Experimental study on bending resistance of steel-UHPC composite slabs

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Abstract. The local cracking problem of steel-UHPC composite slab structure layer under negative bending moment is a basic research topic for the application and development of this new type composite bridge deck structure system. Combined with the performance of UHPC, the mechanical behavior of composite slab before ultimate load was analyzed by designing a pure bending test model, and the mechanical indexes such as cracking load and ultimate load were obtained. The results show that the reinforcement and the combination effect can effectively limit the development of tensile crack in UHPC layer and improve the bearing capacity of the slab. The reinforced steel-UHPC composite slab earns good ductility. The material properties of UHPC should not be ignored in the analysis and calculation of mechanical properties of composite slabs. The combined effect can limit the development of tensile cracking and change its failure mode of the UHPC layer. The thickness of longitudinal reinforcement protective layer of steel-UHPC composite slab can significantly affect its flexural behavior. The application range of the equivalent section method based on linear elasticity is limited, and it is necessary to develop the analysis and calculation method that can accurately reflect the cooperative working effect of each member of the steel-UHPC composite plate.

1. Introduce
Fatigue cracking of steel bridge decks and vulnerability details of deck pavement are the difficulties that restrict the sustainable development and application of orthotropic steel bridge decks. Scholars proposed the steel-UHPC (ultra-high-performance concrete) composite bridge deck structure system\(^1\)-\(^3\) by introducing the ultrahigh performance concrete structure layer and combining the stress system of stud shear connectors and orthotropic steel bridge deck. Many experimental and theoretical research of this composite bridge deck structure has been carried out from different aspects\(^4\), and steel-UHPC composite bridge deck structure system has been successfully applied in many long-span Bridges in China at present\(^5\). The research suggested: UHPC earns excellent mechanical properties, good bearing capacity and durability\(^6\)-\(^7\); The strength of ultra-thin UHPC layer can meet the design requirements of composite bridge\(^8\); Steel-UHPC composite bridge deck structure is one of the effective ways to solve the fatigue problem of steel bridge deck at the structural system level\(^9\)-\(^13\). However, there is a risk of local cracking when the new structure is subjected to negative bending moment\(^14\).

In view of the local cracking risk of steel-UHPC composite slab under the negative bending moment, the experimental method is mostly used to analyze the mechanical behavior. Domestic and overseas scholars have studied the flexural performance of steel-UHPC composite slab with steel...
reinforcement by model test, and summarized the influence of reinforcement ratio and UHPC protective layer thickness on the flexural performance of steel-UHPC composite slab. The related research has laid an important foundation for the deep understanding of the mechanical characteristics of steel-UHPC composite bridge deck structure system, and promoted its application and development. About the existing research methods, the crack load and crack strength of steel-UHPC composite slabs are mainly calculated based on tests and the linear converted cross-section method. Thus, many research and theoretical analysis have been obtained of the slab cracking development.

The above research results are insufficient in relation to the flexural properties of UHPC itself to analysis and discuss the mechanical properties of composite slabs. In this paper, the mechanical properties of steel-high performance concrete composite slabs under pure bending action are analysed through design tests and combined with the flexural resistance of UHPC, and the mechanical properties before ultimate load are explored.

2. Test condition

2.1. Performance of UHPC

The components of the UHPC used in the test are shown in Table 1. Short straight steel fiber with length of 12mm and diameter of 0.2mm is added and the volume content of steel fiber is 2.5%. The elastic modulus of UHPC is 44.6GPa and the compressive strength is 119.7MPa.

| Component       | kg/m³ |
|-----------------|-------|
| Cement          | 875   |
| Silica sand     | 900   |
| Silica fume     | 250   |
| Composite agent | 25    |
| Steel fiber     | 200   |
| Water           | 190   |

2.2. Pure bending test

Three test specimens are designed condition one UHPC reinforcement slab and two steel-UHPC reinforcement composite slabs. The UHPC reinforcement slab is named as S-1 to investigated the influence of reinforcement on bearing capacity and ductility of UHPC slab. Two steel-UHPC reinforcement composite slabs with different protection layer of steel bar are designed to analyze the effect of the thickness of the longitudinal reinforcement protective layer on the mechanical properties of the composite structure under pure bending load. The number of the steel-UHPC reinforcement composite slab are S-2 and S-3. The basic size of the specimen is shown in Table 2.

| Test specimen       | Parameters | Size/m     | No.  |
|---------------------|------------|------------|------|
| UHPC slab           | reinforcement | 1.40×0.40×0.06 | S-1  |
| steel-UHPC          | reinforcement | 1.40×0.40×0.07 | S-2  |
| composite slab      | reinforcement | 1.40×0.40×0.07 | S-3  |

The structure of the specimen is shown in Figure 1. The UHPC is equipped with HRB400 steel mesh, the diameter of the steel bar is 10mm, the thickness of the steel-UHPC reinforced composite steel slab bottom slab is 12mm. The steel material is Q345. The diameter of the steel bottom slab is 16mm with 40mm height of shear nails. The spacing of shear nails is 200mm. The longitudinal bars of S-2 specimen with 35mm protective layer are placed below the transverse bars, and the longitudinal bars of S-3 specimen with 25mm protective layer are placed above the transverse bars.
The schematic diagram of the test loading device is shown in Fig. 2, and the physical photos are shown in Fig. 3. The test loading method is four-point bending loading. During the test process, the vertex displacement of the pure bending region, the crack width of the UHPC tensile surface and the interlaminar slip between the UHPC layer and the steel bottom slab are measured. The collector arrangement is shown in Fig. 4. Linear Variable Differential Transformer (LVDT) is used to measure dis-M of mid-span displacement and dis-L and dis-R of slip of steel-UHPC layer on both sides. The test load is given by the MTS built-in sensor through the displacement control loading method, which is convenient to collect the mid-span displacement and slip of the specimen in the yield strengthening stage.

3. Test results

3.1. Main test results

The numerical summary of the test key points of the specimen is shown in Table 3. The elastic limit refers to the extreme point at which the load-mid-span displacement relationship deviates from the linear stage. The cracks visible to the naked eye are taken as the criterion of cracking, and the corresponding load was defined as the cracking load of the specimen.
### Table 3. Main test results

| No. | Elastic limit | Cracking load/kN | Yield load/kN | Yield Interlayer glide/mm |
|-----|---------------|------------------|---------------|---------------------------|
|     | Max displacement/mm | Max load/kN | Interlayer glide/mm |                               |
| S-1 | 0.67          | 4.07            | -             | 4.07                      | 7.76                       |
| S-2 | 0.71          | 7.11            | 0/0           | 16.06                     | 43.03                      | 0.08/0.09                  |
| S-3 | 0.78          | 7.96            | 0/0           | 17.97                     | 62.59                      | 0.05/0.05                  |

Note: "A/B" means that the slippage at both ends of the specimen collected by LVDT is A and B respectively.

3.2. Test investigation

The load-mid-span displacement curves before ultimate load of each specimen are shown in Fig. 4, hereinafter referred to as $P-\delta$ curve. The $P-\delta$ curves of each specimen show three stages: I elastic stage, II cracking development stage and III yield stage. The S-1 specimen shows linear elastic stage I, the $P-\delta$ curve enters the nonlinear cracking development stage II after the first turning point, and the yield stage III with approximately linear displacement growth after the second obvious turning point. The $P-\delta$ curves of S-2 and S-3 specimens also undergo two obvious turns, showing as linear elastic stage I, nonlinear cracking development stage II and nonlinear undulation yield stage III.

For S-1 specimen, no visible cracks appeared in the elastic stage. In the cracking development stage, visible cracks appear on the top surface of the UHPC layer in the pure bend section, the UHPC cement foundation is gradually withdrawn from work, the tensile force is assumed by the internal steel fiber, and the $P-\delta$ curve still rises after the stress redistribution of the section, which shows the nonlinear cracking development stage. When the load is further increased, UHPC quit working and the steel bar is bearing the tensile force alone. Before the steel bar reaches the yield strength, the $P-\delta$ curve increases linearly in the third stage. The $P-\delta$ curves of S-2 and S-3 specimens show a linear increase elastic stage I at the beginning. After entering the cracking development stage II, UHPC tensile zone is constrained by reinforcement to obtain the strong working ability of cracking. When UHPC enters the strengthening stage, it causes constant stress redistribution in the cross section and presents a relatively stable nonlinear growth stage. After the steel-UHPC composite slab yields, the restriction of longitudinal bars can limit the further development of cracks in the UHPC tensile layer. The UHPC tensile zone will not quit the work immediately, but the continuous occurrence of local UHPC tensile cracking will lead to the dynamic equilibrium state of continuous stress redistribution in the whole tensile zone. This is the reason of yield phase III of the $P-\delta$ curve in Fig. 4 shows the nonlinear growth of the fluctuation. The ultimate load of S-1 specimen is 14.3kN, while the ultimate load of S-2 and S-3 specimen is 58.6kN and 70.7kN.
During the test, the cracking development was observed. The crack initiation of UHPC slab and composite slab is similar. After the end of the elastic stage, the tensile top surface of UHPC layer is the first to observe short and transversely distributed visible cracks, whose width develops steadily and slowly. The short cracks on the surface of S-1 specimen gradually developed with the increase of load in the crack development stage forming multiple penetrating cracks, of which one penetrating crack further developed and penetrated UHPC when yielding. The width of the other associated penetrating cracks remained basically unchanged as shown in Figure 5(a). Short cracks at cracking development phase of S-2 and S-3 specimen continue to appear with load, the crack width in the middle of the crack development stage can still maintain the development of low speed, then horizontal extension through cross section vertical to the bottom of the beam. In pure bending area, several through cracks form and increase with the loading development. The cracks run through the cross section shown in figure 5(b) and 5(c).

3.3. Result analysis

Through the analysis of the above phenomena, it can be concluded that the mechanical properties of the flexural section can be significantly optimized by introducing the steel bottom slab to form the
composite structure. The reinforcement and combination effect can effectively limit the development of tensile cracks in the UHPC layer and improve the bearing capacity of the specimen. Compared with reinforced UHPC slab, the ductility of reinforced steel-UHPC composite slab is better. The material properties of UHPC itself have great influence on the cooperative work of composite slabs. The next step is to analyse the UHPC working state observed in the test during the crack development stage and the yield stage. The thickness of the longitudinal reinforcement protective layer has a significant effect on the cracking restraint of UHPC layer. The bearing capacity of S-3 specimen is obviously better than that of S-2 specimen, so the thickness of longitudinal reinforcement protective layer has an obvious effect on the mechanical properties of composite slab. The bearing capacity of S-3 specimen is about 49% higher than that of S-2 specimen when cracking, while the ultimate bearing capacity is about 20.6% higher.

If the composite slab is considered as a whole and the equivalent section method is used to calculate, the pure bending cracking strength of S-2 specimen is 13.49MPa while the S-3 specimen is 17.1MPa. Literature[14] shows that the crack strength difference of steel-UHPC composite slabs with different structural parameters calculated by equivalent section method can reach 1.77 times. Obviously, it is a general consensus that the cracking strength of any engineering material has nothing to do with its structural form under the same stress mode. When it is necessary to conduct in-depth research on each stress member of composite slab, the cracking strength of UHPC should be the same. The main difference between S-2 and S-3 is the collaborative working efficiency between stressed members caused by the thickness of the protective layer. Therefore, the next step is to develop a calculation method that can analyse the collaborative efficiency of composite slabs. It is of great theoretical significance for engineering application to give full play to the combination effect of each bearing member of steel-UHPC composite slab, in order to improve its bearing capacity and delay the crack development of UHPC layer.

4. Conclusion
The mechanical behavior of UHPC slab and steel-UHPC composite slab under pure bending load was studied by three specimens, and the test phenomena during the test were discussed. The following conclusion can be drawn:
[1]. The combined form can significantly improve the ductility and ultimate bearing capacity of UHPC layer. The cracking load of S-1 specimen is 4.07kN, and the ultimate load is 7.76kN. The cracking loads of S-2 and S-3 specimens are 16.06kN and 17.97kN, while the ultimate loads are 58.6kN and 70.7kN.
[2]. Since the UHPC can continue to work after cracking, the material properties of UHPC cannot be ignored in the analysis and calculation of the mechanical properties of the composite slab.
[3]. The combined effect can limit the development of tensile crack in UHPC layer and change its failure mode. The thickness of the longitudinal reinforcement protective layer, which mainly bears the tensile force, can significantly affect the flexural mechanical behavior of the composite slab.
[4]. The application range of the equivalent section method based on linear elasticity is limited. It is necessary to develop an analysis method that can accurately reflect the various stressed members of the steel-UHPC composite slab.

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