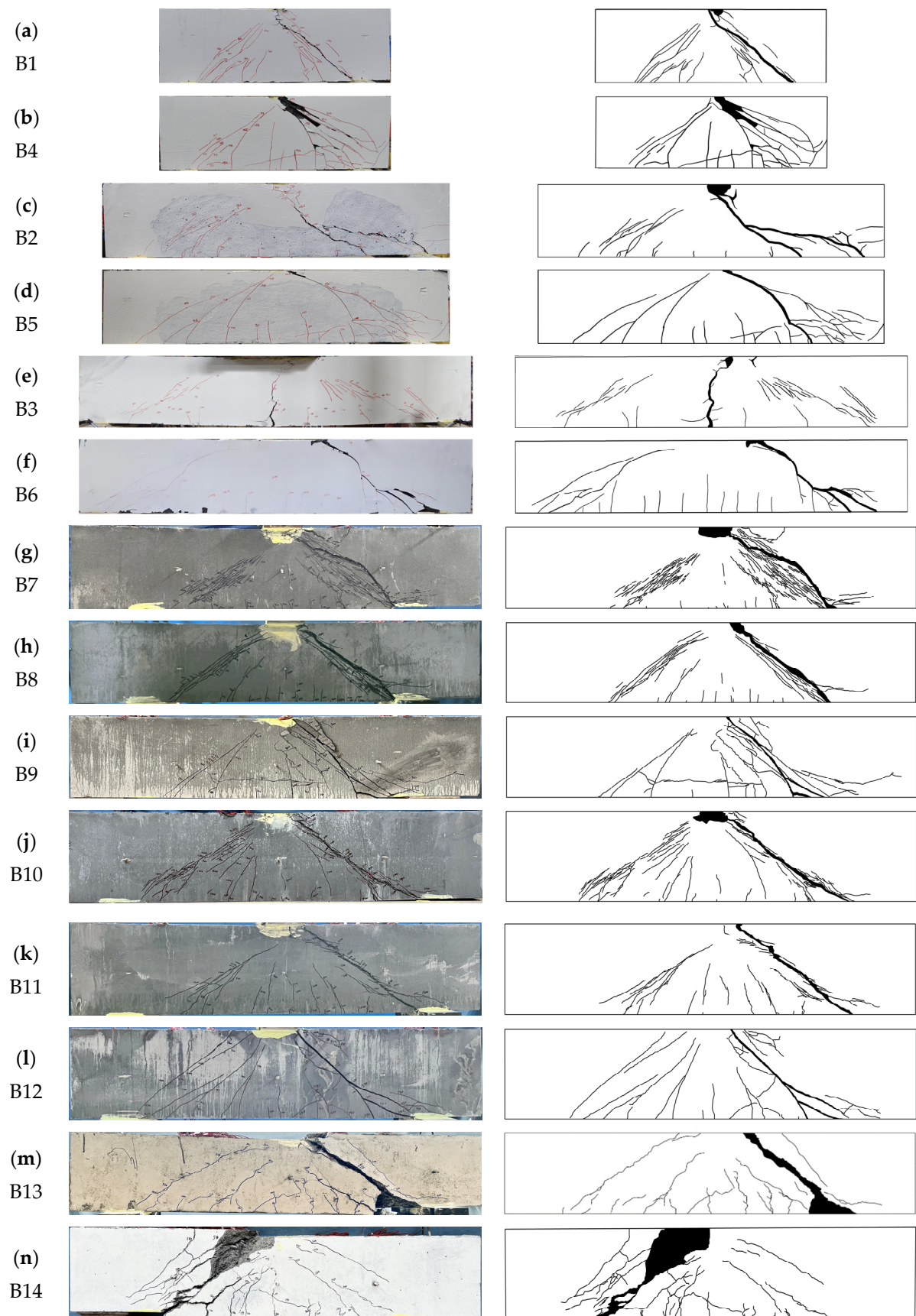


Figure 8. Crack pattern of each tested beam.

Table 6. Summary of key experimental results.

NO.	P_{cr} (kN)	M_{cr} (kN·m)	σ_{cr} (MPa)	P_{ci} (kN)	v_{ci} (MPa)	P_u (kN)	V_u (kN)	τ_u (MPa)	Δ_u (mm)	$P_{failure}$ (kN)	$\Delta_{failure}$ (mm)	P_y (kN)	Δ_y (mm)	μ_Δ	θ	PSCR	Failure Pattern
B1	200	29.3	20.2	519	7.1	1475	737.5	20.1	2.97	1180	3.83	1402	2.86	1.34	45°	65%	SC
B2	134	29.5	20.3	480	6.5	1076	538	14.7	5.00	861	6.53	998	4.14	1.58	33°	55%	SC
B3	94	35.6	24.5	420	5.7	748	374	10.2	21.59	745	23.98	705	7.34	3.26	35°	44%	FF
B4	104	15.3	10.2	141	1.9	868	434	11.8	2.73	694	2.79	851	2.63	1.06	43°	83%	DC
B5	80	17.6	11.7	101	1.4	225	112.5	3.1	1.84	180	2.25	202	1.58	1.42	31°	55%	DT
B6	56	21.2	14.2	56	0.8	346	173	4.7	5.98	69	8.45	323	5.56	1.52	34°	83%	DT
B7	501	145.8	52.2	901	7.7	2500	1250	21.5	5.56	1074	8.67	2480	5.12	1.69	32°	64%	SC
B8	298	86.7	30.9	420	3.6	1862	931	16.0	4.23	1104	4.66	1841	3.99	1.16	38°	77%	SC
B9	197	57.3	19.9	242	2.1	919	459.5	7.9	2.55	627	3.30	883	2.38	1.39	44°	74%	DC
B10	501	170.8	49.1	701	5.1	2167	1083.5	15.9	4.69	1413	6.29	2140	4.46	1.41	38°	68%	SC
B11	400	136.4	39.0	600	4.4	1603	801.5	11.8	4.25	952	5.49	1579	4.10	1.34	38°	63%	SC
B12	203	69.2	19.2	301	2.2	794	397	5.8	2.75	519	3.36	761	2.39	1.41	42°	62%	DT
B13	80	23.3	7.4	259	2.2	591	295.5	5.1	3.93	573	5.66	582	3.27	1.73	39°	56%	DC
B14	80	27.3	6.9	298	2.2	606	303	4.4	2.78	521	4.99	600	2.67	1.87	36°	51%	DC

Notes: The letters SC, DT, DC, and FF represent the failure modes of shear compression failure, diagonal tension failure, diagonal compression failure, and flexural failure, respectively; Δ_u = Midspan deflection of ultimate load; $P_{failure}$ = Failure load, which indicates the load required for the beam to incur significant damage; P_y = Yield load; θ represents the angle between the beam axis and the critical shear diagonal crack.

The bending moment of initial flexural cracking (M_{cr}) is calculating by the following equation:

$$M_{cr} = \frac{P_{cr} \cdot a}{2} \quad (5)$$

where P_{cr} indicates the load of initial flexural cracking; a indicates the length of the shear span.

The flexural cracking strength (σ_{cr}) is calculated by the following equations:

$$\sigma_{cr} = \frac{M_{cr} \cdot y}{I} \quad (6)$$

$$I = \alpha_{Es} A_s (d - x)^2 \quad (7)$$

$$y = d - x \quad (8)$$

$$x = \frac{\alpha_{Es} A_s}{b} \left(\sqrt{1 + \frac{2bd}{\alpha_{Es} A_s}} - 1 \right) \quad (9)$$

$$\alpha_{Es} = \frac{E_s}{E_c} \quad (10)$$

where y indicates the centroid height; I represents the moment inertia of conversion section; α_{Es} indicates the section conversion factor; A_s indicates the cross-section area of longitudinal reinforcement; b and d denote the beam width and the effective depth of the beam, respectively; E_s and E_c represent the modulus of longitudinal reinforcement and concrete, respectively.

The diagonal cracking strength (v_{ci}) is calculated by the following equation:

$$v_{ci} = \frac{P_{ci}/2}{bd} \quad (11)$$

where P_{ci} indicates the load of initial diagonal crack; b and d indicate the beam width and the effective depth of the beam, respectively.

The peak shear load V_u is calculated by the following equation:

$$V_u = \frac{P_u}{2} \quad (12)$$

where P_u indicates the ultimate load.

The ultimate shear strength (τ_u) is given by the following equation:

$$\tau_u = \frac{V_u}{bd} \quad (13)$$

PCSR denotes the post-diagonal-cracking shear resistance, which is calculated by the following equations:

$$PCSR = \frac{V_u - V_{ci}}{V_u} \times 100\% \quad (14)$$

$$V_{ci} = \frac{P_{ci}}{2} \quad (15)$$

The ductility coefficients (μ_Δ) are given by:

$$\mu_\Delta = \frac{\Delta_{failure}}{\Delta_y} \quad (16)$$

where $\Delta_{failure}$ indicates the midspan deflection of failure load; Δ_y indicates the midspan deflection of yield load.

4.2. Load–Deflection Relationships

Figure 9 shows the load mid-span deflection curves for all of the tested beams, demonstrating the results for beams with different shear span-to-effective-depths (λ), steel fiber volume contents, and beam heights.

4.2.1. Effect of Shear Span-to-Effective-Depth

By comparing the load–midspan deflection curves of beams B1, B2, B3 and B4, B5, B6 in Figure 9a–c, it can be inferred that the stiffness of the beams decreased significantly as the shear span-to-effective-depth ratio (λ) increased. This indicates that λ has a considerable effect on the stiffness of the beams. Specifically, the stiffness of the beam is found to decrease as the shear span-to-effective-depth ratio (λ) increases. This effect was also observed by Li et al. [46] in the non-stirrup UHPC beams with a beam width of 200 mm, which indicates that the beam width has a minimal influence on this effect.

4.2.2. Effect of Steel Fiber Volume Content

As shown in Figure 9d–h, for the same ratio of shear span to effective depth (λ), the incorporation of steel fibers could significantly increase the stiffness and ductility of the beam. It should be noted that beam B5 was affected by unknown factors, resulting in an abnormal decrease in its ultimate shear strength. Therefore, the behavior of beam B5 is not taken into consideration. By comparing the load–midspan deflection curves of beams B1 and B4, B3 and B6, B7 and B9, as well as B10 and B12, it can be concluded that the effect of steel fibers on the stiffness of the beams was more pronounced when the λ was relatively small. However, when λ was small enough by a certain extent, this effect could be neglected. This is because, when λ is smaller, the load-bearing properties of the beam are mainly determined by the compressive properties of the concrete. When the shear span-to-effective-depth ratio is large enough by a certain extent, the load-bearing properties of the beams are mainly determined by the longitudinal reinforcement. At these times, the effect of steel fibers cannot be fully utilized.

By comparing the load–midspan deflection curves of beams B1, B4, and B7, B9, as well as B10 and B12, it is also noteworthy that the enhancement of beam ductility by the incorporation of steel fibers is more pronounced at relatively larger shear span-to-effective-depth ratios. The midspan deflections of the ultimate load (Δ_u) for U-W150-H30-V2-1.2 (B1) and U-W200-H35-V2-2.0 (B7) beams were increased by 8.8% and 118.0%, respectively, compared to U-W150-H30-V0-1.2 (B4) and U-W200-H35-V0-2.0 (B9) beams, as shown in Figure 9d,g. This demonstrates that the synergistic effect of steel fiber and longitudinal reinforcement is better exploited at appropriate shear span-to-effective-depth ratios.

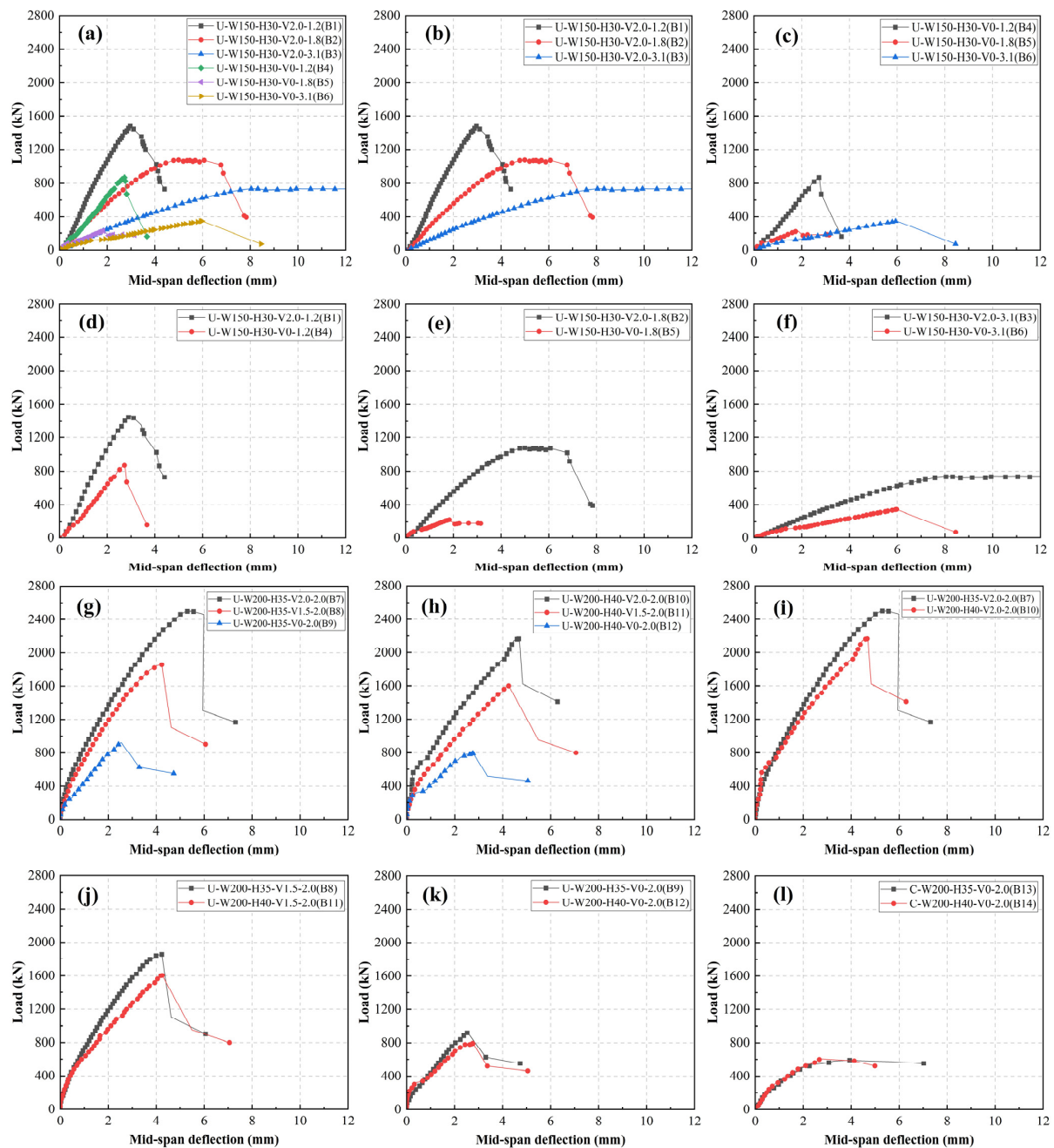


Figure 9. Load–midspan deflection curves of the tested beams. (a) Load–midspan deflection of the beams with a beam width of 150 mm; (b) Effect of shear span-to-effective-depth ratio on the beams with a steel fiber volume content of 2.0%; (c) Effect of shear span-to-effective-depth ratio on the beams with a steel fiber volume content of 0%; (d) Effect of steel fiber volume content on the beams with a shear span-to-effective-depth ratio of 1.2; (e) Effect of steel fiber volume content on the beams with a shear span-to-effective-depth ratio of 1.8; (f) Effect of steel fiber volume content on the beams with a shear span-to-effective-depth ratio of 3.1; (g) Effect of steel fiber volume content on the beams with a beam height of 350 mm; (h) Effect of steel fiber volume content on the beams with a beam height of 400 mm; (i) Effect of beam height on the beams with a steel fiber volume content of 2.0%; (j) Effect of beam height on the beams with a steel fiber volume content of 1.5%; (k) Effect of beam height on the beams with a steel fiber volume content of 0%; (l) Effect of beam height on the normal concrete beams.

4.2.3. Effect of Beam Height

Figure 9i–l demonstrates that the load–midspan deflection curves of the tested beams with a beam height of 350 mm closely match those of the beams with a beam height of 400 mm. This suggests that beam height has a minor or insignificant effect on the stiffness and ductility of the beams.

4.3. Strain Response

4.3.1. Strain Response of Longitudinal Reinforcements

The load–strain relationships of the longitudinal reinforcement for U-W150-H30-V0-*, U-W150-H30-V2-*, U (C)-W200-H35-V*-2.0 and U (C)-W200-H40-V*-2.0 beams are shown in Figure 10a–d. To ensure precise evaluation of the strain of longitudinal reinforcement, a typical strain gauge was selected from the pre-embedded gauges of each beam to depict the load–strain curves of the longitudinal reinforcements. The detail of the selection was presented in the label of Figure 10. The yield strengths of the 25 mm and 32 mm diameter ribbed reinforcements were assumed to be 425 MPa and 419 MPa, respectively, with an elastic modulus of 2.0×10^5 MPa. Therefore, the yield strain of the 25 mm and 32 mm diameter ribbed reinforcements were approximately 2125 $\mu\epsilon$ and 2095 $\mu\epsilon$, respectively. These values are also marked as a vertical dashed line.

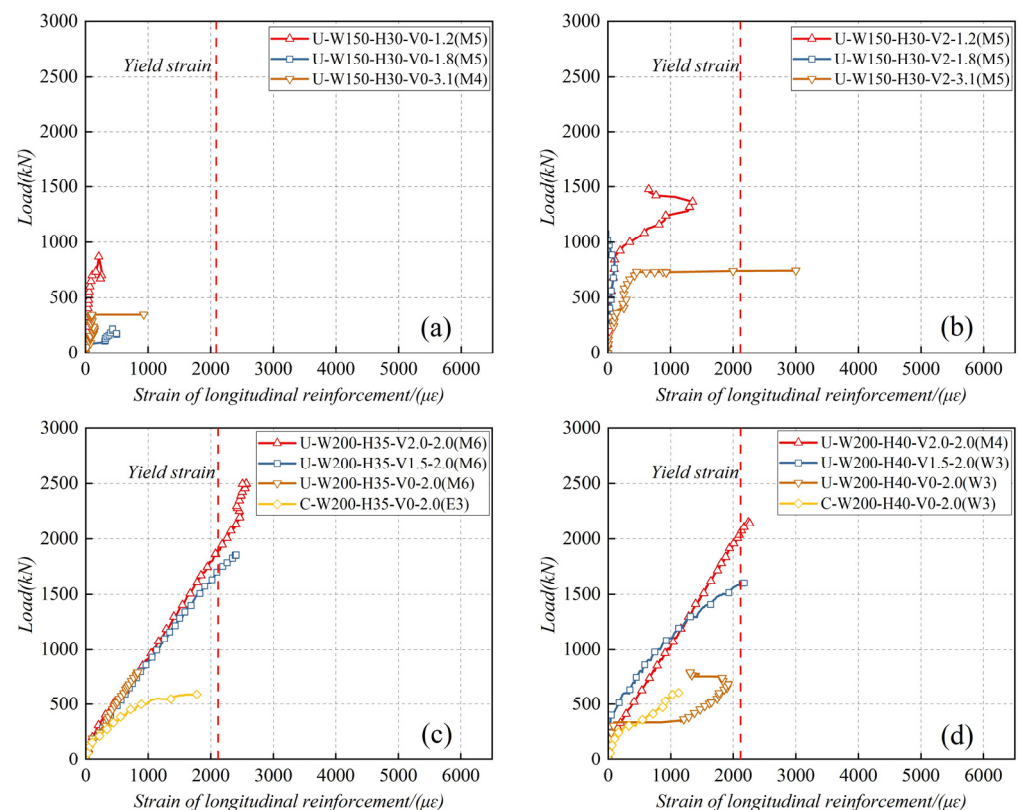


Figure 10. Load-strain curves of longitudinal reinforcements. (a) U-W150-H30-V0-* beams; (b) U-W150-H30-V2-* beams; (c) U (C)-W200-H35-V*-2.0 beams; and (d) U (C)-W200-H40-V*-2.0 beams.

As shown in Figure 10, the longitudinal reinforcement strain of beam U-W150-H30-V0-1.2 (B4) remained relatively constant until the peak load was reached. This was because of the small shear span-to-effective-depth ratio and the lack of steel fiber in B4. As the load increased, diagonal compression failure occurred due to the crushing of concrete in the beam web. At this point, the load-bearing capacity of the beam is primarily determined by the compressive capacity of the concrete. For beams B5, B6, B9, and B12, the longitudinal reinforcement strains were far from the yield strains before the beams reached their peak load. This was caused by the lack of the bridging action of the steel fibers. The longitudinal

reinforcements were not fully utilized as the beams failed quickly after cracking. It should be noted that beam B5 was affected by unknown factors, resulting in an abnormal decrease in its ultimate shear strength. Due to the fact that the experimental process had been rigorously controlled, the abnormal B5 beam could be attributed to manufacturing issues with the UHPC material at the factory. Therefore, the behavior of beam B5 is not taken into consideration. Figure 10b–d shows that the longitudinal reinforcement strains of the beams B1, B3, B7, B10, B8, and B11 gradually increased with the load improvement due to the incorporation of steel fibers at 2.0% and 1.5% by volume, respectively. The steel fibers of the beams interacted synergistically with the longitudinal reinforcements, resulting in improvement in the load-bearing capacity of the beams. This demonstrates that the incorporation of steel fibers can effectively enhance the shear load-bearing capacity of the beams. It should be noted that, for beams U-W200-H35-V2.0-2.0 (B7) and U-W200-H40-V2.0-2.0 (B10), the loads at which the longitudinal reinforcements yielded increased by up to 12.9% and 28.4%, respectively, compared to beams U-W200-H35-V1.5-2.0 (B8) and U-W200-H40-V1.5-2.0 (B11). This finding further supports the synergistic effect of steel fibers with longitudinal reinforcement. Increasing the volume content of steel fiber within a certain range can effectively enhance its synergistic effect with longitudinal reinforcement, thereby improving the shear load-bearing capacity.

4.3.2. Strain Response of Stirrups

To ensure the accuracy of measurement, a suitable strain gauge was selected from the pre-embedded strain gauges to evaluate the strains of the stirrups. The load–strain curves of the stirrups for beams C-W200-H35-V0-2.0 (B13) and C-W200-H40-V0-2.0 (B14) are depicted in Figure 11. The stirrup's yield strength and elastic modulus were assumed to be 415 MPa and 2.0×10^5 MPa, respectively. The yield strain of the stirrup was therefore approximately $2075 \mu\epsilon$, which is also marked as a vertical dashed line.

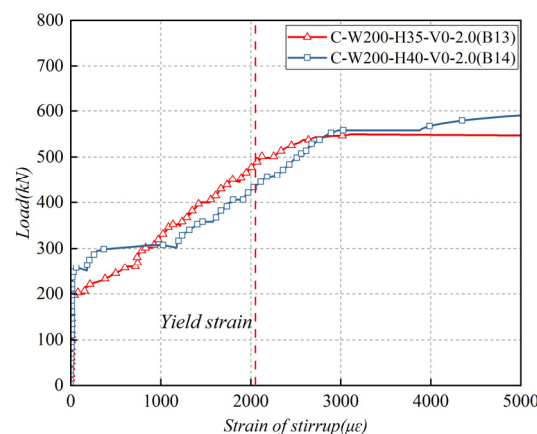


Figure 11. Load–strain curves of the stirrups.

As shown in Figure 11, the strain of the stirrups barely changed prior to the emergence of the diagonal crack. Once the diagonal crack appeared, the strain of the stirrup arrived at a turning point and increased almost linearly with the increase of load, eventually exceeding the yield strain. After reaching the peak load, there was a sudden increase in the strain of the stirrup. These experimental results demonstrate that the stirrups were subjected to minimal stress until diagonal cracks appeared. Following the emergence of the diagonal crack, the stress was redistributed, and the concrete lost some of its tensile strength, causing the stress originally borne by the concrete to be transferred to the stirrups, leading to a turning point in the strain of the stirrups. After the peak load was reached, the concrete lost almost all of its bearing capacity, and the majority of the stresses were transferred to the stirrups. This is the reason of the abrupt growth of the strain in the stirrups. Furthermore, it has been demonstrated that the stirrups in both B13 and B14 had yielded before reaching

the peak loads. It can be concluded that the stirrups in B13 and B14 were maximized to resist the shear force and are important for the load-bearing capacities of the beams.

4.3.3. Strain Response of Concrete Diagonal Sections

The principal tensile strains ε_t and principal compression strains ε_c were determined using the following Equation (17), where ε_x , ε_{45° and ε_y , represent the strains of the strain gauges positioned at 0° , 45° , and 90° , respectively. The positive calculations denote the principal tensile strain, and the negative calculations indicate the principal compressive strain.

$$\begin{cases} \varepsilon_t \\ \varepsilon_c \end{cases} = \frac{\varepsilon_x + \varepsilon_y}{2} \pm \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \left(\frac{\varepsilon_x + \varepsilon_y}{2} - \varepsilon_{45^\circ}\right)^2} \quad (17)$$

Figure 12 shows the load–principal strain relationships for all of the tested beams at different measurement points on the diagonal section. As illustrated in Figure 12, the compressive strain at the concrete diagonal sections was markedly greater than the tensile strain at a smaller shear span-to-effective-depth ratio. This indicates that the concrete was predominantly subjected to compressive stresses at this juncture. In the case of larger shear span-to-effective-depth ratios, applying a minimal load resulted in a notable increase in the principal strain of the concrete, with tensile strains becoming the dominant type. This indicates that an increase in the shear span-to-effective-depth ratio leads to a notable rise in tensile stresses in UHPC beams.

4.4. Ultimate Shear Strengths

4.4.1. Influence of the Volume Content of Steel Fiber

As illustrated in Figure 13a,b, the non-stirrup UHPC beams had shear strengths equal to or even much greater than those of the NC beams, demonstrating the feasibility of removing the stirrups. Additionally, the ultimate shear strength of UHPC beams could be markedly enhanced through the incorporation of steel fibers. At a shear span-to-effective-depth ratio (λ) of 2.0, the ultimate shear strength can be increased by approximately 100% and 170% with the incorporation of 1.5% and 2.0% volume content of steel fibers, respectively. It can also be concluded that an increase in the volume content of steel fiber within a certain range could significantly improve the ultimate shear strength. In comparison with the test results from the previous study conducted by Zhang et al. [44], it can be discovered that the enhancement of ultimate shear strength by the addition of steel fibers is more pronounced as the shear span-to-effective-depth ratio decreases from 2.8 to 2.0. It is thus can be inferred that the shear span-to-effective-depth ratios exert an influence on the effect of the volume content of steel fibers.

4.4.2. Influence of the Shear Span-to-Effective-Depth Ratio

As shown in Figure 13c, for the same volume content of steel fiber, the ultimate shear strength of the UHPC beams decreases significantly as the shear span-to-effective-depth ratio (λ) increases. This demonstrates that the λ has a significant impact on the ultimate shear strength of the beams. It should be noted that beam B5 was affected by unknown factors, resulting in an abnormal decrease in its ultimate shear strength. Therefore, the ultimate shear strength of beam B5 is not taken into consideration. For beams B1, B3, B4, and B6, it was discovered that the enhancement of the ultimate shear strength by steel fibers increased with the increase of λ due to the excellent tensile property of the UHPC mixture. This is because a greater shear span-to-effective-depth ratio results in a large tensile stress and a small compressive stress on the shear bending section, necessitating a high tensile property of the beam's material. UHPC's excellent tensile property is fully utilized in this scenario.

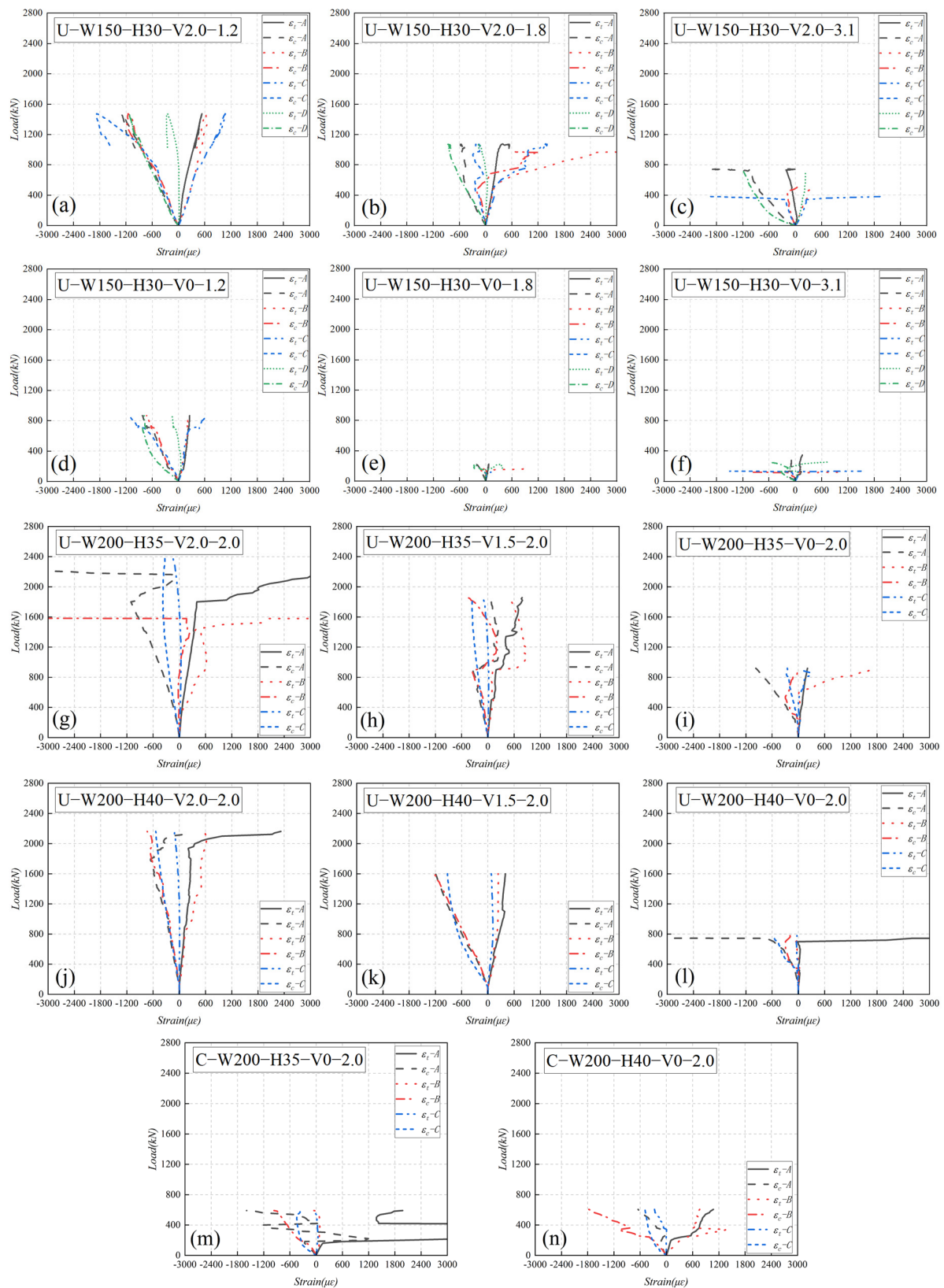


Figure 12. Load–principal stress relationship for concrete diagonal section. (a) B1; (b) B2; (c) B3; (d) B4; (e) B5; (f) B6; (g) B7; (h) B8; (i) B9; (j) B10; (k) B11; (l) B12; (m) B13; and (n) B14.

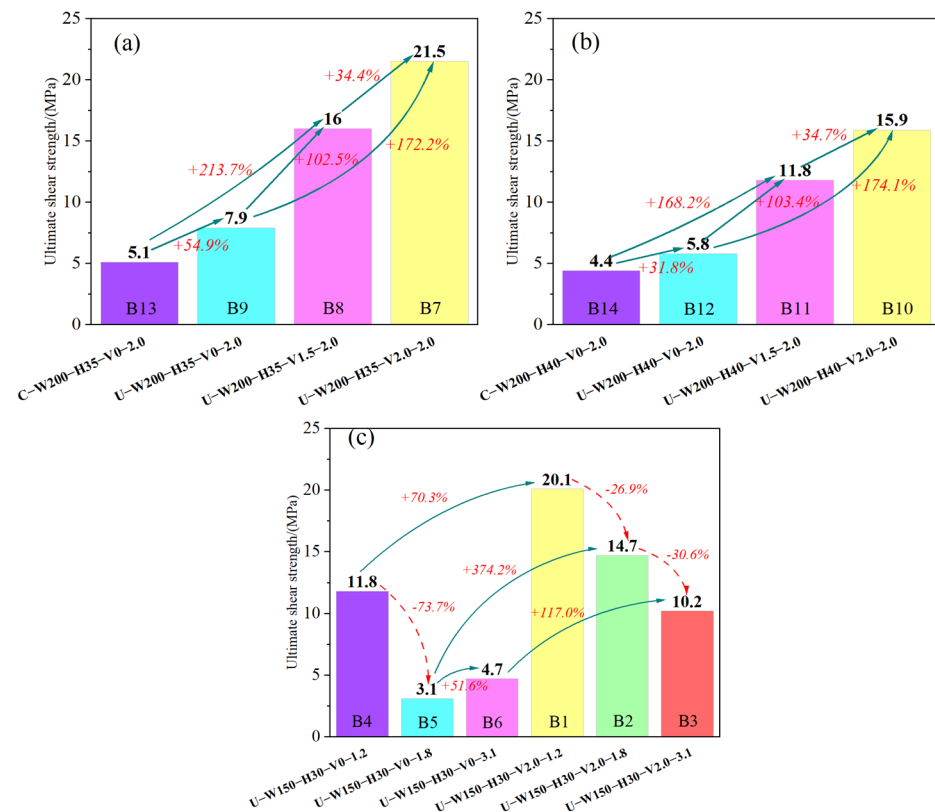


Figure 13. Effect of experimental variables on ultimate shear strength. (a) Effect of concrete type and steel fiber volume content on ultimate shear strength of 350 mm high beams; (b) effect of concrete type and steel fiber volume content on ultimate shear strength of 400 mm high beams; and (c) effect of steel fiber volume content and shear span-to-effective-depth ratio on ultimate shear strength of 300 mm high beams.

4.5. The Formation and Propagation of Shear Cracks

Figure 14a illustrates a comprehensive analysis of shear crack development. The crack deformation was accurately measured by a DIC non-contact strain testing system. Specifically, the system permits the selection of two virtual markers on the sample, as shown in Figure 14b. The initial positions of the two virtual markers were designated as P_0 and P_1 . When the tested beams reached their ultimate load-bearing capacity, the positions of the two virtual markers were P'_0 and P'_1 . By analyzing the total crack deformation Δ , the formation and propagation of shear cracks can be drawn.

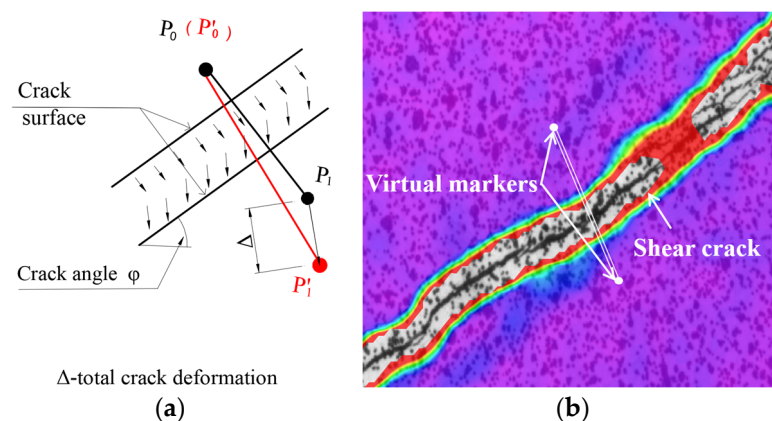


Figure 14. Illustration of shear crack development. (a) Schematic definition of crack opening and sliding and (b) marking of feature points from DIC software of Vic-3D 9 version.

4.5.1. The Effect of Steel Fiber Volume Content on the Formation and Propagation of Shear Cracks

To determine the effect of steel fiber volume content on the shear crack development of non-stirrup UHPC beams, Figure 15 shows the load–crack deformation curves for six UHPC beams of the second batch, presenting the results for the beams with different steel fiber volume contents. As shown in Figure 15, before the emergence of a shear crack, the crack deformation of the beams remained insignificant. However, as soon as a shear crack emerged, a significant increase of the crack deformation was observed. It can be found that the loads at the turning point of beams B7, B8, B10, and B11 were obviously larger than the loads of B9 and B12. Because of the lack of bridging action of steel fibers, beams B9 and B12 quickly lost their load-bearing capacity with a very small extent of crack deformation. At the same load, the crack deformation of the specimens with 1.5% and 2.0% steel fiber volume content was much smaller than those of the specimens without steel fiber, which implied that the incorporation of steel fiber could effectively prevent the development of crack deformation. In addition, as the steel fiber volume content increased from 1.5% to 2.0%, the crack deformation at the ultimate load of B7 and B10 could be increased by up to 39% and 6%, compared to B8 and B11, respectively. This demonstrates that increasing the steel fiber volume content within a certain extent can enhance the post-cracking load-bearing performance of non-stirrup UHPC beams.

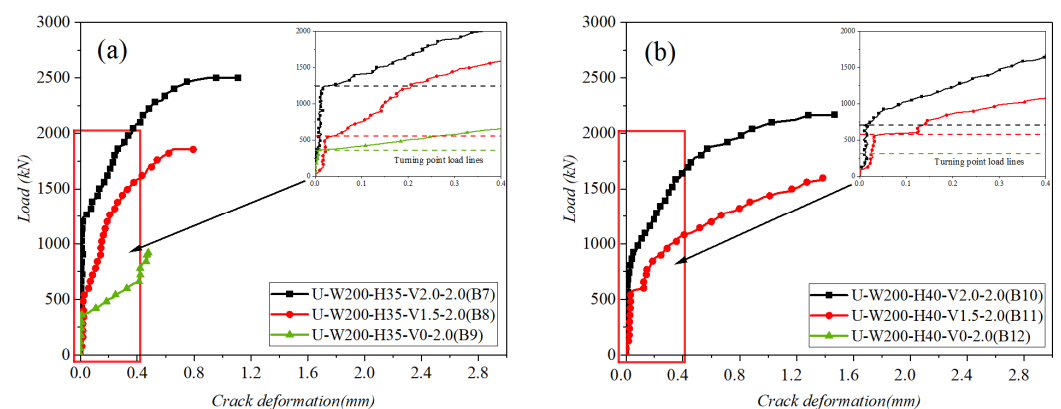


Figure 15. Load–crack deformation curves. (a) U-W200-H35-V*-2.0 beams; (b) U-W200-H40-V*-2.0 beams.

4.5.2. The Effect of Beam Height on the Formation and Propagation of Shear Cracks

To determine the effect of beam height on the formation and propagation of shear cracks, the specimens with different beam heights were analysed in groups. As shown in Figure 15, for beams B7 and B10, as the beam height increased from 350 mm to 400 mm, the crack deformation at the turning point of these two beams was approximately 0.025 mm for both. However, the crack deformation at the ultimate load for beams B10 was 1.47 mm, representing a 32.4% increase compared to the 1.11 mm for beams B7. For beams B8 and B11, as the beam height increased from 350 mm to 400 mm, the crack deformation at the turning point of these two beams was approximately 0.030 mm for both. However, the crack deformation at the ultimate load for beams B11 was 1.38 mm, representing a 72.5% increase compared to the 0.80 mm for beams B8. For beams B9 and B12, as the beam height increased from 350 mm to 400 mm, the crack deformation at the turning point of these two beams was both approximately 0.010 mm. However, the crack deformation at the ultimate load for beams B12 was 1.11 mm, representing a 136.2% increase compared to the 0.47 mm for beams B9. Consequently, it can be concluded that the beam height has a minor effect on the crack deformation at the turning point but can significantly influence the crack deformation at the ultimate load. Larger crack deformation at the ultimate load can be achieved by increasing the beam height.

4.6. Load–Concrete Strain Relationships in the Shear–Bending Section

Figure 16 illustrates the load–concrete strain relationships in the shear span of six non-stirrup UHPC beams from the second batch. Six non-contact strain checking lines at an angle of 45° to the horizontal were employed to quantify the load–concrete strain relationships (load–compressive strain at 45° and load–tensile strain at 45°) in the shear span. The strain checking lines (L1, L2, and L3) were employed to measure compressive strain, while the strain checking lines (L4, L5, and L6) were used to measure tensile strain. The layout of the strain checking lines for each beam is illustrated in Figure 16e,f,i,j,o,r.

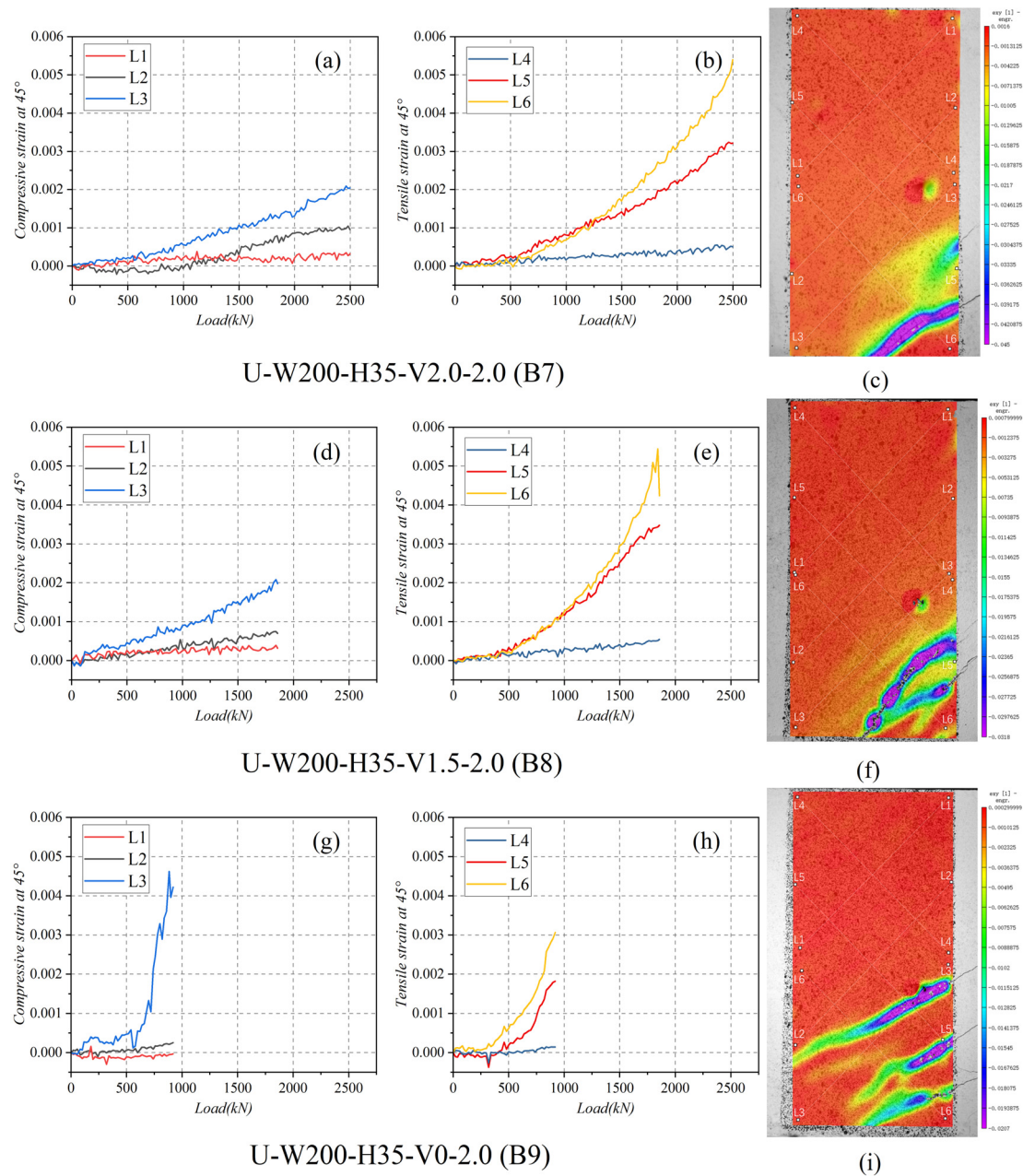


Figure 16. Cont.

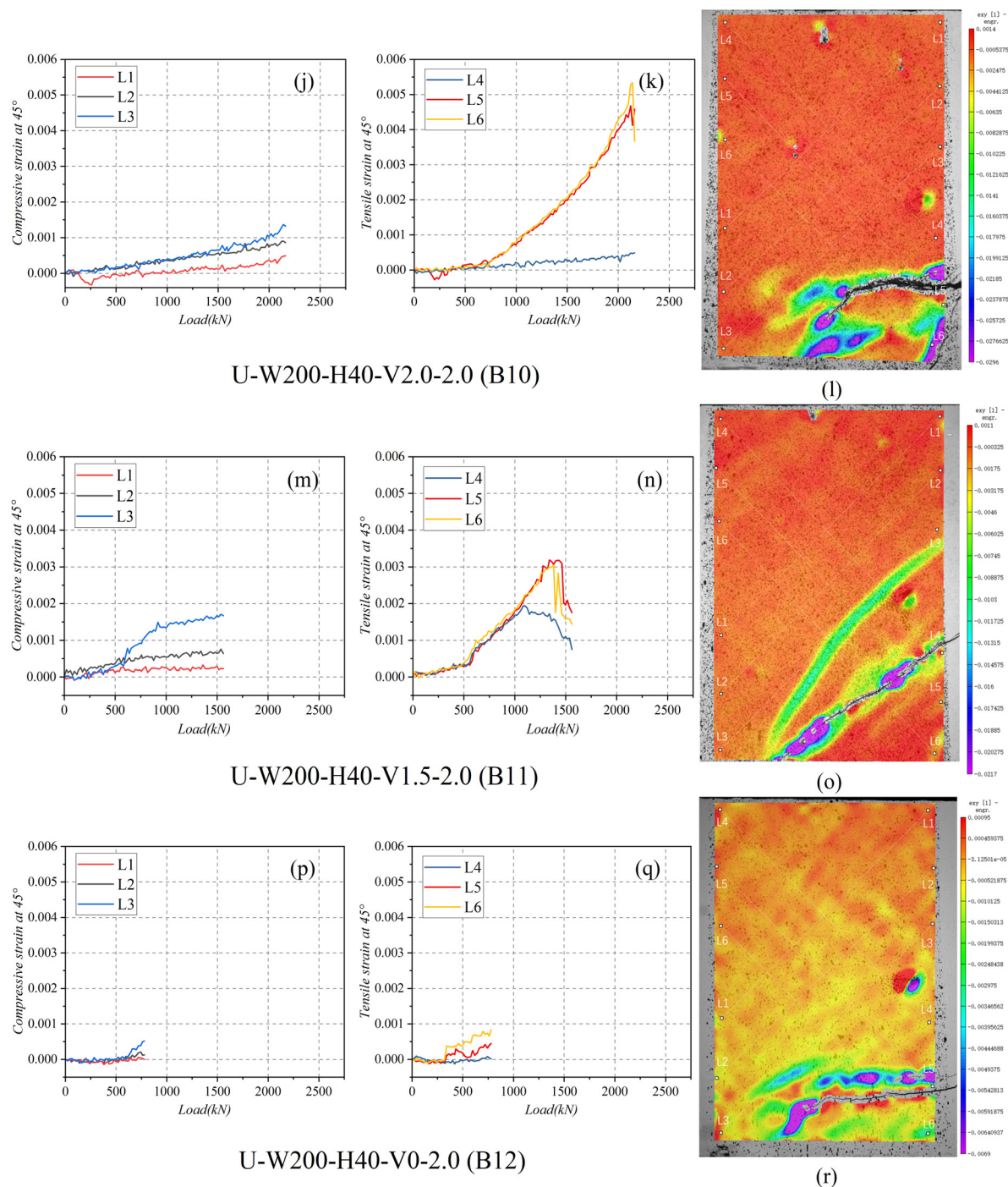


Figure 16. Load–concrete strain relationships. (a,d,g,j,m,p) are the load–compressive strain relationships of each beam, (b,e,h,k,n,q) are the load–tensile strain relationships of each beam, and (c,f,i,l,o,r) are the images of each beam.

As depicted in Figure 16, prior to the formation of an initial shear crack, the tensile strain curve exhibited minimal variation and continued to ascend at a gradual rate below $500 \mu\epsilon$. Once the shear crack was generated, the curve exhibited a distinct upward trend. The value of $500 \mu\epsilon$ could be taken as the characteristic strain. It was found that an increase in the volume content of steel fiber resulted in a corresponding increase in the maximum value of the tensile strain at 45° for the specimens. For beams B7 and B8, because of the incorporation of steel fiber volume content at 2.0% and 1.5%, the maximum value of the tensile strain at 45° of these two beams increased by up to 77.4% and 74.2%, respectively, in

comparison to beams B9. For beams B10 and B11, because of the incorporation of steel fiber volume content at 2.0% and 1.5%, the maximum value of the tensile strain at 45° of these two beams increased by up to 488.9% and 266.7%, respectively, compared to beams B12. These findings demonstrate that the steel fiber volume content has a significant impact on the post-cracking load-bearing performance of non-stirrup UHPC beams, and this effect is more pronounced at a larger beam height. Furthermore, it was observed that, as the beam height increased from 350 mm to 400 mm, the maximum value of the tensile strain at 45° of beams B7, B8, and B9 decreased by 3.6%, 38.9%, and 71.0%, respectively, compared to beams B10, B11, and B12. This suggests that the maximum value of the tensile strain can also be influenced by the beam height, and this effect appears to diminish gradually with an increase in the volume content of steel fibers.

5. Shear Design Recommendations for UHPC Beams

5.1. French Standard Formulae

In accordance with the French standard NF P 18-710-2016 [52], the shear strength of UHPC beams is principally composed of three resistance terms: the contribution of the UHPC matrix V_c , the contribution of stirrup V_s and the contribution of steel fiber V_f . In consequence, the formula for calculating the shear capacity (V_{u1}) of UHPC beam can be expressed as follows:

$$V_{u1} = V_c + V_s + V_{f1} \quad (18)$$

The contribution of the UHPC matrix V_c is calculated using the following equation:

$$V_{c1} = \frac{0.21}{\gamma_{cf}\gamma_E} k_1 \sqrt{f_{cu}} b d \quad (19)$$

where the comprehensive safety factor $\gamma_{cf}\gamma_E$ is here set at 1.0. The prestressing improvement factor k_1 is equal to 1.0 since no prestressing was applied to the tested beams in this research. The variables f_{cu} , b , and d represent the cubic compressive strength, beam breadth, and effective depth of UHPC, respectively.

The contribution of the stirrup V_s is calculated using the following equation:

$$V_s = \frac{A_{sv}}{s} z f_y \cot \theta \quad (20)$$

where A_{sv} represents the cross-sectional area of the stirrups employed, s represents the distance between the stirrups, z is calculated as $0.9d$ to ascertain the lever arm of internal forces, f_y represents the yielding strength of the stirrup, and θ represents the angle between the beam axis and the critical shear diagonal crack. The values of θ are presented in Table 6. It is assumed that non-stirrup UHPC beams do not have any shear contribution from stirrups.

The equation employed calculating the contribution of steel fibers (V_f) is as follows:

$$V_{f1} = A_b \sigma_{f1} \cot \theta \quad (21)$$

where A_b represents the projected area on the cross-section of the bevel on which the fibers act and is equal to the value of bz . σ_{f1} represents the post-cracking strength with values listed in Table 4.

5.2. PCI-2021 Formulae

According to the PCI-2021 report [53], the shear strength of UHPC beams primarily consists of three resistance terms: the tensile strength of UHPC V_{cf} , the contribution of effective prestressing force V_p acting in the direction of applied shear, and the resistance

provided by shear reinforcement V_s . Accordingly, the shear load-bearing capacity V_{u2} can be obtained through the following calculation:

$$V_{u2} = V_{cf} + V_s + V_p \quad (22)$$

$$V_c = \left(\frac{4f_{rr}}{3} \right) bz \cot \theta \quad (23)$$

$$V_s = \frac{A_{sv} f_y z \cot \theta}{s} \quad (24)$$

$$\theta = 29^\circ + 3500\epsilon_s \quad (25)$$

where the longitudinal strain ϵ_s is constrained to a maximum value of -0.40×10^{-3} under compressive stress and 6.0×10^{-3} under tensile stress, which respectively correspond to an angle of 27.6° and 50.0° . In order to guarantee the precision of the calculated outcomes, this paper employs the value of $\theta = 45^\circ$. The residual tensile strength (f_{rr}) can be found in Table 4. The UHPC beams tested in this study were devoid of any prestressing tendons or stirrups, and thus V_p and V_s were assumed to be zero.

5.3. Xu's Formulae

Xu's formulae [54] provide empirical equations for calculating the shear load-bearing capacity of UHPC beams. The equations account for the impact of prestressing force, steel fibers and shear span-to-depth ratio. Accordingly, the shear load-bearing capacity V_{u3} of UHPC beams can be calculated using the following equations:

$$V_{u3} = V_{c3} + V_s + V_{f3} \quad (26)$$

$$V_{c3} = k_2 \left(\frac{2}{\lambda - 0.7} - 0.8 \right) \sqrt{f_c} b d \quad (27)$$

$$V_s = (0.18 + 0.35\lambda) \rho_s f_y b d \quad (28)$$

$$V_{f3} = (0.99 - 0.12\lambda) \lambda f_t b d \quad (29)$$

$$f_t = 0.0353 f_c \quad (30)$$

where ρ_s represents the stirrup ratio, when $\lambda > 1.5$, λ is taken as 1.5, and when $\lambda > 3.0$, λ is taken as 3.0. The variable k_2 represents the enhancement factor for prestressing. In the case of UHPC beams that are not prestressed, the value of k_2 is equal to 1.0, whereas in the case of prestressed UHPC beams, its value is equal to 1.25. Given the absence of stirrup reinforcement in the UHPC beams, it is assumed that the corresponding shear contribution from the stirrups is negligible.

5.4. Comparison of Calculated Values

Table 7 presents the calculated values of the shear capacity V_{u1} (French Standard formulae), V_{u2} (PCI-2021 formulae), and V_{u3} (Xu's formulae), along with the corresponding ratios $V_{u1}/V_{u,test}$, $V_{u2}/V_{u,test}$, and $V_{u3}/V_{u,test}$, where $V_{u,test}$ indicates the ultimate shear load. Since beam B3 experienced flexural failure and beam B5 was affected by unknown factors resulting in an abnormal decrease in its shear capacity, their calculated values are not taken into consideration.

For the French standard formulae, the ratio $V_{u1}/V_{u,test}$ ranged from 0.20 to 1.00, with a mean of 0.59, an STDEV of 0.24, and a coefficient of variation of 0.42. At a steel fiber volume content of 0%, the formulae greatly underestimated the shear capacity of the non-stirrup UHPC beams. The calculated values of the formulae were found to be closer to the tested results for beams B7–B12 when the beam height was 400 mm, compared to 350 mm. This indicates that the French standard formulae are more accurate for relatively higher beam heights. Moreover, the formulae were found to be more accurate at a steel fiber volume content of 2.0% compared to 1.5%. Additionally, the experimental findings of this paper

and those of Zhang et al. [44] and Li et al. [45] collectively demonstrate that the French formula is more accurate for larger shear span-to-effective-depth ratios.

Table 7. Comparison between experimental results and calculated values.

Experimental Results		French Standard Formulae					PCI-2021 Formulae					Xu's Formulae				
NO.	$V_{u,test}$	V_c	V_s	V_f	V_{u1}	$V_{u1}/V_{u,test}$	V_{cf}	V_s	V_{u2}	$V_{u2}/V_{u,test}$	V_c	V_s	V_f	V_{u3}	$V_{u3}/V_{u,test}$	
B1	737.5	97.1	0	287.2	384.2	0.53	550.7	0	550.7	0.75	1398.5	0	186.6	1585.1	2.15	
B2	538	97.1	0	442.2	539.2	1.00	550.7	0	550.7	1.02	445.0	0	256.1	701.1	1.30	
B3	374	97.1	0	421.4	518.5	1.39	550.7	0	550.7	1.47	14.6	0	352.2	366.8	0.98	
B4	434	86.5	0	0	86.5	0.20	209.8	0	209.8	0.48	1210.0	0	0	1210.0	2.79	
B5	112.5	86.5	0	0	86.5	0.77	209.8	0	209.8	1.86	385.0	0	0	385.0	3.42	
B6	173	86.5	0	0	86.5	0.50	209.8	0	209.8	1.21	12.6	0	0	12.6	0.07	
B7	1250	154.7	0	749.4	904.1	0.72	1323.4	0	1323.4	1.06	523.7	0	457.6	981.4	0.79	
B8	931	152.2	0	376.8	528.9	0.57	948.8	0	948.8	1.02	506.9	0	428.7	935.6	1.00	
B9	459.5	130.4	0	0	130.4	0.28	299.6	0	299.6	0.65	409.8	0	0	409.8	0.89	
B10	1083.5	181.3	0	702.4	883.7	0.82	1550.8	0	1550.8	1.43	613.7	0	536.3	1150.0	1.06	
B11	801.5	178.3	0	441.5	619.8	0.77	1111.9	0	1111.9	1.39	594.0	0	502.3	1096.3	1.37	
B12	397	152.8	0	0	152.8	0.38	351.1	0	351.1	0.88	480.2	0	0	480.2	1.21	
Average:						0.59	Average:				1.07	Average:				1.26
STDEV:						0.24	STDEV:				0.43	STDEV:				0.71
CV:						0.42	CV:				0.40	CV:				0.56

For the PCI-2021 formulae, the ratio $V_{u2}/V_{u,test}$ ranged from 0.48 to 1.43, with a mean of 1.07, an STDEV of 0.43, and a coefficient of variation of 0.40. For beams B7, B8, B10, and B11, the calculated values of the PCI-2021 formulae were closer to the tested results when the beam height was 350 mm compared to 400 mm. This demonstrates that the formulae are more precise when the beam height is relatively lower. Additionally, it was found that the formulae underestimated the shear capacity of the non-stirrup UHPC beams when the steel fiber volume content was 0%.

For Xu's formulae, the ratio $V_{u3}/V_{u,test}$ ranged from 0.07 to 2.79, with an average of 1.26, an STDEV of 0.71, and a coefficient of variation of 0.56. For beams B1 and B4, it was discovered that the formulae significantly overestimated the shear capacity of the non-stirrup UHPC beams with a shear span-to-effective-depth ratio (λ) of 1.2. However, for beams B2, B7, B8, B9, B10, B11, and B12, the calculated values of the formulae were closer to the tested results when the λ increased to 1.8 and 2.0, respectively. Additionally, the formulae were found to vastly underestimate the shear capacity of non-stirrup UHPC beams with a λ of 3.1 at a steel fiber volume content of 0%. These results suggest that Xu's formulae are more accurate for larger shear span-to-effective-depth ratios within a certain range.

The comparison of calculated values obtained from the three formulae demonstrates that the French standard formulae are more accurate for relatively higher beam heights. Furthermore, the formulae demonstrated greater accuracy at a steel fiber volume content of 2.0% in comparison to 1.5%. The PCI formulae are more precise when the beam height is relatively lower. Xu's formulae are more accurate for larger shear span-to-effective-depth ratios within a certain range.

6. Contribution of Steel Fiber and UHPC Matrix

Tables 8 and 9 show the calculated values for the contribution of steel fiber and UHPC matrix to the shear capacity of the UHPC beams, and the calculated values for the contribution of steel fiber and UHPC matrix using the French standard formulae. The beams B15, B16, B17, B15*, B16*, and B17* indicate six non-stirrup UHPC beams B7, B8, B9, B4, B5, and B6 from the study of Li et al. [45]. These beams had the same parameters as the first batch of beams, including a total beam height of 300 mm, two steel fiber volume content of 2.0% and 0%, as well as three shear span-to-effective-depth ratios (λ) of 1.2, 1.8, and 3.1. The only difference was an increase in beam width from 150 mm to 200 mm. The

beams B18, B19, B20, B21, B22, and B23 indicate six non-stirrup UHPC beams B1, B2, B4, B5, B3, and B6 from the study of Zhang et al. [44]. These beams had the same parameters as the second batch of six non-stirrup UHPC beams, including a total beam width of 200 mm and two beam height of 350 mm and 400 mm, as well as three steel fiber volume content of 2.0%, 1.5% and 0%. The only difference was an increase in λ from 2.0 to 2.8.

Table 8. Comparison of the Contribution of steel fiber and UHPC matrix.

NO.	$V_{u,test}$ (kN)	V_{u0} (kN)	V_{fc} (kN)	$\frac{V_{fc}}{b_z}$ (MPa)	$\frac{V_{u0}}{V_{u,test}}$	$\frac{V_{fc}}{V_{u,test}}$
B1	737.5	434.0	303.5	9.2	0.59	0.41
B2	538.0	112.5	425.5	12.9	0.21	0.79
B15	935.5	783.0	152.5	3.5	0.84	0.16
B16	723.0	317.0	406.0	9.2	0.44	0.56
B17	570.5	174.5	396.0	9.0	0.31	0.69
B7	1250.0	459.5	790.5	15.1	0.37	0.63
B8	931.0	459.5	471.5	9.0	0.49	0.51
B10	1083.5	397.0	686.5	11.2	0.37	0.63
B11	801.5	397.0	404.5	6.6	0.50	0.50
B18	670.0	259.5	410.5	7.8	0.39	0.61
B19	739.0	259.5	479.5	9.2	0.35	0.65
B20	770.0	247.5	522.5	8.5	0.32	0.68
B21	742.5	248.0	494.5	8.1	0.33	0.67
Average:					0.42	0.58
STDEV:					0.15	0.15
CV:					0.36	0.26

Table 9. Comparison of the contribution of steel fiber and UHPC matrix.

NO.	$V_{u,test}$ (kN)	V_{fc} (kN)	V_{f1} (kN)	$\sqrt{f_{cu}}bd$ (kN)	$\frac{V_{fc}}{V_{f1}}$	$\frac{V_{u,test}}{\sqrt{f_{cu}}bd}$
B1	737.5	303.5	287.2	/	1.06	/
B2	538.0	425.5	442.2	/	0.96	/
B15	935.5	152.5	321.3	/	0.47	/
B16	723.0	406.0	567.7	/	0.72	/
B17	570.5	396.0	637.2	/	0.62	/
B7	1250.0	790.5	749.4	/	1.05	/
B8	931.0	471.5	376.8	/	1.25	/
B10	1083.5	686.5	702.4	/	0.98	/
B11	801.5	404.5	441.5	/	0.92	/
B18	670.0	410.5	743.1	/	0.55	/
B19	739.0	479.5	434.1	/	1.10	/
B20	770.0	522.5	1056.0	/	0.49	/
B21	742.5	494.5	613.4	/	0.81	/
B4	434.0	0	0	411.8	/	1.05
B5	112.5	0	0	411.8	/	0.27
B6	173.0	0	0	411.8	/	0.42
B15 *	783.0	0	0	549.0	/	1.43
B16 *	317.0	0	0	549.0	/	0.58
B17 *	174.5	0	0	549.0	/	0.32
B9	459.5	0	0	620.9	/	0.74
B12	397.0	0	0	727.5	/	0.55
B22	259.5	0	0	633.6	/	0.41
B23	247.5	0	0	742.4	/	0.33
Average:					0.84	0.61
STDEV:					0.23	0.37
CV:					0.27	0.61

6.1. Contribution of Steel Fiber and UHPC Matrix to the Shear Capacity of UHPC Beams

As shown in Table 8, V_{fc} indicates the contributions of steel fiber, where $V_{fc} = V_{u,test} - V_{u0}$, and V_{u0} indicates the contributions of UHPC matrix, which is equal to the peak shear load of the UHPC beam without steel fiber for corresponding size. For example, the V_{u0} of the beam B1 is the peak shear load of the beam B4, which indicates the contributions of UHPC matrix in beam B1.

6.1.1. Effect of Shear Span-to-Effective-Depth Ratio

Table 8 shows that, for beams B1 and B2, the contribution of steel fiber to the shear capacity of the UHPC beams increased from 0.41 to 0.79 as the shear span-to-effective-depth ratio (λ) increased from 1.2 to 1.8. The contribution of steel fiber in beams B15, B16, and B17 increased from 0.16 to 0.56 and 0.69 as λ increased from 1.2 to 1.8 to 3.1. Similarly, for beams B7, B8, B10, B11, B18, B19, B20, and B21, the average value of the contribution of steel fiber in the shear capacity of the UHPC beams increased from 0.57 to 0.65 as the λ increased from 2.0 to 2.8. The results indicate that the contribution of steel fiber to the shear capacity of the UHPC beams increases with an increase in the shear span-to-effective-depth ratio (λ), whereas the contribution of UHPC matrix is diminished as λ increases. This effect is particularly pronounced at lower values of λ . This is due to the fact that, at lower shear span-to-effective-depth ratios, the predominant failure mode of the beam is diagonal compression failure, and the load-bearing capacity is primarily determined by the compressive strength of the concrete. Consequently, the exceptional tensile properties offered by steel fibers for UHPC cannot be fully exploited.

6.1.2. Effect of Steel Fiber Volume Content

As illustrated in Table 8, the shear capacity contribution of steel fiber to beams B7, B8, and B10, B11 ($\lambda = 2.0$) decreased from 0.63 to 0.51 and 0.50, respectively. However, for beams B18, B19, and B20, B21 ($\lambda = 2.8$), the contribution of steel fiber to the shear capacity of the UHPC beams remained almost unchanged despite the decrease in steel fiber volume content from 2.0% to 1.5%. These results show that the steel fiber contribution to the shear capacity of UHPC beams decreases as the steel fiber volume content decreases and the contribution of UHPC matrix increases as the steel fiber volume content decreases, but when the ratio of shear span-to-effective-depth is large, the effect of the steel fiber volume content is almost negligible.

6.1.3. Effect of Beam Height

For beams B7, B8, B10, B11, B18, B19, B20, and B21, the contribution of steel fiber and UHPC matrix to the shear capacity of the UHPC beams remained almost unchanged despite an increase in beam height from 350 mm to 400 mm, indicating a minor or insignificant effect of beam height on the contribution of steel fiber and UHPC matrix to the shear capacity of the UHPC beams.

6.1.4. Effect of Beam Width

For beams B1, B2, B15, and B16, the average contribution of steel fiber to the shear capacity of the UHPC beams was observed to decrease from 0.60 to 0.36 as the beam width increased from 150 mm to 200 mm. It can thus be concluded that the contribution of steel fiber to the shear capacity of UHPC beams is inversely proportional to the width of the beams. The contribution of UHPC matrix increases as the beam width increases.

6.2. Discussion of the Calculated Values for the Steel Fiber Contribution and UHPC Matrix Using Theoretical Formulas

As shown in Table 9, the values V_{f1} and $\sqrt{f_{cu}bd}$ indicate the calculated contribution of steel fibers and UHPC matrix, respectively, employing the French standard formulae.

6.2.1. The Calculated Values for the Steel Fiber Contribution V_f

For beams B7, B8, B10, and B11 as well as B18, B19, B20, and B21, as the shear span-to-effective-depth ratio (λ) increased from 2.0 to 2.8, the mean value of $\frac{V_{fc}}{V_{f1}}$ decreased from 1.05 to 0.74, representing a reduction of 29.5%. In the case of beams B15, B16, and B17, the mean value of $\frac{V_{fc}}{V_{f1}}$ was observed to increase from 0.47 to 0.72 and then decrease to 0.62 as the λ increased from 1.2 to 1.8 and then to 3.1. It can thus be inferred that the French standard formulae tend to overestimate the contribution of steel fibers, and the calculation results are more accurate for UHPC beams with a moderate shear span-to-effective-depth ratio (around 2.0).

For beams B7, B8, B10, B11, B18, B19, B20, and B21, as the beam height increased from 350 mm to 400 mm, the mean value of $\frac{V_{fc}}{V_{f1}}$ of beams B7 and B8 as well as B18 and B19 decreased from 1.15 and 0.83 to 0.95 and 0.65, respectively, compared to beams B10 and B11 as well as B20 and B21, representing a reduction of 17.4% and 21.7%, respectively. This suggests that the French standard formulae tend to overestimate the contribution of steel fibers as the beam height increases.

For beams B1, B2, B15, and B16, as the beam width increased from 150 mm to 200 mm, the mean value of $\frac{V_{fc}}{V_{f1}}$ of beams B1 and B2 decreased from 1.01 to 0.60, representing a reduction of 40.6%, compared to B15 and B16. This suggests that the French standard formulae tend to underestimate the contribution of steel fibers as the beam width increases.

6.2.2. The Calculated Values for the UHPC Matrix Contribution V_c

As illustrated in Table 9, the French standard formulae demonstrated a tendency to underestimate the contribution of UHPC matrix, and this phenomenon was more pronounced at a smaller shear span-to-effective-depth ratio. As the shear span-to-effective-depth ratio increased, the calculated values for the UHPC matrix contribution became increasingly accurate. Furthermore, the French standard formulae exhibited greater accuracy at a larger beam height for calculating the contribution of UHPC matrix. After removing the beams with the shear span-to-effective-depth (λ) < 1.8, the mean value of $\frac{V_{u, test}}{\sqrt{f_{cu}bd}}$ for the remaining eight tested beams was 0.45, with a standard deviation of 0.16.

7. Conclusions

In this study, twelve non-stirrup UHPC beams and two compared NC beams were designed and fabricated to determine the effect of steel fiber volume content, shear span-to-effective-depth ratio, beam width, and beam height on the shear behavior. Specially, the shear contribution of steel fibers and UHPC was discussed in depth. Based on the test results, the following conclusions can be drawn:

- (1) The addition of steel fibers in the concrete mix exerted a pivotal impact on the failure mode of the tested beams. The failure modes of UHPC beams without steel fibers were typically brittle, whereas those reinforced with steel fibers exhibited ductile failure. In particular, the tested beams generally exhibited shear compression failure at steel fiber volume contents of 2.0% and 1.5%. Conversely, the beams with steel fiber volume content of 0% exhibited diagonal tension failure or diagonal compression failure.
- (2) The shear resistance of UHPC beams could be significantly enhanced by the addition of steel fibers in the concrete mix. At a shear span-to-effective-depth ratio (λ) of 2.0, the ultimate shear strength can be increased by approximately 100% and 170% with the addition of 1.5% and 2.0% volume content of steel fibers, respectively. Furthermore, an increase in the shear span-to-effective-depth ratio (λ) was observed to result in a notable decline in the ultimate shear strength of the UHPC beams.
- (3) The addition of steel fibers in the concrete mix could markedly improve the post-cracking load-bearing performance of non-stirrup UHPC beams. As the steel fiber volume content increased from 1.5% to 2.0%, the crack deformation at the ultimate

load of specimens B7 and B10 could be increased by up to 39% and 6%, compared to B8 and B11, respectively. The beam height had a minor effect on the crack deformation at the turning point; however, it could significantly influence the crack deformation at the ultimate load.

- (4) The maximum value of the tensile strain on the diagonal section of the concrete was found to be markedly influenced by the beam height, with this effect diminishing gradually with an increase in the volume content of steel fiber. This finding demonstrates that the volume content of steel fiber also has a significant impact on the tensile strain on the diagonal section of the concrete.
- (5) The French standard formulae are more accurate for a relatively larger beam height. Furthermore, the formulae demonstrated greater accuracy at a steel fiber volume content of 2.0% in comparison to 1.5%. The PCI formulae were more precise when the beam height is relatively lower. Xu's formulae demonstrated greater accuracy at larger shear span-to-effective-depth ratios.
- (6) The contribution of steel fiber to the shear capacity of the UHPC beams was observed to increase as the shear span-to-effective-depth ratio (λ) increased. Moreover, the contribution of steel fiber to the shear capacity of the UHPC beams was found to be inversely proportional to the width of the beams.
- (7) The contribution of UHPC matrix to the shear capacity of the UHPC beams was found to decrease as the shear span-to-effective-depth ratio (λ) increased. Furthermore, it was observed that the contribution of UHPC matrix to the shear capacity of UHPC beams increased as the steel fiber volume content decreased. The beam height was found to have a minor effect on the contribution of UHPC matrix to the shear capacity of UHPC beams.
- (8) The French standard formulae demonstrated a tendency to overestimate the contribution of steel fibers as the beam height and beam width increased. The calculation results were found to be more accurate for UHPC beams with a moderate shear span-to-effective-depth ratio (around 2.0). As the shear span-to-effective-depth ratio increased, the calculated values of the formulae for the UHPC matrix contribution became increasingly accurate.

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