SUPER LONG-SPAN LONGITUDINAL PRESTRESSED UHPC BOX GIRDER BRIDGE

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Abstract

Based on the superior mechanical properties of the ultra-high performance concrete (UHPC), an innovative longitudinal prestressed UHPC box girder (LPUBG) bridge was proposed to overcome the weaknesses of the conventional long-span prestressed concrete box girder (PCBG) such as numerous cracks, excessive deflection of mid-span and massive self-weight of the superstructure. A trial design of the bridge was conducted to preliminarily evaluate the feasibility of the proposed LPUBG. During the past five years, extensive studies have been performed to investigate the basic performance of the LPUBG, including the torsional behaviour of the box girder, the bi-directional mechanical behaviour of top slab under wheel loads, the shear performance of joint at webs, and the alternative competive span length of LPUBG bridges. In addition, the anchoring structure for the external prestressing tendons was proposed to accommodate to the thin-walled LPUBG. The aforementioned research indicates that the proposed LPUBG is a competitive alternative for long-span bridges owing to its good performance in both static behaviours and favorable economic advantages, especially when considering its life cycle cost.

Résumé

En s'appuyant sur les propriétés mécaniques supérieures du béton fibré à ultra-hautes performances (BFUP), un nouveau caisson BFUP précontraint a été proposé pour résoudre les limites des caissons en béton ordinaire précontraint pour les grands portées : nombreuses fissures, déformations excessives en milieu de travée et poids propre excessif du tablier. Un avant-projet de pont a été effectué préalablement pour déterminer la faisabilité du concept proposé. Depuis 5 ans, des études générales ont été réalisées pour évaluer les performances de base du caisson en BFUP précontraint, prenant en compte le comportement à la torsion du caisson, le comportement mécanique bidirectionnel du hourdis sous la charge des roues, la résistance au cisaillement des joints au niveau des âmes, et les portées où cette solution est compétitive. De plus, il a été proposé une solution spécifique d'ancrage des câbles de précontrainte extérieure qui s'adapte aux fines parois du caisson BFUP. La recherche conclut que le caisson BFUP proposé est une alternative compétitive pour les ponts de grande portée en raison de ses bonnes performances vis-à-vis de son comportement en statique et de ses avantages économiques, particulièrement lorsque l'on considère son cycle de vie.

1. INTRODUCTION

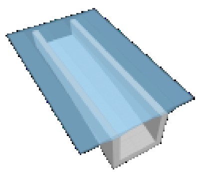
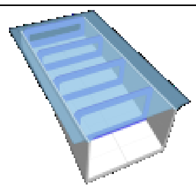
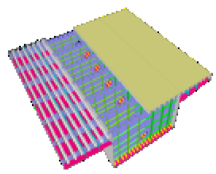
Currently, the conventional long-span prestressed concrete box girder (PCBG) bridges are widely used in those bridges with the main span less than 300m because of its economic performance and convenient facility in construction. However, there are three kinds of inherent drawbacks in conventional long-span PCBG bridges including numerous cracks, excessive deflection of mid-span and massive self-weight of superstructure [1]. The main reasons lie in the fact that the ordinary concrete owns low tensile strength and large creep coefficient. Furthermore, the ratio of dead load to the total load always reaches 70 % to 90 % for traditional long-span PCBG bridges, which extremely limits the spanning ability of this type of bridge.

Since developed in 1990s, ultra-high performance concrete (UHPC) exhibits promising perspective due to its excellent performance [2]. UHPC presents much more satisfied properties, such as ultra-high strength, ultra-high toughness, better durability, low shrinkage and creep coefficient over normal concrete [3]. The distinguished mechanical performance and competitive economic advantages (especially when considering its life cycle cost) of UHPC make this high performance materials has the potential to become a trend for the development of bridges in the future [4].

To address the foregoing disadvantages of the conventional PCBG bridges, the research group at Hunan University in China proposed an innovative box girder bridge structure based on UHPC, namely longitudinal prestressed UHPC box girder (LPUBG) bridge in 2012, which may provide a new alternative scheme for bridges with main span of 400m or more [5]. Since that time, the research group performed a series of tests and studies to investigate its static behaviour and range of alternative competitive span length as well, together with the corresponding joints and the anchoring structure for the external tendons in LPUBG.

2. DESIGN CONCEPTION OF LPUBG

Table 1: Comparison of three types of box girder

	PCBG	LPUBG	SBG
Schematic scenario			
Plates	thick	thinner	thinnest
Diaphragms	few	dense	dense
Stiffeners	none	none	dense
Prestressing	three-direction	one-direction (only longitudinal)	none

Considering the fact that the material properties of UHPC lie between ordinary concrete and steel, from the structural concept point of view, the structural characteristics of LPUBG should be an intermediate combination between the traditional PCBG and steel box girder (SBG), as illustrated in Table 1.

In LPUBG bridge structure, as shown in Fig. 1, the thickness of components in box girder are extremely reduced while the diaphragms are densely distributed along the longitudinal direction of the bridge. Attributed to the distinguished material performance of UHPC and densely distributed diaphragms, the LPUBG bridge structure has the following features:

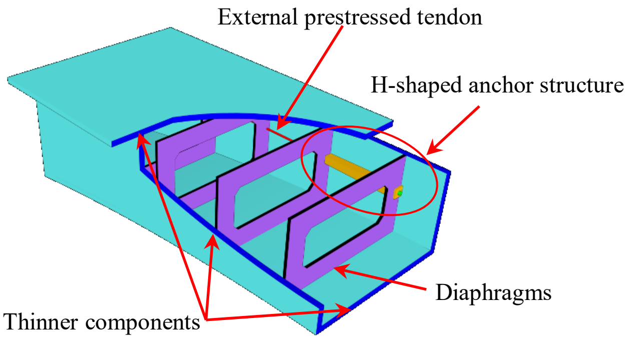


Figure 1: LPUBG structure

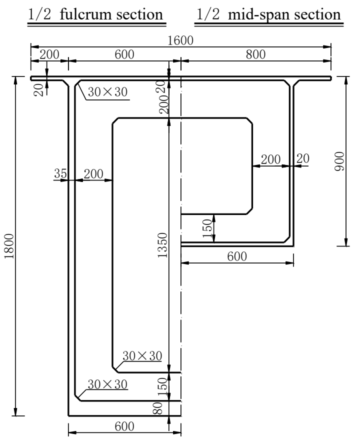


Figure 2: Main cross sections of LPUBG (unit: cm)

(1) Thinner components and lightweight superstructure. Due to the excellent performance of UHPC, the thickness of LPUBG's walls can be significantly reduced and the self-weight of superstructure is decreased notably. The previous studies [6] indicated that compared to traditional PCBG bridge, the superstructure deadweight of LPUBG bridge could be dropped by 40% to 60%, resulting in a larger spanning ability.

(2) Densely distributed diaphragms with spacing at 3~5m along the longitudinal direction of the bridge. Dense diaphragms are set to strengthen the top slab, webs and bottom plate as well as decrease the torsional distortion deformation of LPUBG.

(3) One-directional (only longitudinal) prestressing tendons and partial external prestressing system. The vertical and transverse prestressing tendons could be cancelled in LPUBG bridge structure compared with the conventional PCBG bridges, owing to the reason that the top slab and webs are enhanced by dense diaphragms and that UHPC owns higher tensile strength. As a result, the conventional three-directional prestressed system could be transformed into one-directional prestressed system, so as to reduce the construction complexity of prestressing system. On the other hand, the longitudinal prestressing tendons can be designed in the forms of both internal and external tendons to accommodate the thin walls in the box girder. Meanwhile, the densely distributed diaphragms make it convenient for external tendons to be steered and anchored.

(4) Precast segmental cantilever construction. The curing condition has a great effect on the mechanical properties of UHPC [3]. In this case, the segments of LPUBG are preferred to be prefabricated and steam cured in the factory so as to guarantee excellent mechanical properties. Then they can be transported to the construction site for cantilever construction.

3. TRIAL DESIGN OF LPUBG BRIDGE

An optimal trial design was conducted for a continuous LPUBG bridge with the spans of 240 m + 400 m + 240 m. Fig. 2 illustrates the main cross sections of the LPUBG bridge. The spacing and thickness of diaphragms are 4m and 0.12 m, respectively.

The main analysis results are shown in Table 2. It was indicated that the maximum principal compression stress of the bridge, caused by combined design loads, was 42.0 MPa, and the maximum principal tensile stress was 3.8 MPa. The maximum deflection of the bridge caused by vehicle loads was 223 mm, which was 1/1329 of the main span. All of the calculated results met the design specifications in China. Three different spacing of diaphragms were investigated and compared, and the analysis indicated that the diaphragm spacing influences the tensile stress of the top slab significantly. When the diaphragm spacing was 4 m, the maximum local tensile stress in the top slab caused by wheel loads was only 3.5 MPa. By contrast, when the diaphragm spacing was 12 m or when the diaphragms were cancelled, the maximum local tensile stress was 8.6 MPa and 16.0 MPa, respectively. This implied that the application of densely distributed diaphragms in the proposed new structure could significantly reduce the local stresses in the top slab under wheel loads.

In the optimal trial design, the material consumptions were estimated as follows: within an unit area (i.e. 1 m^2) of the bridge deck, the overall material consumptions of the UHPC and prestressing tendons are about 1.1 m^3 and 129 kg, respectively.

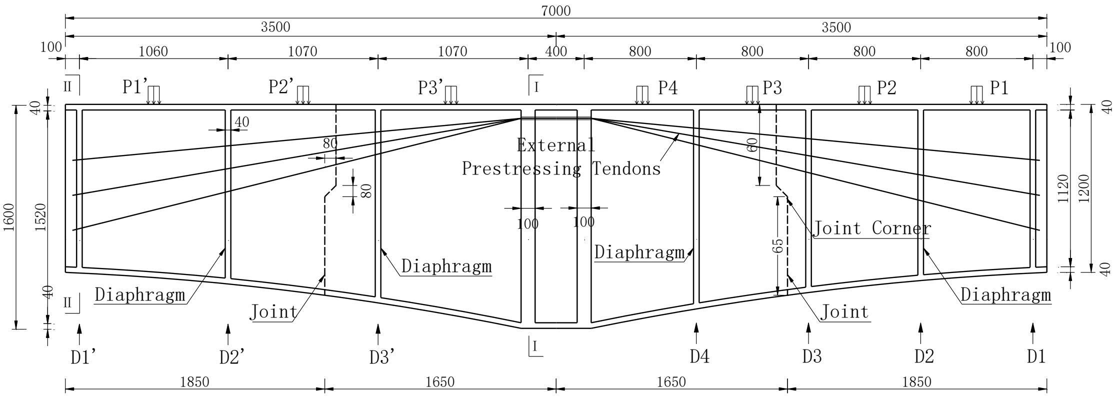
Table 2: Main analysis results of LPUBG bridge

Item		Unit	Value
Integral calculation	Principal Compressive Stress	MPa	42.0
	Principal Tensile Stress		3.8
	Deflection	mm	233(1/1717)
Maximum local tensile stress	Diaphragm Spacing of 4m	MPa	3.5
	Diaphragm Spacing of 12m		8.6
	None		16.0
Material consumptions	UHPC	m^3/m^2	1.1
	Prestressing Tendons	kg/m^2	129

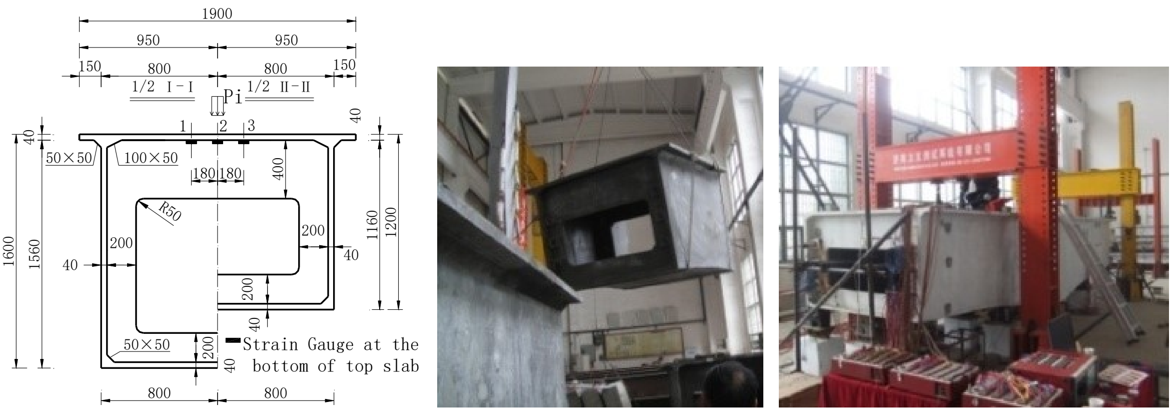
4. FUNDAMENTAL RESEARCH OF LPUBG

4.1 Static behaviour

To investigate the performance of the proposed LPUBG bridge, a large-scale specimen of the LPUBG with double cantilevers and variable cross-section was designed and fabricated, as shown in Fig. 3. To study the effects of the spacing of diaphragms on the behaviours of the LPUBG, three diaphragms were arranged at the left cantilever while four diaphragms were placed at the right cantilever, as illustrated in Fig. 3(a). In addition, the number of diaphragms and top slabs are numbered as Fig. 3(a). The box girder model was assembled with three segments. The photograph of the assembling process of the box girder is displayed in Fig. 3(c). After the process of assembling, the longitudinal external prestressing was imposed on the girder. The photograph of LPUBG model before test is shown in Fig. 3(d). In this box girder model, the experiment of the elastic torsional performance and elastic static behaviour of top slab under wheel loads as well as the shear performance of joint at webs were conducted one after another.



(a) elevation view (unit: mm)



(b) sectional view(unit: mm) (c) assembling and fabrication (d) overview of model before test

Figure 3: Test model of LPUBG

4.1.1 Torsional and distortion effect

To study the torsional and distortion performance of LPUBG, the torsional tests were conducted at elastic stage of the box girder [7]. The test results showed that, compared with that on the three-diaphragms cantilever side, the stress and deflection due to torsion and distortion on the four-diaphragm cantilever side reduced 30.6% and 42%, respectively. On the other hand, the ratios of the warping stresses to the flexural stresses ranged from 14.1 % to 22.4 % on the cantilever side with three diaphragms while those on the cantilever side with four diaphragms ranged from 10.4 % to 23.8 %. The test results illustrated that diaphragms can effectively reduce the warping stress and deformation of LPUBG. However, the warping stresses still cannot be completely ignored.

4.1.2 Bidirectional mechanical behaviour of the top slab

To understand the mechanical behaviour of LPUBG's bridge deck slab with densely distributed diaphragms, the analyses on the characteristics of the internal force distribution of LPUBG's bridge deck slab were performed [8]. It is noted that the layout of wheel load and strain gauges are shown in Fig. 3(b).

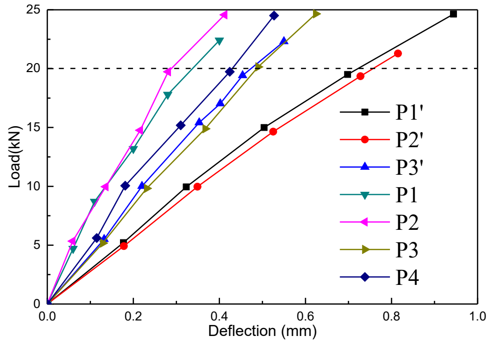
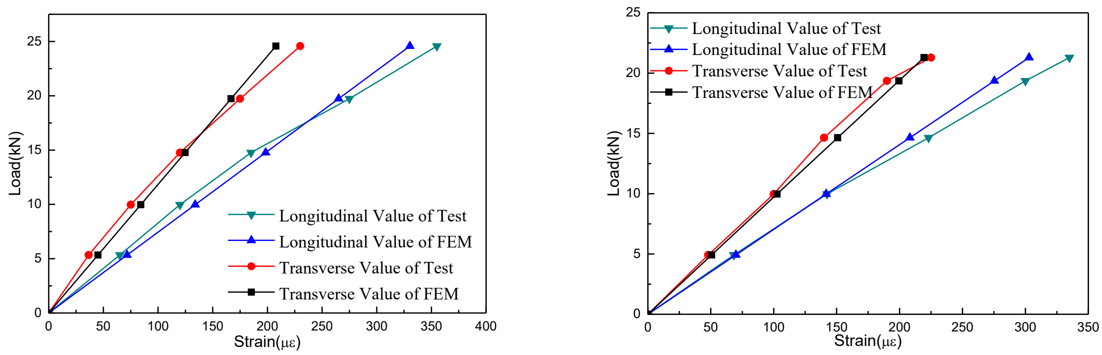


Figure 4: Load-deflection curve of top slabs



(a) top slab P2 at four-diaphragm side (b) top slab P2' at three-diaphragm side

Figure 5: Load-strain curve of measuring point 2

The load-deflection curves of measuring point 2 at various top slabs (P1~P4 and P1'~P3'), as shown in Fig. 4, illustrate that the LPUBG still remained in elastic stage under the wheel load of 20 kN, which was equivalent to 5.5 times of the design wheel load in Chinese code according to the stress equivalent principle. In addition, load versus strain curves of measuring point 2 at the bottom of top slab P2 and P2' is given in Fig. 5. As can be seen in Fig. 5, the test values were in agreement with FEM results. The calculating values of longitudinal and transverse strain in the top slab P2 at four-diaphragm side, were 265 $\mu\varepsilon$ and 167 $\mu\varepsilon$ (with the ratio of 1.59), respectively. As for top slab P2' at three-diaphragm side, the calculation values of longitudinal and transverse strain respectively were 275 $\mu\varepsilon$ and 199 $\mu\varepsilon$ (with the ratio of 1.38). Therefore, totally different from the performance of the PCBG deck slabs, the LPUBG bridge deck with dense diaphragms behaves as a bidirectional load transferring component with the main transferring direction as longitudinal direction, while the PCBG deck is always considered as a one-directional load transferring component and the wheel load are transfered along transverse direction owing to the significant larger span length along longitudinal direction. As a result, the elastic stage of the deck slabs is expanded.

4.1.3 Shear performance of joint at webs

With the precast segment cantilever method, a bracket joint (Fig. 6) between segments was developed for the LPUBG. The optimized dimensions of bracket joint was investigated by Zhang et al [9]. According to the optimization results, a double cantilever box girder model with bracket joint was designed and the shear performance of joint at web was tested (Fig. 3).

The load versus average diagonal tensile strain curve of web joint corner is presented as Fig. 7. It is noted that when the visible cracks (width: 0.03 mm) appeared at the joint corner of the four-diaphragm side, the test load was 1610 kN and the diagonal tensile strain was 576 $\mu\varepsilon$. Whereas at three-diaphragm side, the test load was 1212 kN and the diagonal tensile strain was 455 $\mu\varepsilon$ when the visible cracks occurred. Moreover, the load-strain curve of three-diaphragm side agreed with that of four-diaphragm side at the elastic stage. However, when the average diagonal tensile strain increased nonlinearly, the average diagonal tensile strain of the joint at the four-diaphragm side were much smaller than that of the corresponding position at the three-diaphragm side under the same load. The experimental results revealed that the shear capacity of web's joint was strong enough, and its shear performance, especially the post-cracking shear performance can be increased by dense diaphragms in LPUBG. Consequently, the proposed bracket joint is feasible in the construction of LPUBG bridge.

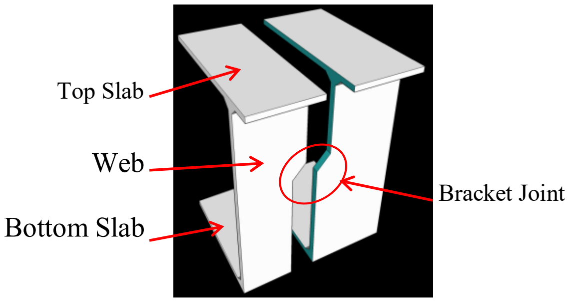


Figure 6: Schematic diagram of bracket joint

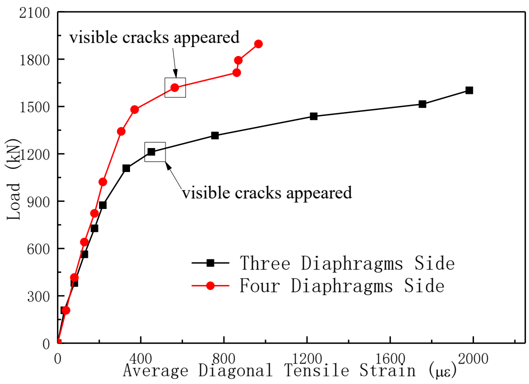
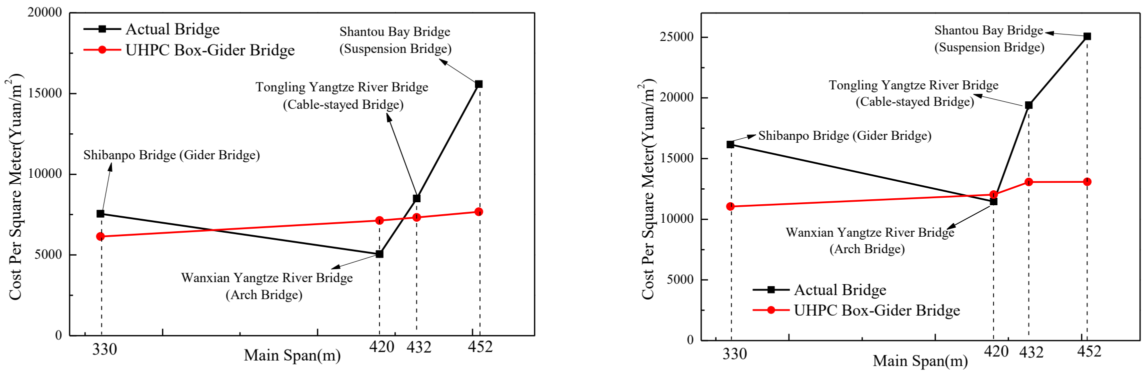


Figure 7: Load-strain curve of the web joint

4.2 Alternative competitive span length

The preliminary design of LPUBG bridges with main spans of 300~500 m for typical girder bridge, arch bridge, cable-stayed bridge and suspension bridge were conducted to study its reasonable span [10]. It is noted that the main span of the proposed LPUBG bridge are exactly same as that of the selected four different types of actual bridges. Fig. 8 shows the construction cost and the life-cycle cost for the actual bridge and corresponding LPUBG bridge, respectively. It can be seen that both the construction cost and the life-cycle cost of LPUBG bridge were lower than those of the girder bridge, the cable-stayed bridge and the suspension bridge but slightly higher than the arch bridge. Considering the 200 years' life of UHPC over 100 years' life of conventional normal concrete, the life-cycle cost of LPUBG bridge should be significantly lower than those four different types of bridges. Thus, the LPUBG bridge shows significant potential in economics and feasibility for the successful application to bridges with the main span of 300~500 m.

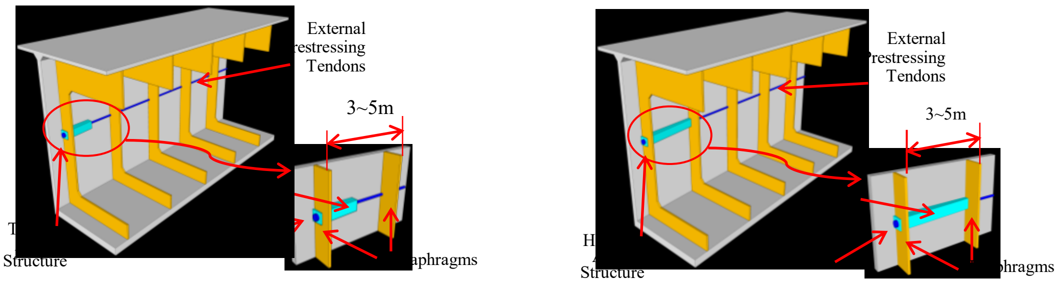


(a) construction cost (b) whole life-cycle cost

Figure 8: Cost comparison between actual bridges and LPUBG bridges

4.3 Anchorage of structure of external tendons

Based on the features of LPUBG and its prestressing system, the H-shape anchor structure for external tendons in LPUBG bridge was proposed [11].



(a) T-shape anchor structure (b) H-shape anchor structure

Figure 9: Schematic diagram of anchor structure in LPUBG

As shown in Fig. 9(b), the anchor block was placed between two diaphragms, forming a H-shape anchor structure to resist the great eccentric prestressing load. Compared with the T-shape anchor structure (Fig. 9(a)), the H-shape anchor system has a higher rigidity and bearing capacity. Under the prestressing load of 4570 kN (27 strands with diameter of 15.2 mm for each steel strand), the maximum principal tensile stress in the web's surface was 4.03 MPa for H-shape anchor structure but 11.30 MPa for the T-shape anchor structure.

5. CONCLUSIONS

To address the issues in the conventional PCBG, the research group at Hunan University proposed an innovative longitudinal prestressed UHPC box girder (LPUBG) bridge. This paper focuses on evaluating the feasibility and performance of the LPUBG based on trial design and experimental tests. The following conclusions can be drawn:

(1) Compared with the conventional PCBG, the LPUBG is characterized with thinner components, densely distributed diaphragms, and unidirectional (longitudinal) prestressing system. Moreover, the self-weight of the superstructure of the LPUBG bridge is only about 40~60% of that in the PCBG bridge, resulting in a better spanning ability of the LPUBG.

(2) Owing to dense diaphragms, the warping stress and deformation in the LPUBG can be effectively reduced and the elastic stage of deck slabs is expanded. Besides, the shear-resisting performance of the joint at the web is improved; especially, the post-cracking shear performance is significantly enhanced.

(3) The LPUBG has excellent performances under static loads and has satisfactory economic performance with the main span length of 300~500m, making it a competitive alternative for long-span bridges with the main span length of 300~500m.

(4) The H-shape anchor structure, which significantly reduces the principal tensile stress of the web, is a feasible anchoring scheme for the external tendons in LPUBG.

ACKNOWLEDGEMENTS

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