Construction Key Techniques of Upper Cross-beam for Main Tower of Super-Kilometer Span Rail-cum-Road Suspension Bridge

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Abstract: As the span of the suspension bridge increases, the height of the main tower and the force on the tower increase. The beam profile volume and pouring weight become larger, which increases the risk of high-altitude construction of the main tower and the upper cross beam. The main bridge of Wufengshan Changjiang River Bridge of Lianzhen Railway is the first rail-cum-road suspension bridge in China. The main span reaches 1092m and the total height of the tower is 191.5m. Taking the engineering practice of the upper cross beam of the main tower of Wufengshan Changjiang River Bridge of Lianzhen Railway as an example, this paper introduces the construction difficulties of the upper cross beam of the main tower, the selection of the upper cross beam construction support, the structural characteristics of the support and the construction process. The upper cross beam is constructed asynchronously with the tower. From the bottom of the upper cross beam to the top of the lower cross beam is 121.5m. The upper cross beam was poured in six times with a total concrete volume of 1918m³. The method of small trusses with bracket and floor steel pipe support is used for construction. The finite element analysis software is used to calculate the super-high support of the upper cross beam, and the support strength, rigidity and stability meet the requirements of the specification. At present, the bridge has been partially put into use, which verifies the rationality of the design and construction of the beam support on the main tower. It has strong reference and guiding value.

1. Introduction
With the development of urban construction and expressway and railway construction in China, the span of bridges is constantly breaking through. The long-span cable-stayed bridge or suspension bridge will also become an inevitable trend. When the span of the bridge exceeds 600m and above, the suspension bridge is often considered first. Compared with highway suspension bridges, railway suspension bridges started a little later. At present, a number of rail-cum-road suspension bridge have been built at home and abroad, and the span has exceeded the threshold of 1000 meters[1]. The parameters are shown in Table 1.
Table 1. The large span rail-cum-road suspension bridge at home and abroad

| Name of the bridge                          | Year of completion | The main span | Tower height |
|--------------------------------------------|--------------------|---------------|--------------|
| The New Bay Bridge, US                     | 1936               | 704m          | 160m         |
| The April 25th Bridge, Portugal             | 1966               | 1013m         | 190m         |
| The Great Naruto Bridge, Japan              | 1985               | 876m          | 125.93m      |
| The Seto Bridge, Japan                      | 1988               | 1100m         | 194m         |
| The Tsing Ma Bridge, Hong Kong              | 1997               | 1377m         | 206m         |
| The April 25th Bridge, Portugal             | 1966               | 1013m         | 190m         |
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| The Seto Bridge, Japan                      | 1988               | 1100m         | 194m         |
| The Tsing Ma Bridge, Hong Kong              | 1997               | 1377m         | 206m         |
| The Messina Strait Bridge, Italy            | Under construction | 3300m         | 370m         |
| Wufengshan Changjiang River Bridge, Chain   | 2020               | 1092m         | 191.5m       |

The Wufengshan Changjiang River Bridge is the first rail-cum-road suspension bridge in inland China. It is also the suspension bridge with the fastest running speed and the largest running load in the world. Its calculation theory, design method and construction technology have all faced many technical tests, thus breaking a number of new technical records. The cross beam is not only an important force transmission structure for the tower, but its construction is also a key link in the construction of the tower. Due to the large size, irregular shape, and large height of the upper cross beam structure, the construction is generally divided into multiple pourings and the process is complicated. Therefore, how to design a safe, economic, and convenient super-high support system to complete the construction of the upper cross beam is an important technical problem.

2. Project Overview

The Wufengshan Changjiang River Bridge of Lianzhen Railway is an important part of the railway line in Lianzhen, which adopts a double-tower single-span suspension steel truss girder suspension structure. The main cable span is (350+1092+350) m and the stiffening beam span is (84 + 84 + 1092 + 84 + 84) m. The overall layout of Wufengshan Changjiang River Bridge is shown in Figure 1.

![Figure 1. Arrangement of Main Bridge of Wufengshan Changjiang River Bridge (Unit: m)](image)

The Wufengshan Changjiang River Bridge adopts a double deck layout, the upper level is an eight-lane highway and the lower level is a four-line high-speed railway. The bridge tower adopts reinforced concrete frame structure. The total height of the tower is 191.5m (calculated from the top face of the tower to the bottom of the saddle), which is respectively composed of upper, middle and lower tower columns, upper and lower cross beams and saddle housings on the top of the tower. The tower is made of C55 grade concrete and HRB400 steel bar. In order to reduce the wind resistance coefficient, the tower section is chamfered at 100×150cm around. The upper and lower cross beams are prestressed concrete structures.

The upper cross beam of the main tower is a single-box and single-chamber structure. The height gradually changing from 11m in the middle (not counting the height of the beam crown) to 32.8m on both sides. The length of the transverse bridge is about 34.4m, and the width of the bridge is 7.5m. The thickness of the top, bottom and web are 0.8m. There are manholes on the top surface. The structure of main tower and beam is shown in Figure 2.
3. Difficulties in construction of upper cross beam
Different from the lower cross beam and tower construction synchronous, the upper cross beam and tower construction asynchronous in order not to affect the progress of the top sealing of the tower. The upper cross beam has a large height and a complex structure. The construction difficulties are as follows:

- The bottom of the upper cross beam is 121.5m away from the lower cross beam. The installation and disassembly of the support is difficult, and the safety risk is high.
- The total casting height of the upper cross beam is as high as 32.7m, with many times of layered casting and long casting cycle.
- The height of the upper cross beam gradually changes from 10.0m in the middle to 23.2m on both sides. The decorative block on both sides is a special-shaped structure and has a large height difference. The support and other formwork system should consider the construction needs of the beam and decorative blocks.

The concrete cubic volume of upper cross beam is 1918m³, which is divided into six layers for pouring. The upper cross beam support structure is considered to bear the total weight load of the first, second, and third layers of concrete pouring. The volume of the concrete is shown in Table 2.

| Layered pouring | Pouring part                        | Layered thickness (m) | Volume (m³) | Pouring time (h) |
|-----------------|-------------------------------------|-----------------------|-------------|-----------------|
| The first layer | Lower decorative block              | 6.7                   | 194.2       | 4               |
| The second layer| Top of lower decorative block       | 6                     | 198.1       | 4               |
| The third layer | Beam bottom plate and side wall     | 5.5                   | 660.7       | 14              |
| The fourth layer| Beam side walls                     | 3                     | 219.3       | 4.5             |
| The fifth layer | Beam side wall and roof             | 3                     | 387         | 8               |
| The sixth layer | Upper decorative block              | 8.5                   | 258.9       | 5.5             |
| **Total**       |                                     | **32.7**              | **1918**    |                 |

4. Upper cross beam support design

4.1 Determination of upper cross beam support
The construction of the upper cross beam on the main tower is a typical high-altitude operation, which
is difficult to construct and has a large safety factor. Generally, the form of large brackets with corbels is more \cite{2}. Considering economic efficiency, construction period, and hazard source control, since the lower cross beam of Wufengshan Changjiang River Bridge uses floor-standing supports and the amount of steel pipes is large, the upper cross beam support adopts the form of small truss with bracket and steel column support. After the lower cross beam component is removed, it is repaired and used for the upper cross beam support. The steel column of the lower cross beam can be recycled, which is convenient for disassembly and transportation. In order to ensure that the force condition at the lower decorative block of the upper cross beam meets the requirements, a tripod and a corbel are provided at the lower ends of the upper cross beam. The bottom mold and the outer mold of the upper cross beam special-shaped decorative block adopt large-scale combined steel template, which is designed by a professional template factory. After being processed, it is transported to the site.

4.2 The structure and characteristics of the upper cross beam support

The upper cross beam supports are arranged in order from top to bottom: transverse distribution beam, bailey beam (type 321), main transverse beam, triangle truss and bracket, steel column, horizontal bracing, buttress and inclined strut. The main component material types are shown in Table 3. The bracket layout is shown in Figure 3.

| component                      | type specification | materials |
|--------------------------------|--------------------|-----------|
| Transverse distribution beam   | 114a/2114a         | Q235B     |
| Bailey beam                    | type 321           | Q235B     |
| Main transverse beam           | 2HN900×300         | Q235B     |
| Triangle truss                 | 2HN900×300, 2HM588×300 | Q235B  |
| Bracket                        | 2HN900×300         | Q235B     |
| Steel column                   | Ø1000×16           | Q235B     |
| Horizontal bracing             | Ø630×8, Ø426×6     | Q235B     |
| steel pipe attached to the tower| Ø630×8, Ø426×6     | Q235B     |
| Inclined strut                  | Ø426×6             | Q235B     |

Figure 3. Elevation plan of upper cross beam
Features of upper cross beam support:

- The overall height of the upper cross beam bracket is more than 100 meters, and it is a high-rise structure. Wind vibration is more likely to occur under strong wind. The "Building Structure Load Code" should be used to calculate the wind load [3].
- There are 4 groups of triangle truss at both ends of the support, with an interval of \((1.8 \times 2 + 4.4 + 1.8 \times 2)\) m. The upper bracket of the triangle truss is under tension and the lower bracket is under pressure.
- The lower part of the upper cross beam and the adjacent tower should be equipped with formwork pair tie rods, and two layers of cushion beams and support beams should be added between the bottom mold of the decorative block and its adjacent Steel columns to increase the horizontal rigidity and reduce the lateral deformation of the bottom mold.
- Affected by wind load, the steel pipe attached to the tower is subject to greater horizontal force. The steel pipe and the tower are connected in a consolidated form. The horizontal bracing and inclined strut are added between adjacent steel pipes attached to the tower to increase the rigidity of the steel pipe.
- According to the horizontal bracing elevation of the upper cross beam support, a reasonable arrangement of the active lateral brace of tower. The support can take into account the active lateral brace of the middle tower, which provides convenience for its installation and removal.
- In order to realize the asynchronous construction of the upper cross beam and the main tower, pre-embedded parts of the triangle truss bracket are embedded in the tower. The upper cross beam is constructed by layered pouring of the floor steel pipe support and triangle truss. The support force is clear and the construction is convenient.

4.3 Finite element calculation of the upper cross beam support

The finite element calculation model of the upper cross beam support and the calculation results of the most unfavorable conditions are shown in Figure 3. The calculation of the support does not consider the beneficial effects of prestressing.

The constraint conditions of the model is as follows:

- The steel column is consolidated at the bottom of the column.
- The steel pipe attached to the tower is consolidated at the connection of the tower.
- The main transverse beam is hinged with the steel column.
- The main beam is elastically connected with bailey and the triangle truss.
- The transverse distribution beam is elastically connected with the Bailey.
- The bracket of triangle truss is consolidated with the tower.

The load of the upper cross beam support includes: the weight of the support and the upper cross beam, the weight of the formwork system, the load of the construction personnel and equipment, the concrete dumping and vibrating load, and the wind load.
5. **Checking the overall stability of the upper cross beam support**

The finite element software is used to analyze the buckling of the overall beam support structure (Figure 5). The buckling analysis principle is: constant load + buckling coefficient × variable load = buckling load. The calculated eigenvalue coefficient of the buckling mode of the structure is 5.1, which is greater than 4. The overall stability of the support meets the requirements of use. 

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Figure 4. The calculation model of upper cross beam support and its calculation results
Figure 5. Buckling analysis and calculation of upper cross beam support

6. Construction process of upper cross beam support
Due to the asynchronous construction of the upper cross beam and the tower, the upper cross beam steel bars are pre-embedded during the construction of the tower column. At the same time, the installation of the upper cross beam support and the formwork system is carried out. After the topping of the upper tower column is completed, the inner climbing frame is removed. The bottom formwork of the beam is installed, and the upper cross beam is constructed in layers from bottom to top by conventional techniques. The steel columns are connected by flanges. Each section is about 8m long and the unit weight is about 4t. All components are assembled on the ground as much as possible to reduce the amount of aerial welding. After the construction of the lower cross beam is completed, the dismantled steel columns, beams, distribution beams, bailey and other components are repaired and turned over for use in the construction of the upper cross beam.

The construction process of upper cross beam support installation is as follows:
Install support embedded parts →Repair treatment of lower cross beam components →Install the first section of steel column and the first and second floors of horizontal bracing by tower crane →Installation of the third and fourth floors of steel columns →Active lateral brace installation →Install the remaining steel columns and horizontal bracing →Installation of triangle truss and main transverse beam →Bailey beam installation→Installation of transverse distribution beam →Special-shaped mold of the decorative block and triangle truss installation →Lay and fine-tune the bottom formwork.

The upper and lower concrete of the same floor are poured simultaneously to reduce the uneven deformation of the support. When the strength and elastic modulus of the last layer of concrete reach 90% of the design value, the upper cross beam can be prestressed. The support can be removed only after the construction of the beam prestress is completed. The top-down demolition technology is adopted. The pre-pull force of the active lateral brace is removed in advance when the active cross brace is encountered.

The construction process for the removal of the upper cross beam support is as follows:
Cleaning up debris→ Cutting off the unloading block→ Removing the bottom formwork→ Removing the distribution beams one by one →Removing the Bailey frame and the triangle truss→Removing the main transverse beam of the 10-ton winch →Removing the steel column and horizontal bracing→ Repair the embedded parts of the tower and the lower cross beam.

7. Conclusion
Wufengshan Changjiang River Bridge is the most difficult part of the whole route construction. Its railway bridge has been officially put into use with the opening of Huaiyang Town Railway in December 2020, and the construction of the highway bridge is still in progress and is expected to be officially opened to traffic at the end of June 2021. The main tower is not only the key control project for the construction of Wufengshan Changjiang River Bridge, but also the facade project of the bridge.
The existing recommendations are as follows:

- The beam of the main tower is large in volume and span. Using the existing construction environment conditions, it adopts the construction form of small truss and floor steel pipe support. The floor support design reaches 120 meters and the overall construction of the upper cross beam is smooth with good quality control. The on-site installation of the cross-beam support is shown in Figure 6, which can provide technical support and reference for similar projects.

- The asynchronous construction of the upper cross beam and the tower can reduce the influence of the upper cross beam construction on the construction progress of the tower top sealing, steel truss beam erection, and suspension cable erection [5]. The safety of the tower structure can be ensured and construction requirements can be met with a reasonable arrangement of active cross brace of the tower.

- There are many forms of the beam cross support. The upper beam support of this project uses floor-standing steel pipes, which the amount of steel used is very large. On the condition that it not only meets the construction requirements but also saves costs, other support forms can also be used. At present, the type of bracket with corbel is used more and more in the construction of the upper beam, but the force of corbel is usually not big. The type of bracket with large-tonnage and heavy-duty corbel are suitable for the construction of large-height and large-volume beams. It will be a development trend in the future beam construction process, which is worthy of further study.

(a) The lower cross beam  
(b) The upper cross beam

Figure 6. On-site cross beam construction of Wufengshan Changjiang River Bridge

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