WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2022.140657
ARCHIVES OF CIVIL ENGINEERING
Vol. LXVIII ISSUE 2 2022

pp. 531 –548

Research paper

Analysis of static performance of cable-stayed arch cooperative bridge without back cable

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Abstract: In this paper, the stiffness and internal force of the finite element model of a cable-stayed bridge, arch bridge and cooperative system bridge with the same span are analyzed, and the stress characteristics of cooperative system bridge compared with arch bridge and cable-stayed bridge are studied. In the stiffness analysis, the live load deflections of the arch bridge (maximum deflection –6.07 mm) and the cooperative system bridge (maximum deflection –6.00 mm) are similar, while the cable-stayed bridge (maximum deflection –16.27 mm) has a larger deflection. In the internal force analysis, compared with the internal force of the main girder, it can be seen that the girder of the cooperative system bridge reduces the girder-column effect compared with the cable-stayed bridge. The main girder of the cooperative system bridge reserves more stress than the arch bridge. In the stress analysis of arch rib, the axial force and bending moment of arch rib under dead load of cooperative system bridges are greater than the cooperative system bridge. The maximum difference of axial force and bending moment between arch bridge and cooperative system bridge is 16.2% and 58.8%, but there is no obvious difference under live load. In the stress analysis of the cable tower, the advantages of the cooperative system bridge are more obvious under dead load and live load. In the comparative analysis between the cable and the derrick, the dead load and live load are mainly carried by the derrick, and the derrick bears 84% dead load and 97% live load. The research results can provide reference for the stress analysis of similar bridge structures.

Keywords: arch rib, collaborative system bridge, internal force analysis, stiffness analysis force, stay-cables

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1. Introduction

As an important structural form of bridge, cable-stayed bridge appeared in the 17th century and developed in the 20th century [1, 2]. In the early 20th century, cable-stayed bridges developed rapidly with the development, improvement and production of high-strength and high-elastic steel wire and its anchor system, as well as the improvement of orthotropic steel bridge decks [3–5]. The typical ones are: Severin Bridge built in Cologne, Germany in 1959; Normandy Cable-Stayed Bridge, France; The steel box girder cable-stayed bridge of the South Branch of the Second Nanjing Yangtze River Bridge and the Russian Island Bridge, built in 2012, ranked first with a span of 1104 m. However, with the increase of the span of the cable-stayed bridge, the stability of the cantilever section of the stiffening girder before closing is difficult to be guaranteed. The axial force of the stiffening girder increases obviously, the deadweight ratio of the stiffening girder increases, the height of the bridge tower increases, and the sag effect of the cables is obvious. As one of the basic forms of bridges, arch bridge has a history of more than 3,000 years [6, 7]. With the continuous innovation of arch bridge construction materials, construction technology and design theory, from the stone arch bridge in BC to the concrete arch bridge and simple steel arch bridge in the 19th century, and then to the truss arch bridge and concretefilled steel tube arch bridge in the 20th century, until now, the span and structural form of arch bridge have made great breakthroughs. For example, Chaotianmen Yangtze River Bridge, which opened to traffic in China in 2009, is the largest arch bridge with the main span in the world. The main bridge adopts the structure of (190 + 552 + 190 m) continuous steel-truss tie-arch bridge. The main span is installed with full arm assisted by cable tower, arch first and then girder, and closed in the middle span. However, with the breakthrough of arch bridge structure and span, a series of shortcomings have been exposed. With the increase of span, the deadweight of traditional arch bridge increases, and the difficulty of cable construction increases. On the other hand, the concrete filled steel tube arch bridge is prone to corrosion and concrete emptiness in the pipe. Steel arch bridge has high cost, high maintenance cost and outstanding stability problem. Cable-stayed bridge and arch bridge are the types of long-span bridge widely used in the world at present, but their shortcomings restrict the further development of bridge span, and their existing problems need to be solved urgently.

In recent years, people have increasingly high requirements for bridge aesthetics, and the engineering field has proposed many cooperative system bridges of cable-stayed bridge or arch bridge. This new type of bridge can give full play to the respective advantages of cable-stayed bridge and arch bridge, increase the span capacity of the structure and improve its own stiffness and stability [8–12]. Cable-stayed bridge, or arch bridge of cooperation system bridge, though a time early, but development is very slow, mainly due to the complexity of cooperation system bridge structure mechanical characteristics, related design theory is not mature, construction management is not perfect, some of the traffic cooperative system bridge accidents, make people remain sceptical of bridges of cooperation system, However, the development of the related cooperative system bridge plays a great role in the breakthrough of the bridge industry. At present, the theoretical research on cable-stayed arch cooperative bridge system is still in its initial stage, and some scholars have carried out the following researches:

Zhao Yueyu et al. [13] studied the mechanical characteristics of cable-stayed arch bridge and the difference of internal force distribution between the bridge and the ordinary arch bridge through example calculation, and obtained the optimal results of the internal force of the arch structure by the cable in the cable-stayed arch bridge. By comparing the bridge with the common arch bridge and analyzing the variation of the angle of the cable, the mechanical characteristics and economic performance of the bridge are given, which can provide a reference for the design and scheme selection of the new bridge. Sun Quansheng [14] et al. took Dalian Xiangfenghe cable-stayed arch bridge without back cables as the main research background, established a spatial finite element model with the help of finite element calculation software MIDAS/Civil. They analyzed the stress characteristics of the arch bridge without back cables, obtained the cable-stayed cable force and suspender cable force of the structure in different construction stages, and summarized the variation trend of cable force. The variation trend of the internal forces of the main girder and arch ribs under various design combinations is analyzed. Yi Zhuangpeng et al. [15] compared the similarities and differences between cable-stayed arch bridge, cable-stayed bridge and arch bridge, analyzed the structural characteristics of cable-stayed arch bridge, discussed the influence of the change of the Angle of the cable on the static performance of the bridge, and obtained the distribution law of the internal force of the main arch and stability coefficient when the Angle of the cable changes. Kang Houjun et al. [16] conducted a comparative study on the two cable-stayed arch bridges from the perspective of structural system and construction. Taking the fourth Xiangjiang River Bridge under construction in Xiangtan City as an example, the three-dimensional finite element model of the cable-stayed arch bridge was established by using ANSYS software. The influence of cable arrangement on the static and dynamic characteristics of cable-stayed arch bridge is analyzed, which provides reference for the design and construction of cable-stayed arch bridge. Yan Xiaoxin [17] et al. studied the in-plane nonlinear stability of cable-stayed arch bridges under different boundary conditions and load conditions by analyzing the cable-stayed arch bridges, and discussed the influence of cable parameters on the in-plane stability of the cable-stayed arch bridges.

2. Background

Xiangfeng River Bridge is a cooperative system of cable-stayed bridge without back cables and special-shaped arch bridge, with a span layout of 40 m + 90.5 m. The total width of the bridge deck is 39–43 m, two-way six lanes, and the design load is highway – I level. The bridge span is orthogonal to the road design line and oblique to the river line. The longitudinal slope of the bridge deck is 2.029% for small piles and 1.794% for large piles. The vertical curve is a circular arc with a radius of $R = 1500$ m. The carriageway shall be provided with a cross-slope of 1.5% in both directions, and the sidewalk shall be provided with a one-way (inward) cross-slope of 1%.

The main girder is prestressed concrete cast-in-place box girder with a girder height of 2.7–3.8 m. The tower is a concrete section with a height of 59.5 m above the bridge deck. The stay cable distance is 8.5 m, a total of 8; The arch ribs are two pieces of steel box structure, only concrete is poured at the arch foot. The elevation of the bridge deck is 25.80 m. The suspender cable distance is 4.25 m, and the whole bridge is 38.00 m long in total. The pier is a solid pier, the abutments are light abutments, and the foundation is a bearing abutment with bored cast-in-place piles.

The present situation of Xiangfeng River Bridge is shown in Figure 1, and the layout diagram of the bridge is shown in Figure 2.

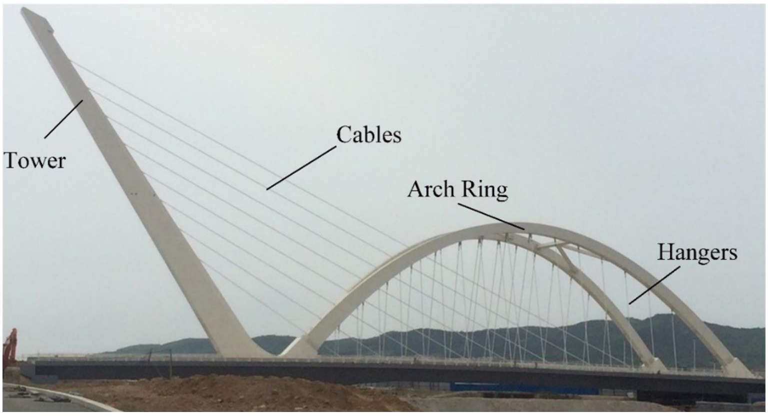

Fig. 1. Present situation of Xiangfeng River Bridge

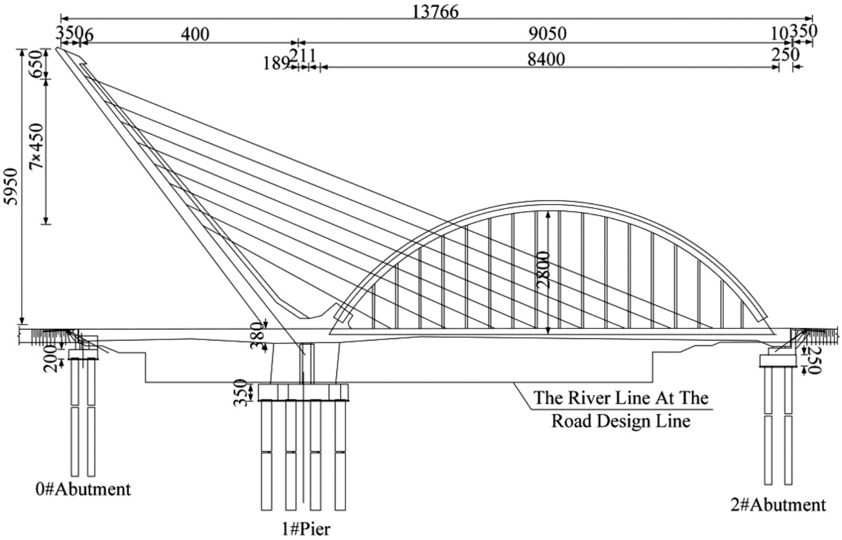

Fig. 2. Schematic diagram of Xiangfeng River Bridge (Unit: cm)

3. Static performance analysis of cable-stayed arch cooperative bridge system

3.1. Stress characteristics of cable-stayed arch cooperative bridge

The cable-stayed arch cooperative system bridge is a new type of composite bridge, which is composed of main girder, cable tower, arch rib, stay cable, suspender, foundation and so on. When the bridge is completed, the self-weight and external load of the structure are borne by the cable towers, arch ribs, main girders, stay cables and suspenders. Its stress characteristics are the main arch ring under pressure, with the tension of the tower, the advantages of the cable-stayed bridge without back cable and arch bridge are integrated, in the case of reducing the height of the cable-stayed bridge without back cable, shortening the length of the cable stayed cable, reducing the area of the tower, the Angle of the tower and the arch ratio to meet the requirements of the same span and width of bridge design. Suspension research by the coordination system of arch bridges and derrick anchor cable on main girder, the girders of multi-point flexible support, increased the number of statically indeterminate, greatly reducing the span of the bending moment and axial force, increase the leaping ability of main girder, and the existence of the arch rib is also improved the outside surface of the whole structure of the bridge wind resistance stability, increase the integral stiffness, increase the natural frequency of vibration, reduce the effect of long sag of stay cables and improve the stability of bridges [18–20].

The dead and live loads of the main girder are transmitted to the cable tower, the derrick to the arch rib, and then to the pier and foundation through the cable tower and the arch rib, respectively. In addition to the bending moment, the main girder also bears the huge axial pressure from the cable, and there exists the girder-column effect. The main girder of the cable-stayed arch cooperative system bridge studied is a multi-chamber prestressed concrete box girder with a width of 39–43 m. The dead-weight of the main girder is large, which means that a lot of load and weight of the main girder need to be balanced per unit tower weight. The commonly used methods include increasing the angle of the tower or increasing the section of the tower. The arch ribs assist the tower to bear the load, and the load of the main girder can be balanced without increasing the angle of the tower or the section of the tower. Under the distributed load, the unbalance force of the middle span and side span is mainly borne by the arch rib and transmitted to the pier, and the force of the cable tower is very small, so the bending moment of the tower root can be greatly reduced in the cable-stayed arch cooperative system bridge. Under the live load, the stiffness of cooperative system bridge shows the stiffness characteristics of arch bridge. The live load is basically transferred by the suspender. The live load is transferred to the suspender through the main girder, and the suspender is transferred to the arch rib, and then the arch rib is transferred to the substructure. Therefore, the cable-stayed arch cooperative system bridge can greatly reduce the tower bending moment. Compared with the arch bridge, the main girder of the cooperative bridge has more compressive stress under dead load, and less prestressed steel bundles can be prepared. The girder-column effect of cooperative bridge is less than that of cable-stayed bridge. Under the heavy load, the cooperative system bridge has more advantages than the arch bridge. Compared with the arch bridge, the span of the cooperative system bridge can be larger.

Although the theory of cable-stayed arch cooperative bridge system is not mature and is seldom used, it cannot be denied that the bridge system has its unique advantages. The cable-stayed arch cooperative system bridge not only displays the characteristics of arch bridge and cable-stayed bridge, but also makes the advantages of the two types of bridge complement each other, and gets a better structural system than the cable-stayed bridge and arch bridge.

Based on the Xiangfeng River Bridge in Dalian, the second cable-stayed arch cooperative bridge under construction in China, this paper analyzes the stiffness and internal forces of the cable-stayed bridge, arch bridge and cooperative system bridge with the same span, and obtains the stress characteristics of the cooperative system bridge compared with the arch bridge and cable-stayed bridge. It provides reference for the design and construction of similar bridges, and promotes the development of this type of bridges.

3.2. Stiffness analysis of cable-stayed arch cooperative bridge system

Taking Xiangfeng River Bridge as the research object, three finite element models are established respectively: The arch bridge, cable-stayed bridge and cable-stayed arch cooperative system bridge are simulated. Regardless of the influence of construction stage, the three models have the same linear shape, main girder material, cable tower material and arch rib material except for the different structure forms. The cable towers and arch ribs are removed respectively on the basis of the cable-stayed arch cooperative system bridge. By increasing the section size of the cable tower of the cable-stayed bridge, compounding the cable, adjusting the tension of the cable and adjusting the tension of the suspender of the arch bridge, the deformation of the three models under dead load is equivalent (3.36 mm, 3.55 mm and 3.44 mm, respectively).

According to the structural parameters of the three proposed above, the stiffness characteristics are analysed. The live load is highway class I, with six lanes, and the lateral reduction of the lane is 0.55. Considering the partial load coefficient and length reduction coefficient, the main span is calculated under the adverse situation of full live load. The deflection curves of the three bridges are shown in Figure 3.

It can be seen from Figure 3 that the live load deflection of arch bridge (maximum deflection –6.07 mm) and cooperative system bridge (maximum deflection –6.00 mm) is similar, while that of cable-stayed bridge (maximum deflection –16.27 mm) is larger. Compared with the cable-stayed bridge, the stiffness of arch bridge and cooperative system bridge is greatly improved. In addition, it can be seen from the figure that the live load of the main span has little influence on the side span. This is because the arch of the tower girder is consolidated at Pier 1 with large stiffness. The live load of the main span is mainly transferred to the foundation through Pier 1.

Based on the same live load, the deformation curve of the half-span near the No. 1 pier is analyzed under asymmetric loading. For the half-span of the main span, the corresponding deflection curve is shown in Figure 4.

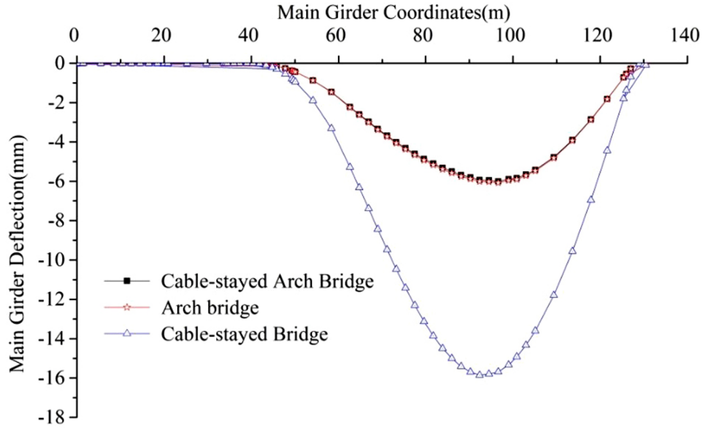

Fig. 3. Deflection curve of main span under full span loading

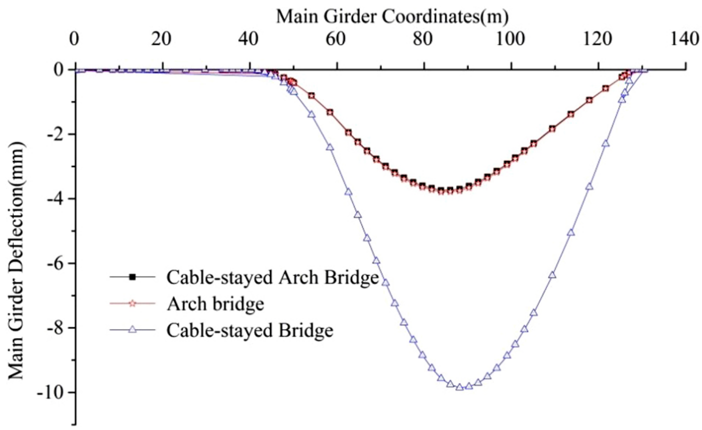

Fig. 4. Loading deflection curve of main span and half span

When half span is loaded, the deflection trend of main girder is the same as that of full span. The maximum deflection of arch bridge is 3.78 mm, that of cable-stayed bridge is 9.85 mm, and that of cooperative bridge is 3.74 mm. The maximum deflection position of main girder is shifted to pier 1#, arch bridge and cooperative system bridge is shifted to pier 1# by 12.75 m, cable-stayed bridge is only shifted by 2.12 m. It may be due to the following reasons: Cooperation system bridge under live load, the stiffness of arch bridge rigidity characteristics, basic by the boom of live load. Live load effect through the main girder is passed to the boom, boom is passed to the arch rib, again by the arch rib is passed to the lower structure. When applying partial load to load on one side of the derrick stress is larger, and partial load lateral offset from the position of maximum deflection. However, the live load of the cable-stayed bridge is mainly borne by the cable near the No. 1 pier side, so the load position has relatively little influence on its maximum deflection position.

3.3. Internal force analysis of cable-stayed arch cooperative bridge

In the structure of cable-stayed bridge, the main girder is affected by the horizontal component force of the cable, which produces great axial pressure. This structural system will directly affect the size of the main girder. The main tower is subjected to the vertical component force of the stay cable to produce axial pressure. At the same time, the unbalanced bending moment is caused by the unbalanced horizontal component force of the cable, and the girder-column effect will increase the bending moment of the tower root. In the arch bridge structure, due to the horizontal reaction force at the support, the bending moment of the arch is much smaller than that of the girder with the same span, so the arch is mainly under the state of axial pressure. The cable-stayed arch cooperative bridge takes into account the stress characteristics of both the cable-stayed bridge and the arch bridge, but there are obvious differences. In order to study the differences of internal forces among the three bridges, the same structure as above is adopted to compare the internal forces of the same span arch bridge, cable-stayed bridge and cooperative system bridge under dead load and live load.

3.3.1. Contrastive analysis of main girder forces

Under dead load, the axial force and bending moment of main girder of arch bridge, cable-stayed bridge and cooperative system bridge are shown in Figure 5 and Figure 6. Under live load, the maximum axial force and maximum bending moment of the main girder are shown in Figure 7 and Figure 8. The pressure is negative and the pull is positive.

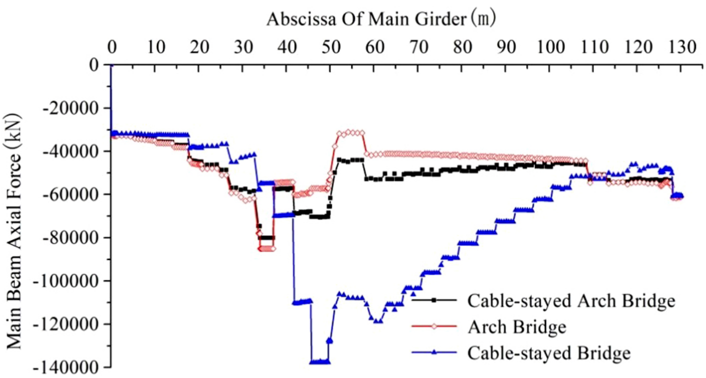

Fig. 5. Axial force diagram of the main girder under the dead load

It can be seen from Figure 5 to Figure 8 that the axial force and bending moment of the three structural systems under the dead load and the live load have the same variation trend due to the same main girder size. Under live load, the axial force and bending moment of arch bridge and cooperative system bridge are basically the same, while the axial force of cable-stayed bridge is relatively small and the bending moment is relatively large.

Under the dead load, the main girder is in a state of full compression. The axial force of the main girder increases first and then decreases. It reaches the maximum at pier 1#.

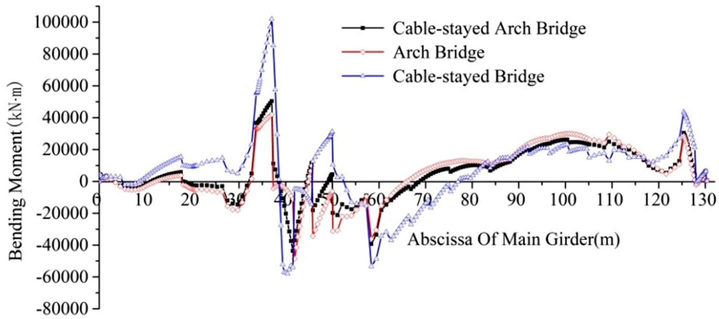

Fig. 6. Bending moment diagram of the main girder under the dead load

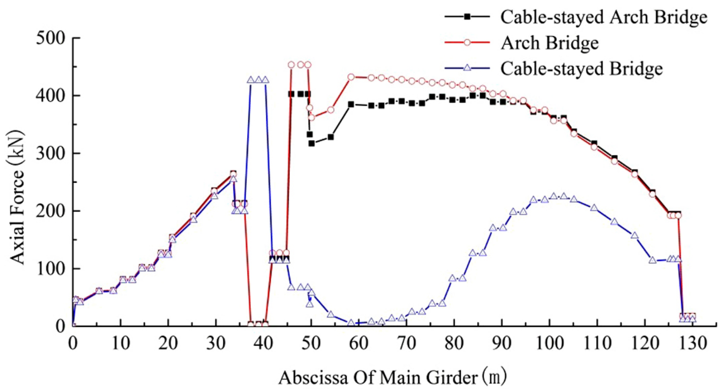

Fig. 7. Maximum axial force diagram of main girder under the live load

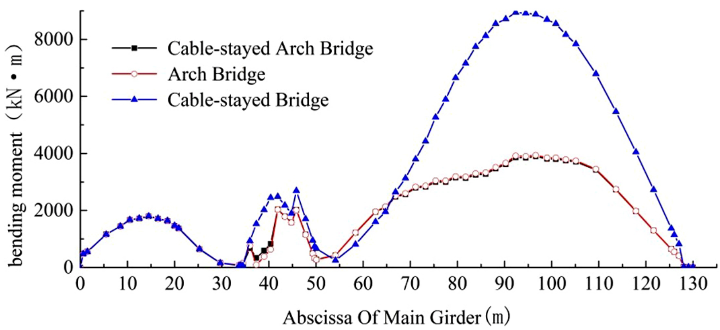

Fig. 8. Maximum bending moment diagram of main girder under the live load

The main girders of arch bridge, cable-stayed bridge and cooperative system bridge are all equipped with the same prestressed steel girders, which make the main girders under compression. The cable-stayed bridge with the side span and near the 2# pier area has the smallest axial force, followed by the cooperative system bridge. The arch bridge has the largest axial force. In the cable or suspender area, the arch bridge has the smallest axial force (–30893 kN), followed by the cooperative system bridge (–43602 kN), and the cable-stayed bridge has the largest axial force (–137930 kN). Where the pressure is negative and the tension is positive. Due to the synergistic force of suspension rods and cables, the tension of suspension rod and cable is smaller than that of arch bridge and cable-stayed bridge. The axial force of the main girder of the cooperative system bridge and cable-stayed bridge is affected by the horizontal component force of the cable, so the axial force in the cable area is relatively large, while the cable tension of the cable-stayed bridge is larger than that of the cooperative system bridge. The axial force in the cable area of the cable-stayed bridge is the largest. Therefore, compared with the arch bridge, the main girder of the cooperative system bridge with the same span has more compressive stress under dead load, and less prestressed steel bundles can be prepared.

Under the action of dead load, the bending moment of the side span increases obviously except the position near 4 m of the cable tower. The bending moment of the main girder reaches the maximum at the junction of the tower and girder. The bending moment of the cooperative system bridge is 50429 kN·m, the bending moment of the arch bridge is 41971 kN·m, and the bending moment of the cable-stayed bridge is 102027 kN·m. Because there is girder-column effect in cable-stayed bridge, and the force of cable-stayed bridge tower is greater than that of cooperative bridge, so it has a greater influence on the main girder. The bending moment of main girder of cable-stayed bridge changes most obviously along the span direction, and the bending moment of main girder of cooperative bridge is less than that of arch bridge.

Under the action of live load, the maximum axial force of side span main girder of the three bridges is basically the same and increases gradually along the span direction. At the arch junction of tower girder, the maximum axial force of main girder of arch bridge and cooperative system bridge decreases first and then increases, while that of cable-stayed bridge increases first and then decreases. The maximum axial force of the main girder of the main span arch bridge and the cooperative system bridge gradually decreases, while the cable-stayed bridge presents the trend of sinusoidal curve. The maximum axial force of the cooperative bridge is 403 kN, and the maximum axial force of the arch bridge is 453 kN, which occurs at the junction of the arch girders. The maximum axial force of the cable-stayed bridge is 426 kN, which occurs at the junction of the tower and girder. The bending moment of main girder under live load can be divided into three sections: side span section, arch junction section of tower girder and main span section. All the three sections show an overall trend of increasing at first and then decreasing. The maximum bending moment of the cooperative girder bridge is 3895 kN·m, the maximum bending moment of the arch bridge is 3938 kN·m, and the maximum bending moment of the cable-stayed bridge is 8943 kN·m, all of which occur in the mid-span position of the main span.

Under the action of dead load, the main girder belongs to the compression bending state. Under the action of live load, the main girder is in a stretch-bending state. The maximum axial force of the main girder of the cooperative system bridge under dead load is –108.2 times of that under live load, and the maximum bending moment is 12.9 times of that under live load, which shows that the proportion of the structure under dead load is large.

3.3.2. Contrastive analysis of stress on arch ribs

Under dead load, the axial force diagram and bending moment diagram of the arch rib are shown in Figure 9 and Figure 10, while under live load, the maximum axial force diagram and bending moment diagram of the arch rib are shown in Figure 11 and Figure 12.

According to Figure 9–12, under dead load, the arch rib axial force and bending moment of the arch bridge are both larger than those of the cooperative system bridge. The maximum

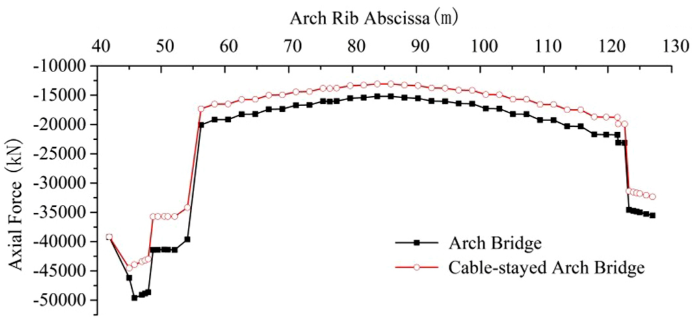

Fig. 9. Axial force diagram of arch ribs under dead load

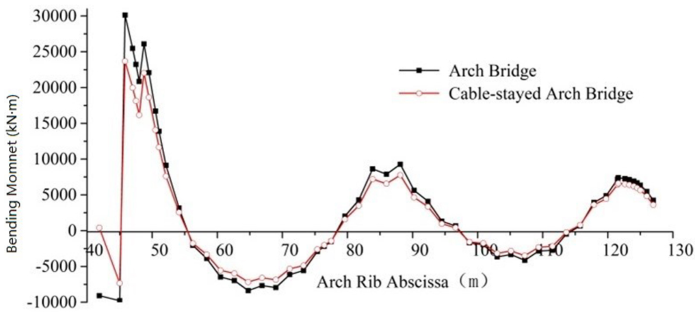

Fig. 10. Bending moment diagram of arch ribs under the dead load

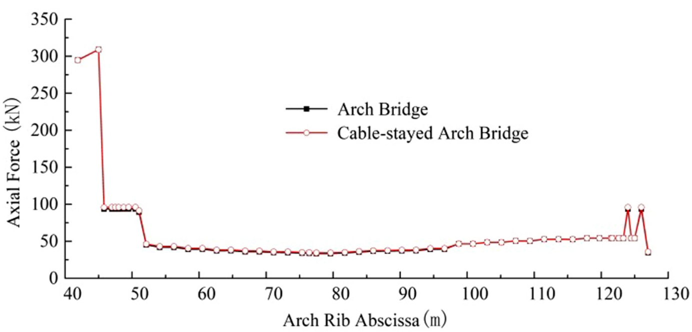

Fig. 11. Maximum axial diagram of arch ribs under the live load

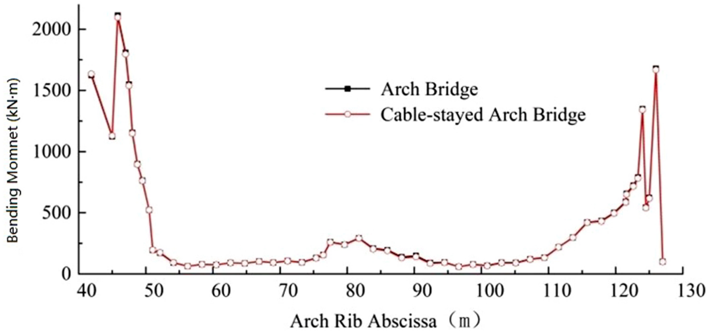

Fig. 12. Maximum bending moment diagram of arch ribs under the live load

difference between the arch bridge and the cooperative system bridge is 16.2% in axial force and 58.8% in bending moment. Under live load, the maximum difference of axial force and bending moment between arch bridge and cooperative system bridge is 3.0% and 6.0% respectively. In other words, the internal forces of the arch ribs of the cooperative bridge under dead load are better than those of the arch bridge. Under live load, there is no obvious difference in the internal forces of arch rib between arch bridge and cooperative bridge. The dead load internal force is far greater than the live load internal force which means under the action of large load, the advantages of the cooperative system bridge are more prominent than the arch bridge. The span of the cooperative system bridge can be larger than the arch bridge.

3.3.3. Force comparison analysis of cable tower

Under dead load, the axial force diagram and bending moment diagram of the cable pylon are shown in Figure 13 and Figure 14. Under live load, the maximum axial force diagram and bending moment diagram of the cable pylon are shown in Figure 15 and Figure 16.

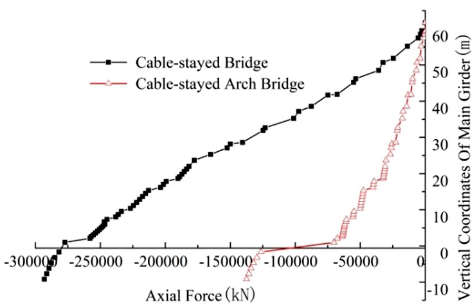

Fig. 13. Axial force diagram of tower under dead load

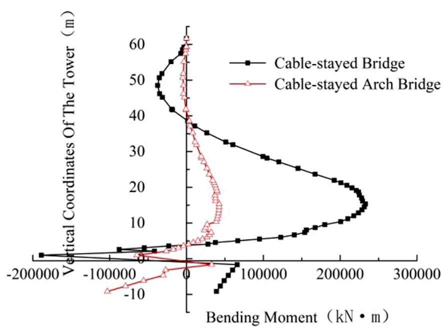

Fig. 14. Bending moment diagram of tower under dead load

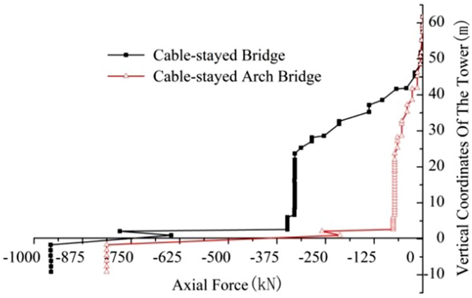

Fig. 15. Axial force diagram of tower under live load

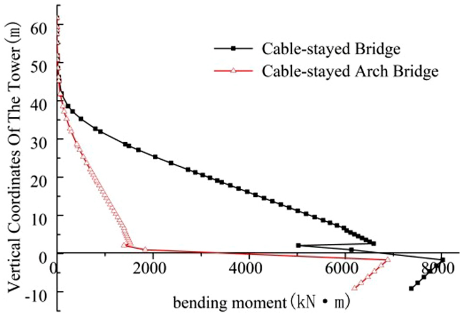

Fig. 16. Bending moment diagram of tower under live load

As shown in Figure 13 to Figure 16, under dead load, the maximum axial force of the cooperative system bridge is –137431.23 kN. The maximum axial force of the cable-stayed bridge is –293012.81 kN, which is 2.13 times that of the cooperative system bridge. The maximum positive bending moment of the cooperative system bridge is 42,525 kN·m, and the maximum positive bending moment of the same section of the cable-stayed bridge is 232,965 kN·m, which is 5.48 times that of the cooperative system bridge. Under live load, the maximum axial force of the cable-stayed bridge is 1.18 times that of the cooperative bridge, and the maximum bending moment of the cable-stayed bridge is 1.17 times that of the cooperative bridge.

It can be seen that the stress of the cooperative bridge pylon is less than that of the cable-stayed bridge under dead load and live load, especially in the area with lower pylon, the superiority of the cooperative bridge is more obvious. Since the cable tower is consolidated with the main girder and the model is a rod system model, there is a sudden change in the force in the junction area between the main girder and the cable tower. But the main girder shares part of the load for the cable tower in the junction area. The cable tower is a bending structure under dead load and live load, and the force near the tower root is large.

3.3.4. Force analysis of stay cable and derrick

In order to analyze the cooperative force characteristics of the suspension and stay cables of the cooperative system bridge, the suspension and stay cables are removed respectively in the cooperative system bridge. The internal forces of the suspension and stay cables corresponding to the cooperative system bridge under dead load are compared. The corresponding internal force values are shown in Figure 18 and Figure 19 respectively, and the internal force variables are shown in Table 1. Among them, the numbers of the stay cables from the root to the top of the tower are S01–S08, and the numbers of the derrick are shown in Figure 17. Since the left arch rib and the right arch rib are arranged symmetrically, the force under symmetrical load is the same, so only the internal force of the left arch rib hanger is listed in this paper.

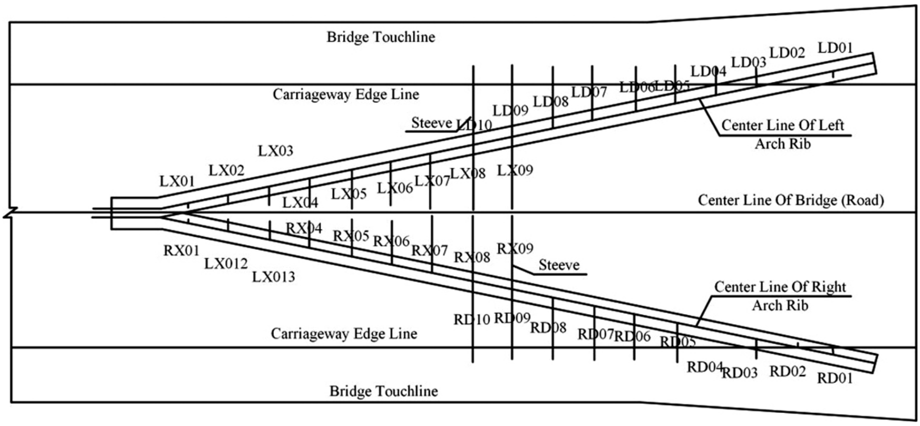

Fig. 17. Schematic diagram of suspension rod numbers of cooperative system bridge

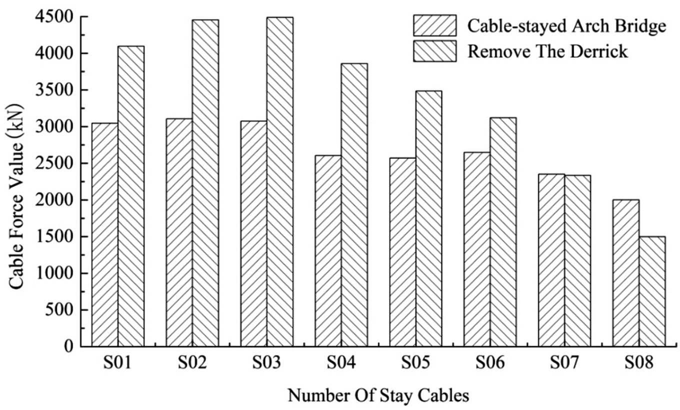

Fig. 18. Comparison of internal forces under dead load on cables

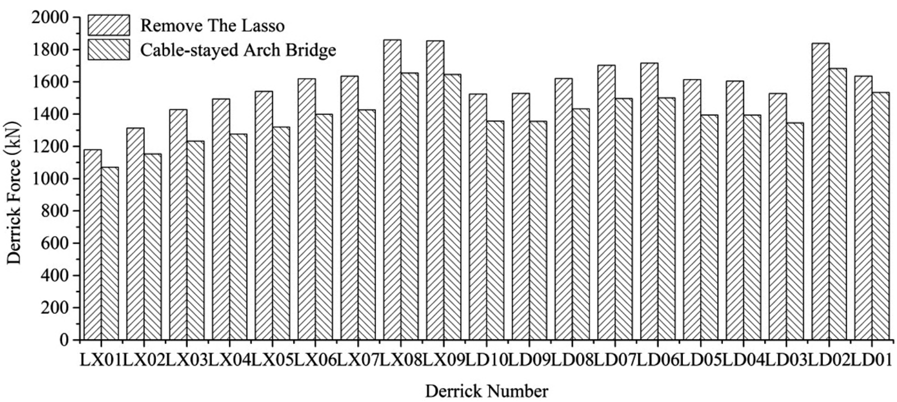

Fig. 19. Comparison of internal force under dead load on derrick

Table 1. Variables of internal force under dead load

Serial number	Variable	Serial number	Variable	Serial number	Variable
S01	34.50%	LX02	14.00%	LD09	12.80%
S02	43.50%	LX03	15.90%	LD08	13.10%
S03	45.90%	LX04	17.00%	LD07	13.70%
S04	48.10%	LX05	16.70%	LD06	14.40%
S05	35.60%	LX06	15.80%	LD05	15.80%
S06	17.80%	LX07	14.70%	LD04	15.10%
S07	–0.70%	LX08	12.40%	LD03	13.50%
S08	–25.10%	LX09	12.70%	LD02	9.30%
LX01	10.10%	LD10	12.40%	LD01	6.60%

As can be seen from Figure 18, Figure 19 and Table 1, under dead load, the internal force value of cable or hanger under separate force is larger than that under joint action. The maximum increment of internal force of cables and hangers is 48.1% and 17.0% respectively, and the internal force of hanger changes more evenly. The number of hanger rods is 4.75 times of the number of stay cables, so the change of internal force of the hanger rods is smaller than that of the stay cables when the force is applied alone. This also indicates that the internal force of the derricks is less affected by the stay cables. Under dead load, the internal forces of cables and derricks have the same trend, the internal forces of cable decrease from the root to the top of the tower, and the internal forces of derricks show a gentle "hump-shape".

Internal force of cables and derricks under dead and live loads are shown in Figure 20 and Figure 21. According to the figures, under dead load, the average cable force value of the stay cable is 2676 kN, and the average hanger force of the hanger rod is 1403 kN. Under the action of live load, the average cable force value of the stay cable is 26 kN, and the

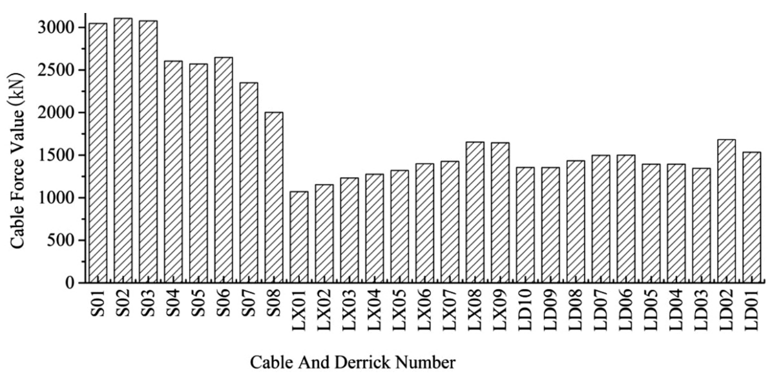

Fig. 20. Internal force value under dead load

average derrick force is 74 kN. The load of the main span of the bridge deck is transmitted to the foundation through the arch ribs and pylons. Both the dead load and the live load are mainly borne by the hangers. The cables bear 16% dead load and the hangers bear 84% dead load. While the cables bear 3% live load and the hangers bear 97% live load.

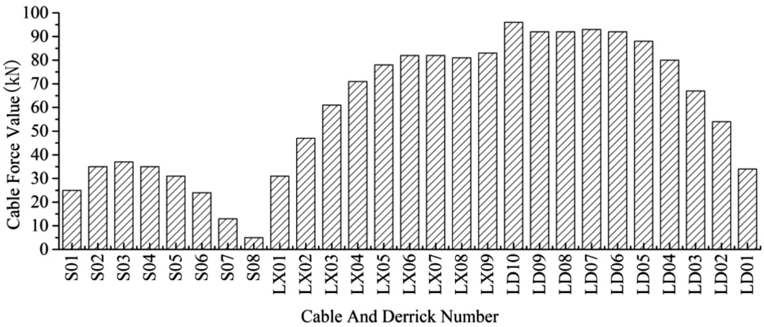

Fig. 21. Internal force value under live load

4. Conclusions

In this paper, the static performance of cable-stayed arch cooperative system bridge, cable-stayed bridge and arch bridge with the same span are compared and analyzed. The following conclusions can be drawn:

1. Under the same live load, the live load deflections of arch bridge and cooperative system bridge are similar, while those of cable-stayed bridge are larger. The stiffness of cooperative system bridge under live load is the stiffness characteristic of arch bridge. The live load is transferred to the suspender by the main girder, and the suspender is transferred to the arch rib, and then the arch rib is transferred to the substructure.
2. From the internal force analysis, it can be seen that the main girder of the cooperative system bridge reserves more compressive stress than the arch bridge under dead load, so less prestressed steel bundles can be prepared. Compared with the cable-stayed bridge, the girder-column effect of the cooperative bridge can be reduced. Under live load, the main girder axial force and bending moment of arch bridge and cooperative system bridge are similar, the main span axial force of cable-stayed bridge is less than that of arch bridge and cooperative system bridge, and the bending moment is vice versa. The internal forces of the arch ribs of the cooperative bridge under dead load are better than those of the arch bridge. Under the action of live load, there is no obvious difference in the internal forces of arch rib between arch bridge and cooperative bridge. That is to say, under the action of large load, cooperative bridge has more advantages than arch bridge. Compared with arch bridge, cooperative bridge has a larger span. Under dead load and live load, the force of the cable tower of the cooperative system bridge is less than that of the cable-stayed bridge, and the

main girder shares part of the load for the cable tower in the connection area of the tower and girder. The cable tower is a bending structure under dead load and live load, and the force near the tower root is large.

3. Under the action of dead load, the main girder belongs to the pressure-bending structure, and under the action of live load, the main girder is in the tension-bending state. The maximum axial force of the main girder of the cooperative system bridge under dead load is –108.2 times of that under live load, and the maximum bending moment is 12.9 times of that under live load, which shows that the proportion of the structure under dead load is large.
4. Under dead load, the internal force of cable or hanger is greater when the cable or hanger are acted separately than when they act together. The maximum increment of internal force of cable and hanger is 48.1% and 17.0% respectively, and the change of internal force of hanger is more uniform. Dead load and live load are mainly supported by derricks. The cables bear 16% dead load and the hangers bear 84% dead load. While the cables bear 3% live load and the hangers bear 97% live load.

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Received: 01.11.2021, Revised: 01.02.2022