Optimization of Cable Forces of Completed Asymmetric Hybrid-Girder Cable-Stayed Bridge with Fish-Shuttle-Shaped Single Tower Based on Midas Civil

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Abstract. The emergency of asymmetric hybrid-girder cable-stayed bridges with different shapes of main single tower brings numerous challenges to the analysis of cable forces of completed bridges. In this paper, based on an asymmetric hybrid-girder cable-stayed bridge with fish-shuttle-shaped single tower in China, the finite element software Midas Civil was adopted to build the model of the cable-stayed bridge. On the basis of the designed cable forces, the influence matrix method was used to optimize the cable forces of the completed cable-stayed bridge, and the reasonable completed bridge state was determined. The results indicated that the error of cable forces of the entire bridge was controlled within ±10%, namely, the cable-stayed bridge could reach a reasonable completed bridge state by adjusting the cable forces in a small range. In addition, it was practical to adopt influence matric method to optimize the completed bridge cable forces of asymmetric hybrid-girder cable-stayed bridge with fish-shuttle-shaped single tower, and the optimized cable forces was reasonable. The tendency of the bending moment of main girder under optimized cable forces was the same as that under designed cable forces, and the maximum positive and negative bending moments decreased by 49.84% and 27.35%, respectively. Compared with the designed cable forces, the maximum positive and negative displacements of the main girder and the maximum deviation displacement of the main tower along the bridge under optimized cable forces decreased by 76.33%, 39.20%, and 6.59%, respectively, leading to a smoother alignment of the main girder and tower. Compared with the designed cable forces, the support reaction forces were significantly reduced under the optimized cable forces, with a maximum reduction of 41.61%, which provided a larger pressure reserve to support and no negative reaction forces occurred. The optimized cable forces using the influence matrix method had obvious improvement effects on the bending moment, deformation and bearing force of the overall structure, which met the requirements of reasonable completed bridge state for cable-stayed bridges. The research results can provide reference for the optimization of cable forces in similar completed cable-stayed bridges.

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1 Introduction

With the rapid development of the global economy, large-scale urbanization movements have been unfolded globally, and demands on bridges for span, economy, aesthetics, and other aspects are also increasingly growing. Cable-stayed bridges are characterized in its large crossing ability, various structure forms and beautiful appearance, which have become one of the fastest developing and most competitive types of bridge in the world at present [1-2]. Cable-stayed bridges are a high-order statically indeterminate composite structural system composed of stay cables, bridge towers, and stiffening girders [3]. Since the completion construction of the world's first modern cable-stayed bridge, Stromsund Bridge, in 1956 [4], the cable-stayed bridges have flourished around the world. Nowadays, historic breakthroughs in large-span, ultra-long span, and composite structural system have been achieved in cable-stayed bridges [5], such as the Yavuz Sultan Selim Bridge (Turkey, 1408 m), the Russky Island Bridge (Russia, 1104 m), the Sutong Yangtze River Bridge (China, 1088 m), etc.

At the same time, with the flourishing development of modern construction technology and architectural aesthetics, cable-stayed bridges with various beautiful appearance and shapes have been constructed worldwide. There are multiple ways to divide cable-stayed bridges based on different factors [6], for example, according to the materials of main girder, they can be divided into cable-stayed bridges with steel main girder, concrete main girder, steel-concrete composite girder, steel-concrete hybrid-girder, etc. In accordance with the number of cable towers, cable-stayed bridges can be separated into single tower, double towers, and multi towers cable-stayed bridges. Among them, cable-stayed bridges with single tower can be divided into single span and double spans according to the span arrangement, and double spans single tower cable-stayed bridges can be further divided into equal spans and unequal spans. Based on the shape of the cable tower, the cable-stayed bridges can be classified into cable-stayed bridges with straight tower, stay tower, and irregular tower. The cable tower of asymmetric cable-stayed bridges with single tower can be flexibly built on the side with good geological conditions, which can not only reduce the difficulty of construction, but also decrease the engineering costs [7]. The main girder of the hybrid-girder cable-stayed bridges is composed of two different materials. The main span of main girder is made of steel with a smaller self-weight, which has the advantages of large span capacity and good seismic performance. While the material of the side span of the main girder is a heavier self-weight concrete to anchor and compress the whole cable-stayed bridges, which can effectively reduce the deformation and internal forces of the girder body of the main span [8]. Meanwhile, the hybrid-girder cable-stayed bridges with irregular tower have advantages of unique shape and strong adaptability to terrain, which can be seen as landmarks of the city and are more loved by people. Therefore, the hybrid-girder cable-stayed bridges with irregular tower are provided with significant engineering application values.

The goals of the cable-stayed bridges in the process of design can always be achieving the reasonable completed bridge state. The reasonable completed bridge state requires that under the dead load of the completed bridges, the internal forces of the main girder and the tower are evenly distributed, and the shape of the main girder need to be smooth [9]. Under dead load, the total energy contained in the basic structural system of cable-stayed bridges (excluding cables) is a constant value. On the one hand, by optimizing the cable forces, the distribution of the energy in components of the basic structural system can be adjusted. On the other hand, the distribution of the energy in components applied to the structure by cables itself can be adjusted. The aim of optimizing the cable forces is to denote a certain indicator of structure stress to be optimal, and ensure the rationality of the completed bridge state [10]. At present, the optimization methods for cable forces of cable-stayed bridges can be generally classified into the following five categories [9-24]: (1) Given structure state, such as rigid support continuous girder method, zero displacement method, internal forces balance method, etc. (2) Unconstrained cable forces optimization, like minimum bending energy method, minimum sum of squares of bending moments method. (3) Mathematic optimization methods, such as linear programming algorithm, nonlinear programming algorithm, intelligent optimization algorithm, etc. (4) Comprehensive optimization method for cable forces of completed bridge and construction, for example, influence matrix method. (5) Comprehensive optimization method, for instance, stepwise optimization method. The methods above are characterized in their clear mechanical concepts and optimization objectives, demonstrating their respective applicability to different types of cable-stayed bridges.

The optimization questions of completed hybrid-girder cable-stayed bridges with irregular tower, especially the asymmetric one, has become a hot topic of research which attracts a lot of researchers to study. Zhang [25] optimized and adjusted the cable forces of an asymmetric hybrid-girder cable-stayed bridge with aquarius-shaped single tower by adopting influence matrix method, and the results indicated that using the influence matrix method to adjust the cables could make the cable forces of the completed bridge more uniform, leading to more rational internal forces and deformation of main tower and girder. Due to the applicability and drawbacks of various optimization methods for cable forces of completed bridge, as well as the development of modern construction technology and architectural aesthetics, people tend to pursue cable towers with beautiful appearance and diverse shapes. However, using a single optimization method to obtain cable forces may not fully meet the requirements for the reasonable completed bridge state of cable-stayed bridges. Therefore, combining several methods or conducting secondary optimization based on the design of cable forces are conducted by many researchers to determine the reasonable completed bridge state of hybrid-girder cable-stayed bridges with irregular tower. Zhang [26] combined the minimum bending energy method and genetic algorithm to iteratively calculate the reasonable cable forces of an asymmetric hybrid cable-stayed bridge with an arch-shaped single tower. The results showed that the optimized cable forces, internal forces and deformations of the main tower and main girder could be more rational. Wang and Feng [27] used the influence matrix method to optimize and adjust the cable forces of a completed hybrid-girder cable-stayed bridge with irregular tower based on the designed cable forces, and the results indicated that the optimized internal cable forces tended to approach the designed cable forces. In addition, after optimizing the cable forces, the overall distribution of bending moment of the main girder of the cable-stayed bridge was more uniform, and the shape of the main girder also tended to be the ideal completed bridge state. To summarize, people's demand for bridge span, economy and aesthetics and the booming development of modern construction technology promotes the generation of asymmetric hybrid-girder cable-stayed bridges with irregular tower. Since it is a new type of bridge structure, the related research is relatively lacking, especially on the optimization method of completed bridge cable forces. Currently, researchers have studied the hybrid structure cable-stayed bridges with different main tower morphologies and proposed applicable methods to optimize the completed bridge cable force for specific engineering backgrounds. However, the overall curved fish-shuttle-shaped main tower brings great challenges to the analysis, and few researches study it, which needs systematic study.

In view of this, based on an asymmetric hybrid-girder cable-stayed bridge with fish-shuttle-shaped single tower in a certain engineering background in China, the finite element software Midas Civil was adopted to build the model of the bridge in this paper. Based on the designed cable forces, the influence matrix method was adopted to optimize the cable forces of this completed cable-stayed bridge, and its reasonable completed bridge state was determined. The results of this study can provide reference for the optimization of cable forces in similar completed cable-stayed bridges.

2 Profile of Project

The studied bridge was a cable-stayed bridge with a single tower, double cable planes, and a tower-girder-pier consolidation system, which has a length of 384 m and a span arrangement of 256 m + 50 m + 40 m + 40 m as shown in Fig. 1. The numbering rule for the stay cables was that the stay cables of the main span was numbered from right to left, with M1 on the far right and M19 on the far left, while that of the edge span was numbered from left to right, with S1 on the far left and S19 on the far right. The support pm17 worked as the end support at the main span of the main girder, and the supports was numbered as pm18, pm19, pm20, and pm21 from left to right, respectively. The layout of the bridge is depicted in Fig. 1.

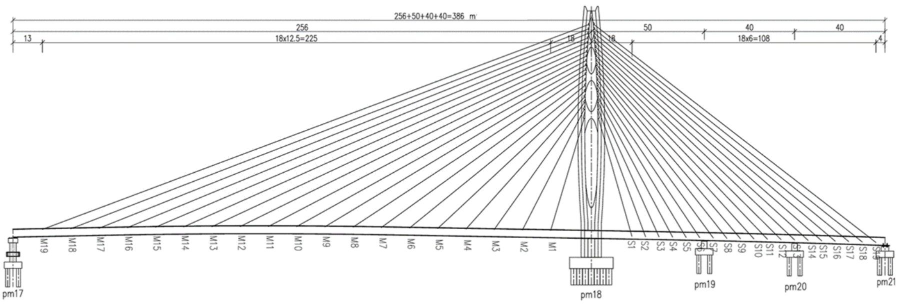


Fig. 1. Layout of the bridge

The type of the main bridge was the asymmetric hybrid-girder cable-stayed bridge with single tower. The steel box girder as main span and the concrete box girder as side span were adopted in the main girder. The fish-shuttle-shaped concrete cable tower with a hexagonal column cross-section and an arched steel cross girder at the top of the tower was used as the main tower. The steel-concrete joint surface was set on the side of the main span which was 12 m away from the centerline of the main tower. The specific design parameters of the materials are listed in Table 1.

Table 1. Parameters of the main materials

Component	Material	Elastic modulus (GPa)	Unit weight ($kN{\cdot}m^{-3}$)
Steel box girder	Q345qc	206.0	78.5
Concrete box girder	C55	35.5	25.0
Main tower	C60	36.0	25.0
Arched steel crossbeam	Q345qc	206.0	78.5
Stay cable	1860 steel strand	195.0	78.5

3 Establishment of Finite Element Model

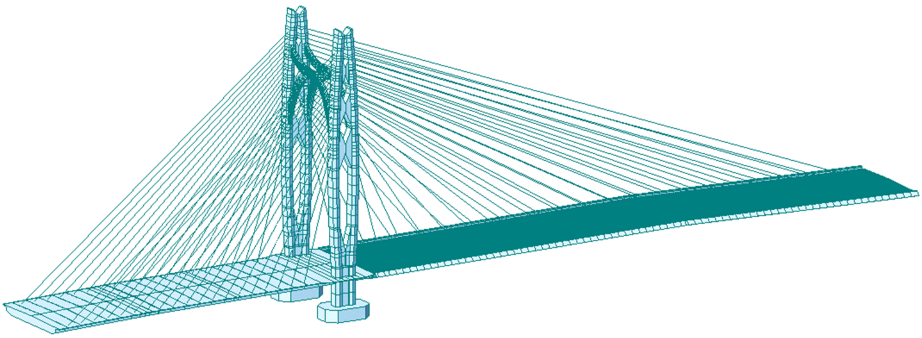


Fig. 2. Finite element model of the cable-stayed bridge

The finite element software Midas Civil was adopted to build the spatial rod system model of the cable-stayed bridge, as shown in Fig. 2. The entire bridge was divided into 509 nodes and 494 units, and the coordinate positions of the main girder and tower units were established according to the actual design elevations. The X-axis, Y-axis of the coordinate system were respectively parallel to the longitudinal and transverse sections of the main girder, and Z-axis was perpendicular to the XY plane. The beam elements were used to simulate the main girder, main tower, and bearing platform, while the stay cables are simulated using truss elements. The consolidation position of the main beam and tower beam was simulated through multi-point rigid connections with the main tower. The shared nodes were adopted to simulate steel-concrete joint section between the steel box girder and concrete box girder. The nodes at the support of the transition pier were used to constrain the translational displacements of UY and UZ, as well as the angular displacements of RX and RZ. The nodes at the bottom of the main tower adopted fixed end constraints. According to the anchor point coordinates of the stay cables, the rigid elements were adopted to connect the stay cables to the main girder and the stay cables to the main tower.

4 Principles of Cable Forces Optimization

The original designed cable forces were obtained by the minimum bending energy method and were adjusted according to the empirical values, which could ensure the satisfaction of the forces and deformations of the cable-stayed bridge, but the reasonable completed bridge state was not reached. The influence matrix method is widely used in the optimization study of cable-stayed bridges with irregular towers, and better optimization results can be achieved [25,27]. The influence matrix method [9] can quickly and efficiently calculate the distribution of the cable force for each tension cable by establishing the relationship between each cable force and bridge response (e.g., displacement, bending moment, etc.). This method is characterized in high computational efficiency and can reasonably adjust the multi-cable structure in a short time, especially for the complex bridge structure such as hybrid structure cable-stayed bridge with irregular tower. Therefore, based on the finite element model established in Section 3 and the designed cable forces, the influence matrix method was adopted to optimize the cable forces of the completed cable-stayed bridge, aiming to minimize the vertical displacements and bending moments of the main girder, and the reasonable completed bridge state was determined.

The specific process of calculation in this paper was as follows: The step 1 was that based on the finite element model of the completed bridge, the cable forces T_0 of the cable-stayed bridge in completed bridge state were calculated. T_0 was calculated by regarding the designed cable forces T of the completed cable-stayed bridge as initial tension F_0, and comprehensively considering the deformation of structure and stress stiffening effect based on self-weight, dead load of phase II and prestressing effect of cable-stayed bridge. The step 2 was to obtain the modulated vector M of stay cables form the differences of T and T_0. The step 3 was that when initial tension force of the cable numbered i in the cable-stayed bridge underwent unit changes, the corresponding bending moment and vertical displacement changes D_i of the main girder generated by each stay cable could be seen as the influence vectors (see Equation (1)). At this time, the influence matrix D of initial tension of cable-stayed bridge was constituted by D_i with a number of n (see Equation (2)). The adjustment vector P of initial tension of stay cables was obtained according to D and M in the step 4 (see Equation (3)). The step 5 was to calculate the optimized initial tension F according to P and F_0 (see Equation (4)). The relative error Δ between T and T_0, and the maximum relative error Δ_{max} of the stay cables was calculated and determined in the step 6. In step 7, the reasonable initial tension determination criteria for cable-stayed bridges was defined, namely $\Delta_{max} \leq 10\%$. If the calculated initial tension of the stay cables of the cable-stayed bridge met the criteria in step 7, the optimization process was completed, and the initial tension of the stay cables at this time was the desired results. If not, the steps 2-6 needed to be repeated until the initial tension results met the criteria above.

$$D_i = (d_{i1}, d_{i2}, \ldots, d_{in})^{\mathrm{T}} \tag{1}$$

where d_{in} is the corresponding bending moment and vertical displacement change of the main girder generated by the n^{th} cable when the initial tension force of the i^{th} cable undergoes a unit change.

$$D_i = \left[D_1, D_2, \ldots, D_n\right] = \begin{bmatrix} d_{11} & d_{21} & \ldots & d_{n1} \\ d_{12} & d_{22} & \ldots & d_{n2} \\ \ldots & \ldots & \ldots & \ldots \\ d_{1n} & d_{2n} & \ldots & d_{nn} \end{bmatrix} \tag{2}$$

$$P=M \cdot D^{-1} \tag{3}$$

$$F=F_0+P \tag{4}$$

5 Analysis of the Optimization Results

5.1 Cable Force

The comparison of designed and optimized cable forces can be seen in Fig. 3. Fig. 3 depicts that the distribution characteristics of large on both sides and small in the middle are satisfied by both designed and optimized cable forces [28]. Overall, the cable forces of short cables are relatively small, while the cable forces of long cables are relatively large, which indicates a gradually increase of cable force from short to long cables. For both designed and optimized cable forces, the cable force from S1 to S19 gradually increases with the increase of cable number, and except for the local mutation in M1, M3, M18 and M19, the cable force from M1 to M19 also meets the trend above, and the differences between the mutation cables and their adjacent cables are within 7%, which indicate that overall circumstance of being too large or too small does not occur. It can be seen that both the designed and optimized cable forces meet the requirements for the reasonable completed bridge state of cable-stayed bridge [28].

The designed cable forces are between 3390~7600 kN, while the optimized cable forces are between 3051~7600 kN. The minimum and maximum cable forces are generated at M3 and S19, respectively. The maximum and minimum differences between the designed and optimized cable forces are 10% and 0%, respectively. The cable force error of the entire bridge is controlled within ± 10%, with an average cable force error of +4.21% on the main span and -3.68% on the side span. It can be seen that the difference between the designed and optimized forces is relatively small, i.e., the cable-stayed bridge can be brought to a reasonable state by adjusting the forces in a smaller range. Results suggest that the optimized cable forces are reasonable enough, and it is feasible to use the influence matrix method to optimize the cable forces of an asymmetric hybrid-girder cable-stayed bridge with fish-shuttle-shaped single tower.

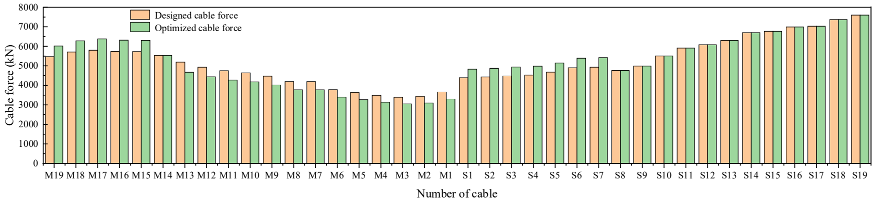
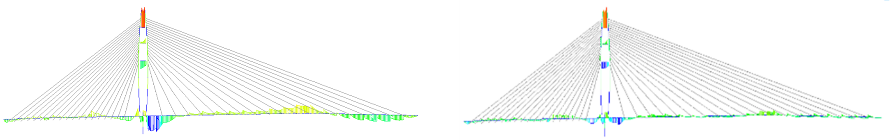


Fig. 3. Comparison of the designed and the optimized cable forces

5.2 Bending Moment

The comparison of bending moments of overall bridge and main girder under designed and optimized cable forces are shown in Figs. 4-5. As shown in the figures, the bending moment of the main span of main girder under designed cable forces is significantly reduced and more uniform, while the bending moment of the side span has no significant changes. The bending moment of the lower tower column of the main tower is significantly reduced, while the bending moment of the upper tower column has no obvious changes. The results above indicate that the bending moment of the overall bridge under designed cable forces is more reasonable. The change tendency of the bending moment of main girder under optimized cable forces is identical to that under designed cable forces, but the bending moment under optimized cable forces decreases significantly and more uniform. The maximum positive bending moment under optimized and designed cable forces are both located at the steel-concrete joint section, where significant positive bending moments are observed in the vicinity. The reason is that in the steel-concrete joint section, stress concentration is occurred by the sudden changes in the stiffness of material, resulting in an increase in bending moment concentration at that location. At the same time, the geometric nonlinearity effect of asymmetric cable-stayed bridge is significant enough to amplify the distribution of the internal forces of the structure, further increasing the bending moment. The maximum positive bending moment under both the designed and optimized cable forces are seated at 12.50 m (x=12.50 m) from the centerline of the main tower on the side of the main span. The maximum positive bending moment under the designed cable forces is 64919.60 kN·m, while the that under the optimized cable forces is 32564.24 kN·m, which decreases by 49.84% compared to that under the designed cable forces. The maximum negative bending moment under the designed cable forces is located near the mid span of the main span, while that under the optimized cable forces is located at the consolidation position of the tower and girder. This is due to the significant geometric nonlinear effect of asymmetric cable-stayed bridges that under the cable forces, the girder at the mid span is prone to "arching" deformation, resulting in a large negative bending moment. For the cable-stayed bridge under optimized cable forces, the shape of it becomes smoother, and the "arching" deformation of the girder at the mid-span reduces, thereby decreasing the negative bending moment at that location to below that of the tower girder consolidation position. The maximum negative bending moments under the designed and optimized cable forces are situated at 144.56 m (x = 144.56 m) and 1.13 m (x = 1.13 m) from the centerline of the main tower on the main span, with values of -34472.00 kN·m and -25042.40 kN·m, respectively. The maximum negative bending moment under the optimized cable forces decreases 27.35% compared to that under the design cable forces. It can be seen that optimization of cable forces has a significant improvement effect on the bending moment of the overall structure, leading to more reasonable stress of main girder, which meets the requirements of the reasonable completed bridge state for the cable-stayed bridge [28].



(a) Designed cable forces (b) Optimized cable forces

Fig. 4. Comparison of bending moments of overall bridge under the designed and optimized cable forces (unit: kN·m)

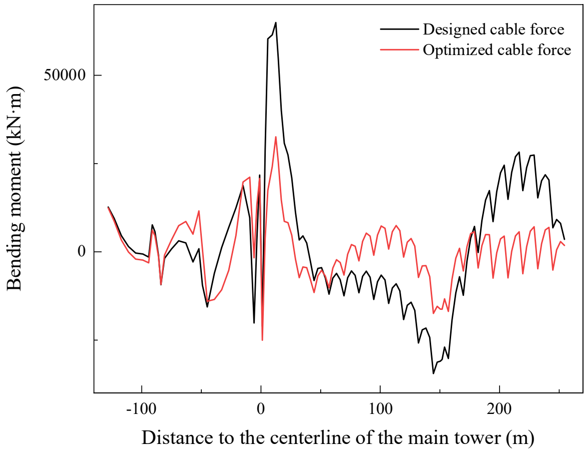
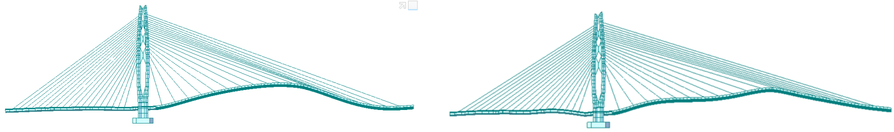


Fig. 5. Comparison of bending moments of main girder under the designed and optimized cable forces

5.3 Displacement

The comparisons of the vertical displacements of the main girder and the deviation displacements of the main tower along the bridge under the designed and optimized cable forces are depicted in Figs. 6-7 and Table 2. The figures indicate that there is a great difference in the shape of the main girder before and after optimization, which shows a more reasonable displacement of the entire bridge under the optimized cable forces. The vertical displacement of the main span of the main girder decreases significantly and become more uniform, while the change of the overall vertical displacement of the side span is not obvious. The deviation displacement of the main tower along the bridge also decreases. The variation trend of vertical displacement of the side span of main girder under optimized cable forces coincides with that of designed cable forces, but the overall values of the vertical displacement diagram of the main span under optimized cable forces tend to be smaller and more stable, showing a significant change in the variation of the vertical displacement of the main span. The maximum vertical positive displacement under optimized and designed cable forces is both at the middle of the main span, where significant vertical positive displacement occurs. This is due to the fact that under uniformly distributed loads, the bending deformation effect of the bridge at the mid-span is the greatest, and the deformation at the mid-span is affected by the great geometric nonlinearity of the asymmetric cable-stayed bridge with single tower, making its vertical positive displacement more prominent. The maximum vertical positive displacement under designed cable forces is located at 127.38 m (x=127.38 m) from the centerline of the main tower on the side of the main span, with a value of 61.01 mm, and that under optimized cable forces is located at 149.25 m (x=149.25 m) from the centerline of the main tower on the side of the main span, with a value of 14.44 mm which reduces 76.33% compared to that under the designed cable forces. The maximum vertical negative displacement under the designed cable forces is located at the 9/10 position of the main span, while that under the optimized cable forces is located near the S1 cable of the side span, both of which are close to the positions of the supports and support points at cables. The reason is that at positions close to the supports or support points at cables, significant vertical negative displacement is induced by the combined effect of great shear force and cable tension. The maximum vertical negative displacement under designed and optimized cable forces is located at 230.50 m (x=230.50 m) and 12.00 m (x=-12.00 m) from the centerline of the main tower on the side of the main span, with values of -5.00 mm and -3.04 mm, respectively. The maximum vertical negative displacement under optimized cable forces decreases 39.20% compared to that under the designed cable forces. In addition, the maximum deviation displacement of the main tower along the bridge under the designed cable forces is 45.5 mm, and that under optimized cable forces is 42.5 mm, which is 6.59% lower than under the designed cable forces, indicating a straighter shape of main tower and lower deviation displacement of main tower along the bridge under optimized cable force. It can be seen that optimizing the cable forces has a significant improvement on the deformation of the overall bridge, which can effectively reduce the vertical displacement of the main girder in the area of main span and the displacement of the main tower along the bridge is limited. In addition, the shapes of both the main girder and the main tower become smoother, meeting the requirements of the reasonable completed bridge state for cable-stayed bridge [28].



(a) Designed cable forces (b) Optimized cable forces

Fig. 6. Comparison of vertical displacements of overall bridge under the designed and optimized cable forces

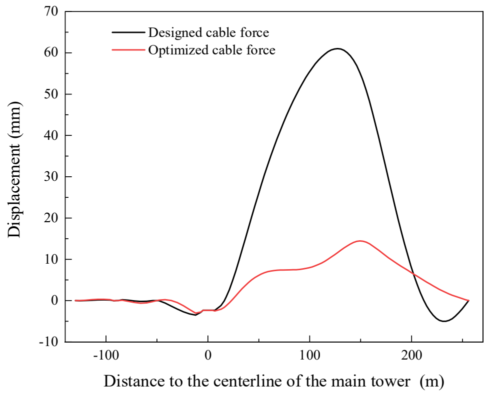


Fig. 7. Comparison of vertical displacements of main girder under the designed and optimized cable forces

Table 2. Comparison of deviation displacements of main tower along the bridge under the designed and optimized cable forces (unit: mm)

Cable force	Deviation displacement	Decrease percentage
Designed cable force	45.5	6.59%
Optimized cable force	42.5	

5.4 Reaction Force of Support

The comparison of reaction forces of support under the designed and optimized cable forces can be seen in Table 3. The reaction force of the support of entire bridge under optimized cable forces is more reasonable, and the support of entire bridge obtains greater pressure reserve with no negative reaction force. The reaction forces of pm17 and pm19 under optimized cable forces are 1474.50 kN and 11536.10 kN with a decrease of 41.61% and 24.28% compared to those under the designed cable forces, respectively, indicating a significantly reduction. The reaction forces of pm18, pm20, and pm21 under optimized cable forces are 261063.20 kN, 11896.90 kN, and 9316.10 kN, respectively, which show no significant changes compared to those under the designed cable forces. The reaction forces of pm18 and pm20 increase by 0.90% and 1.82%, respectively, while the reaction force of pm21 decreases by 1.27%. After the optimization of cable forces, the reaction forces of pm17 and pm19 decrease significantly, obtaining a larger pressure reserve, and the reaction forces of pm18, pm20, and pm21 are not significantly changed. During the process of optimization of cable forces, the cable forces of M15 to M19 and S1 to S7 are increased, with pm17 approaching the support points of M15 to M19 and pm19 approaching the support points of S1 to S7. The stay cables transfer a portion of the vertical load transmitted from the bridge deck to the tower column, then transmit it to the foundation through the tower column. Meanwhile, the tension exerted by the cable on the main girder to some extent offsets the downward pressure of the load of bridge deck on the support, and the upward tension provided directly reduces the reaction force of support, which greatly reduces the vertical load borne by the support close to the cable, resulting in a significant decrease in the reaction force of support. Therefore, the reaction force of support of the overall bridge is significantly improved by optimizing the cable forces, which can effectively reduce the reaction force of support. In addition, greater pressure reserve of supports is obtained with no presence of negative reaction force, which conforms to the reasonable completed bridge state for cable-stayed bridge [28].

Table 3. Comparison of reaction forces of support under the designed and optimized cable forces (unit: kN)

Number of support	Reaction force of support		
	Designed cable force	Optimized cable force	Decrease percentage
pm17	2525.30	1474.50	41.61%
pm18	258734.90	261063.20	-0.90%
pm19	15234.40	11536.10	24.28%
pm20	11684.80	11896.90	-1.82%
pm21	9435.70	9316.10	1.27%

6 Conclusions

Based on an asymmetric hybrid-girder cable-stayed bridge with fish-shuttle-shaped single tower in China, the finite element software Midas Civil is adopted to build the model of the cable-stayed bridge in this paper. According to the designed cable forces, the influence matrix method is used to optimize the cable forces of the completed cable-stayed bridge, and the reasonable completed bridge state is determined. The main conclusions are as follows:

(1) The optimized cable forces range from 3051 to 7600 kN, and no situation of the cable force is too large or too small. On the whole, the cable forces of the short cables are relatively small, while those of the long cables are opposite, which indicates that the cable forces gradually increase with the increase of the length of the cable. Compared with the designed cable forces, the error of overall cable forces is controlled within ±10%, namely, the cable-stayed bridge can reach a reasonable completed bridge

state by adjusting the cable forces in a small range. In addition, it is practical to adopt influence matric method to optimize the completed bridge cable forces of asymmetric hybrid-girder cable-stayed bridge with fish-shuttle-shaped single tower, and the optimized cable forces is reasonable.

(2) The trend of the bending moment of main girder under optimized cable forces is the same as that under the designed cable forces, but the bending moment of main girder under optimized cable forces is significantly reduced with a decrease of the maximum positive and negative bending moments by 49.84% and 27.35%, respectively, and becomes more uniform. Adopting the influence matric method to optimize cable forces bring obvious improvement on the bending moment of overall structure, leading to more reasonable force on main girder.

(3) Compared with the designed cable forces, the maximum positive and negative displacements of main girder and maximum deviation displacement of the main tower along the bridge direction under optimized cable forces are reduced by 76.33%, 39.20%, and 6.59%, respectively, showing a great improvement of the deformation of the whole bridge which can effectively reduce the vertical displacement of the main girder in the main span area. Using the influence matric method to optimize cable forces bring obvious improvement on the deformation of entire structure, leading to smoother linear of main girder and main tower.

(4) Compared with the designed cable forces, the reaction force of support is significantly decreased by optimizing the cable forces, with a maximum reduction of 41.61%, indicating a significant improvement on the reaction force of support of the overall bridge, which effectively reduces the support reaction force. Meanwhile, greater pressure reserve of support is obtained with no presence of negative reaction force. Adopting the influence matric method to optimize cable forces bring obvious improvement on the support reaction of overall structure.

(5) The research object of this paper is an asymmetric hybrid-girder cable-stayed bridge with fish-shuttle-shaped single tower. Currently, cases of cable-stayed bridges with overall curved shapes are not studied extensively, bringing considerable challenges to the analysis of cable forces of the completed bridge like the bridge studied in this paper, which is worth to study. Further research can be conducted on the optimization of cable forces of cable-stayed bridges with curved shapes such as octopus-shaped and crab-shaped.

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