Mesoscale design theory and innovative structural system of UHPC Bridges

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Abstract: The comprehensive studies from materials properties to structural innovations have been conducted aiming at combining the fundamental theory and structural analysis and applications using ultra high-performance concrete (UHPC). Firstly, experimental and theoretical investigations on fiber-UHPC interfacial behavior were performed and two new indices were proposed to evaluate the fiber-matrix interfacial bond behavior from the structural perspective. A mesoscale constitutive model was then proposed, taking into account uniform distribution, embedment length, and orientation of fibers for the multi-scale mechanics analysis. A theoretical method, termed the mesoscale fiber-matrix discrete model (MFDM), was developed to calculate the shear strength of UHPC beams based on the concept of effective fiber distributed region where fibers were efficient at providing shear resistance. The proposed MFDM offered an alternative perspective in understanding the shear behavior of UHPC beams, especially the shear resistance of fibers at a mesoscale level. On the basis of modeling and design methods, five different types of high-performance structural systems for bridges were proposed utilizing UHPC and other innovative construction materials. The structural systems cover various applications including the large stud-UHPC composite structure, light-weight FRP truss-UHPC bridge decks, self-centering precast segmental bridge columns, precast segmental box-girder with large shear key connection. Lastly, some practical engineering applications in China are presented including Vanke pedestrian bridge (the first precast segmental UHPC Arch Bridge in China) and Nanjing 5th Yangtze River Bridge engineering in which the proposed design theory and structural systems were applied.

Keywords: UHPC; mesoscale design theory; composite structure; large studs; FRP truss-UHPC bridge decks; self-centering; precast segmental bridge columns; large shear key connection

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1. Introduction

Recent advances of ultra high-performance concrete (UHPC) material research have been emphasizing on improving the microstructure, ductility, durability. For example, the addition of carbon nano-fibers has been shown to improve the compressive and flexural strength of cement composites as well as mitigating the autogenous shrinkage and associated cracking (Parveen et al.

2013). Extensive research has been conducted to reduce the autogenous shrinkage of UHPC by means of saturated lightweight sand, superabsorbent polymers, presoaked aggregate or so (AzariJafari et al. 2016; Kong et al. 2015; Valipour and Khayat 2018). Moreover, the UHPC involving steel and synthetic fibers are also being popular studied and good results in improving the ductility and toughness of UHPC was achieved (Park et al. 2012).

However, there are still a lot of issues currently involved with the engineering structures such as their low performances, non-resilient and great impacts on environment and traffic during construction. The data has shown that the delivered compressive strength of commercial concrete is usually much higher than the specified strength. On the other hand, structural members such as shear walls and beam-column-joints are heavily reinforced. Nevertheless, many structures are still very vulnerable to extreme events such as earthquake and blasts.

So, the question we faced is how do we link the exceptional material properties that we have obtained so far with the structural performances? In other words, how do we turn the high-performance materials into high-performance structures? The joint study of materials scientists and structural engineers is a solution to solve the current problem. A potential solution is to develop robust modeling and design tools that can fully utilize the material properties. The goal of our group is to bridge the fundamental theory and structures for this innovative construction material.

2. Fiber-UHPC Interfacial Behavior

The interfacial bond behavior between fibers and UHPC plays an important role in governing the mechanical properties and even the structural performance of fiber reinforced concrete and can be the bridge between material and structural behavior. Three steel fibers, including one straight fiber and two hooked-end fibers, were aligned at 0°, 30°and 45°with respect to the loading direction. The fibers were pulled out from non-fiberous UHPC matrix with a compressive strength of 151.5 MPa. Experimental results (Qi et al. 2018b) showed that when the fiber embedded angle increased from 0° to 30° and 45°, the average bond strengths of straight fibers were increased by 19.2% and 52.9%, while the average bond strengths of hooked-end fibers were increased by 10.3–13.6% and 16.2–26.1%, respectively. This phenomenon indicates that straight fibers exhibit the highest sensitivity to the fiber embedded angle. However, the percentage of end hook contribution to total pullout energy ranged from 50% to 56.8%, indicating significant mechanical anchorage contribution. Thus the effect of embedded angle was less pronounced for hooked end fibers. Two types of fiber failure modes, including fiber pullout failure and fracture failure, were found, depending on fiber angles.

3. Mesoscale Design Theory

3.1. Multiscale Flexural Design Theory

A constitutive model is proposed, including a bilinear model for compression and a drop-down model for tension, taking into account uniform distribution, embedment length, and orientation of fibers for the multi-scale mechanics analysis (see Figure 1).

The assumption of plane sections remain plane is adopted for the development of the proposed flexural strength model. The stress distribution in the compression zone can be obtained using the compression model. The distribution of the compressive stress satisfies a linear function. The stress distribution at the tension side can be obtained using the previously discussed tension model.

Derivations of the height of the cracked section *k*, depth of compression zone *c* can be found in Qi et al. (2018b).

The moment capacity of the section can be calculated using the equation of statics, as expressed with Equation (1)

$$M_u = C \cdot \frac{2}{3}c + T_1 \cdot \frac{2}{3}k(d-c) + T_2 \frac{1}{2}(1+k)(d-c) + T_s \cdot (d-c) \tag{1}$$

Calculations with the proposed model provide good predictions of the flexural strength of HSS-UHPFRC beams when compared with test results in Qi et al. (2018), the calculation procedure is very simple and convenient.

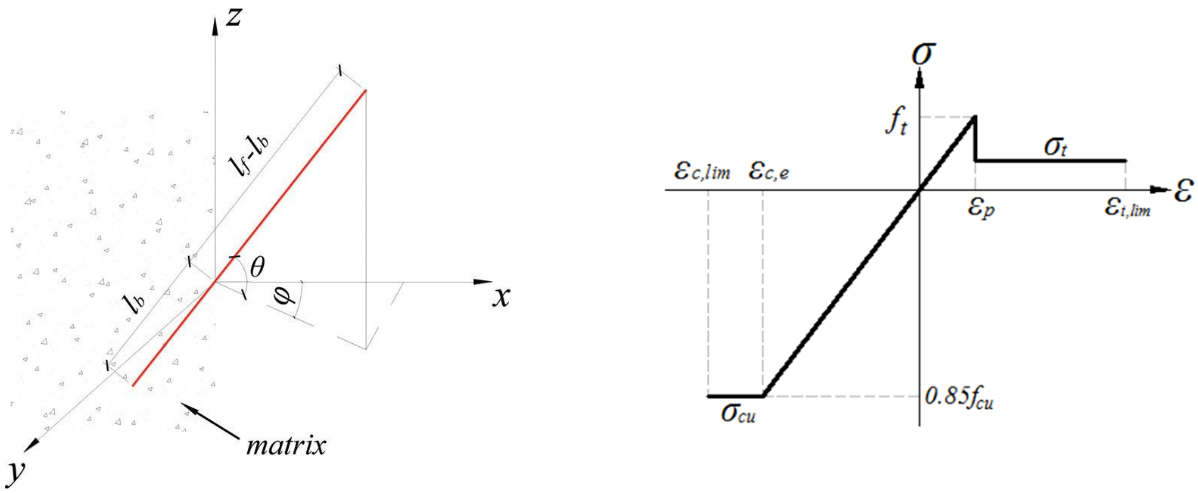


Figure 1. Ultra-high-performance fiber reinforced concrete constitutive model in compression and tension (Qi et al. 2018b)

3.2. Mesoscale Fiber-Matrix Discrete Shear Theory

In MFDM model, the fibers and matrix are treated as two individual materials working together via bonding stress between the interfaces. The normal component and tangential component of a single fiber are calculated respectively with the consideration of a fiber's orientation and embedment length. Then, the fiber's contribution is calculated by the summation of all fibers' forces.

In the development of the shear-strength model, the following assumptions are made:

• The distribution of fibers is uniform inside the beam;

• All fibers pull out from the side of the crack with a shorter embedment length; and

• Deformation of fibers induced by elastic strains is neglected because of the relatively small value compared to slip between the fibers and matrix, as well as the bending stiffness of a fiber.

According to the proposed model, the shear strength of UHPC beams can be calculated by

$$V_u = V_c + V_s + V_f \tag{2}$$

where V_c = shear resistance of compression zone; V_s = shear contribution of stirrups; and V_f = shear resistance of steel fibers.

According to the Qi et al. (2017), V_c, V_s, V_f can be written as follows:

$$V_f = \frac{n}{n_c} \sum F_y \cos\theta = \frac{8\rho_f bdFw_e \cot\theta}{\pi^2 l_f d_f^2} \qquad (3)$$

where l_f and d_f = length and diameter of steel fibers respectively and ρ_f = fraction volume of steel fibers; w_e = width of the effective fiber distributed region (EDR); d = effective depth of the beam; andθ = angle of critical diagonal shear crack and Figure 2 shows the concepts to determine the width of EDR: (1) probability theory and (2) the basis of the pullout load slip relationship. The *Vc* determined by the Rankine's failure criteria and *Vs* determined by the truss mod. The details of derivation can be acquired from the Qi et al. (2017). Through comparison with test results, the proposed model shows good agreement with testing results.

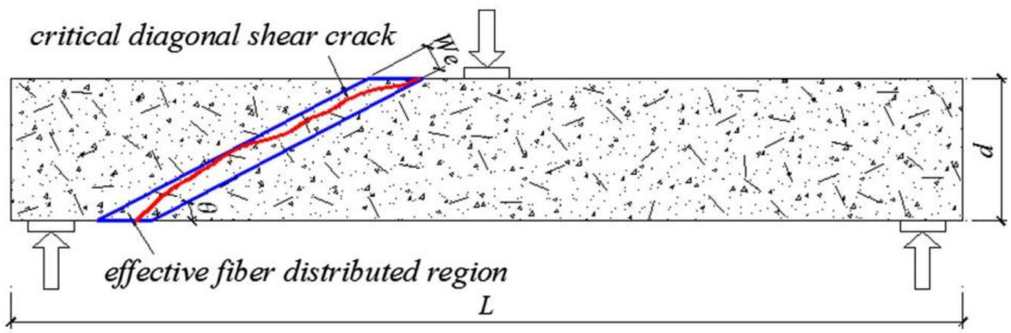


Figure 2. Effective fiber distributed region (EDR) in a beam

4. Innovative Structural System

4.1. Large Stud-UHPC Composite Structure

The commonly adopted 19mm or 22mm studs in current practices have shown many disadvantages in high shear regions when a great number of studs are required. The use of large headed stud was then proposed to address the problem, which in normal concrete, however, might result in stress concentration and lower shear strength. Thus the large stud with diameter of 30mm in paired with UHPC might successfully overcome the shortcomings. The investigation on two main large stud-UHPC connection composite bridge systems were performed as shown in Figure 3, referring to the single and grouped large stud arrangement in cast-in-place or precast UHPC slab. Parameters including the stud diameter, concrete strength, stud aspect ratio and slab thickness were taken into consideration. Failure pattern of UHPC specimens was dominated by stud fracture without visible a crack in the slabs (Wang et al. 2018). Also, it can be found that the shear capacity improved significantly when the largely headed stud embedded in the UHPC slab.

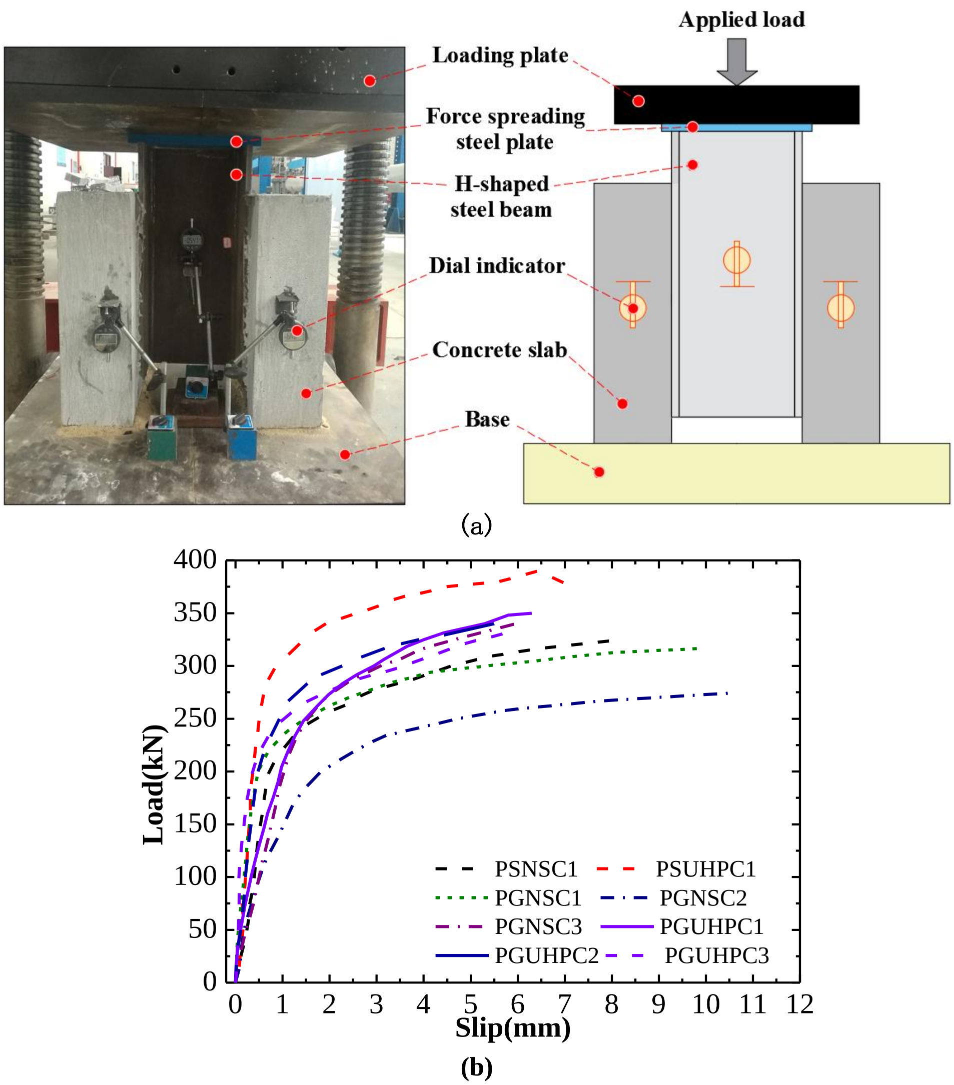
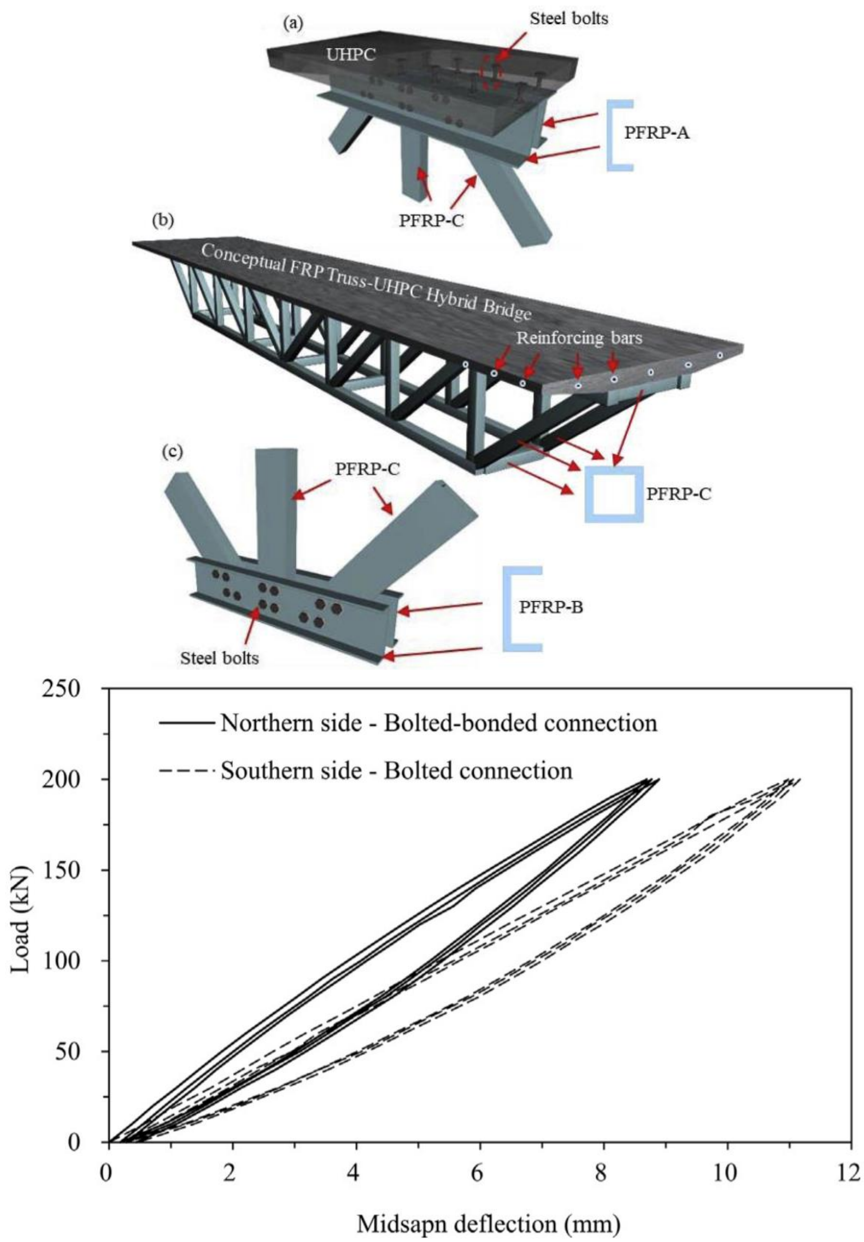


Figure 3. (a) Push-out test setup, (b) load-slip responses (Wang et al. 2018)

4.2. Light-Weight FRP Truss-UHPC Bridge Decks

As deflection is currently the main unsolved problem for fiber reinforced polymer (FRP) truss and space frames withstanding heavy loads. A UHPC slab can be incorporated in the all-FRP truss system to further improve the ultimate capacity and the rigidity (see Figure 4). A 7.2m long, simply-supported full-scale FRP truss-UHPC hybrid bridge model was constructed. Two panel trusses, one with bolted connections and the other with bolted-bonded connections as FRP joints, were constructed separately and then assembled into a whole bridge. The connection of FRP-UHPC and FRP joints were experimentally studied before the construction of the hybrid bridge model.



(a)

(b)

Figure 4. (a) The proposed FRP truss-UHPC slab hybrid bridge, (b) load-deflection response of cyclic loading (Zou and Wang (2018)).

According to the study by Zou and Wang (2018), it can be found that the simply-supported full-scale FRP truss-UHPC hybrid bridge model can withstand a static road load. The deflection, instead of the stress of FRP members and UHPC slab, is the governing factor of the design. Nevertheless, the current design can meet the design requirements for road loads. The usage of FRP can be reduced by 80% compared with another all FRP truss road bridge in this kind of structures.

4.3. Self-Centering Precast Segmental Bridge Columns

UHPC with high ductility can ensure low damage at the column toe when self-centering precast bridge columns are subjected to severe earthquake, which means that the loss of posttensioning force is mitigated and self-centering capacity can be significantly improved. For this type of bridge column, unbonded posttensioned tendons provide self-centering capacity. UHPC decreases concrete crush at column toe. Energy dissipating (ED) bars improve energy dissipation capacity. Unbonded length avoids premature tensile failure. The results in Wang et al. (2017) showed that all specimens fail in the first fracture of ED bars. Those specimens show good deformation and self-centering capacity as shown in Figure 5. The maximum drift is not less than 8%. The axial compression ratio limit should be 0.25 when the ratio of ED bars is <1.5%.

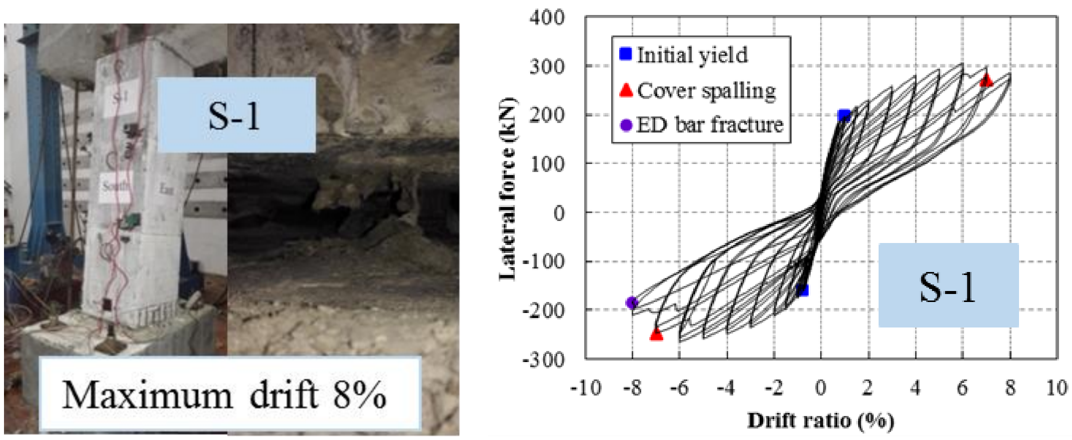


Figure 5. The experimental results（Wang et al. (2017)）

4.4. Precast Segmental Box-Girder with Large Shear Key Connection

UHPC segmental bridge system based on the large shear key is proposed, the shear transfer of dry joints between UHPC segments is one of the major concerns. 34 specimens were tested to investigate the shear behavior and direct shear tests of UHPC joints. Confining stress was applied to the lateral joint surface to simulate the effect of prestressing in segmental bridges as shown in Figure 6.

The ultimate shear strength of the keyed joints increased with an increase in the tensile strength of the concrete matrix, and it may further increase with the addition of fibers in the same matrix. The shear capacity of single-keyed UHPC joints was 8.7% higher than that of single-keyed UHPC-NF joints under a confining ratio of 0.2. The simplified formula (Liu et al. 2019) for UHPC joints was found to show better agreement with the shear test results, with an average ratio of 0.96 and a standard deviation of 0.24, compared with 1.41 and 0.38 in the AASHTO (2012) provisions.

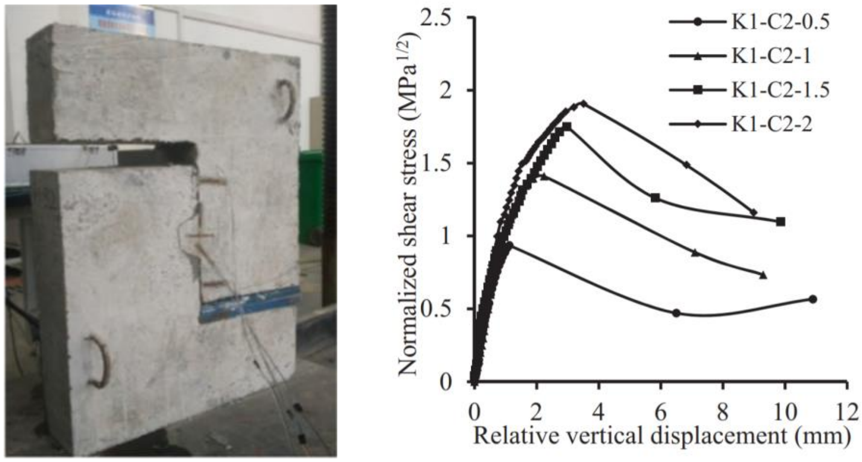


Figure 6. The model of large shear key connection

5. Engineering Applications

Vanke pedestrian bridge is the first precast segmental UHPC Arch Bridge in China as presented in Figure 7. The bridge is divided into three sections, the left and right arches were prefabricated, the middle span arch section was cast-in-place, which connected the two prefabricated segments. Due to the simplified flexural strength model and Mesoscale fiber-matrix discrete shear theory was used in the design of it, the rib of arch is light and thin.

Figure 7. Load test of Vanke pedestrian bridge

The Nanjing 5th Yangtze River Bridge is a three-tower composite beam cable-stayed bridge with a span of (80+218+600+600+218+80) m located in Nanjing, China. Figure 10 shows the elevation configuration and the three-dimension view of standard segmental units. The main girder adopts integral open steel box girder-precast UHPC deck slab composite beam due to excellent torsion resistance. The thickness of the UHPC deck slab is 170mm which is approximately 2/3 of the normal strength concrete deck slab thickness of the same type bridge deck. The innovative steel-UHPC composite system using large grouped studs was used in the Nanjing 5th Yangtze River Bridge engineering.

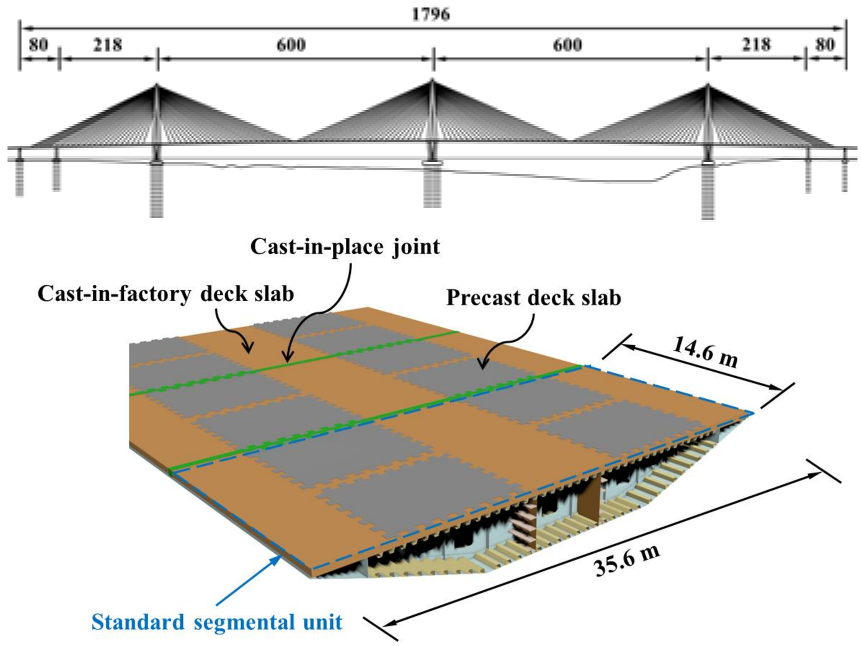


Figure 8. The Nanjing 5th Yangtze River Bridge

6. Conclusions

(1) A mesoscale constitutive model and fiber-matrix shear strength model are established. The proposed model offers a new insight into the fiber force resistance mechanism.

(2) Five structural systems are proposed, including large stud-UHPC composite system, FRP-UHPC composite system, Self-centering precast bridge columns, large shear keys precast segmental system and an innovative dovetail UHPC joint system.

(3) The established design theory and proposed structural systems are applied to practical engineering.

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