Parametric Design and Application of Steel Anchor Box for Main Girder of Long Span Cable-Stayed Bridge

Wei Qifen
Hubei Provincial Communication Planning and Design Institute Co., Ltd., Wuhan, China
420876152@qq.com

Abstract. The cable anchorage zone is the key part of cable-stayed bridge design. Many large-span cable-stayed bridges at home and abroad have carried out special analysis and research on the anchorage zone. Combined with engineering examples, the angle relationship between the cable and steel anchor box was derived through geometric method, and the relationship between the azimuth angle of the tangent direction of the anchor box plate and cable anchor point was established, and related parameter equations were compiled to construct a complex space steel anchor box. Through the calculation formula, a complex space steel anchor box will be constructed to achieve parametric design, which will greatly reduce the workload of the designer and improve the design accuracy.

1. Introduction
Most of the world's long-span cable-stayed bridges are steel box girders or steel-concrete composite beams. The effect of the cable girder anchorage structure is to transmit the huge cable tension acting on it to the girder section reliably and smoothly. When designing, the force line should be smoothed to prevent excessive stress concentration, otherwise fatigue or strength damage may occur under long-term dynamic and static loads. Therefore, as a key part of a cable-stayed bridge, the reliability of cable-stayed anchorage structure is directly related to the safety of the entire bridge [1].

The commonly used cable girder anchorage forms for long-span steel cable-stayed bridges mainly include four types of anchorage box type, pin hinge type, anchor pipe type and anchor pull type [2].

| Bridge name                        | Span (Unit: m) | Type                |
|-----------------------------------|----------------|---------------------|
| Sutong Yangtze River Bridge       | 1088           | Anchor box type     |
| Edong Yangtze River Bridge        | 926            | Anchor box type     |
| Jiayu Yangtze River Bridge        | 920            | Anchor box type     |
| Dodoro Bridge, Japan              | 890            | Anchor box type     |
| Normandy Bridge, France           | 865            | Pin hinge type      |
| Zhoushan Taoyuanmen Bridge        | 580            | Pin hinge type      |
| Qingzhou Lancang River Bridge     | 605            | Anchor pull type    |
| Shantou Stone Bridge              | 518            | Anchor tube type    |
The anchor box type anchoring structure is arranged in the box and the structure is relatively complicated. As the cable anchors are anchored on the bottom of the anchor box, beam end tensioning can be used to provide benefits for the long cable stays. There are many examples of its application, as shown in Table 1.

Technically, the anchor box type anchorage structure is mature and reliable. In the design process, the complex space steel anchor boxes need to be classified according to the angle of stay cables. In the anchor coordinate parameters, the space coordinate system needs to be converted into a local coordinate system. In addition, the size of the plate is irregular and the calculation workload is large. The author uses the coordinate system conversion, geometric projection and other mathematical methods, the parameter design of the anchor box, can greatly reduce the workload, while improving the design accuracy.

2. Engineering Applications
The main bridge of a certain bridge adopts a symmetric 820m double-tower and six-span asymmetric hybrid beam cable-stayed bridge scheme. The bridge span is arranged as a (75+75+75+820+300+100) meter steel box hybrid girder cable-stayed bridge, as shown in Figure 1. Both the concrete girder and the steel main girder adopt the PK box girder section of the separate bilateral box; the tower uses the A model. The standard cable distance for the main box steel girder bridge section is 15m, the standard cable distance for the northern section of the concrete box girder section is 7.5m, the standard cable distance for the south end of the steel box girder section is 12m, and the cable stays are arranged in a fan-shaped layout. 4 × 26 pairs of stay cables, standard tensile strength ≥ 1770MPa.

![Figure 1. Main bridge layout](image1)

The bridge cable and the anchorage zone of the main girder are connected by an anchor box, and the anchor box is installed on the outer side of the outer girder of the main girder, and welded together into one. Three stiffening ribs are provided on the anchor plate and one large stiffening plate is arranged between the anchoring plates. A small stiffening plate is arranged on the inner side of the anchor box and the web of the box girder. The specific structure is shown in Figure 2 and Figure 3.

3. Structural features of steel anchor boxes
The anchor box type connection is to set the anchor beam (block), and the anchor beam (block) is connected or welded with the main beam with high-strength bolts, and the oblique cable is anchored on the anchor beam (block). The anchor box type (pressure-bearing type) is the most widely used and mature one, with many application examples and mature technology. The disadvantage is that the anchoring structure is arranged in the box, the structure is relatively complicated, the number of plates is large, the operating space is small, the welding is difficult, and the inspection and maintenance are not easy in the future. [3~4]
Figure 2. Steel anchor box structure photo

Since the main tower is shaped as an A-shape, the angle between the anchorage of the cable and the steel main beam is affected not only by the anchorage along the bridge along the cable, but also by the lateral inclination of the main tower at the anchorage point of the tower, i.e. each cable. There is a spatial change in the main beam anchorage. The cable-to-shaft projection angle is 22.5°~80.2°, and the horizontal bridge projection angle is 3.2°~4.4°. In order to better transmit the cable stay cable force to the outer web of the main girder, the angle between the plane of the cable and the outer web of the main girder shall be minimized, and the outer web of the girder shall be inclined at 6.2° to the center of the main girder. Considering the change of cable angle space, the inclination of the outer girder of the main beam and the change of the longitudinal gradient of the main bridge, the design of the main beam steel anchor box becomes extremely complicated and the design workload is very large [5].

4. Parametric design ideas

The design requires that the anchorage plate N9 of the cable and the stiffener N6 and N6' of the outer web be located perpendicular to the cable and perpendicular to the plane where the outer web is located. The edges of N6 are close to the top plate and the outer web. Due to the spatial inclination of the cable stay cable, the transverse slope, longitudinal slope, and the inclination of the outer web of the steel box girder are also considered. The shape of the two stiffened plates is complex.

The angle $\gamma$ between the upper edge of the N6 plate and the edge of the web is the projection angle of the angle $\gamma_0$ between the top plate of the steel box girder and the outer web on the cross-
bridge plumb surface in the N6 plane. To design the stiffening plate by using the cable's spatial angle parameter at the anchorage point, the tangent of the cable at the anchorage point needs to be projected to the plane where the outer web is located, and the angle $\beta$ between the plane where the N6 panel is located and the plumb face of the transverse bridge is calculated. Then, the angle $\gamma_0$ is projected onto the surface of N6 along the bridge direction, and the space problem is transformed into a plane problem to be solved. Considering the inclination of the outer web and the influence of the cross slope and longitudinal slope of the bridge deck at the anchorage point, the calculation can be decomposed into two steps. The tangent of the cable is first calculated irrespective of the longitudinal slope of the steel box girder and the influence of the cross slope. The angle $\beta$ between the projection on the outer web and the horizontal plane. Then, in calculating the projection angles of the longitudinal slope and the cross slope in the desired plane, the plane angles that take into account the influence of the longitudinal slope and the cross slope of the steel box girder roof are obtained.

As shown in Fig. 5, the x-axis is along the main beam, the y-axis is along the transverse direction, and the z-axis is along the height of the tower. The angle between the tangent of the cable at the anchor point and the XOY plane is $\alpha$. The projection on the XOZ plane and the included angle of the bridge is $\beta$. The angle between the projection and the horizontal bridge on the YOZ plane is $\gamma$. The angle between the projection on the XOY plane and the forward direction is $\theta$.

Figure 6. Cable projection on the outer web

The lateral slope and longitudinal slope of the transverse roof are not taken into account in order to calculate the angle $\beta$ between the projection of the tangent of the cable on the outer web and the horizontal plane. Move the outer web plane OBEG to the anchorage point O of the cable, the OA is the tangent of the cable, and the inclination $\delta$ of the outer web is $\angle KBE$. As shown in Figure 6, A is the vertical line AP of BE in plane KBDA, then:

$$\begin{align*}
AP \perp BP & \Rightarrow AP \perp OB \\
AP \perp OB & \Rightarrow AP \perp OBEF
\end{align*}$$

AP is the normal plane of the outer web plane. OP is the projection of the tangent of the cable on the outer web, and the angle between the projection of the cable tangent on the outer web and the horizontal plane $\beta = \angle POB$. The angle between the tangent of the cable and the plane where the outer web lies $\alpha' = \angle POA$, $\angle AOD = \alpha$, $\angle KOB = \beta$, $\angle ABD = \gamma$, $\angle BOD = \theta$. Let AB's length = $r$ then:
\[ BP = \frac{r \cos \alpha \sin \theta}{\cos \gamma} \sin(\Delta + \gamma), \quad OB = r \cos \alpha \cos \theta; \]

\[ \beta' = \angle POB = \tan^{-1} \left( \frac{BP}{OB} \right) = \tan \left( \frac{\tan \theta}{\cos \gamma} \right) \sin(\delta + \gamma); \]

\[ \alpha' = \angle POA = \sin \left( \frac{AP}{OA} \right) \cos(\delta + \gamma); \]

Considering the vertical slope of the top plate, the included angle \( \angle BON \) of the top plate and the horizontal plane is \( \angle BOM \) when the angle between the plane of the outer web is \( \angle BOM \), and the angle of inclination of the outer web is \( \delta \), then:

\[ \beta' = \angle BOM = \tan \frac{\angle BON}{\cos \angle MBN} = \tan \frac{i}{\cos \delta}; \]

Therefore, the angle between the projection of the cable tangent on the outer web and the top of the steel box girder \( \beta = \angle POM = \beta + \beta' \).

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**Figure 7. Board N6 space schematic**

After calculating the angle \( \beta' \) between the projection of the tangent of the cable on the outer web and the horizontal plane, the dimensions of N6 and N6' can be solved. The angle \( \beta' \) between the projection of the tangent of the cable on the outer web and the horizontal plane is rotated around the cross-axis direction of the anchor point O (y-direction), and the angle \( \beta' \) between the projection of the tangent of the cable on the outer web and the horizontal plane is OCSR where N6 is located.

\[ RE = DF = r \sin \alpha \tan \delta \quad SC = r \sin \alpha / \cos \beta; \]

\[ \gamma' = 90^\circ + a \tan \frac{RE}{SC} = 90^\circ + a \tan(\tan \delta \cos \beta'); \quad \gamma' = a \tan \frac{i}{\cos \beta}; \]

\[ \gamma_1 = \gamma + \gamma' = 90^\circ + a \tan(\tan \delta \cos \beta') + a \tan \frac{i}{\cos \beta}; \]

\( \gamma_1 \) is the angle between the N6 plate and the top plate outer web.
Figure 8. Board N6’ space schematic

As shown in Figure 8, the plane D’C’M’M’ is an inclined floor plane, the inclination angle $\angle M’D’B’ = \eta$, and the plane B’E’F’ is the outer web plane, and the plane R’S’C’O’. For the face, 
$\angle H’C’S’ = \beta$, then:

$$
\frac{OB’}{\cos \beta} = \frac{BM’}{\cos \beta} = \frac{OC’}{\cos \beta} = r \cos \alpha \sin \theta \frac{\tan \eta}{\cos \beta},
$$

$$
\gamma_3 = 90^\circ - \frac{\tan \eta}{\cos \beta},
$$

$$
\gamma_2 = 270^\circ - \gamma_1 - \gamma_3.
$$

5. Conclusion

The angle of the board is calculated and the space design is transformed into a plane design problem. Using EXCEL as the variable editing formula can achieve parameterized design. In the overall calculation process, with the adjustment of the cable force, the space angles of the anchor points of different steel anchor boxes are extracted, and the formulas of the steel anchor box at different anchor points and the plate structure can be obtained by entering the formula. Parametric design can greatly reduce the workload and improve the designer's design accuracy.

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