

Experimental Study on Shear Mechanical Properties of Light Composite Bridge in Bending Moment Zone

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Abstract: This study conducted shear resistance tests on steel-UHPC composite beams, focusing on structural stiffness changes during the test process, strain analysis of UHPC panels, internal reinforcement bars, steel structures, and shear connectors, as well as the failure processes and modes of UHPC panels and the structure. Through theoretical analysis, the contribution of UHPC panels to the overall vertical shear resistance capability was clarified. A shear load-bearing capacity calculation method was established, thereby considering the combined beam shear bearing capacity calculation formula of the UHPC panel and the steel beam web.

Keywords: Steel-UHPC composite beam; Positive moment zone; Shear resistance test; Bridge design theory and calculation method

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1. Introduction

Prefabricated composite bridge structures represent a crucial pathway for industrializing bridge construction^[1]. However, traditional prefabricated bridges face two major challenges: (1) Bridges using conventional concrete materials are prone to cracking during operation, leading to water infiltration and durability issues; (2) Although beams can be manufactured in factories, on-site processes like welding assembly, prestressing installation, and shear wall pouring still require extensive time, causing significant traffic. Current research on the shear resistance of steel-UHPC composite beams predominantly focuses on lightweight composite deck structures, emphasizing longitudinal shear performance of shear connectors like anchors. However, studies on vertical shear resistance remain scarce. Research indicates that UHPC's inherent steel reinforcement provides significant shear strength. Zhu *et al.*^[2] conducted experimental studies on vertical shear performance of steel-UHPC waffle plate composite beams, revealing that the web section contributes only about 50% to overall shear resistance, while the UHPC flanges play a crucial role. Consequently, using code-specified methods that account solely for web strength when calculating shear capacity under steel-UHPC composite beams would result in overly conservative estimates.

Notably, load-bearing conditions for these composite beams differ from conventional concrete structures in terms of effective lateral width, shear calculation methods, and transverse-bending load-bearing capacity assessment approaches [3].

In short, this study employs a combination of experimental research and theoretical analysis to investigate the fundamental mechanical behavior of shear resistance in the positive bending moment zone of light composite bridges. Building on these findings, we aim to elucidate the synergistic load-sharing mechanisms during service and propose corresponding design theories and computational methods. The research constitutes a crucial component of composite bridge system design theory, with its outcomes contributing to enhanced bridge systems in the future.

2. Study overview

The test girders are shown in **Figure 1**. All girders measure 4.30 meters in length with a clear span of 4.0 meters. The UHPC panels are 700 mm wide and 65 mm thick, featuring longitudinal and transverse reinforcement bars of HRB400 grade (Hot-Rolled Ribbed Bars, yield strength ≥ 400 MPa). The reinforcement system consists of longitudinal bars (LR: 7 Φ 16 mm) and transverse bars (TR: Φ 12@100 mm). The I-beam girders, constructed from Q345 steel (yield strength ≥ 345 MPa), have a total height of 440 mm with a top flange measuring 140 mm $\times$ 6 mm and a bottom flange measuring 250 mm $\times$ 10 mm. The web is 8 mm thick, and Φ 16 $\times$ 50 mm shear connectors are used to bond the UHPC panels to the I-beam girders.

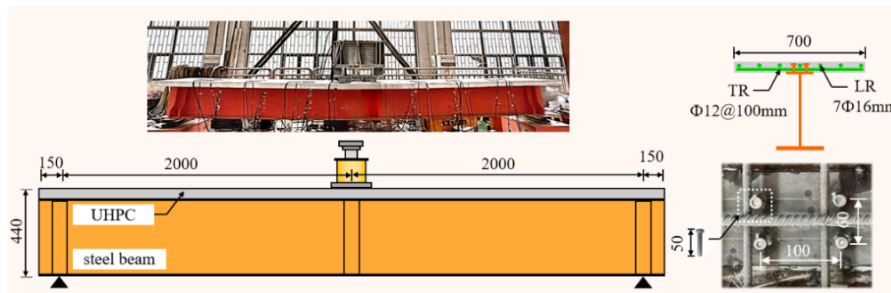


Figure 1. Test beam profile (unit: mm)

The hydraulic jack was used to apply loading to the test beam. As shown in the figure above, this experiment employed a three-point loading method. Both ends of the test beam were mounted on a steel platform: one end was equipped with a movable hinge bracket for free sliding, while the other had a fixed hinge bracket to restrict lateral movement. The three-point loading configuration directly positioned the jack precisely above the beam's mid-point.

The UHPC material used in this test is a commercial dry powder (Xingguli), with primary components including cement, quartz powder, high-efficiency water reducer, and steel fibers (8 mm $\times$ 0.12 mm straight steel fibers, 2% by volume). The testing methods for compressive strength, flexural strength, and elastic modulus of the UHPC material follow GB/T 31387-2015. The fundamental mechanical properties of the UHPC are summarized in Table 1. The lower steel structure of the test beam employs Q345 steel, while the UHPC panel uses HRB400 grade reinforcement. The material properties of steel plates and reinforcement are determined through performance testing, with a Poisson's ratio of 0.3. The mechanical properties of the steel are detailed in Table 2.

Table 1. Mechanical properties of UHPC materials

Curing condition	Compression strength (MPa)	Rupture strength (MPa)	Modulus of elasticity (GPa)
Steam-cured	139.8	24.6	45.1

Table 2. Mechanical properties of steel

Material	Yield strength (MPa)	Ultimate strength (MPa)	Modulus of elasticity (GPa)
6 mm (steel plate)	394.3	525.6	206
8 mm (steel plate)	390.4	545.2	
10 mm (steel plate)	363.7	498.4	
Reinforcing bar	466.7	572.4	200
Steel beam	350	/	200

3. Results and discussion

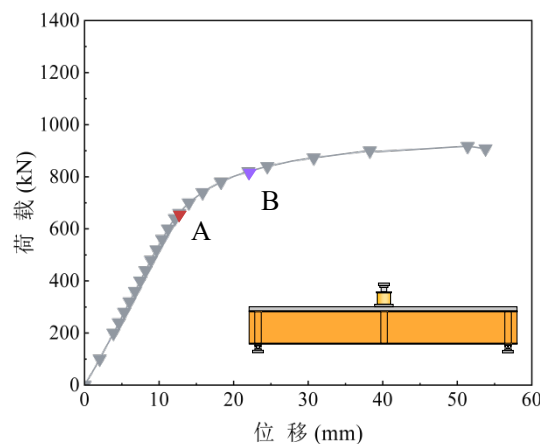
3.1. Destruction process and mode

After completing the tests, the failure process can be categorized into four distinct phases based on observed phenomena and results. Phase I: Initial Synergy Stage. During the initial loading phase, all test beams demonstrated effective joint performance. When the load reached approximately 400 kN, audible “squeaking” noises were detected as steel fibers were extracted from the UHMPc matrix. Microscopic cracks appeared at the steel-UHMPc interface near the loading point.

Among them, the ultimate load of the test beam is 917 kN. At this time, an obvious slip occurs between the upper edge of the steel beam and the bottom of the UHPC panel. The observed strain shows that both the upper and lower edges reach the yield value ($394.3 \text{ MPa} / 206 \text{ GPa} = 1914$), that is, the test beam reaches the full section yield of the steel beam when it breaks.

3.2. Load-displacement response

The deformation of the test beam with the development of the load was tested, and the load-span deflection curve is drawn as shown in **Figure 2**.

**Figure 2.** Test load-deflection curve at mid-span

As can be seen in **Figure 2**, the load-deflection curve of the test beam basically changes in the same way, which can be roughly divided into three stages: elastic stage, elastoplastic stage, and failure stage.

Phase I: Elastic Stage (O~A). During this phase, the beam stiffness is provided by both the steel beam and the UHPC panel. The specimen exhibits relatively straight load-displacement curves, indicating structural compliance. Phase II: Elastoplastic Stage (A~B). As loading intensifies, the curve develops deflection. Near the loading point, numerous transverse cracks appear at the bottom of the UHPC panel and gradually penetrate through. Simultaneously, localized buckling occurs in the steel beam flanges, leading to reduced stiffness, accelerated deflection growth, and a steeper slope in the curve. Phase III: Failure Stage (B~C). At this stage, the lower edge of the composite beam's steel section reaches yield strain while the upper UHPC panel collapses. Significant mid-span deflection occurs, reaching the ultimate load, where further loading becomes impossible. The displacement growth rate intensifies, prompting termination of the test.

3.3. Load-strain response

To investigate the longitudinal strain of UHPC panels across mid-sections under load variations and the transverse strain along the width direction on the top surface of the same section, we plotted the surface strain changes of the experimental beam's UHPC panel as shown in Figure 3. The figure reveals that the strain growth rate at the central axis (EUn2) of the bridge deck plate increases more rapidly with greater amplitude, while the edge positions (EUn1 and EUn3) show relatively slower strain progression and smaller deformation ranges. This indicates a “lagged release” of shear force in the central region or “delayed response” at the edges, meaning the central axis area bears more longitudinal deformation while the shear force fails to fully extend laterally to the periphery.

For further analysis, the shear lag coefficient of the experimental beam was calculated using the formula (mid/edge), where mid represents the strain at the panel's center (e.g., EUn2) and edge denotes the strain at the panel's edge (e.g., EUn1/3). The calculated shear span ratio of the experimental beam was 3.96. Under concentrated loading at mid-span, the central axis strain was significantly higher than that in the edge region (up to 1.75), indicating a severe shear lag effect. This demonstrates that concentrated loading is more likely to cause stress concentration and limit shear diffusion.

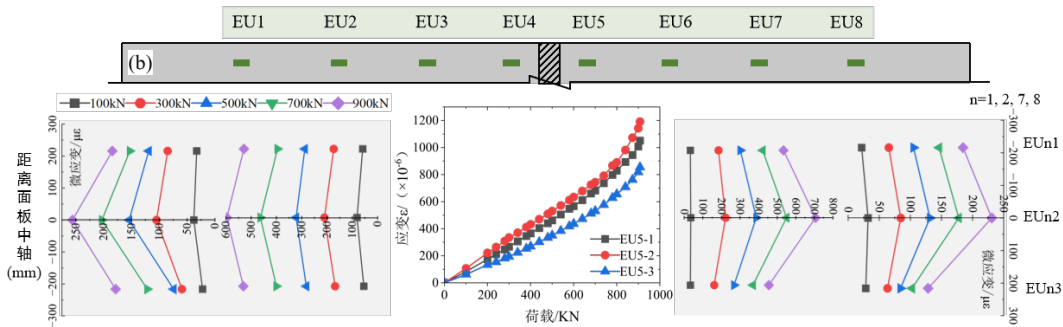


Figure 3. Strain of test beam panels

4. Calculation of shear bearing capacity

Current international standards for calculating shear resistance in steel-concrete composite beams exclude concrete flange contributions, assuming all vertical shear forces are borne solely by the steel web. However, literature analysis reveals that concrete flanges significantly enhance shear performance, with more pronounced improvements as concrete strength increases. This study emphasizes the critical role of UHMWPE (Ultra-High Molecular Weight Polyethylene) concrete in steel-UHMPE composite beams. Employing the superposition principle, we develop a composite beam shear resistance calculation formula that incorporates both UHMWPE

concrete panels and steel web elements.

The shear bearing capacity of the I-beam, according to China's "Code for Design of Steel Structures" (GB50017-2003), only considers the shear resistance of the steel beam's web as the contribution of the steel beam's shear resistance.

$$V_s = f_{sy} h_w t_w \sqrt{3}$$

In the formula, f is the yield strength of the steel beam web, and h , t are the height and width of the steel beam web, respectively. Substituting the experimental values yields the shear contribution of 764.5 kN of the steel beam.

The shear bearing capacity of UHPC panels is calculated by referring to the calculation formula proposed in the French UHPC structural design code^[4], which is mature and has been widely used.

The UHPC section of the reinforcement is calculated according to the following formula.

$$V_c = \frac{0.21}{\gamma_{cf} \gamma_E} k_N f_{ck}^{0.5} b h_0$$

In the formula, b represents the width of the rectangular cross-section; UHPC is the effective height of the rectangular section; the coefficients are the load or prestress enhancement factor (set to 1.5), and UHPC denotes the partial coefficient for tensile materials and safety factor, respectively (both set to 1.5). Substituting these values into the calculation yields a shear contribution value of 113 kN for the UHPC panel. Based on the combined formulas, the shear load-bearing capacity of the composite beam using the superposition principle is calculated as follows:

$$V_u = V_c + V_s$$

Substituting the above formula, it can be calculated that 877.5 kN is close to the experimental result of 917 kN with an error of 4.3%. The contribution value of the UHPC panel to the shear bearing capacity of the composite beam is 13%.

5. Conclusion

This paper studied the basic mechanical properties of shear resistance in the bending moment zone of light composite beams and drew the following conclusions:

- (1) The test beam is a three-point loaded specimen. Under the centralized loading at the mid-span, the strain of the central axis is significantly higher than that of the edge region (up to 1.75, showing an extremely serious shear lag effect. Centralized loading is more likely to cause stress concentration and shear diffusion limitation.
- (2) For the calculation of the shear bearing capacity of the test beam, the superposition principle is used to consider the combined beam shear bearing capacity calculation formula of the UHPC panel and the steel beam web. The comparison results show that the shear bearing capacity calculation formula proposed in this paper has higher accuracy.

Disclosure statement

The authors declare no conflict of interest.

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