

# Key Design Technologies of New Cable-Stayed and Steel Truss Composite Bridge



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**Abstract** Taking Ningbo Yongjiang Sanguantang Bridge as the engineering background, the plan of new cable-stayed and steel truss combined bridge is created, according to the Construction conditions including navigation and aviation restriction and engineering geology, as a new combined bridge system from the combination of extradosed cable-stayed bridge and steel truss. This paper makes a deep study and coMPArison of four systems, such as 3 span continuous rigid frame bridge, 3 span continuous girder bridge, single cantilever rigid frame with rigid hinge, single cantilever beam with rigid hinge, and a structural system suitable for this type of bridge has been found: that is single cantilever beam with rigid hinge system. On the basis of the study and analysis of the structure system, the key technology of the anchor position at the end of the truss, and the integral static and dynamic performance and seismic performance, this paper has completed the conceptual design of the new bridge structure, and it shows that the bridge has excellent static and dynamic mechanical properties and implementable performance.

**Keywords** New bridge system · Cable-stayed and steel truss · Combined bridge system · Bridge structure system · Bridge key technologies

## 1 Introduction

### 1.1 Introduction

Ningbo Sanguantang bridge is planned to be located on the Yongjiang River in Ningbo City, Zhejiang Province, China, which is downstream of Chang Hong Road Tunnel. The main span of the bridge is about 465 m, and the aviation height limit is 50–56 m, so the conventional cable stayed bridge, arch bridge and suspension bridge is difficult to meet those requirements. The steel truss bridge is one of the

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bridge types with low height and long span capacity, which is more suitable for the project. However, the traditional steel truss girder bridge has some disadvantages in the aspects such as landscape and structure. It has too many and disorderly truss members [1], which is also difficult to construct the main span on the river, and it is not as economical as the cable-stayed bridge. Therefore, this design does not want to copy the traditional steel truss beam structure scheme, but wants to design a new bridge type scheme to meet the special bridge construction conditions, which is also consistent with the planning of modern buildings on both river sides.

The existing bridges on Yongjiang River are mainly cable-stayed bridges and suspension bridges. It is very reasonable and economical to use the cable-stayed bridge type for this span bridge, and it is convenient to use the cantilever construction technology which does not affect the channel. However, the requirement of aviation height limit makes the conventional cable-stayed bridge scheme about 40–50 m higher than the limit height, which is impossible to implement. The extradosed bridge can effectively reduce the height of the cable tower, which is about  $1/8$ – $1/12$  of the main span, about  $1/2$  of the general cable-stayed bridge tower. However, due to the technical limitations of the beam height ( $1/30$ – $1/60$  in middle,  $1/20$ – $1/40$  in fulcrum) and reasonable span of 300 m or so, it is difficult to apply the bridge type scheme here. Based on the extradosed bridge, the height of bridge tower can be reduced by using Y-shape. However, to meet the aviation height limit, the opening angle of the cable towers are more than  $120^\circ$ , and its horizontal length is almost about 200 m, and the influence factors such as the sag of the cable, the included angle of tower column and the ground about  $30^\circ$ , lead to the unreasonable mechanics of the structure.

In this scheme, the layout of the middle span of the extradosed bridge is retained. The “Y-shaped cable tower” and the whole side span form an integral structure, with a steel-truss cantilever beam, which can balance the main beam of the middle cable-stayed span. In this way, a new type of bridge structure is formed: the bridge structure of the cooperative system of cable-stayed and cantilever steel truss beam. The main span of this structure can be constructed by cantilever section like the cable-stayed bridge, which will not affect the navigation of the channel during the construction (Fig. 1).



**Fig. 1** The daytime rendering of the bridge

## **1.2 Construction Conditions**

The construction site is flat. The river here is about 390 m wide. The main river channel is located in the northwest side, and the southeast side has nearly 90 m shoal area. The deepest elevation of the river bottom is about  $-9.2$  m, and the depth of the constant water level is within 10 m. The ground elevation of both shores is about 2.5 m. The distance between the north levee and the south is about 430 m.

The foundation soil of Yongjiang River is composed of Quaternary sedimentary layer and Cretaceous bedrock layer within 121.2 m below the ground, and soft soil foundation is distributed within the bearing layer of piles foundation.

The navigation grade of Yongjiang River is class III sea channel, with a clear width of 180 m and a clear height of 20 m. It is demanded that no pier is allowed within the river.

There is an airport 3.3 km away from the west side of the bridge. According to the aviation height limit, the building height should below 60 m.

## **1.3 Technical Standard**

1. Road grade: urban main road; design speed of main line: 60 km/h;
2. Lane width: single lane width 3.5 m, 8 lanes.
3. Design load: automobile load: urban-A; crowd load: according to the specifications.
4. Building height: the height of the building shall meet the aviation limit of 50–56 m.
5. Navigation standard: Class III sea channel, with a clear width of 180 m and a clear height of 20 m; the highest navigable water level is 2.23 m (1985 National elevation system).

# **2 General Layout and Structural Design**

## **2.1 General Layout**

The main bridge adopts the cooperative system of cable-stayed and cantilever steel truss beam, with the span of  $160 + 465 + 160 = 785$  m, all steel structure. The large section steel truss cantilever beam structure [2] is adopted for the anchor span on both sides, which bears the force together with the orthotropic steel deck. The double side steel box girder cable-stayed structure is adopted in the middle span.

Expansion joints are set in the joint piers of the main and approach bridges on both sides and in the middle of the mid span respectively. The longitudinal fixed and transverse movable supports are set under each truss on the middle pier [3].

The two truss supports on the top of the joint pier are all longitudinally movable and the transverse bridge is fixed to one truss while the other is released. The rigid hinge is set in the middle of the main span to transfer the longitudinal and transverse bending moment and shear force and release the temperature force.

The clear width of the carriageway is 32 m, the width of the truss structure is 3.5 m, and the width of the pedestrian and non-motor vehicle is 4.25 m respectively on both sides. The height of truss beam above the bridge deck is 26.25 m, and the elevation is arranged in two layers, and 14.25 m below the bridge deck, with a total height of 40.5 M; the longitudinal truss joint length is 20 m, and the web member between each layer is arranged according to the “N” type, and the wind support adopts the “-” type; the highest point of truss from the ground is 50.0 m. The longitudinal spacing of the stay cable on the beam is 10.0 m, while at the truss end the cable is evenly distributed and anchored in the triangle area at the end of the cantilever truss. The stay cables corresponding to each truss are arranged as the double cable plane (Figs. 2, 3).

### 2.2 Steel Truss

The steel trusses are arranged in two pieces. The two pieces are parallel with a center distance of 35.5 m. The facade of each truss is arranged in the form of multi fold sides. The upper part of the bridge deck is divided into two layers, with the layer height of 14.0 m. The web members of each layer are arranged in the form of “N”; the truss below the bridge deck forms a V-shape and closes to the top of the bearing platform at the middle pier, with the height of 16.0 m. The truss joint length is 20.0 m.

The upper and lower chord and the web members of the truss adopt box section, and the width is 3.5 m. The height of the top chord is 3.0 m, the height of the diagonal chord below the bridge deck and around the truss is 3.0 m, and the height of the bottom chord connected to the steel bridge deck is 3.5 m. The height of middle horizontal bar, straight and diagonal web bar is 1.60 m. The whole section of the cable anchorage area is closed, which is a solid triangle.

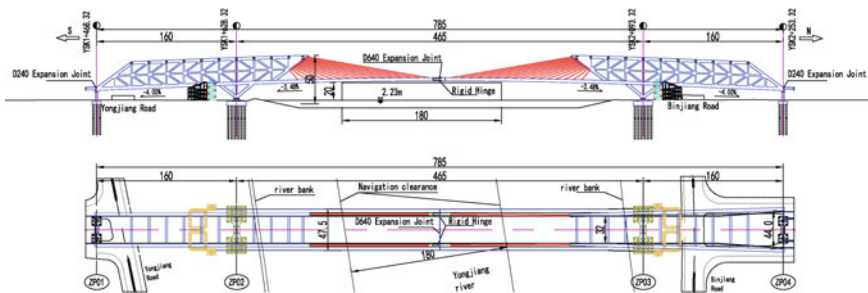


Fig. 2 The recommended bridge layout

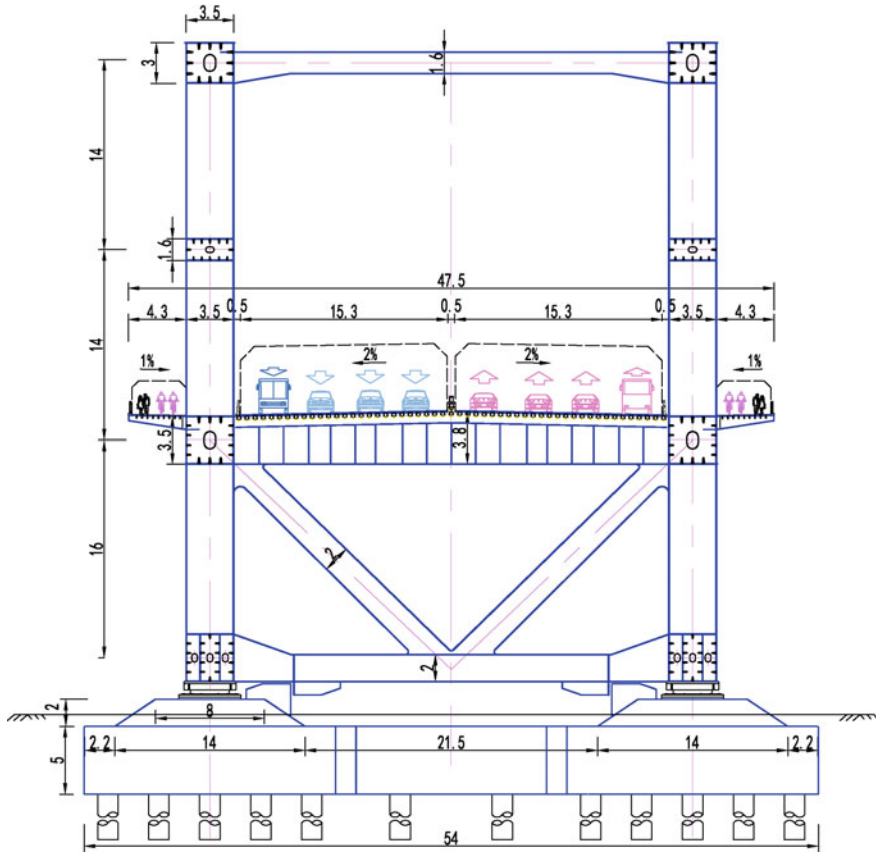


Fig. 3 The fulcrum section of the recommended bridge

The thickness of chord plate is between 30 and 50 mm. For some sections with more stress, two webs shall be added in the box room, and the thickness of additional webs shall be 30 mm. The thickness of web plate is between 20 and 40 mm.

The connection of steel truss joint adopts the integral joint and the full welding form. Q345 grade steel is mainly used, and Q420 grade steel is used for upper, lower and inclined chords near some stressed sections such as fulcrum.

### 2.3 Steel Girder and Steel Deck Structure

The main beam adopts a double side steel box form, and the bridge deck is of orthotropic steel deck structure. The side box girder is  $3.5 \times 3.5$  m, the thickness of upper and lower flange and web is determined according to the stress demand, and

the plate thickness varies from 16 to 40 mm. The orthotropic steel bridge deck adopts U-shaped stiffening rib, the thickness of the bridge deck is not less than 16 mm, and the spacing between the diaphragms is 3.3–3.4 m. It is arranged at the same height as the side box girder, and the reinforced diaphragm beams are arranged near the corresponding truss nodes and cable anchor points. The web thickness of the common diaphragm is 12 mm, the bottom plate is  $12 \times 400$  mm, the web thickness of reinforced diaphragm is 16 mm, and the bottom plate is  $16 \times 400$  mm.

Q345 grade steel is used for steel deck and main girder, and Q420 grade steel is used for some parts.

## **2.4 Cables**

The twisted parallel steel wires stay cable and cold cast anchor are adopted, and the standard strength of steel wire is 1670 MPa. There are 64 stay cables in the whole bridge, the longest one is about 142 m, and the largest one is  $253 \phi 7$ .

The standard spacing of stay cable in steel box girder is 10 m, the total length of non-cable section girder near the truss is 30 m, and the length of non-cable section in midspan is about 25 m.

## **2.5 Foundation**

The main pier and side pier are both located on land, so the bored pile foundation can be directly used in the design. The foundation is designed as friction pile with a diameter of  $\Phi 1.5$  m. The bearing layers of the main and side pier pile foundation are all selected at the tenth layer containing the cohesive round gravel layer, and the pile length is about 80 m. Dumbbell type arrangement is adopted for main pier and side pier cushion cap. 64  $\Phi 1.5$  m pile foundations are arranged for main pier and 18  $\Phi 1.5$  m bored piles are arranged for side pier.

## **3 Key Technology**

The detailed study, clear elaboration and expression of bridge type, structural system and key structural problems is one of the important works to strongly support the technical feasibility of the scheme, and also one of the core technologies of the innovative scheme.

### 3.1 Structure System

Under the general layout condition, there are four types of structural system: (1) three span continuous rigid frame system, deck continuous, V-shape support and main pier cap consolidated, Fig. 4; (2) three span continuous beam system, deck continuous, V-shape support and main pier cap connected by large tonnage seismic isolation bearings, Fig. 5; (3) single cantilever rigid frame and rigid hinge system, rigid hinge is set in the middle of main span [4, 5], V-shape support and main pier cap consolidated, Fig. 6; (4) Single cantilever beam and rigid hinge system, rigid hinge is set in the middle of main span, V-shape support and bearing platform of main pier are connected by large tonnage seismic isolation bearing, Figs. 4, 5, 6, 7.

The main advantages of system 1 are: (1) V-shape support and main pier cap are consolidated, the main pier avoids the setting of large tonnage bearing and saves bearing cost; (2) compared with the rigid hinge system, the rigid hinge is avoided in the middle of main span, and the structure is simple; there are less number of bridge expansion joints, and more comfortable of car travel; (3) the structural rigidity is large, and the displacement of truss and midspan is small; (4) because the main pier can bear the longitudinal bending moment of the bridge, and the tension of the side pier is relatively small, which can reduce the balance weight of the structural transition pier. The main disadvantages of system 1 are: (1) due to the consolidation of V-shape support and main pier cap, the main span in the normal use stage, the temperature effect produces a large horizontal force in the pier; (2) under the E2 earthquake, the main pier is subject to a large horizontal force, so the foundation scale of the main pier needs to be large; (3) under the earthquake, the V-shape support bears a large seismic effect, which is adverse to the structural stress safety. Compared with the advantages and disadvantages of system 1, relatively speaking, the disadvantages are more prominent, the project cost is higher, and it is not beneficial to the structural safety, so this kind of structural system is not recommended.



Fig. 4 3 span continuous rigid frame system (system 1)



Fig. 5 3 span continuous girder system (system 2)



**Fig. 6** Single cantilever rigid frame with rigid hinge system (system 3)



**Fig. 7** Single cantilever beam with rigid hinge system (system 4)

The main advantages of system 2 are: (1) the bridge structure is continuous, the vertical stiffness of the structure is larger than that of the system with rigid hinges, there are less number of bridge expansion joints, and more comfortable of car travel. The ratio of deflection to span of the structure is  $(0.620 + 0.026)/465 = L/720$ , and the overall rigidity of the structure meets the requirements of the code; (2) compared with the system with rigid hinge, the setting of rigid hinge is avoided in the main span, and the structure is simple; (3) the stress system of the structure is clear, and the force transmission path is simple. The main disadvantages of system 2 are: (1) the longitudinal displacement of the structure is large, large displacement expansion joints need to be set, and the displacement distance of the support is required to be large; (2) the horizontal force under the wind load is carried by a middle pier, the horizontal force of the fixed pier under the longitudinal wind load reaches 14,000 kn, large tonnage support is required, and the pile foundation is required to be strict, and large-scale foundation needs to be set.

The main advantages of system 3 are: (1) the temperature force is released by setting the rigid hinge in the middle of the span, and the horizontal force supported by the main pier is small in the normal use stage; (2) under the longitudinal wind load, the horizontal force is supported by two middle piers respectively. The main disadvantages of system 3 are: (1) the seismic force of the main pier is very large, the horizontal reaction force of a main pier reaches 90,000 kn, and the force on the lower foundation and V-shape support is very unfavorable; (2) compared with the system without rigid hinge, the vertical stiffness and transverse stiffness of the structure are relatively small.

The main advantages of system 4 are: (1) the temperature force is released by setting rigid hinge in the middle span, and the horizontal force supported by the main pier is small in normal use; (2) under the action of longitudinal wind load, the horizontal force is supported by two middle piers respectively; (3) through setting seismic isolation bearing, the seismic effect is obviously reduced, and the horizontal reaction force of one main pier under the action of earthquake is 14,000 kn. The main disadvantages of system 4 are: compared with the system without rigid hinge, the vertical stiffness and transverse stiffness of the structure are slightly reduced, the



ratio of deflection to span of the structure is:  $(0.632 + 0.018)/465 = L/715$ , and the overall stiffness of the structure meets the requirements of the code.

Based on the above analysis and comparison, system 4 is finally recommended.

### 3.2 Structure of Cable Anchorage Zone at Truss End

The bridge adopts a truss cable-stayed cooperative system. The cable is anchored at the end of the cantilever truss, which makes the anchorage zone become the key part of the stress. In the design, the triangle area at the end is closed as a whole, and longitudinal and transverse stiffeners and diaphragms are set inside. The cable force is transmitted to the box web of the anchorage area through the anchor tube and stiffener plate, and then to the upper and lower chord of the truss through the anchor web and the longitudinal and transverse box chamber set inside (Fig. 8).

The plate and shell element model is adopted for the calculation of truss anchor cable area, the most unfavorable standard combination is adopted for the cable force of stay cable, and the boundary of truss chord is consolidated.

There are stress distribution diagram of side steel plate and main internal plate of anchor cable area (Fig. 9). It can be seen from the calculation results that the stress distribution of the main plates in the anchorage zone is relatively uniform, except that there is local stress concentration at the inner corner of the position where the anchorage web and the upper chord are connected, there is no obvious stress concentration phenomenon. The maximum stress level of the plate is not higher than 300 MPa on the lower flange plate near the position where the upper chord and the anchorage zone are connected, and the local right angle of the area can be adjusted to a small circle. The arc angle is used to eliminate the stress concentration, so the structural arrangement of the cable anchorage area is more reasonable in general.

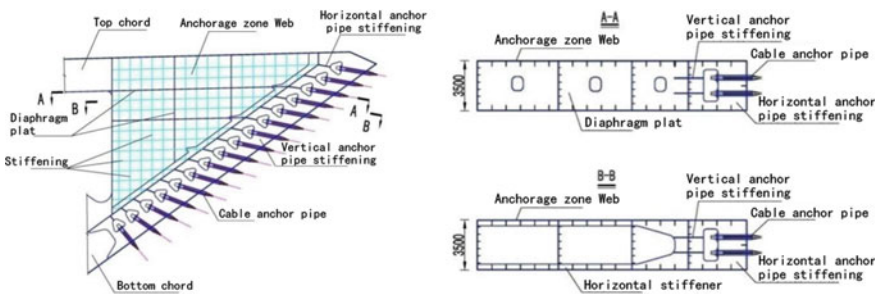


Fig. 8 The anchorage zone at the end of the truss

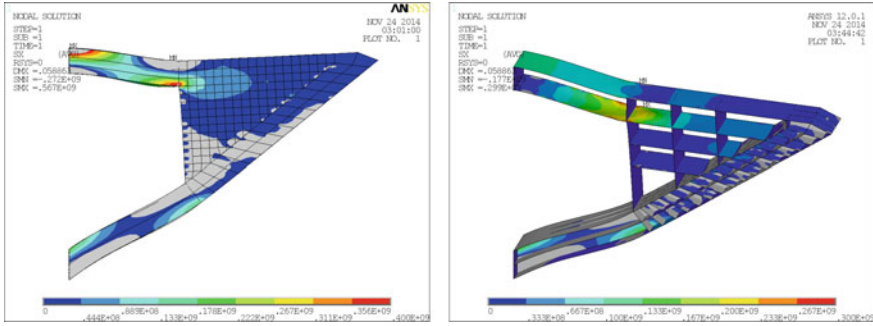


Fig. 9 The stress of the web and the stress of the inside plate

## 4 Overall Calculation and Analysis

### 4.1 Calculation Parameters and Model

The vehicle load is urban-A, two-way 8 lanes, with a reduction factor of 0.50; the pedestrian load is 4.0 m wide on both sides of the bridge deck, with a value according to the specification; the temperature rise is +25 °C, with a temperature down of -25 °C; the local temperature difference of the bridge deck is taken according to the specification; the settlement is 1 cm for the side pier, 3 cm for the middle pier; the design basic wind speed is 31.3 m/s. Unless otherwise noted, the displacement is in m, the internal force is in kn and m, and the stress is in MPa (tension is positive);

The model is calculated by Midas civil 2012 versus 8.05 program. The model has 3784 nodes and 5922 units. The cable is simulated by only tension truss element, and the other elements are simulated by beam element.

### 4.2 Overall Rigidity of Structure

According to the Guidelines for Design of Highway Cable-stayed Bridge (JTG/T d65-01-2007), the maximum vertical deflection value of the main girder of cable-stayed bridges caused by Lane load (excluding impact force) shall not be greater than 1/400 of the span. Under live load, the maximum vertical displacement of the middle span is  $0.632 + 0.243 = 0.875 \text{ m} < 465/400 = 1.163 \text{ m}$ , and the rigidity of the main beam meets the specification requirements (Figs. 10, 11).

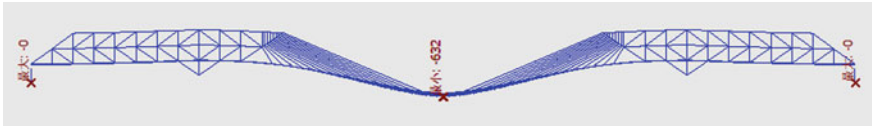


Fig. 10 The deflection under vehicle load

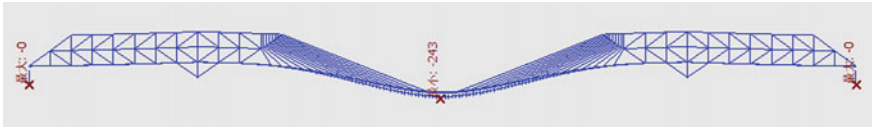


Fig. 11 The deflection under crowd load

### 4.3 The Static Response Under Characteristic Combination

Figures 12, 13 show the stress diagram of steel box girder under characteristic combination. In the characteristic combination at the later stage of completion of the bridge, the maximum compressive stress of the upper edge is 190 MPa, the maximum tensile stress is 38 MPa, the maximum compressive stress of the lower edge is 247 MPa, and the maximum tensile stress is 133 MPa, which meets the specification requirements; the section of the main girder near the main pier shall be made of Q420D steel

The maximum tensile force of the truss is 16,164 kn, which appears on the top chord of the truss and the top of the support; the maximum pressure is 97,360 kn, which is on the V-shape support. The maximum compressive stress is 211 MPa, and the maximum tensile stress is 230 MPa; Q420d steel is used in areas with high stress (Figs. 14, 15).

Under the action of characteristic combination, the maximum two cable force is 12,904 kn (pes7-253), and the minimum two cable force is 2801 kn (pes7-91); the safety factor of each stay cable is greater than 2.5, and the stress amplitude is less than 200 MPa according to the fatigue calculation requirements, meeting the design requirements.

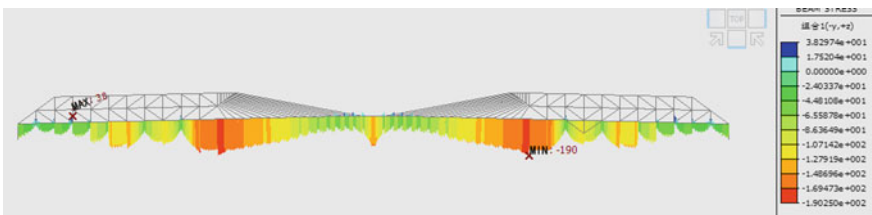


Fig. 12 The beam stress of the upper edge under characteristic combination

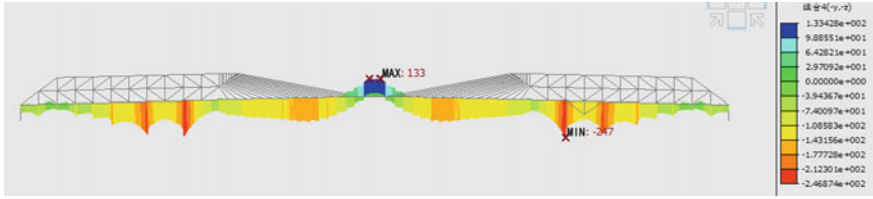


Fig. 13 The beam stress of the lower edge under characteristic combination

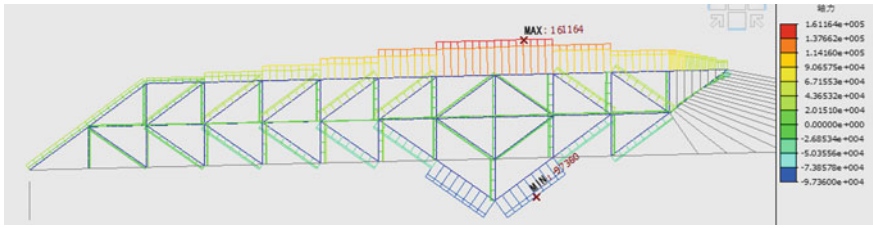


Fig. 14 The axial force of the truss under characteristic combination

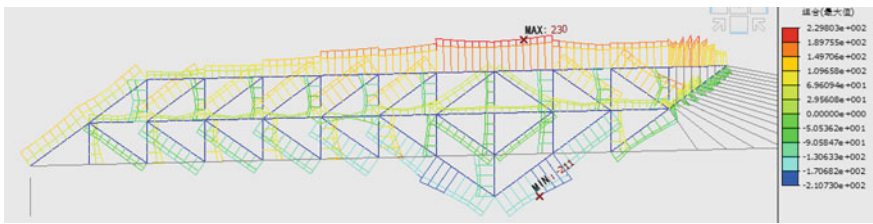


Fig. 15 The stress of the truss under characteristic combination

Table 1 The support reaction of the side and middle pier under characteristic combination (kN)

Position	Maximum support force	Minimum support force	Remarks
Side pier	10,829	827	Single support
Mid pier	129,732	111,037	

See Table 1 for reaction force of middle pier and side pier under standard combination.

#### 4.4 *Dynamic Characteristic Analysis*

The main vibration characteristics of the structure. The first mode is out of plane translation with a period of 3.147 s and a frequency of 0.318 Hz; the second is vertical vibration with a period of 3.124 s and a frequency of 0.320 Hz; the third is first-order torsion with a period of 2.323 s and a frequency of 0.430 Hz; the fourth is second-order vertical vibration with a period of 1.967 s and a frequency of 0. The fifth order is the second-order torsional vibration with a period of 1.94 s and a frequency of 0.515 Hz.

### 5 Conclusion

1. Taking Sanguantang bridge in Ningbo as the engineering background, a new type of cable-stayed steel truss cooperation system bridge is designed innovatively. The span combination is  $160 + 465 + 160 = 785$  m, all steel structure. Large section steel truss cantilever beam structure is adopted for the side span on both sides, which bears the force together with the orthotropic steel bridge deck, and double side steel box girder short tower cable-stayed bridge structure is adopted for the middle span. This type of bridge not only meets the navigation requirements of crossing Yongjiang River, but also meets the requirements of 50–56 m aviation height limit, and avoids the complicated truss members of traditional steel truss continuous beams, which has poor aesthetic effect.
2. In this paper, the important technical problems such as the structural system and the structure of the cable anchorage zone are analyzed and discussed in detail. The steel truss single cantilever beam and rigid hinge system is recommended for the structural system. The cable anchorage structure is set in the triangle area of the cantilever end of the closed steel truss box. The cable transmits the cable force to the box web of the anchorage zone through the anchor pipe and the stiffening plate, and then through the anchor web and its inside Part of the vertical and horizontal box chambers distribute the force to the upper and lower inclined chords of the truss.
3. The results of static, dynamic and aseismic calculation show that the strength, rigidity and stability of the main bridge can meet the stress requirements. The new cable-stayed steel truss bridge structure has good mechanical properties.

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