Investigations on Integrally Lifted Prefabricated High-Performance Concrete Cap Beams

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Abstract—This research proposes two new types of prefabricated high-performance concrete cap beam structures, which solve the problem that the traditional large cap beam needs to be split into two to three parts during assembly construction, and the construction efficiency is reduced. Using new materials such as ultra-high performance concrete (UHPC) and new technology such as high-performance composite structure, two new types of cap beams are studied. Taking prestressed concrete cap beams as the control group, the calculation model of each cap beam is established, and then the mechanical performance of each cap beam is tested and analyzed. At the same time, the self-weight, cross-sectional size, quantity of prestressed steel bars, and manufacturing material cost of each cap beam are also analyzed and compared, and the applicability of each cap beam is given. The research results show that compared with ordinary concrete, the use of UHPC can significantly improve the mechanical performance of the cap beam, reduce the cross-sectional size of the cap beam, and reduce the self-weight of the cap beam. Calculation results show that the steel-UHPC composite cap beam can achieve the smallest lifting weight. In summary, the two new prefabricated high-performance concrete cap beams proposed in this paper can significantly reduce the self-weight of the cap beam and improve the construction efficiency.

1. Introduction
At present, the girder bridge is one of the most widely used bridge types in highway bridges. As the force transmission structure between the main beam and the pier, the cap beam is crucial to ensure the safety of the bridge structure [1]. Generally, the cap beam has a large volume, and it needs to be split into two or three parts to be hoisted separately in assembly construction [2], which restricts the construction efficiency [3,4]. This study aims to put forward the high-performance concrete cap beams, which can significantly reduce the weight and can be lifted integrally to improve the construction efficiency.

Ultra-high performance concrete (abbreviated as UHPC) is a high-performance material obtained by combining cement with other materials. It has great advantages in strength, toughness, and durability [5]. It also has reliable mechanical properties under extreme load conditions such as impact load [6]. Wu [7] conducted a series of simulations on the UHPC large cantilever cap beam structure, which showed that hollow UHPC cap beam could reduce the self-weight and keep safe. Another researcher
Chen [8] proposed a fabricated UHPC cap beam and conducted research and analysis on its mechanical performance, which concluded that UHPC cap beams could achieve better economic benefits through saving material consumption and shortening the construction period. Li and Shao of Hunan University [9, 10] proposed prestressed lightweight UHPC thin-walled cap beams. The large-scale model test results showed that the proposed UHPC cap beam had good deformation performance and crack resistance. Theoretical calculation method for the load capacity and width of cracks was proposed.

In summary, UHPC can further improve the cap beam performance, but the existing designs still need to be optimized. This article will propose new types of high-performance concrete cap beam structures, and summarize design and application suggestions based on comparison research.

2. Project Background
Take a simply supported beam bridge as an example. The bridge span is 30m, the main girder is made of concrete box girder. The main bridge is designed according to two-way six lanes, first-class highway, and the design speed is 80km/h. The bridge cap beam length is 33.03m. The center of the cap beam is 2.7m high, the end is 1.7m high, and the cap beam is 2.8m wide. A single cap beam weighs 529t. The elevation and side views of the cap beam are shown in Figure 1 below.

![Fig. 1 Elevation of the cap beam and piers of the project](image)

The prestressed cap beam is made of C50 concrete and HRB400 steel bars. The prestressed steel strand has a diameter of \( F_s = 15.2 \text{mm} \), and the tensile strength of \( f_{pk} = 1860 \text{MPa} \). The Ultra-High Performance Concrete (UHPC) grade used in the new cap beams of this study is U120. According to the "Specification for Application of Highway Ultra High Performance Concrete Bridge and Culverts" (draft for comments), the design value of axial compressive strength is 58MPa. The axial tensile strength grade is UT7, the axial tensile strength design value is 4.5MPa, and the elastic modulus is \( 41.9 \times 10^3 \text{MPa} \). The flexural strength of U120 UHPC can be tested to 22MPa. The steel plate in this study is Q345 steel.

| Material       | Design value of axial compressive strength /MPa | Modulus /MPa |
|----------------|-----------------------------------------------|--------------|
| C50 Concrete   | 22.4                                          | 34500        |
| UHPC 120       | 58.0                                          | 41900        |


| Material            | Design strength /MPa | Modulus /MPa |
|---------------------|-----------------------|--------------|
| HRB400 steel rebar  | 330                   | 200000       |
| 1860 Steel strand   | 1260                  | 195000       |
| Q345 Steel plate    | 270                   | 207000       |

3. High-performance concrete cap beam design

3.1. Prestressed concrete cap beam
The prestressed concrete cap beam is shown in Figure 2. A total of 18 prestressed steel strands in 3 rows need to be used to provide prestress in this design. The cap beam is 33.03m long. The center height of the cap beam is 2.7m, the end height is 1.7m, the width is 2.8m, and the hoisting weight of a single cap beam is about 529t.

![Fig. 2 Diagram of prestressed concrete cap beam](image)

3.2. Full UHPC cap beam
The full UHPC cap beam is shown in Figure 3. In order to reduce its own weight, a hollow section is adopted and the height and width are reduced. A total of 18 prestressed steel strands in 3 rows are required in this design. The cap beam is 33.03m long. The center height of the cap beam is 2.3m, the end height is 1.5m, and the width is 2.0m. The hoisting weight of a single cap beam is about 210t.

![Fig. 3 Diagram of full UHPC cap beam](image)

3.3. Steel-UHPC composite cap beam
A steel plate is added on the top of the cap beam to form a composite cap beam as shown in Figure 4. The cap beam can be inverted during the concrete pouring, and the steel plate can also be used as a template. The cap beam is 33.03m long. The center height of the cap beam is 2.02m, the end height is 1.22m, the width is 2.0m. The hoisting weight of a single cap beam is about 181t.
4. Simulation and Analysis

4.1. Calculation assumptions and parameters
Establish a pier column cap beam model in Midas, apply the main beam as a load to the cap beam. The concrete is C50, the prestressed steel is Strand1860, and the UHPC material is 120MPa. The material parameters are taken according to the bridge specification and test results. The calculation model of the cap beam pier column is established according to the actual cross section of the example project, as shown in Figure 5. The cap beam uses variable cross-section elements.

![Diagram of steel-UHPC composite cap beam](image)

4.2. Prestressed concrete cap beam
The maximum bending moment at the root of the cap beam is 31184 kN·m. The concrete on the top of the cap beam is basically under compression, and the maximum tensile stress does not exceed 1 MPa. The maximum compressive stress of the concrete at the bottom of the cap beam is 16.8MPa, which has a high safety reserve. The root of the cap beam bears a shear force of 9785kN, and the design value of the shear capacity is 39207kN, which has a high safety reserve.
4.3. Full UHPC cap beam

Due to the light weight of the cap beam, the maximum bending moment at the root of the cap beam is 29000kN·m. The concrete on the top of the cap beam is under compression. The maximum compressive stress of the concrete at the bottom of the cap beam is 35.8MPa, which has a high safety reserve. The root of the cap beam bears a shear force of 8391kN, and the design value of the shear bearing capacity is 18082kN, which has a high safety reserve.
4.4. Steel-UHPC composite cap beam
The maximum bending moment at the root of the cap beam is 36896 kN·m. Since there is no need to check the crack width after the steel roof is adopted, the tensile stress control of the concrete at the top of the cap beam can be appropriately relaxed, and the arrangement of prestressed steel bars can be reduced to 12. The tensile stress of the steel roof is 93.0 MPa. The maximum compressive stress of the concrete at the bottom of the cap beam is 50.9 MPa, which is lower than the design value of the material strength. The root of the cap beam bears a shear force of 9147 kN, and the design value of the shear bearing capacity is 16719 kN, which has a high safety reserve.

4.5. Comparison between different cap beams
Compare the proposed prestressed concrete cap beam, full UHPC cap beam, and steel-UHPC composite cap beam, on self-weight, cap beam height, material cost estimation, and construction difficulty. The existing conventional prestressed concrete cap beam obviously cannot meet the requirements of the overall hoisting weight required for rapid assembly construction. After the introduction of UHPC materials, the self-weight of the cap beam can be greatly reduced, and the overall hoisting of the cap beam can be realized. Adding a steel plate can reduce the number of prestressed steel bars and reduce the cost of cap beam materials. Among all the designs, the steel-UHPC composite cap beam has the lightest lifting weight. When the lifting weight limit of the cap beam is relatively strict, the steel-UHPC composite cap beam is more suggested to be used.

The cost estimation of each cap beam in the following table only considers the material cost. After the actual use of the high-performance concrete cap beam, by reducing its own weight, facilitating transportation, speeding up construction, and improving durability, it will save more costs for the entire project in the whole life cycle. Therefore, in projects considering more about the life-cycle costs, the new high-performance concrete cap beams proposed in this study are suggested to be used.
Table 3 Comprehensive comparison of cap beams

| Cap beam type                  | Prestressed concrete | Full UHPC | Steel-UHPC composite structure |
|-------------------------------|----------------------|-----------|--------------------------------|
| Self-Weight / t               | 529                  | 210       | 181                            |
| Coping height / m             | 2.7                  | 2.3       | 2.02                           |
| Number of prestressed steel bars | 18                  | 18        | 12                             |
| Material cost estimation / CNY| 360000               | 1120000   | 1000000                        |
| Construction difficulty       | Cannot be hoisted as a whole | Can be hoisted | Easy hoisting |

5. Conclusion

Traditional prestressed concrete large prefabricated cap beams are hard to be lifted integrally and the cap beam self-weight needs to be reduced to enhance the construction efficiency. According to the design conditions of the background project, new types of full UHPC cap beam and steel-UHPC composite cap beam are proposed. Based on numerical analysis and structure comparison, the main conclusions are as follows:

(1) Replacing ordinary concrete with UHPC can significantly improve the stress performance, reduce the cross section, and reduce the self-weight of the cap beam. The weight of the UHPC cap beam can keep the weight within the limit of the lifting capacity.

(2) The use of steel-UHPC composite structure can further optimize the cross section of the cap beams. The calculation results show that the composite cap beams can achieve the smallest lifting weight. In the case of extremely limited lifting capacity, the steel-UHPC composite cap beam is more suggested to be used.

(3) Although the high-performance concrete cap beams proposed in this research do not have an advantage in material costs, considering the cost savings through the whole life cycle of the bridge, it is expected to be economical. The new high-performance concrete cap beams will be more and more used in prefabricated bridges where large cap beams need to be lifted integrally.

In the follow-up research work, cap beam tests will be designed based on the above numerical comparison and analysis results to further study the performance of each new cap beam.

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