CONSTRUCTIONAL METHOD OF UHPC ON STEEL DECK OF LONG SPAN SUSPENSION BRIDGE AND IN-SITE EXPERIMENTAL TEST

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Abstract

The Second Dongting Lake (SDTL) Bridge is the longest steel truss girder suspension bridge in China, which has a main span of 1480 m. To alleviate deterioration issues in the orthotropic steel deck (OSD), the steel-ultra high performance concrete (UHPC) lightweight composite deck (LWCD) was proposed for the SDTL Bridge. The LWCD is composed of a 12 mm OSD and a 45-mm UHPC layer, with the two components connected through headed studs. As the first time of LWCD to be used in the long-span flexible bridge, the constructional method of casting UHPC was carefully developed. Considering that the area of the bridge deck is about 65000 m^2, the UHPC layer was divided in to 12 zones and the zones were cast step-by-step. Water tanks were deployed on the bridge deck prior to casting UHPC, and during the casting of each UHPC zone, the corresponding water tanks within the current zone were removed. By doing so, the deflection and rotation of the truss girder as well as the tensile stress in UHPC could be controllable. This paper validate the feasibility of the proposed construction method by Finite-element analysis. The maximum torsion angles of the truss girder in each construction stage are less than 0.60°. In addition, the strains of UHPC were recorded during construction to analyse the stress in the UHPC layer. The in-site test indicated that the longitudinal and transverse strain of the UHPC layer were stabilized at -50 με ~ 50με and -20 με ~ -120 με after steam curing respectively, which have no cracking risk. Thus, the studies in this paper reveal that the proposed constructional method should be suitable in the construction of UHPC on long-span flexible bridges.

Keywords: *bridge, ultra high performance concrete, steel-UHPC lightweight composite deck, constructional method, shrinkage.*

1. Introduction

As an important structural form of steel bridge decks, orthotropic steel decks (OSDs) has been widely used because of their advantages such as light self-weight, high strength, and constructional convenience, etc. However, with the increase of service time, the OSD+asphalt pavement deck system is inclined to premature deterioration (Wolchuk 1990, Jong 2004, Shao and Cao 2018), i.e. fatigue cracking of the steel deck and frequent damage of the asphalt pavement.

Ultra high performance concrete (UHPC) is a new class of concrete with excellent mechanical properties and exceptional durability. To address the above issues, the authors proposed a new composite deck system (Shao et al 2013) for OSD bridges. The new composite deck system is composed of an OSD and a thin untra high performance concrete (UHPC) layer, with the two components connected through headed studs. Considering the thin thickness of the UHPC layer (usually 35~50 mm), the OSD-UHPC composite deck is also referred to as steel-UHPC lightweight composite deck (LWCD). Extensive researches (Shao and Cao 2018, Shao et al 2013) have shown that the LWCD can highly improve the local thickness of the OSD and thus reduce the fatigue stress in the OSD, which can significantly reduce the risk of fatigue cracking of the steel deck. At the same time, the LWCD also addressed the frequent damage of the asphalt pavement by replacing expensive asphalt pavement with economical concrete pavement.

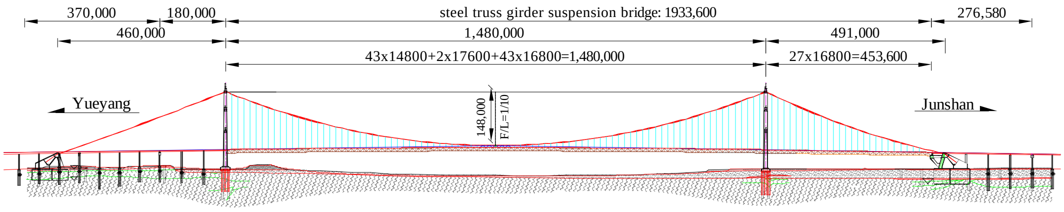
The Second Dongting Lake (SDTL) Bridge is the longest steel truss girder suspension bridge in China, which has a main span of 1480 m. In 2017, the LWCD has been applied to the SDTL Bridge. As the first time of LWCD to be used in the long-span flexible bridge, the constructional method of casting UHPC was carefully developed. Considering that the area of the bridge deck is about 65000 m^2, the UHPC layer was divided in to 12 zones and the zones were cast step-by-step. Water tanks were deployed on the bridge deck prior to casting UHPC, and during the casting of each UHPC zone, the corresponding water tanks within the current zone were replaced by UHPC gradually. By doing so, the deflection and rotation of the truss girder as well as the tensile stress in UHPC could be controllable.

This paper validated the feasibility of the proposed construction method by simulating the constructional phase of UHPC casting in global finite-element (FE) analysis. In addition, the strains of UHPC were recorded during construction to analyse the stress in the UHPC layer.

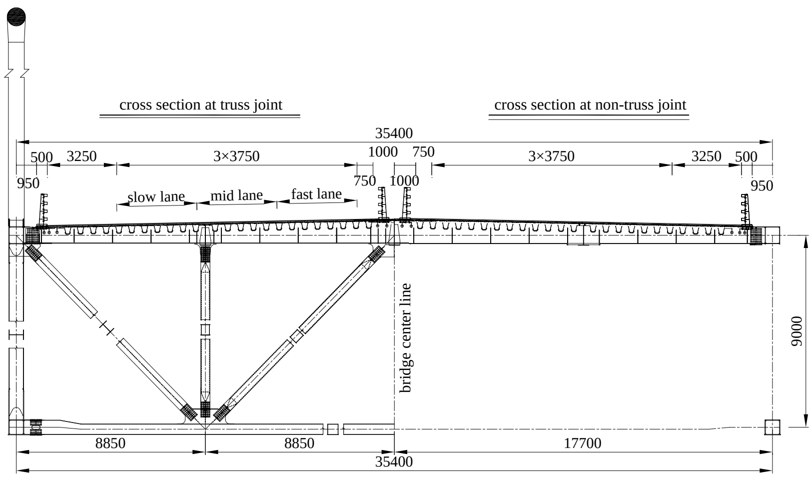
2. Pilot Project: The SDTL Bridge

2.1. Brief Introduction of the SDTL Bridge

The SDTL Bridge is a two-pylon two-span steel truss girder suspension bridge, which has a main span of 1480 m — the longest steel truss girder suspension bridge in China. The layout of the SDTL Bridge is shown in Figure 1. The steel truss girder has a depth of 9.0 m and a width of 35.4 m. The sag ratio of the main cable of the bridge is 1/10. The suspender spacing along the longitudinal direction and transverse direction are 16.8-17.6 m and 35.4 m respectively. The OSD of the SDTL Bridge is 12 mm thick. Stiffened with 8-mm U-shaped ribs spaced at 600 mm, the OSD is supported on the transverse floor beams every 2.8 m.



(a)



(a)

Figure 1. The SDTL Bridge (all dimensions are in millimeters): (a) elevation view; (b) cross section of the steel truss girder.

The LWCD scheme of the SDTL Bridge is shown in Figure 2. The thickness of the asphalt overlay, the UHPC layer, the steel bridge deck are 40 mm, 45 mm, 12 mm respectively. Steel bars with a nominal yield strength of 400 MPa are used to reinforce the UHPC layer. Each steel bar has a diameter of 10 mm and has central spacings of 37.5 mm in the longitudinal and the transverse directions. The steel bridge deck and the UHPC layer are connected through headed studs (13 × 35 mm). The headed studs have spacings of 150 mm along both the longitudinal and the transverse directions.

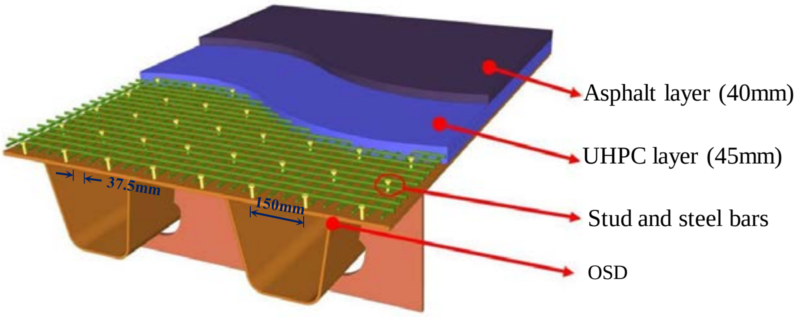


Figure 2. The LWCD scheme of the SDTL Bridge.

2.2. Application of LWCD to the Real Bridge

During the UHPC casting of the SDTL Bridge, the UHPC layer was divided in to 12 zones (Fig. 3) and was cast zone-by-zone. The construction phase are corresponding to the casting of each zone of UHPC. As a long-span flexible bridge, the SDTL Bridge is sensitive to change of dead load on bridge deck. In addition, the UHPC layer was cast asymmetrically during construction. To control the deflection and rotation of the truss girder and avoid negative impact on UHPC, the load-balance constructional scheme (Figs. 4-6) was used in the casting of UHPC. Prior to casting UHPC, water tanks are deployed on the bridge deck and the weight of water tanks is equal to the weight of UHPC to be cast on the bridge deck. During the casting of each UHPC zone, the corresponding water tanks within the current zone are gradually replaced by the UHPC of same weight. In doing so, loads on the bridge deck remain basically unchanged in construction.

The main construction procedures of UHPC were as follows: (1) headed studs were welded to the deck plate; (2) the special-shape steel plate was welded to the deck plate at the bridge center line; (3) steel bars were placed; (4) the UHPC layer was cast in-situ; (5) 2-day moisture-retaining curing and 3-day steam curing with temperature over 80 ℃ were appli (procedures 4-5 were repeated for each UHPC zone); (6) after the steam curing of all UHPC zones was finished, surface roughening was applied to the UHPC layer.

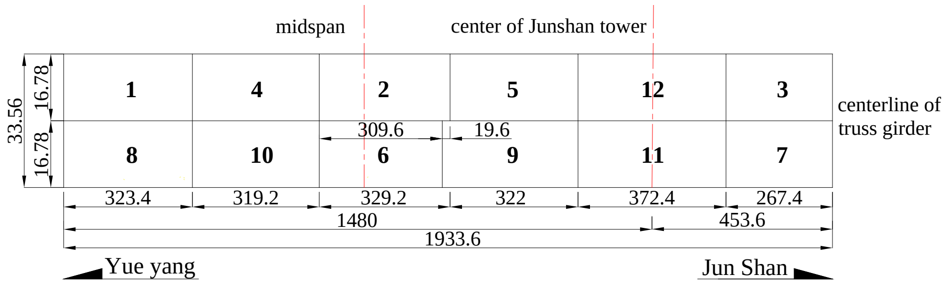


Figure 3. The casting sequence of the UHPC layer (unit: m)

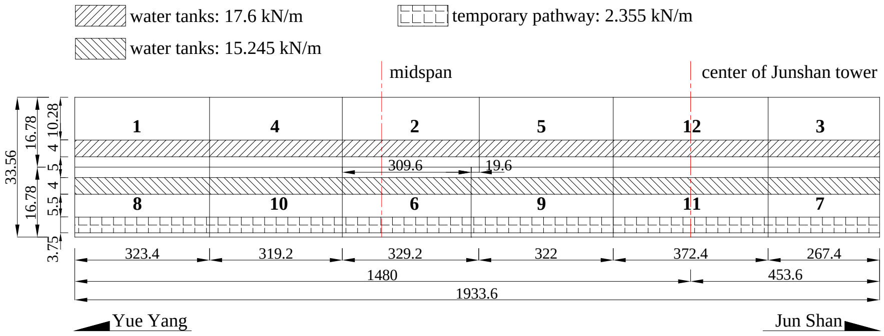


Figure 4. Load-balance constructional scheme used in the casting of 1st - 4th UHPC zones (unit: m)

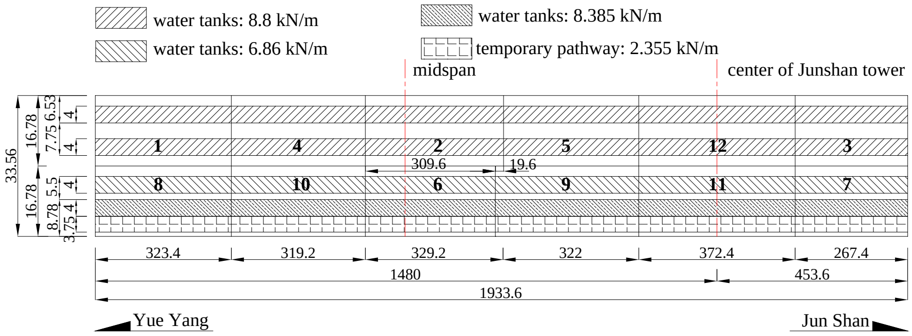


Figure 5. Load-balance constructional scheme used in the casting of 5th - 10th UHPC zones (unit: m)

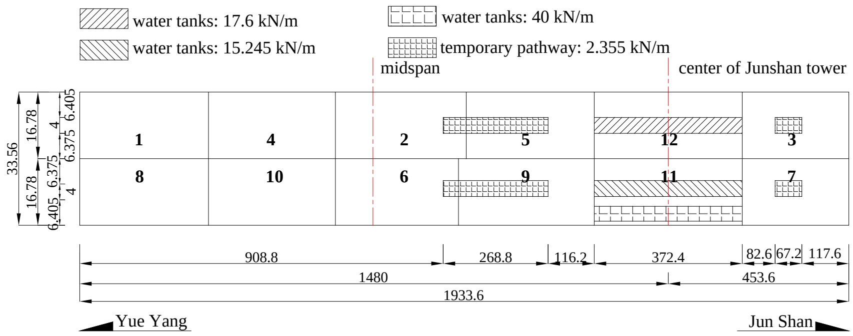


Figure 6. Load-balance constructional scheme used in the casting of 11th - 12th UHPC zones (unit: m)

3. FE Analysis

3.1. FE Analysis of the SDTL Bridge

3.1.1. Global FE Model of the SDTL Bridge

The global FE model of the SDTL Bridge (Fig. 7) was built in the software Midas Civil (Zhang et al 2017). Eleven constructional phases (i.e. constructional phases that 2nd-12th UHPC zones just had been cast) were simulated. The main cable and suspenders were built by using cable element. The concrete bridge tower and the steel truss girder were built by using beam element. The steel bridge deck was built by using shell element. The UHPC layer after steam curing was built by using solid element. The newly casting UHPC layer was considered as pressure load. The elastic modulus, volumetric weight, poisson's ratio of steel bridge deck were 206 GPa, 78.5 kN/m^3, 0.3 respectively. The elastic modulus, volumetric weight, poisson's ratio of the UHPC layer were 40 GPa, 30.04 kN/m^3, 0.2 respectively.

The stiffness at the bottom of bridge towers was defined as the stiffness of pile foundations. As for the end of truss girder near Yueyang bridge tower, its vertical displacement was the same as that of the crossbeam of Yueyang tower, and it only beared transverse compressive stress from the tower column. Other boundary conditions of the global model are illustrated in Figure 7.

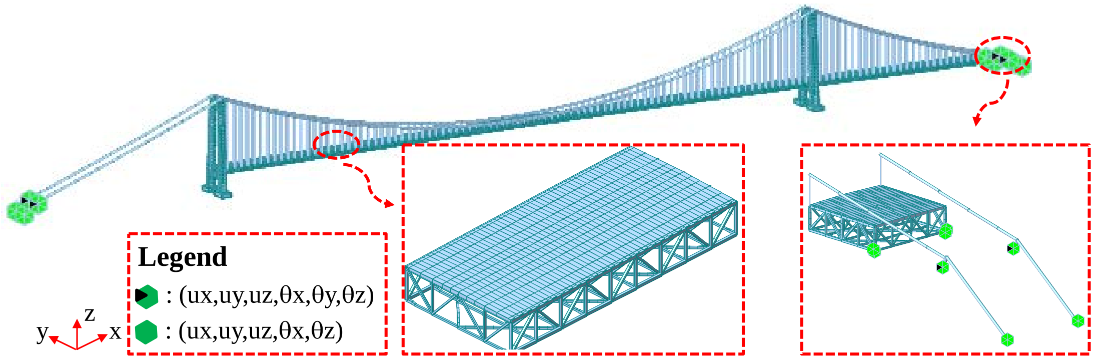


Figure 7. Global FE Model of the SDTL Bridge

3.1.2. Loads

Self-weight and construction loads were considered in the FE analysis. The construction loads contained: the weight of water tanks, the weight of construction vehicles, the weight of construction machines. The load of water tanks was exerted on the bridge deck by means of pressure load (Fig. 4-6). Construction vehicles consisted of a concrete mixer truck of 300 kN, a pump truck of 300 kN. Construction machines consisted of a casting machine of 160 kN, a leveling machine of 110 kN, two construction platforms of 120 kN. The UHPC layer on the SDTL Bridge was cast along the direction from Yueyang to Junshan in the casting of each UHPC zone and constructional phases that 2nd-12th UHPC zone just had been cast were simulated. Thus, loads of construction vehicles and construction machines were exerted on truss girder in the manner shown in Figure 8.

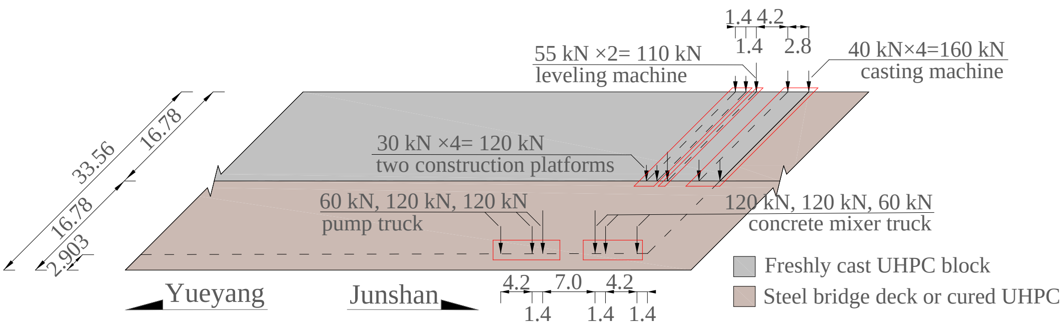


Figure 8. Loads of construction vehicles and construction machines: schematic drawing (unit: m)

3.2. Calculation Results and Discussion

Based on the FE analysis result, this paper validated the feasibility of the proposed construction method in terms of vertical deflection of truss girder, rotation of truss girder and the stress in the UHPC layer.

3.2.1. Vertical Deflection of Truss Girder

The vertical deflections (lineshapes) of truss girder in constructional phases 2-12 are shown in Figure 9. The maximum vertical deflection differences of truss girder between two adjacent constructional phases are shown in Figure 10. The aforementioned vertical deflection of truss girder, is calculated based on the height of truss girder to be opened to traffic, i.e. if the height of truss girder in one constructional phase is equal to the height of truss girder to be opened to traffic, the vertical deflection of truss girder in this constructional phase is 0. The following conclusions were obtained from Figures 9-10:

(1) The lineshapes of truss girder in phases 2-10 were higher than that of the bridge to be opened to traffic. This result could be explained by that the less the load on the truss girder, the higher the lineshape. In addition, the farther the truss girder was away from the bridge tower (abutment), the higher the truss girder in phases 2-10.

(2) The maximum vertical deflection difference of truss girder between two adjacent phases was very small. As for phases 2-10, 11-12, their maximum vertical deflection difference between two adjacent constructional phases were 20 cm~39 cm, 5 cm respectively. This result could be explained by that the load on the truss girder remained basically unchanged during construction because of using the load-balance constructional scheme.

(3) Because of using special load-balance constructional scheme, the lineshape of truss girder in phases 11-12 was different with that of truss girder in phases 2-10. As for the lineshape of in phases 11-12: ① the lineshapes on left side of Junshan tower was changed from upward arch to downward deflection, and reached their maximum vertical deflection of 154cm (phase 11) and 155 cm (phase 12) at 403.2 m away from Junshan tower. ② the upward arch of lineshapes on right side of Yueyang tower increased obviously and reached their maximum vertical deflection of 270 cm (phase 11) and 273cm (phase 12) at 436.8 m away from Yueyang tower.

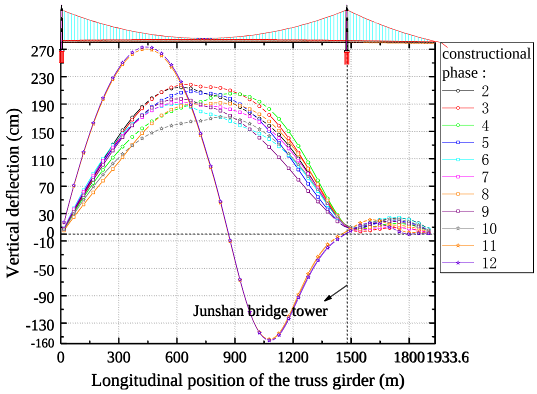


Figure 9. Vertical deflection of truss girder

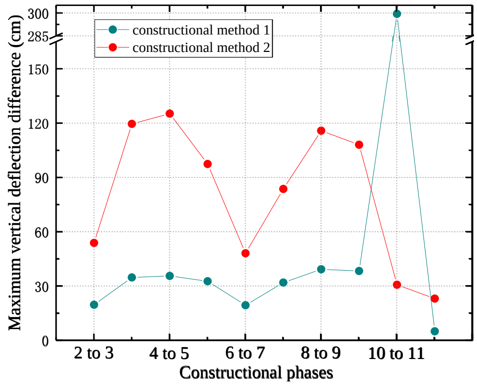


Figure 10. The maximum vertical deflection differences between two adjacent phases

3.2.2. Torsion of Truss Girder

The vertical deflection at the suspension point (the connection point of bridge deck and the suspender) was obtained from FE analysis. Based on this, the torsion angle of truss girder in different constructional phases (the height difference of two suspension points at same transverse section) was calculated and shown in Figure 11. According to Figure 11, the proposed constructional method avoided eccentric load basically and thus, its torsion angles were very small in each constructional phase. The maximum torsion angles in phases 2-12 (except phase 4) were only 0.02°~ 0.38°, while the maximum torsion angle in phase 4 was only 0.60°.

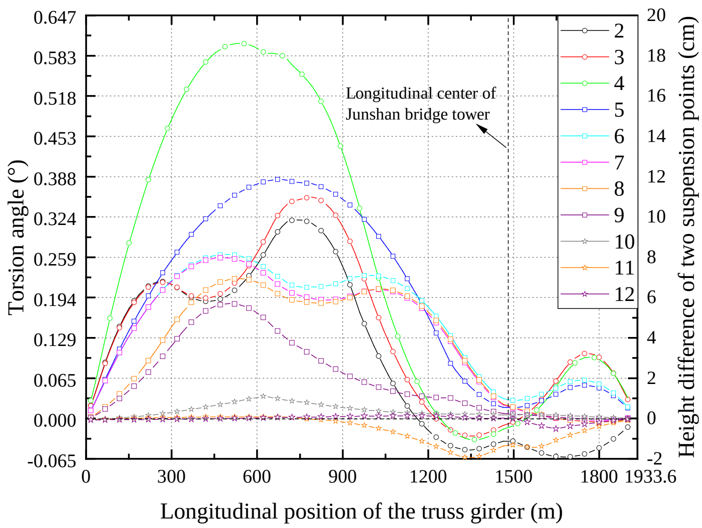


Figure 11. Torsion angle of truss girder

3.2.3. Maximum Tensile Stress of UHPC

In constructional phases 2-12, the maximum longitudinal and transverse tensile stress in the UHPC layer were within the range of 1.72 MPa ~ 2.67 MPa and 0 MPa ~ 0.44 MPa respectively (Fig. 12). According to the research of Shao et al (2013), tensile stress of the UHPC layer is up to 42.7 MPa before tiny cracks appear, which is much greater than the FE analysis result. Thus, the UHPC layer should has no cracking risk during construction.

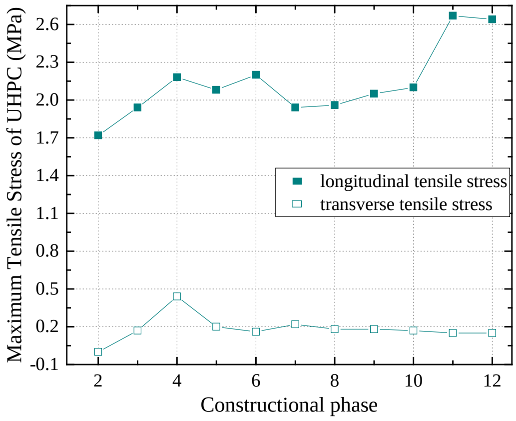


Figure 12. The maximum longitudinal and transverse tensile stress in the UHPC layer

4. In-site experimental test

During construction, 10 transverse sections were selected in 12 UHPC zones (Fig. 13). Prior to casting UHPC, two strain gauges along transverse or longitudinal direction were installed in each UHPC transverse section, which were respectively 2.1 m, 2.55 m away from the boundary of UHPC zone in transverse direction.

The UHPC strain was monitored during construction. According to the monitoring data, the strain development of UHPC performed well during construction: (1) The shrinkage of UHPC was basically completed during curing and had no obvious growth trend after steam curing. (2) After steam curing of each UHPC zone, the UHPC strain returned to around 0 με, and then the longitudinal and transverse strain of UHPC fluctuated within the range of -50 με~50 με and -10 με~-130 με respectively, which had no cracking risk (Shao et al 2013).

The UHPC strain was monitored again 23 days after the steam curing of all UHPC zones. According to the material property test of each UHPC zone, the average elastic modulus of UHPC was 48.5 GPa. Based on the monitored strain and average elastic modulus of UHPC, the UHPC stress was calculated (Fig. 14). According to Figure 14, 23 days after the steam curing of all UHPC zones, the longitudinal strain (stress) and transverse strain (stress) of UHPC were within the range of -65.98 με ~ 41.06 με (-3.20 MPa ~ 1.99 MPa), -94.52 με ~ -41.90 με (-4.58 MPa ~ -2.03 MPa) respectively, which had no cracking risk (Shao et al 2013).

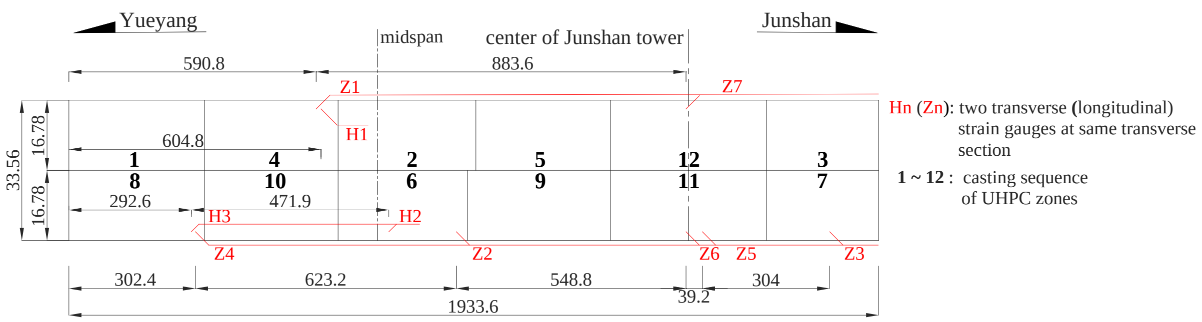


Figure 13. The installation of strain gauges

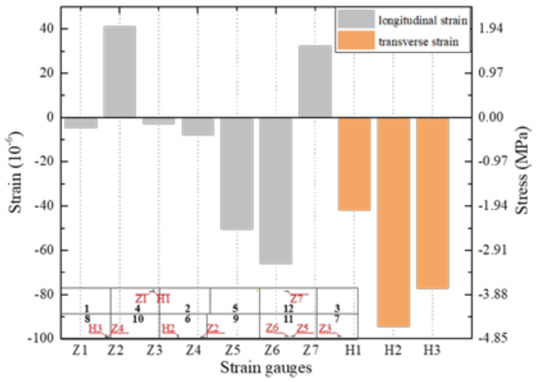


Figure 14. The UHPC strain 23 days after the steam curing of all UHPC

5. Conclusions

This paper presents a case study for the constructional method of UHPC on steel deck of long span suspension bridge and in-site experimental test. According to this study, the following conclusions can be drawn:

(1) According to FE analysis and in-site test, the proposed constructional method is suitable for the construction of UHPC on long-span flexible bridges. During construction, the lineshape changes and torsion of truss girder were small, and the UHPC layer had no cracking risk.

(2) The shrinkage of UHPC was basically completed during curing and had no obvious growth trend after steam curing. After steam curing of each UHPC zone, the UHPC strain returned to around 0 με, and then the longitudinal and transverse strain of UHPC fluctuated within the range of -50 με~50 με and -10 με~-130 με respectively, which had no cracking risk.

(3) Twenty-three days after the steam curing of all UHPC, the longitudinal strain (stress) and transverse strain (stress) of UHPC were within the range of -65.98 με ~ 41.06 με (-3.20 MPa ~1.99 MPa), -94.52 με ~ -41.90 με (-4.58 MPa ~ -2.03 MPa) respectively, which had no cracking risk.

Acknowledgements

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