FULLY PRECAST LIGHT-WEIGHT STEEL-UHPC COMPOSITE STRUCTURE FOR ACCELERATED BRIDGE CONSTRUCTION

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Abstract

With the fast increasing of private cars, public traffic jams in metropolitans are bound to happen, especially somewhere in the field constructions. In order to shorten the in-situ construction working hours of municipal viaduct for accelerate bridge constructions, the paper proposed a fully precast light-weight steel-UHPC (ultra-high performance concrete) composite bridge in the form of simply-supported and continuous bridge structures.

Compared with the conventional design, the ratio of height to span length of this proposed newly bridge structure in trial design decreased about 33 %, and its self-weight reduced by 57 %. The structural ultimate limit state and serviceability limit state analysis of the proposed structure were conducted under the criterion of China and corresponding recommendations in France (The AFGC-SETRA UHPFRC recommendations). Furthermore, FEA (finite element analysis) model of the mechanical performance of the key part of such newly structure were also carried out. The studies indicate that the flexural and shear behaviours of the proposed bridge structure can better meet the requirements of engineering application

Résumé

Avec la croissance rapide du nombre de voitures privées, des bouchons dans les métropoles sont susceptibles de se produire, particulièrement dans les zones de travaux. Afin de diminuer la durée du travail sur chantier pour les viaducs municipaux, et accélérer la construction des ponts, l'article propose un pont mixte léger complétement préfabriqué acier – béton à ultra-hautes performances pouvant former un tablier isostatique ou un ouvrage continu. En comparaison avec la conception conventionnelle, le rapport hauteur / portée de ce nouveau pont au stade de l'étude d'avant-projet est réduit d'environ 33 % et son poids propre est réduit de 57 %. Les calculs à l'état limite ultime et à l'état limite de service ont été menés selon les spécifications Chinoises et les Recommandations Françaises (Recommandations AFGC-SETRA sur les BFUP). De plus, une analyse aux éléments finis de la performance mécanique des parties critiques d'une structure aussi innovante a également été réalisée. Les études indiquent que le comportement en flexion et à l'effort tranchant de la structure du pont proposé peuvent mieux répondre aux spécifications des applications en ingénierie.

1. INTRODUCTION

Ultra-high performance concrete (UHPC) is a new class of concrete that has been developed in recent decades. Compared to the traditional concrete, UHPC tends to exhibit superior properties such as advanced strength, durability, and long-term stability.

UHPC is being increasingly used worldwide in various components of civil infrastructure system. Many researchers around the world have developed concretes that could be classified as UHPC. Although there are differences among types of UHPC, there are also many overall similarities. In particular, many studies have investigated its application to bridge components such as girders, decks, and connection joints owing to its higher strength, stiffness, and durability. Many studies have investigated the use of UHPC as a deck slab component. Saleem et al. [1, 2] developed a low-profile UHPC deck system as an alternative to an open-grid steel deck. Coreslab Structures Inc. developed a waffle-shaped UHPC panel that was installed in a bridge in Little Cedar Creek, Wapello County, Iowa, US [3], and Aaleti and Sritharan [4–6] investigated the structural behavior and proposed a design guide for this panel system, including connections. A UHPC bridge deck can feasibly have a thinner cross-section than a conventional concrete deck, as shown in previous studies [4–11].

Since 1960, composite structures have been widely used owing to their structural efficiency. The typically steps of construction is showing as: 1) Precasting the part of concrete deck in factory; 2) Place the part of concrete deck on the steel beam or concrete beam; 3) Casting concrete shear pockets in field construction; 4) Pouring traditional concrete layer or asphalt layer. Due to a significant increase in traffic volumes and congestion in cities, traffic disruption during maintenance and construction activities frequently results in disruptions to local economies and communities; and raises issues of safety and traffic congestions. The use of traditional technologies and techniques for bridge construction are not effective enough to mitigate these disruptive effects during the construction working hours.

A new type of innovative steel-UHPC (ultra-high performance concrete) composite bridge with waffle-deck was developed. In the first section of this paper, lightweight steel-UHPC composite bridge is described in detail, and an analytical study using the finite-element analysis (FEA) software MIDAS Civil is conducted to evaluate the structural performance of the bridge. The flexural and shear-resistance design is shown in the second part. To obtain the actual negative moment capacity of the critical part, a three-dimensional finite element (FE) model based on ABAQUS is developed to simulate the negative moment region. The cost comparison is shown in the last section.

2. BRIDGE DESCRIPTIONS

As shown in Figure 1, the bridge member in the form of π-shape beam consists of two parallel I-shape section steel girders and the top UHPC deck with transverse ribs and longitudinal ribs (waffle deck). Two π-shape beams can be grouped into a simple-supported steel-UHPC beam bridge with a width of 6.5m to 8.5m. The 3D model and cross section of middle span are shown in figure 1 and figure 2, respectively. The light-weight bridge deck and I-shape section steel girders are factory assembly, which promotes worker safety and becomes an ideal candidate for accelerated bridge construction.

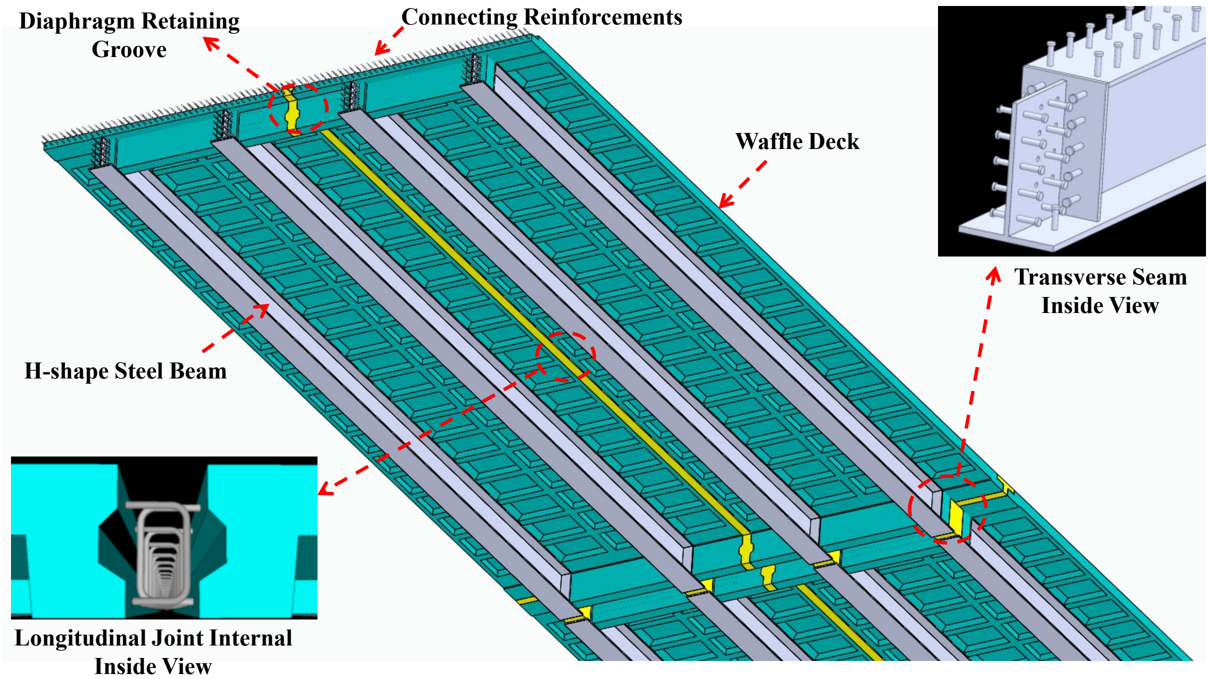

Figure 1: 3D drawing of the lightweight steel-UHPC composite bridge

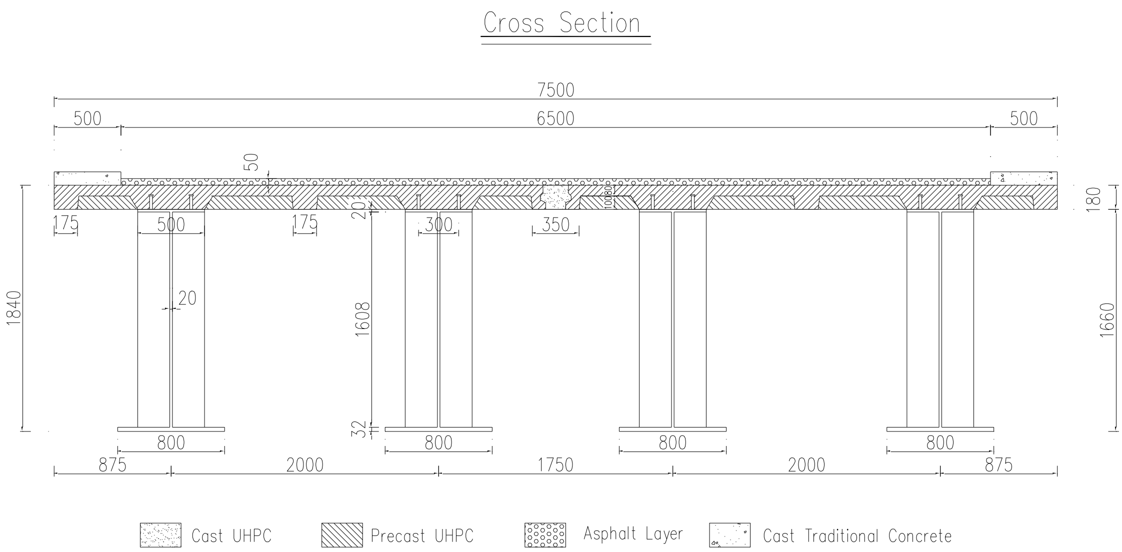

Figure 2: Cross section in mid-span (Unit: mm)

3. ANALYTICAL STUDY ON THE WHOLE STRUCTURE

3.1 Material Properties

According to reference [12], a summary of the mean values of material mechanical parameters for UHPC is presented in Table 1.

Table 1: UHPC Material Properties

Elasticity Modulus (E_c/GPa)	Prism compressive strength (f_c/MPa)	Axial Tensile Strength (f_t/MPa)	Density (ρ/kg/m^3)	Poisson ratio μ
42.8	158.4	7.38	2518	0.19

The UHPC dry mix material composes of a premix powder (cement, silica fume, ground quartz, and sand); water; super plasticizer; and 2.5% metallic fibers by volume. The fibers were mixed with liner fibers (L=8mm, D=0.12mm, v=1.0%) and hooked end fibers (L=13mm, D=0.2mm, 1.5%).

The HRB400 ribbed steel bar is employed for UHPC deck as the distribution reinforcement, its tensile and compression design value are both 330MPa, the Young's modulus is Es=200Gpa. The I-shape section steel girder is composed of Q345 steel, which has the compressive, tensile and bending strength of 270MPa, and shear strength of 155MPa, respectively.

3.2 Load Considerations

A trial design was conducted on the lightweight steel-UHPC bridge with a span of 50m. The bridge width is 7.5m, and the longitudinal slope is not taken into account herein.

The analytical study is performed to evaluate the performance of the precast UHPC waffle deck system of the bridge. According to the standard code of JTG D60-2015[13] and Midas civil software, a FEM model of the bridge considering dead-load and live-load (Highway-I traffic loading) is established to investigate the mechanical performance of the bridge under ultimate limit state and service limit state conditions. The material properties of the UHPC are given in Table 1. Table 2 shows the load combinations of the beam under dead-load and live-load conditions.

Table 2: Load Combinations

Load action and combination		Support shear force(V_d /kN)	Positive moment(kN.m)	Negative moment(kN.m)
SLS	Quasi-permanent combinations	2173	10538	-3615
	Frequent combinations	3720	10946	-6126
ULS	Fundamental combination	7509	16261	-11149

Note: $S_{fre}=S_G+0.7S_Q+0.8S_T$; $S_{qua}=S_G+0.4S_Q$; $S_{fun}=1.1（1.2S_G+1.4S_Q+1.4\times0.75S_T）$；

4. UHPC FLEXURAL DESIGN CONSIDERATIONS

4.1 Positive moment region considerations

Using the load factor design (LFD) methodology, several design parameters were explored to determine their effects on UHPC bridge girders. Calculation results were shown in table 2. The prism compressive-strength values f_c'=158.4MPa for UHPC material was used, and the design compressive strengths were taken to be 0.6fc'. These magnitudes represent the proposed UHPC design compressive strength. In the positive moment area, the strength is determined by the steel girder (bending resistance is M_{+}=16540 kN.m>M_{fun}=16261 kN.m, so the reinforcement design is not considered at this stage.

4.2 Negative moment region considerations

The calculation cross section of the negative moment region is assumed to be a T-shape model as shown in figure 3. According to the standard code of GB 50010-2010 for design of concrete structures [14], the calculation process for the negative region is shown as follow.

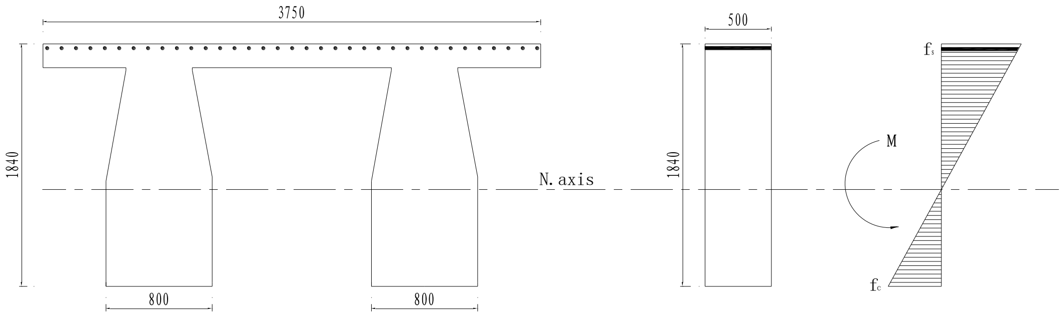

Figure 3: Calculated cross section in negative moment region (Unit: mm)

$$\alpha_1 f_c bx = f_y A_s - f_y A_s' \tag{1}$$

$$M \le \alpha_1 f_c bx(h_0 - \frac{x}{2}) + f_y' A_s'(h_0 - a_s') \tag{2}$$

where here M is the design moment value, α_1 is the coefficient with the value of 0.94, h is the height of cross section, h_0 is the effective height of the cross section, x is the height of compressive region.

According to Eqs. (1) and (2), we can easily attain the negative moment of bending resistance $M_{-} = 11383 kN \cdot m > M_d = 11149 kN \cdot m$ under the conditions of tensile reinforcement area $A_s = 17812.87 mm^2$.

The AFGC-SETRA UHPFRC Recommendation [15] is employed to obtain the calculated values of crack width of the negative region. The calculation process is expressed in Eqs. (3)~(4).

$$W_s = s_{r,\max,f}(\varepsilon_{sm,f} - \varepsilon_{cm,f}) \tag{3}$$

$$\left.\begin{aligned} & s_{r,\max,f} = 2.55\left(l_o + l_t\right) \\ & l_o = 1.33 \cdot c / \delta \\ & l_t = \left[0.3k_2\left(1 - f_{ctfm} / f_{ctm,el}\right) / (\delta\eta)\right]\left(\phi / \rho_{eff}\right) \ge l_f / 2 \\ & \delta = 1 + 0.5\left(f_{ctfm} / f_{ctm,el}\right) \end{aligned}\right\} \tag{3.1}$$

$$\varepsilon_{sm,f} - \varepsilon_{cm,f} = \sigma_s / E_s - f_{ctfm} / E_{cm} - \left[k_t(f_{ctm,el} - f_{ctfm})\left(1/\rho_{eff} + E_s / E_{cm}\right)\right] / E_s \tag{3.2}$$

where W_S is the crack opening at the level of reinforcement, $s_{r,max,f}$ is the maximum crack spacing; $\varepsilon_{sm,f}$ is the mean strain of the reinforcement combined with fibres; $\varepsilon_{cm,f}$ is the mean strain in the concrete among cracks.

The crack width W_t of the chord under highest tension is then calculated by:

$$W_t = W_s\left(h-x-x'\right)/\left(d-x-x'\right) \tag{4}$$

where h is the total height of the cross section; d is the efficient depth of the cross section; x is the compressed height; x' is the uncracked height under tension (stresses between 0 and $f_{ctm,el}$).

Note that the calculation of crack width of the UHPC structure needs to know the neutral axis depth and sectional curvature. With the change of the quantities of the reinforcement, the neutral axis depth and the sectional curvature change, therefore, the procedure to determine the crack width requires an iterative process. The iterative analyses indicate that when reinforcement area As=17812.87mm^2 the crack width Ws=0.011mm. In addition, as shown in the literature [16, 17], when the crack width of UHPC is less than 0.05mm, the crack is not visible and it has no influence on its durability. Therefore, the calculation of crack width is reasonable. The corresponding reinforcement ratio is 1.91 %.

5. SHEAR DESIGN CONSIDERATIONS

Although a wide range numbers of previous studies have clearly shown that UHPC have considerably higher punching shear strength than conventional concrete. However, in this trial design, the shear resistance of steel beam is only considered herein because of the very thin layer of bridge deck.

According to GB 50917-2013 Code for design of steel and concrete composite bridges [18], the shear resistance of lightweight steel-UHPC bridge can be calculated as following fomulas.

$$\gamma_0 V \le h_w t_w f_{vd} \tag{5}$$

where V is design value of shear strength; h_w is the height of web; t_w is the thickness of web; and f_{vd} is the design value of steel shear strength. Therefore, the shear resistance is $V = 9970kN > V_d = 7509kN$ which can meet the requirements of the standard code.

6. FINITE ELEMENT ANALYSIS

A three-dimensional finite element (FE) model was developed using the general purpose nonlinear finite element program ABAQUS/CAE 6.14. Solid elements were used to simulate the all parts of negative moment region. Uniform nodal loads were applied on the top surface of bridge deck to simulate the asphalt layer and crash barrier. The boundary conditions were taken from calculations of MIDAS CIVIL. The model image is shown in figure 4. The model considering steel reinforcement, steel girder and UHPC deck, coupling the nodes of cross section and the reference point which located in the centroid. The node displacement is obtained by Midas Civil and applied to the reference point. The results were shown in the following figures.

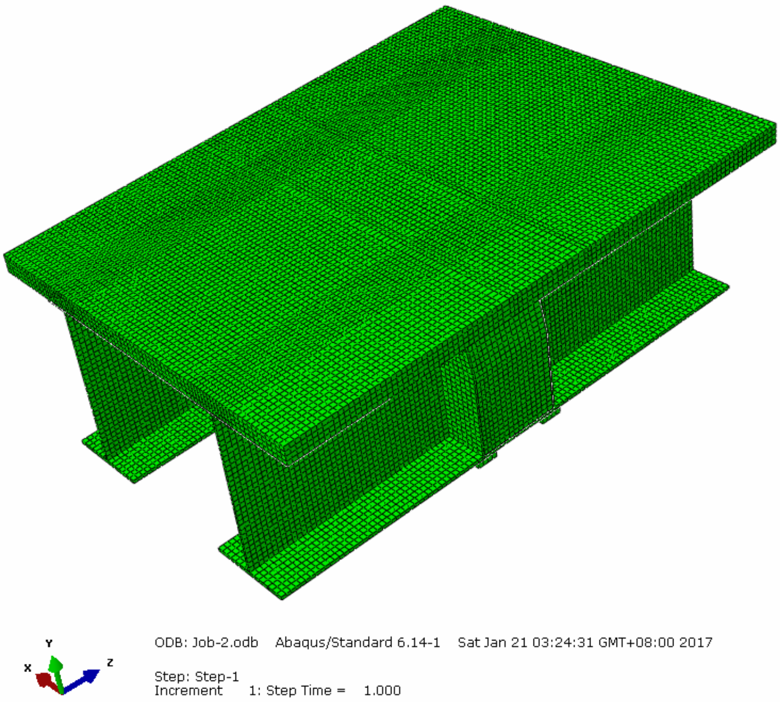

Figure 4: ABAQUS model

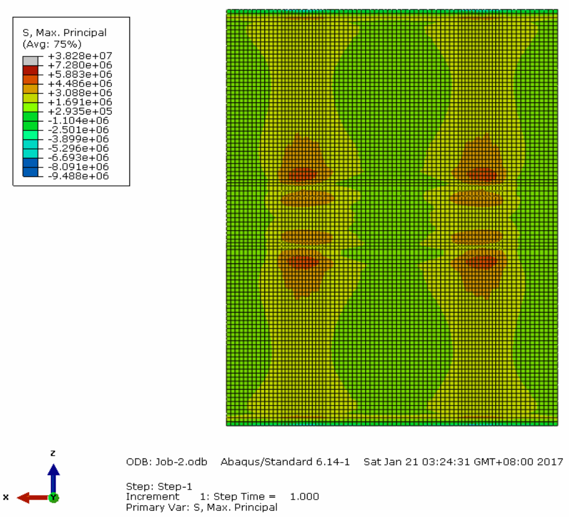

Figure 5: Strength distribution in bridge deck

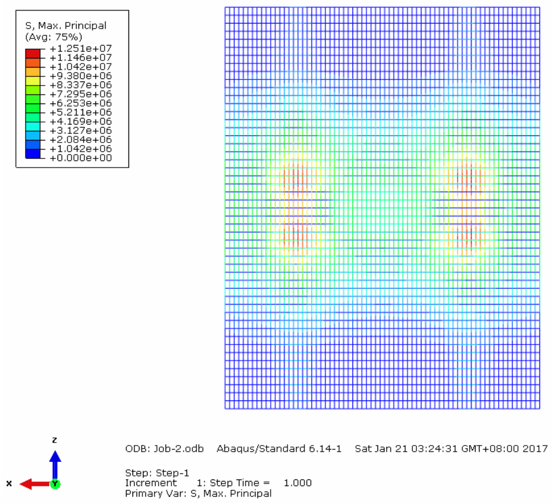

Figure 6: Strength distribution in steel reinforcements

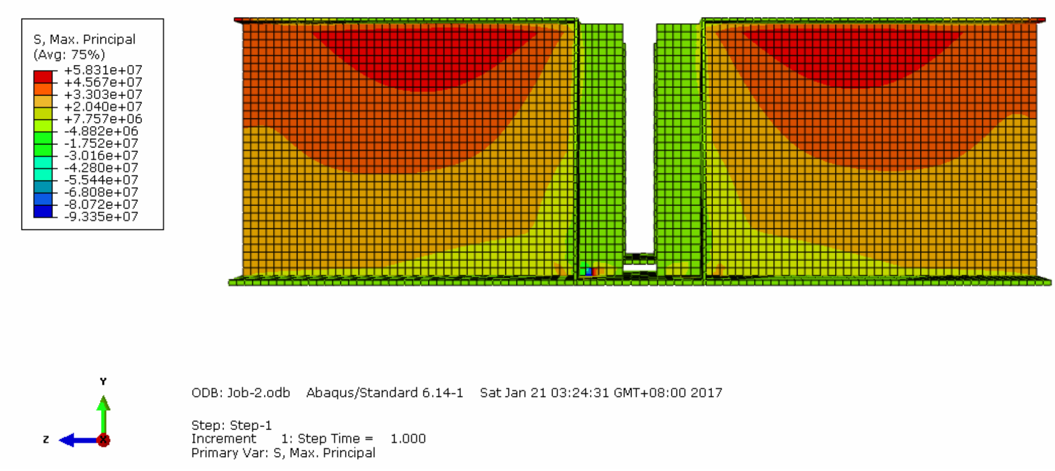

Figure 7: Strength distribution in steel girders

From the calculate results, it can be shown that the stress $S_{max,principal}$ of the UHPC bridge deck, steel reinforcements and steel girders are 7.28MPa, 12.51MPa and 58.31MPa, respectively. And all of them less than their design strength value, which meet the corresponding requirements in the design specifications.

7. COMPARISON OF MAIN MATERIALS

Cost companions in per square meter between the trial design and standard design of bridges proposed by ministry of communications of the people's republic of China is conducted in the following sections. The comparative design has the same span length with the trial design, span width is 12m and constructed by traditional concrete (C50) with T-shape cross section. (See Fig. 8)

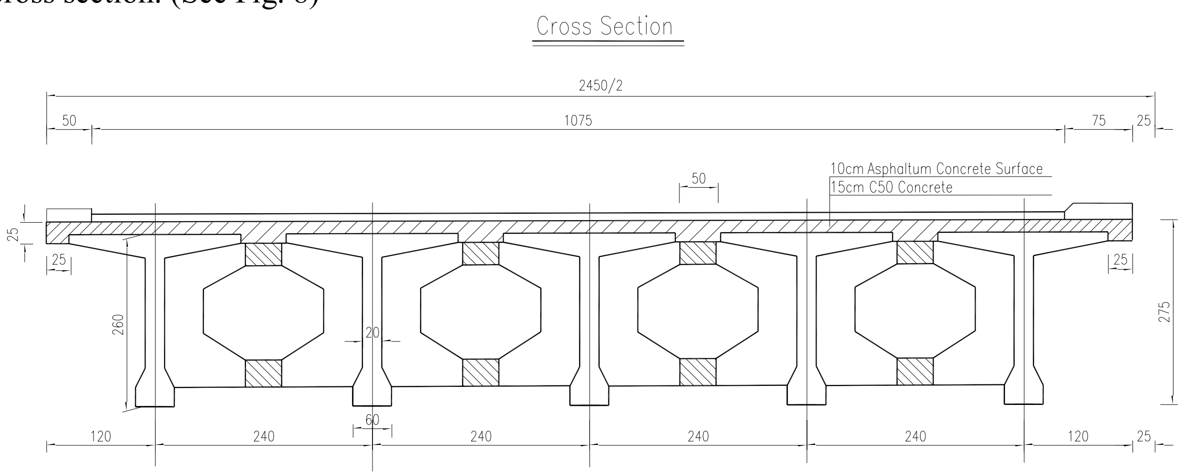

Figure 8: Cross section of a comparative design

The cost comparison results are given in Table 3. It is seen that the trial design shows great advantages in terms of weight with almost 57% less than the conventional design and the height is 33% less. It is worth noting that the price shows a great advantage with only 14% of the traditional one. The light-weight of top steel-UHPC beam can significantly reduce the cost of substructure. Meanwhile, owing to the lightness and outstanding load carrying capacity of the steel-UHPC beams, the total construction depth of the multi-storey overpasses can be obviously decreased. And more importantly, the precast structure can be prefabricated as a whole in the factory, which made transportation and construction process convenient. Consequently, the innovative light-weight steel-UHPC bridge is of great significance to accelerate construction of municipal Viaduct.

Table 3: Mean cost comparison of the two top deck systems

Item	Trial design(UHPC)		Standard design(C50)	
	Single Span-50m	Per m^2	Single Span-50m	Per m^2
Asphaltum Concrete Surface（m^3）	18.75	0.05	60	0.1
C50（m^3）	-	-	2868.86	4.78
UHPC（m^3）	76.42126	0.20	-	-
Steel Girders（kg）	24258.94	64.69	-	-
Stranded Wire（kg）	-	-	60036.90	100.06
Weight（t, t/m^2）	24517.92	65.38	67639.94	112.73
Cost（¥, ¥/m^2）	803297.12	2142.13	9331822.80	15553.04

Note:

ⅰ. Density: Asphaltum concrete is 2.4 t/m^3, normal concrete (with reinforcements) is 2.6 t/m^3, UHPC (with reinforcements) is 2.8 t/m^3.

ⅱ. Price (cover labour and material costs): asphaltum concrete surface is ¥80/m^3, C50 is ¥3000/m^3, UHPC is ¥7000/m^3, steel beam is ¥11000/t, stranded wire is ¥12000/t.

8. CONCLUSIONS

A new type of innovative lightweight steel-UHPC composite structure with advantages of light weight, excellent durability, convenient transportation and construction was developed.

The trial design and analytical study on a 3×50m continuous steel-UHPC beam bridge indicated that its mechanical performances, especially the negative bending regions of the UHPC waffle deck panel, meet the requirements of the standard codes in ultimate limit state (ULS) and service limit state (SLS).

Compared with the conventional structure, the dead weight of the proposed structure decreases by 57%, which indicates obvious economic benefits.

This paper also proposes a simple and practical design method for the lightweight steel-UHPC composite bridge which may do provide critical design procedure to bridge design engineers.

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