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TECHNICAL NOTE

Application of lightweight steel-UHPC composite beam in bridge emergency repair

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Abstract

This paper mainly introduces the emergency repair process for small- and medium-span bridges. The causes of deterioration were analysed by investigating old bridges. After comparison and selection of schemes, the scheme of beam replacement was confirmed using a lightweight steel ultra-high performance concrete (UHPC) composite beam as the superstructure. The main components of the calculations and the design are introduced in detail. Finally, through the load test of the bridge, it was shown that the lightweight steel-UHPC composite beam had good performance and met the requirements of Highway Level I bearing capacity. The lightweight steel-UHPC composite beam described in this paper has the characteristics of high strength, light weight, fast construction, excellent working performance, and remarkable social and economic benefits. It can be popularised and applied in the emergency repair of small- and medium-span bridges and new bridges.

Keywords: Emergency repair, Lightweight steel-UHPC composite beam, Analysis of deterioration, Differential settlement, Fast construction

1 Foreword

The rapid development of China's economy has led to growth in the traffic industry. Several types of bridges have been developed. Among them, a large number of prestressed concrete (PC) bridges have been built in China owing to many advantages and bring huge economic benefits (Editorial Department of China Journal of Highway and Transport 2014). Prefabricated small- and medium-span PC bridges, including hollow slabs, T-shaped beams, and small-box girders, are widely used in engineering construction. However, with the passage of time, these bridges exhibit a large number deterioration, such as cracking damage at the beam bottom owing to various factors that affect the safety and durability of the structures (Wang et al. 2012). Steel bridges have the advantages of light weight, high strength, and good ductility (Zou and Liu 2020), and the disadvantages of easily damaged deck pavement and orthogonal panels that are prone to fatigue cracking (Li and Qian 2006; Zang et al. 2017). Steel–concrete composite beams provide the advantages of both the materials. The weight is lighter compared with traditional PC beam, the crossing ability is good, and the cost is lower than that of steel bridge (Nie et al. 2012). It has been used on bridges with a span of 40–60 m among urban viaducts.

Currently, ultra-high performance concrete (UHPC) has been applied in many projects (Shao et al. 2017; Shao et al. 2021) owing to its ultrahigh mechanical properties and durability (Richard and Cheyrezy 1995; Yoo and Banthia 2016). Heimann designed a waffle-shaped UHPC bridge panel for a two-lane bridge in Wapello County, Iowa, USA (Heimann 2013). Deng proposed a lightweight steel-UHPC bridge that could be prefabricated and quickly erected, which was used for small- and medium-span urban bridges. The bridge panels are also waffle-shaped (Deng et al. 2017). Shao applied UHPC to steel bridge deck paving (Shao et al. 2012) and proposed a lightweight steel-UHPC composite bridge deck (Shao et al. 2018), which solved the fatigue problem of steel bridge decks that had puzzled the engineering field for many years. Li et al. conducted an experimental study on the negative bending resistance of flat steel-UHPC composite bridge panels using Perfobond Leiste (PBL) shear keys (Li et al. 2024). Liu et al. conducted an experimental study on the positive bending resistance of flat steel-UHPC composite bridge panels using PBL shear keys (Liu et al. 2023). The above studies show that flat steel-UHPC composite bridge panels have sufficient flexural strength and ductility. With reference to the design idea of a lightweight steel-UHPC composite bridge deck, a lightweight steel-UHPC composite beam suitable for small and medium spans is proposed and applied to the emergency repair project of a certain bridge. With the technological progress of UHPC materials and the reduction in its price, it is expected to replace traditional PC beams of small- and medium-span bridges in emergency repairs and new construction projects in the future.

2 Project profile

There is a 3×25 m simply supported beam bridge (with a continuous deck pavement) with an east–west layout. Its beams are oblique crossings with a right deflection angle of 55–60°. Its plane line is located on a circular curve with a radius R = 2000 m. The total width of the eastern panel of the bridge beam is 13 m (hereafter referred to as the old bridge).

The standard cross-section of the old bridge is shown in Fig. 1. The upper structure adopts 25 m prestressed (post-tensioned) hollow concrete slabs with the height of 1.0 m. Twelve hollow slabs are arranged horizontally. The substructure consists of a composite abutment, pier, and pile foundation. The bridge deck pavement is 80 mm thick reinforced concrete pavement + 90 mm thick asphalt concrete pavement. The load level of the old bridge is Highway Level I (Specification 2004) (JTG 2004).

The old bridge was opened to traffic in 2011. In July 2022, structural deterioration, such as diagonal cracks at the bottom of the beams, was observed during daily inspection of the old bridge, as shown in Figs. 2 and 3. As the deterioration was serious and could threaten the safety of the structure, experts decided to perform emergency repair of the bridge after relevant testing.

3 Analysis of deterioration

According to the comprehensive analysis of bridge deck alignment (Figs. 4 and 5), bent cap alignment (Fig. 6), and bent cap crack morphology (Fig. 7), the differential settlement of pier #23 was the main cause of bridge deterioration. According to a geological investigation, drift stones were present in the geological exploration holes between piles #1 and #2 on pier #23, and the top elevation of the drift stones was close to the bottom elevation of the pile. It was speculated that the tip of the pile may

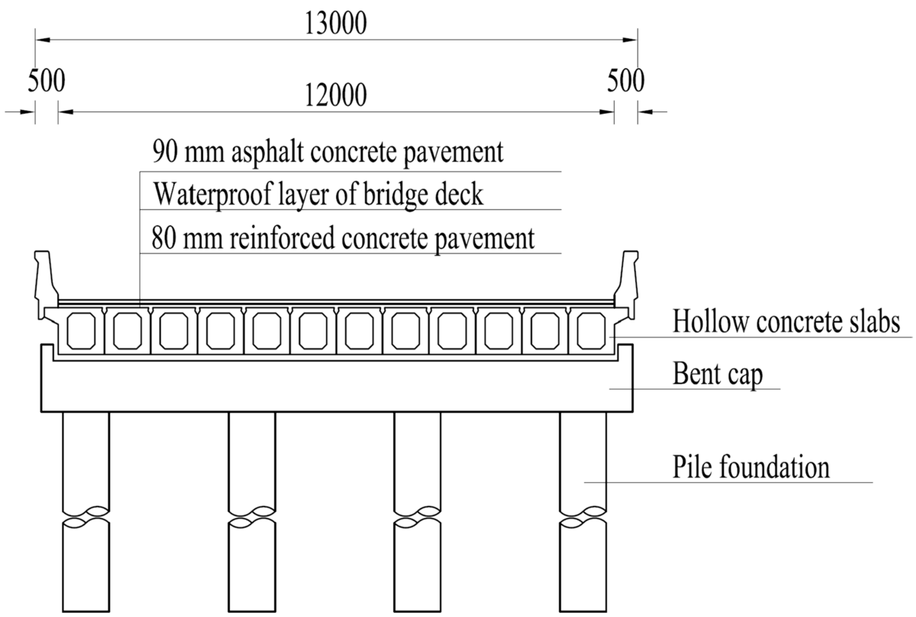

Fig. 1 Standard cross-section of the old bridge (mm)

Fig. 2 Diagonal cracks at the bottom of slabs

fall on top of the drift stone with a steeper slope, and slip and skew under long-term overloading. The settlement of piles #1 and #2 of pier #23 was 0.39 m and 0.22 m, respectively, accompanied by the tilt of the pile (the tilt of pile #1 and #2 were 4.5% and 2.8%, respectively). The uneven settlement caused cracking at the top of the bent cap of pier #23, and the upper hollow slabs on both sides of pier #23 were subjected to bending and twisting. Regular oblique cracks appeared at the bottom of the slabs (Fig. 8). The deck on the west side of the old bridge is depressed (Fig. 9). The facade appeared broken (Fig. 10).

Special emergency and load tests showed that the vertical static stiffness and dynamic stiffness of the old bridge were lower than the theoretical values, and the transverse connection performance was poor, which could not meet the requirements

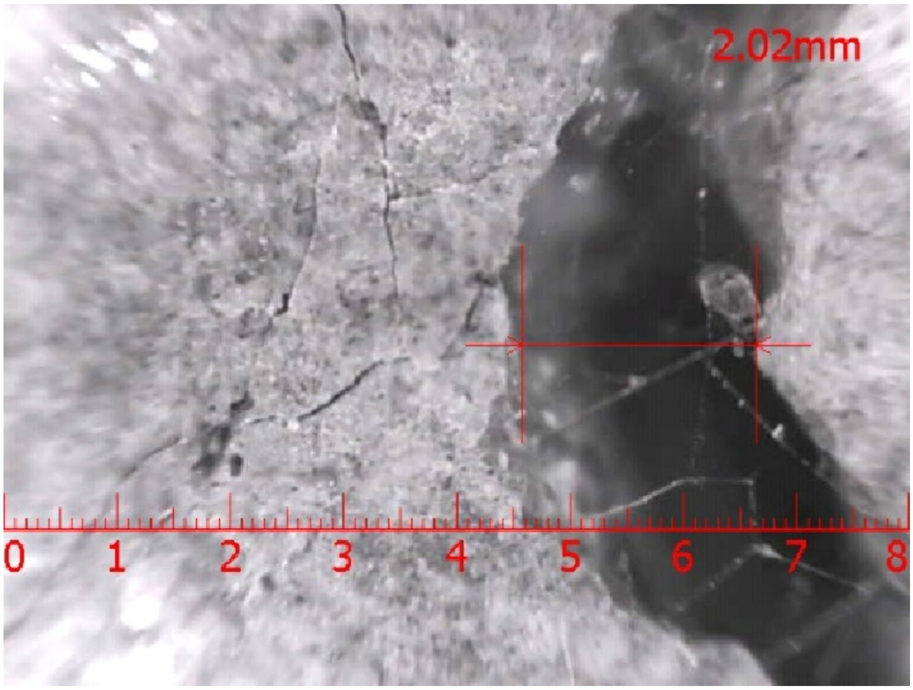

Fig. 3 Maximum width of the crack

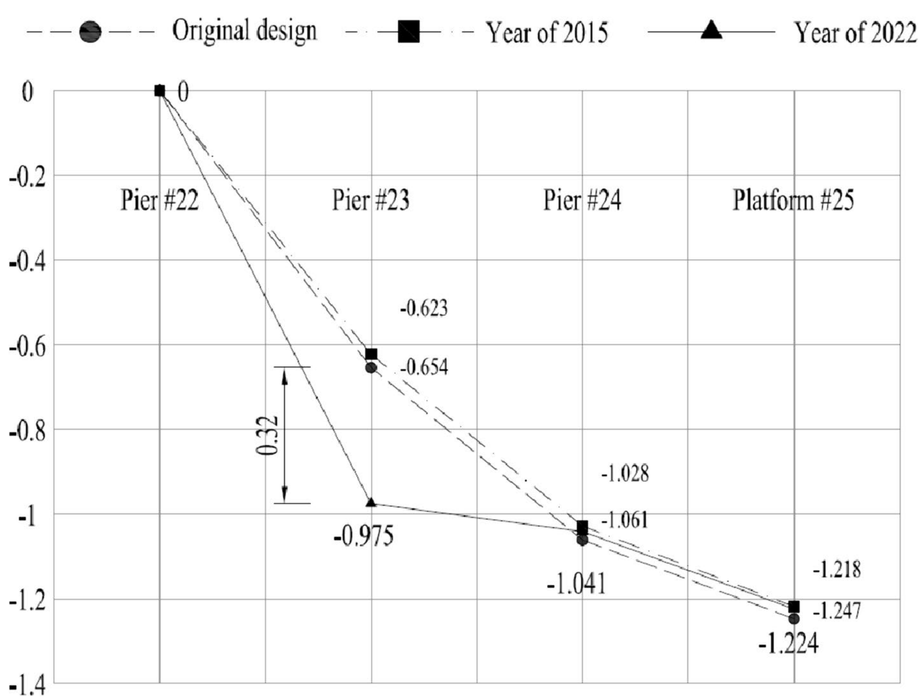

Fig. 4 Relative elevation of bridge deck on the west side

of the original design load capacity (Highway Level I). The overall sound condition assessment grade of the bridge was Grade D, and it needed to be closed to traffic for emergency repairs.

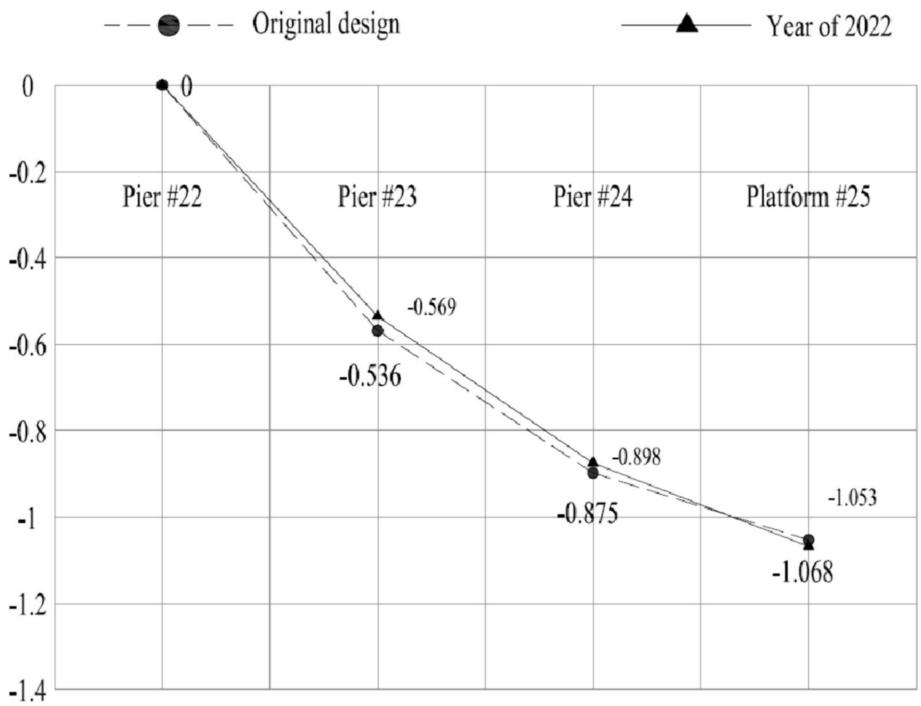

Fig. 5 Relative elevation of bridge deck on the east side

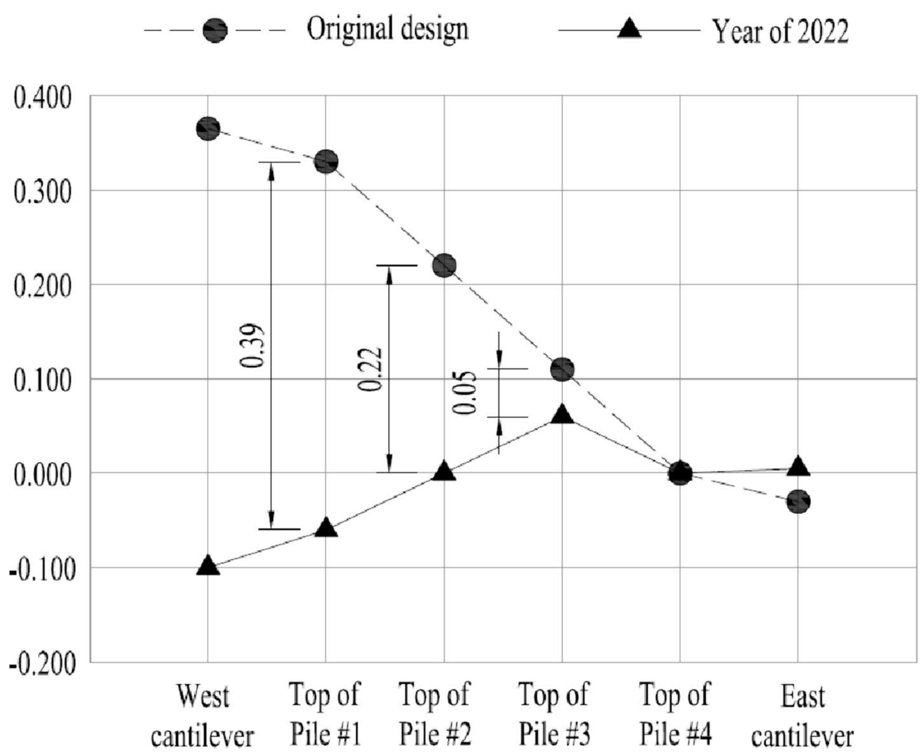

Fig. 6 Relative elevation of bent cap of pier #23

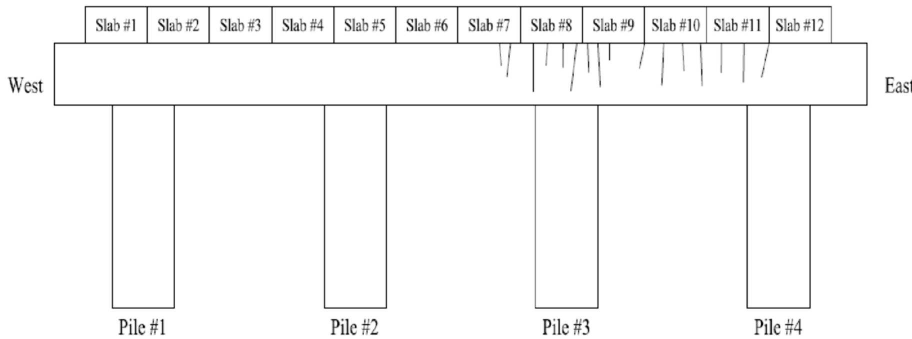

Fig. 7 Cracks of bent cap of pier #23

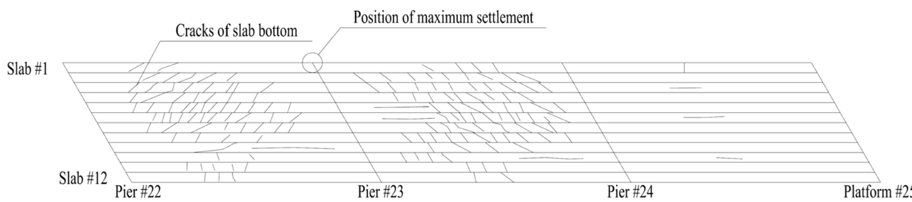

Fig. 8 Cracks of slab bottom

Fig. 9 The bridge deck on the west side of pier #23 had obvious depression

4 Bridge maintenance design

4.1 Design principles

(1) Based on the characteristics of this project as an emergency repair project, to reduce on-site construction operations, facilitate rapid construction, and reduce construction risks, the main structure of the bridge was designed in accordance with the principles of factory, prefabrication, and standardization.

Fig. 10 The facade of pier #23 had a downward folding phenomenon

(2) The bridge was designed based on the principles of "safety, durability, applicability, environmental protection, economy, and beauty".
(3) The adaptability of new and old bridge structures should be fully considered, and the new and old bridge structures to be used should be coordinated with each other.

4.2 Technical norms

(1) Design load: Highway Level I.
(2) Design reference period and service life: 100 years.
(3) Design safety level: Level 1.

4.3 Emergency repair content

This emergency repair mainly involves superstructures and substructures. The maintenance plan for the substructure was to remove the old pier and build a new one, as shown in Fig. 11. However, there is no detailed description. The maintenance plan for the superstructure was to replace all the old hollow slabs.

4.4 Selection of superstructure scheme

The span layout of the new bridge was the same as that of the old bridge, which is 3×25 m. The schematic of the selection process is presented in Table 1.

According to the different materials used in the bridge panels of steel–concrete composite beams, two schemes of C50 ordinary steel–concrete composite beams (Fig. 12) and lightweight steel-UHPC composite beams (Fig. 13) were used for

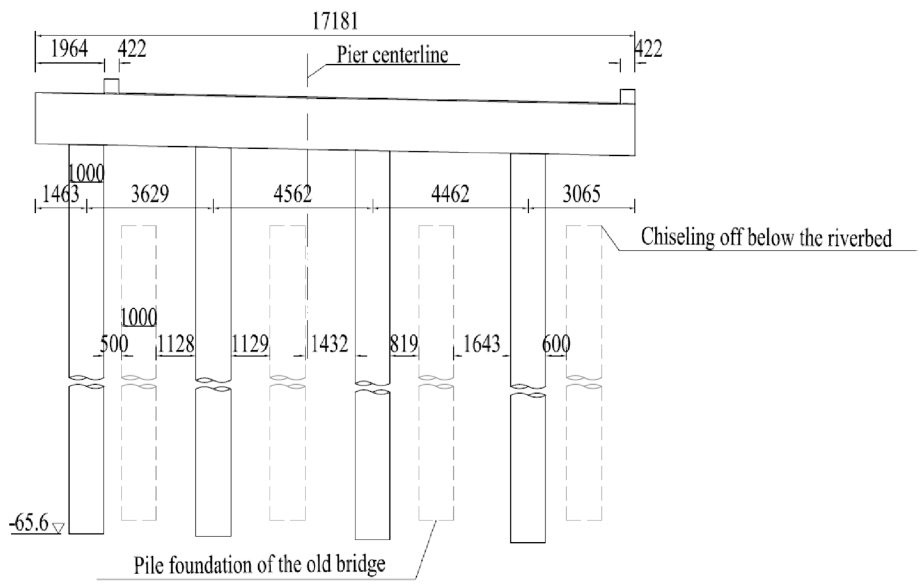

Fig. 11 The maintenance plan of the substructure (mm)

Table 1 Selection of superstructure scheme

Superstructure Form	Advantages and disadvantages	Whether to recommend or not
Prestressed concrete hollow slab	The hinge joint is adopted. It is poor in transverse connection. There are much structural deterioration after several years of operation, which affects the durability of the hollow slab (Lei et al. 2017; Xiang et al. 2013; Gao et al. 2021)	Not recommended
Small prestressed concrete box girder or T-shaped beam	Its dead weight is large and the beam height is high. It is necessary to raise the slope of the bridge and the box girder of the bridge on both sides. The reconstruction is large	Not recommended
Steel box beam	The problem of deck pavement of steel bridge is difficult to completely solve (Li and Qian 2006; Zang et al. 2017)	Not recommended
Steel–concrete composite beam	The beam height is lower than the concrete structure Under the same span, it has the advantages of light structure, large span, and fast construction	Recommended

comparison and selection. The main difference between the two schemes was the bridge panel thickness. The thicknesses of the C50 and UHPC bridge panels were 220 and 120 mm, respectively. Under the condition that the total beam height was unchanged, the steel beam height of the C50 ordinary steel–concrete composite beam was smaller than that of the lightweight steel-UHPC composite beam. It bore a larger part of the dead weight of the bridge panel; therefore, the steel beam needed to adopt thicker top and bottom plates. Compared with the selection results in Table 2, the reduction in the dead load of the superstructure was conducive to reducing the scale and uneven settlement of the foundation. The cost difference between the two schemes was not significant. The comprehensive cost of the lightweight steel-UHPC composite beam was slightly lower. Its high strength and fast construction speed

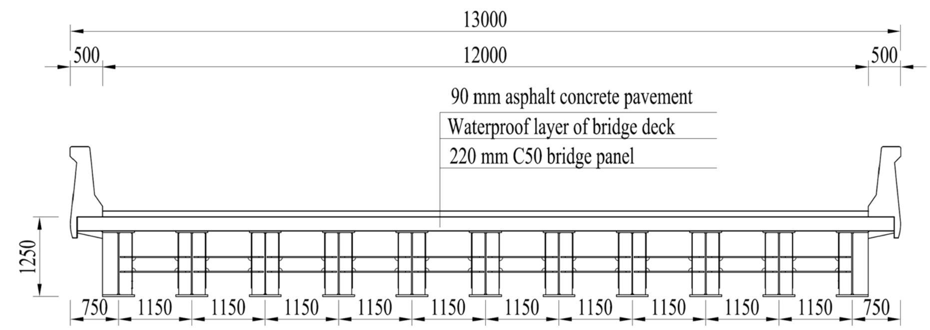

Fig. 12 Standard cross-sectional layout of C50 ordinary steel–concrete composite beam (mm)

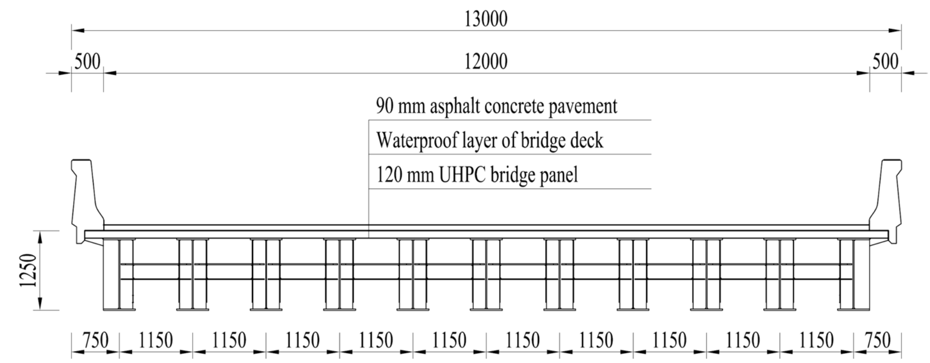

Fig. 13 Standard cross-sectional layout of the lightweight steel-UHPC composite beam (mm)

Table 2 Scheme selection of bridge panel material of composite beam

Scheme	Steel (t)	UHPC (m^3)	C50 concrete (m^3)	Ordinary steel bar (t)	Reduction of upper dead load	Initial construction cost (¥)	Total life cycle cost (¥)
Lightweight steel-UHPC composite beam	331.8	114.9	-	42.6	About 62%	9,079,000	13,483,000
C50 ordinary steel–concrete composite beam	364.5	-	210.9	53.7	About 40%	9,268,000	14,180,000

make it suitable for emergency repair of a project. Therefore, the scheme of the lightweight steel-UHPC composite beam was finally adopted.

4.5 Design of lightweight steel-UHPC composite beam

The lightweight steel-UHPC composite beam is composed of main beams made of Q355D welded I-section steel and a UHPC (strength level UC120, UT9) bridge panel. The main steel beam was monolithically manufactured in a factory, transported to the site for erection, and connected to a cast-in-place UHPC bridge panel.

The design is divided into longitudinal and transverse. For emergency repair works, the current situation imposes various restrictions on design, and the design and construction periods should be compressed as much as possible to resume traffic at the fastest speed.

Longitudinal design: First, considering that the right deflection angle of the bridge beam is 55–60°, if a continuous system is adopted, the negative bending moment of the beam at the pier top is more complicated than that of the orthogonal bridge. The original superstructure of the bridge is also a simply supported beam–bridge system. Therefore, the new superstructure of the bridge adopts a simple supported structure and continuous deck. According to the height of the old bridge and the flood-limiting water level, the composite beam was determined to adopt a height-variable beam with a fulcrum 1.03 m high and a mid-span 1.25 m high. The transition of the broken line was adopted as shown in Fig. 14. The main steel beam adopted was an all-welded steel plate beam with a fulcrum beam 910 mm high and a midspan beam 1130 mm high. The thicknesses of the upper and lower flange plates were 22 mm. The web thickness was 16 mm. The web stiffener measured 12 mm × 150 mm. The upper flange plate was connected to a UHPC bridge panel with M16 × 80 mm studs. The stud layout spacing was 120 mm transversely across the bridge and 200 mm longitudinally across the bridge.

Transverse design: The main steel beam is transversely connected by middle- and end-cross beams. The middle cross-beam is made of 250 mm × 240 mm × 16 mm × 16 mm welded I-section steel with a spacing of 5 m. The span lines were arranged parallel to the middle and end cross-beams. The width of the top flange plate of the end cross-beam was 700 mm, and that of the bottom flange plate was 300 mm. The height of the end cross-beam was 400 mm. The thicknesses of the top and bottom flange plates were 16 mm. Four millimetre steel panels were arranged between the top flange plates of the main steel beam, as shown in Fig. 15, which could be used as the bottom formwork during construction. After the bridge was formed, a composite section was formed with the UHPC bridge panel to improve its mechanical behaviour. The UHPC bridge panel was equipped with a double layer of 12 mm HRB400 steel bars with 100 mm transverse and longitudinal spacings.

5 Structural calculation

5.1 General calculation

Midas Civil was used to establish the space grillage model, and the bridge panel and main steel beams were connected using common nodes. There were 978 units in the model. The model considers the formation process of the composite section, that is, the construction stage was established according to the order of pouring UHPC

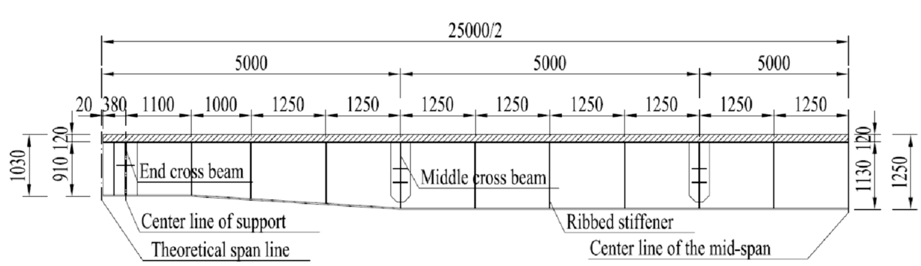

Fig. 14 Facade layout of the lightweight steel-UHPC composite beam (mm)

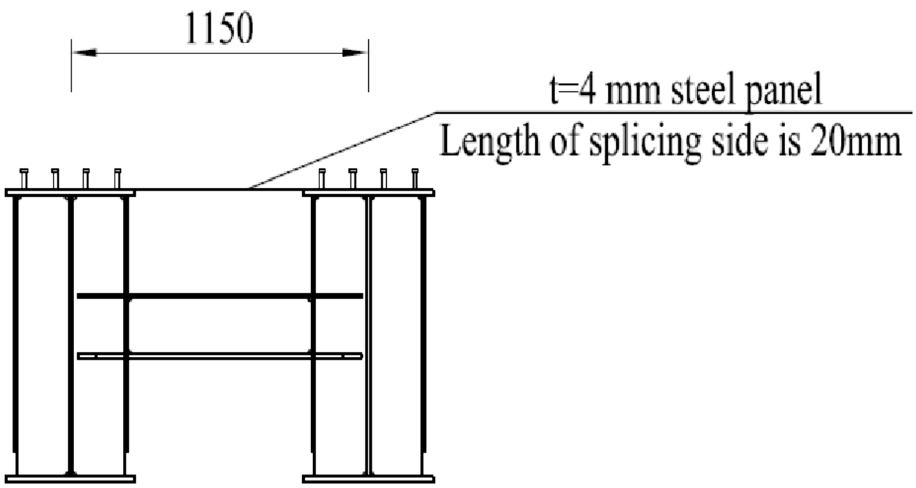

Fig. 15 Layout of steel panel between the main steel beams (mm)

Table 3 Load values

Load type		Loud value
Shrinkage strain $\varepsilon_{cs}(t)$		$0.00035 \times e^{\frac{-2.48}{\sqrt{t-0.86}}}$, ***t*** is the age of the concrete, measured in days
Creep coefficient $\phi(t)$		$0.8 \times \frac{(t-7)^{0.6}}{(t-7)^{0.6}+10}$, ***t*** is the age of the concrete, measured in days
Highway level I lane load		Concentrated load:$P_k = 310\text{kN}$ Uniform load: $q_k = 10.5\text{kN/m}$
Temperature gradient	Gradient heating	Top of bridge panel:14 ℃ Bottom of bridge panel:5.5 ℃ Steel beam:5.5 ℃
	Gradient cooling	Top of bridge panel:-7 ℃ Bottom of bridge panel:-2.75 ℃ Steel beam:-2.75 ℃

(its weight is borne by the steel beam) → forming the composite section → the second phase of construction (the second phase load is borne by the composite section). The load values and load combination complied with the General Specifications for Design of Highway Bridges and Culverts (JTG D60-2015), considering the dead weight, shrinkage and creep, Highway Level I lane load, overall rise and fall in the temperature, and temperature gradient. The shrinkage strain $\varepsilon_{cs}(t)$ and creep coefficient $\phi(t)$ were obtained from the material tests. The load values are listed in Table 3. The boundary condition is that the vertical elastic support is arranged at the end of each steel beam. The material parameters are listed in Table 4, and the overall model is shown in Fig. 16.

The main calculation results:

① Stress of the main steel beam

Table 4 Material parameter table

Material		UHPC	Q355D
Application of structure		Bridge panel	Main steel beam
Mechanical property	Elasticity modulus Ec (Mpa)	41,900	206,000
	Shear modulus Gc (Mpa)	17,458	79,000
	Poisson's ratio γ	0.2	0.31
	Coefficient of linear expansion (°C^{-1})	0.000011	0.000012
	Tensile strength (MPa)	9	\
	Compressive strength (MPa)	120	\
	Yield strength (MPa)	\	355
	Ultimate strength (MPa)	\	450

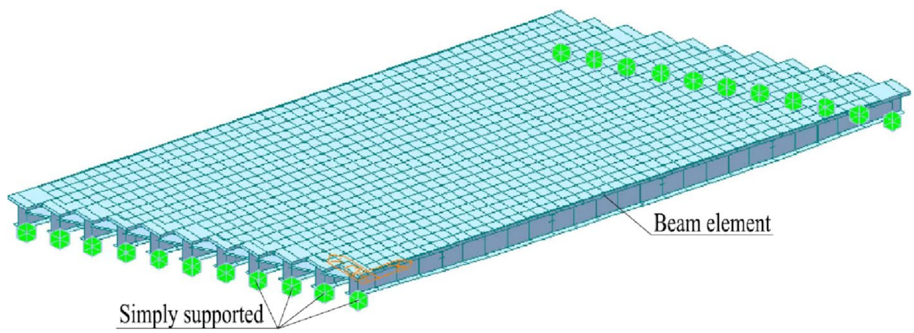

Fig. 16 General model

Table 5 Stress of the main steel beam (MPa)

Project	Steel beam	
	Upper edge	Lower edge
	Max./Min	Max./Min
Fundamental combination of actions	25.9/-156.2	194.5/-37.9
Limit	**270**	**270**
Whether it satisfies or not	**Satisfies**	**Satisfies**

The stress of the main steel beam is listed in Table 5, and satisfies the requirements of the Specifications for Design of Highway Steel Bridges (JTG D64-2015).

② Cracks of UHPC bridge panel

The longitudinal compressive stress of the UHPC bridge panel was much lower than the compressive strength; therefore, cracks were the main concern. Under frequent combinations of actions, the maximum tensile stress of the UHPC bridge panel was located at the beam end. The longitudinal tensile stress is given by

$$f_t = 6.0\text{MPa} < f_{tk}/K_{global} = 7.2\text{MPa}$$

The UHPC was not cracked, and the crack width did not need to be calculated.

③ Structural stiffness

Under the Highway Level I lane load, the maximum deflection of the structure was 14.9 mm in the side beam span, which met the specification requirements of less than L/500 = 50 mm.

5.2 Transverse calculation of bridge panel

According to the Specifications for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts (JTG 3362–2018), bridge panels with a length-to-width ratio exceeding 2 were calculated as one-way slabs. Conservatively, the fulcrum of the transverse bending moment of the UHPC bridge panel was $M = -0.7M_0$, and that of the mid-span was $M = 0.7M_0$. M_0 is the midspan bending moment of a simply supported beam with the same calculated span, and the positions of the midspan and fulcrum of the bridge panel are shown in Fig. 17.

The bending moment per metre of the bridge panel was obtained by calculating the uniform load of the wheel and the load distribution width of the bridge panel.

When calculating the moment capacity, the steel panel under the UHPC panel and the upper flange plate of the steel beam were considered; that is, the moment capacity was calculated based on the UHPC-steel composite section. In the midspan section shown in Fig. 18, the steel panel was considered to be equivalent to the tensile steel bar, referring to the moment capacity calculation method in the Technical Specification for Ultra-High Performance Concrete Girder Bridge (T/CCES27-2021). The tensile strength of the UHPC was considered to have a reduction factor of 0.5. In the fulcrum section shown in Fig. 19, the upper flange plate of the steel beam was considered equivalent to that of the compression steel bar. When calculating the height of the concrete compression zone,

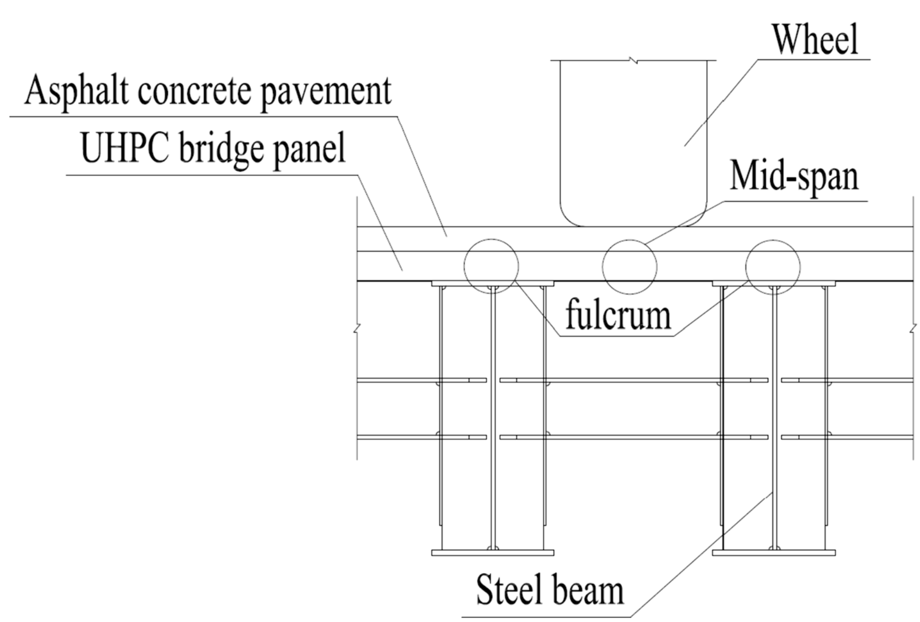

Fig. 17 The position of mid-span and fulcrum of the bridge panel

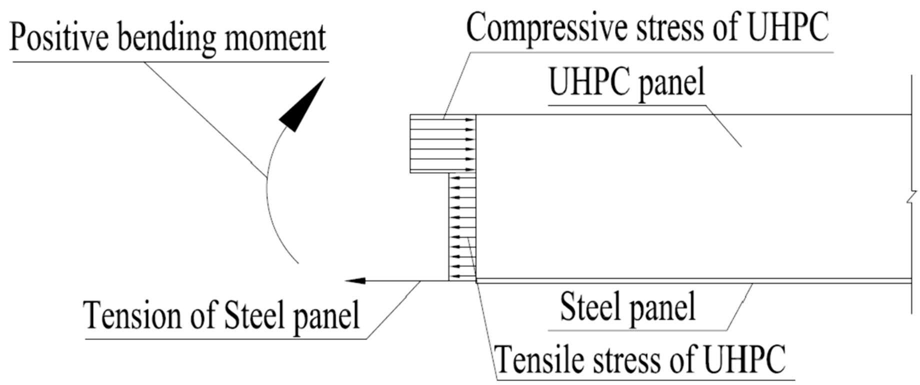

Fig. 18 Force diagram of the mid-span section

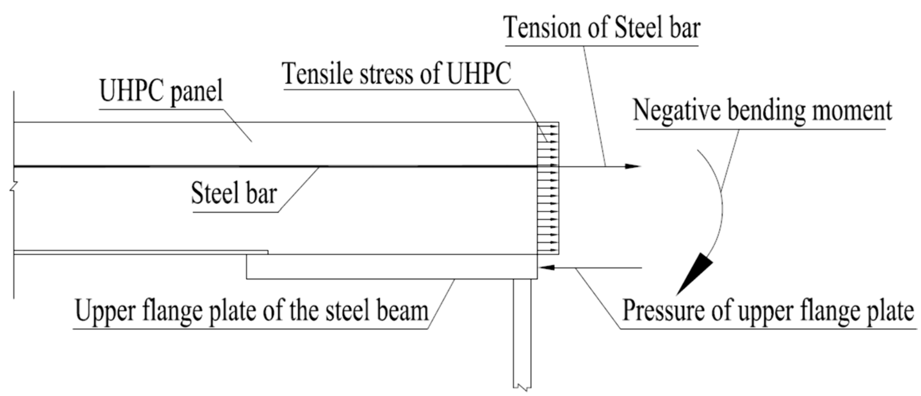

Fig. 19 Force diagram of the fulcrum section

it was found to be negative, indicating that the entire section of the UHPC was under tension at that time. According to the same principle, the tensile strength of the UHPC was considered as a reduction factor of 0.5. It is safe to consider the top edge of the steel beam as a neutral axis for calculating the moment capacity. The calculation results for the moment capacity of the UHPC-steel bridge panel per metre are listed in Table 6. The moment capacity satisfied these requirements.

The stresses of the upper and lower edges of the UHPC were calculated according to the UHPC-steel composite section for frequent combinations, as listed in Table 7.

The transverse stress of the UHPC bridge panel was less than $f_{tk}/K_{global} = 7.2\text{MPa}$ under frequent combinations of actions, indicating that the bridge panel was in an elastic working state, and there was no need to check for cracks.

Table 6 Calculation of moment capacity per meter of bridge panel (kN.m)

Project	Effect $\gamma_0 M_d$	Moment capacity M_u
Mid span	31.6	85.3
Fulcrum	31.6	42.9

Table 7 Transverse stress of bridge panel (MPa)

Position	Fulcrum		Mid span	
	Upper edge	Lower edge	Upper edge	Lower edge
Frequent combination of actions	1.9	-0.9	-3.4	2.5

6 Load test of completed bridge

6.1 Test content

After the completion of the emergency repair, a load test was performed on the bridge. The static load test included the midspan deflection of the main girder and the top and bottom edge strains of the steel beam under partial and medium loads. The load–efficiency ratio in the static load test was 0.87–0.93.

6.2 Test results

The test results were summarized as follows:

1. The strain verification coefficient of each test section of the bridge ranged from 0.54–0.93, less than 1.
2. The maximum residual deformation of the midspan deflection was 14.7%. The maximum residual strain at the main strain measuring point was 15.1%, which is less than 20%. The strain variation of the key measuring point during loading was a linear elasticity.

The load test data indicated that the test indices of the bridge satisfied the Load Test Methods of Highway Bridge (JTG/T J21-01–2015). The moment capacity of the bridge meets Highway level I requirements.

7 Summary

Because the large number of small- and medium-span beam bridges adopt multi-piece main beam structures in the transverse cross-section and have a small spacing between the main beams, the steel panel at the bottom of the UHPC bridge panel can be used as the bottom formwork in construction, which is convenient for construction. Simultaneously, a composite section was formed using a UHPC bridge panel. Bridge panels are still in an elastic state under frequent combinations of actions. Therefore, it is not necessary to solve the higher-order equation for the calculation of cracks in the Technical Specification for Ultra-High Performance Concrete Girder Bridge (T/CCES27-2021), which can shorten the design and construction period and meet the needs of emergency repair projects.

In this study, the lightweight steel-UHPC composite beam is suitable for small- and medium-span bridges with limited beam bottom clearance owing to its small beam height. Simultaneously, its high strength, light weight, and small substructure scale satisfy the requirements of heavy-load traffic and rapid construction. Thus, their social and economic benefits are significant. It can be widely used in the emergency repair of small- and medium-span bridges as well as new bridges.

Authors' contributions
Zhiyong Li: Project management and overall design. Lujia Hong: Structural calculation and writing of the original draft. Yao Peng: Detailed design.

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Availability of data and materials
Most of the data and models generated and used in the study appear in published articles. However, some information is proprietary or confidential in nature and may only be provided with restrictions.

Declarations

Competing interests
The authors have no competing financial interests or personal relationships that could have influenced the work reported in this study.

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