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STUDY ON THE INFLUENCE OF CABLE/SLING DAMAGE ON THE NATURAL VIBRATION CHARACTERISTICS OF SPECIAL-SHAPED CABLE-STAYED ARCH BRIDGE WITHOUT BACK CABLE

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ABSTRACT

In order to study the influence of cable/sling damage on the natural vibration characteristics of a special-shaped cable-stayed arch bridge without back cable. The natural vibration characteristics of the bridge with different cable/sling damage and their different damage degree are analysed. According to the characteristic of self-vibration of cable-stayed arch bridge without back cable, the structural health of bridges can be diagnosed and evaluated.

KEYWORDS

Cable-stayed arch bridge without back cable, Natural vibration frequency, Stay cable, Mode of vibration, Sling

INTRODUCTION

Cable-stayed arch bridge without back cable is a new type of bridge structure which combines backless a cable-stayed bridge with an arch bridge. It has the characteristics of backless cable-stayed bridge and arch bridge, and its unique shape gives people a unique aesthetic feeling [1-3]. The cable-stayed structure can balance the dead weight of the main girder by the inclined bridge tower and enhance the longitudinal bending resistance of the main girder. The special-shaped arch structure ensures the transverse mechanical properties of the broad beam and makes the whole structure work harmonically [4-5]. Due to the material characteristics of cable or sling and the impact of the natural environment, the probability of cable or sling damage will be greatly increased. It is necessary to study the influence of the damage on the performance of the cable-stayed arch bridge without back cable. The damage of the cable or sling will lead to the change of the natural vibration characteristics of the structure. It is a simple and effective method to judge the health condition of cable-stayed arch bridge with the change of the natural frequency of the needle [6-7].

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BACKGROUND

A bridge is a cooperative system of cable-stayed bridge without back cable and special-shaped arch bridge. The span arrangement is 40 m+90 m=130 m for two spans, and the bridge is 39 m ~ 43 m wide, See Figure 1 to Figure 2. The main girder and the bridge tower adopt prestressed concrete structure and reinforced concrete structure respectively, both of which are made of C50 concrete. The sling is made of steel strand extrusion, and the standard tensile strength is 1860 MPa. A total of 19 pairs of slings are arranged longitudinally, two of which are to be pulled against each other. The spacing of arch rib slings is 4.25 m. A total of 8 cables are arranged longitudinally with a cable spacing of 8.5m. The finished cable is made of galvanized steel strand and the standard tensile strength is 1860 MPa. Steel box structure is adopted in the arch ribs, and concrete is poured only at the arch foot. The bridge has a height of 25.8 m above the deck and a cable distance of 4.25 m. The bridge has 38 slings. The substructure is bored pile foundation and light abutment. The elevation and cross-section of the bridge are shown in Figure 1 and Figure 2.

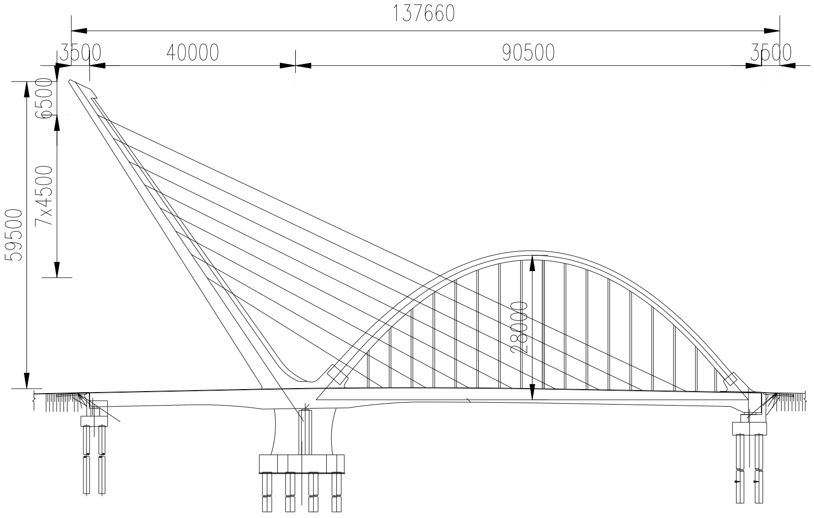


Fig. 1 - Vertical view

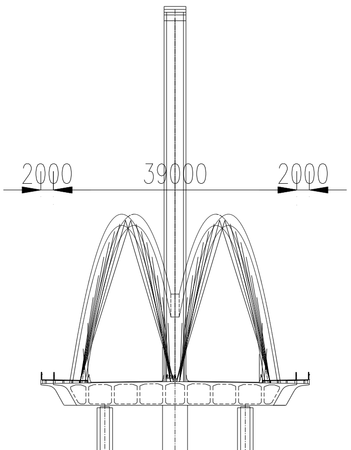


Fig. 2 - Cross section drawing

The finite element software Midas/Civil 2019 was used to establish the analysis model of the cable-stayed arch bridge without back cable. A total of 904 nodes and 1182 units were established, and piers and beams are a consolidated system. The pier, tower, beam, arch and transverse brace are simulated by beam element, while the cable and sling are simulated by truss element. The finite element model of the whole bridge is shown in Figure 3.

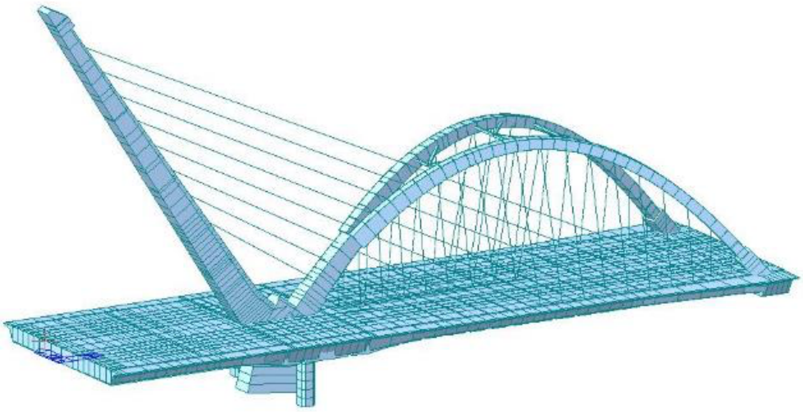
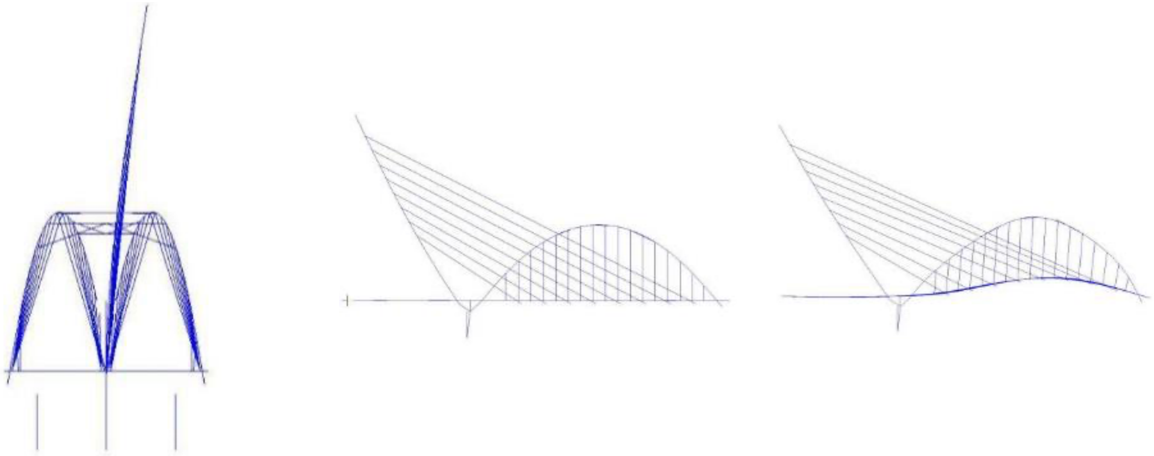


Fig. 3 - Finite element model of bridge

ANALYSIS OF BRIDGE VIBRATION CHARACTERISTICS

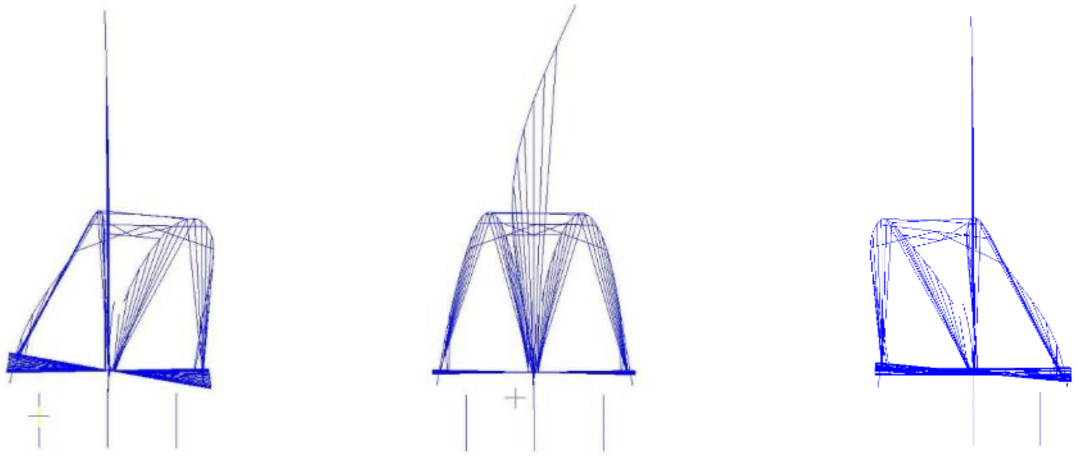
In dynamic analysis, the natural frequencies and main modes of the bridge structure are the most important parameters. The change of bridge stiffness will lead to the change of structural frequency, which is of the great significance to the health of cable-stayed arch bridges without back cables. Figure 4 shows the six main modes of vibration in front of a cable-stayed arch bridge without back cable.



（a） First order mode (tower transverse)

（b） Second order mode (vertical bending of tower)

（c） Third order mode (vertical bending of beam)



（d）Fourth order mode (arch transverse) *（e）Fifth order mode (tower transverse)* *（f）Sixth order mode (arch transverse)*

Fig. 4 - Modal figure

Generally, the first few frequencies play an important role in bridge structure. The first 8 frequencies and modes of natural vibration of the cable-stayed arch bridge without back cables are shown in Table 1.

It can be seen from Table 1, in the first six modes, except the third mode which is the vertical bending mode of the beam, the other modes are the tower bending mode and the arch bending mode. The main beam has a wide cross section and poor transverse stiffness. However, due to the large transverse stiffness provided by the shaped arch, the torsional stiffness of the main girder of the cable-stayed arch bridge without back cable is large, and it has a good resistance to torsional deformation.

Tab. 1 - Material properties

Modal number	Period /s	Vibration mode shape	Modal number	Period /s	Vibration mode shape
1	0.5116	Column transverse bending	5	2.5661	Column transverse bending
2	0.9425	Vertical bending of tower	6	2.8959	Transverse arch bending
3	1.8163	Vertical bending of beam	7	2.8979	Vertical bending of beams + Vertical bending of towers
4	2.0269	Transverse arch bending	8	3.3851	Vertical bending of beams + Vertical bending of towers

ANALYSIS OF THE INFLUENCE OF CABLE DAMAGE ON THE BRIDGE'S NATURAL VIBRATION CHARACTERISTICS

Natural vibration characteristics under different cable damage

The bridge has a total of 8 pairs of cables, cable specifications are GJ15-25, GJ15-31. The cables are numbered from the short cable to the long cable, which are S01 ~ S08 respectively. The specification of S01~S06 is GJ15-31, and that of S07~S08 is GJ15-25. The damage of each cable was simulated by reducing the elastic modulus. S02 represented the short cable, S04 and S06 represented the medium cable, and S08 represented the long cable. The elastic modulus of the cable after damage is 1× 10^{-5} MPa. Statistical frequency variation after cable damage, frequency variation rate = (frequency value after damage - no damage frequency value)/no damage frequency value. The values of frequency and frequency amplitude after damage are shown in Table 2, and the frequency amplitude after cable damage is shown in Figure 5. It can be seen from Table 2 and Figure 5. The cable damage has the greatest influence on the frequency variation of the 1st order transverse and 1st order vertical bending of the main tower of cable-stayed arch bridge, but it has little influence on the beam bending and arch bending modes. As shown in Figure 6 and Figure 7, the 1-order transverse bending frequency of the main tower and the 1-order vertical bending frequency of the main tower were calculated under different cable damage conditions. With the increase of the damage cable number, the natural vibration frequency of the 1st order transverse bending of the girder decreases linearly. When S8 cable is damaged, the 1st order transverse bending natural vibration frequency of the main tower is the smallest, which is 0.3175 Hz, but the change rate is the largest, which is -37.9%. When cable S1 is damaged, the 1st order transverse bending natural vibration frequency of the main tower is the largest, which is 0.506Hz, and the change rate is -1.09%. With the increase of damage cable number, when S8 is damaged, the first-order vertical bending frequency of the main tower is 0.5134, the frequency change rate is -42.35%, and the first-order vertical bending natural vibration frequency of the main tower is linearly decreasing. When cable S1 is damaged, the first-order vertical bending frequency of the main tower is the largest, which is 0.9318 Hz and the rate of change is -0.9318%.

Tab.2 - Frequency and frequency amplitude under cable damage

Order number	Primary frequency /Hz	Frequency after cable damage/Hz				Frequency variation after cable damage /%				Vibration mode shape
		S2	S4	S6	S8	S2	S4	S6	S8	
1	0.5116	0.4994	0.4535	0.3887	0.3175	-2.39	-11.35	-24.02	-37.94	Tower of transverse bending
2	0.9425	0.9160	0.8287	0.6937	0.5434	-2.81	-12.08	-26.40	-42.35	Tower vertical
3	1.8163	1.8139	1.7116	1.6435	1.7480	-0.13	-5.76	-9.51	-3.76	Beam vertical
4	2.0269	2.0204	2.0189	2.0213	2.0237	-0.32	-0.39	-0.28	-0.16	Arch transverse bending
5	2.5661	2.3391	2.3320	2.5643	2.2818	-8.85	-9.12	-0.07	-11.08	Tower of transverse bending
6	2.8959	2.8114	2.7780	2.8463	2.7248	-2.92	-4.07	-1.71	-5.91	Arch transverse bending
7	2.8979	2.8738	2.8940	2.8954	2.8955	-0.83	-0.14	-0.09	-0.08	Beam column vertical bending
8	3.3851	3.1570	3.0430	3.3352	3.0877	-6.74	-10.11	-1.47	-8.79	Beam column vertical bending

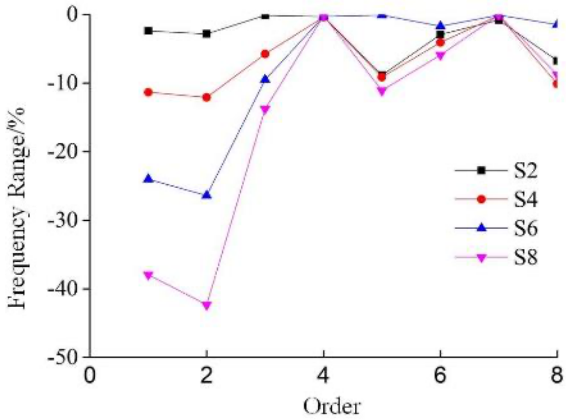


Fig.5 - Frequency variation under different main cable damage

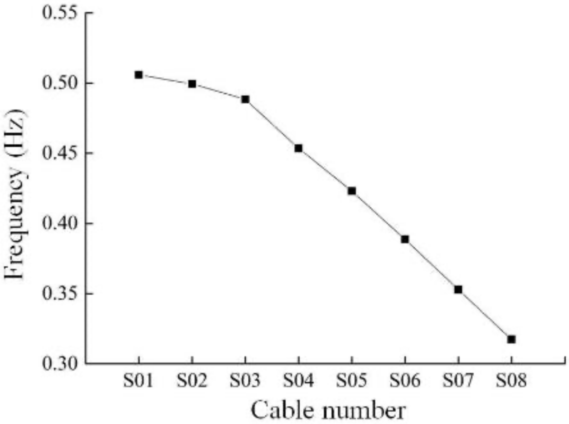


Fig.6 - First order transverse bending frequency of tower under different cable damage

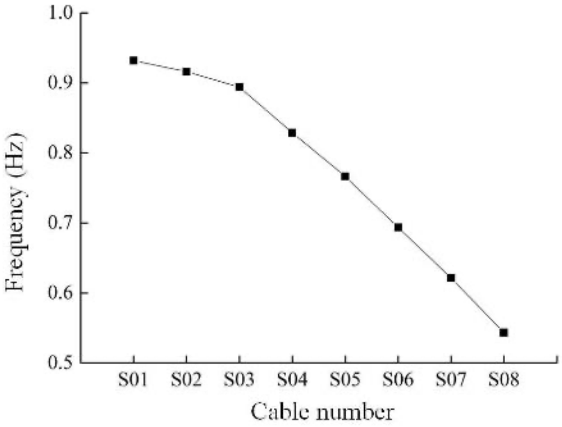


Fig.7 - First order vertical bending frequency of main tower under the different cable damage

Natural vibration characteristics of cables under different damage degrees

In order to explore the influence of different damage degree on bridge natural vibration frequency, three kinds of cable damage of different length were analysed. S01 and S02 were taken as the short rope representatives, S04 and S05 as the middle long rope representatives, S07 and S08 as the long rope representatives. The damage degree was 25%, 50%, 75% and 100% respectively, and the elastic modulus was 1.5×10^5 MPa, 1×10^5 MPa, 0.5×10^5 MPa and 1×10^{-5} MPa respectively. Figure 8, Figure 9 and Figure 10 are the frequency values of short, medium and long cables under different damage degrees. Figure 11, Figure 12 and Figure 13 show the variation amplitude of different damage degrees of S01, S04 and S07 cables. It can be seen from the figure that: under different damage conditions of short cables, the frequency values show regular changes. The damage is mainly reflected in the first-order vertical bending mode of the main tower, and the frequency variation becomes larger and larger with the increase of damage degree. It has little effect on the bending modes of beams and arches.

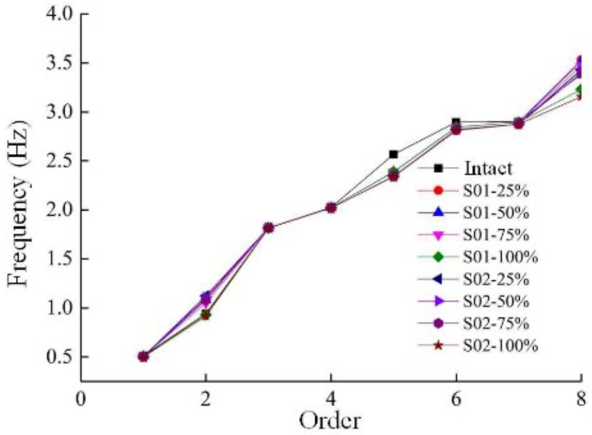


Fig.8 - Different damage frequency of cables S01 and 02

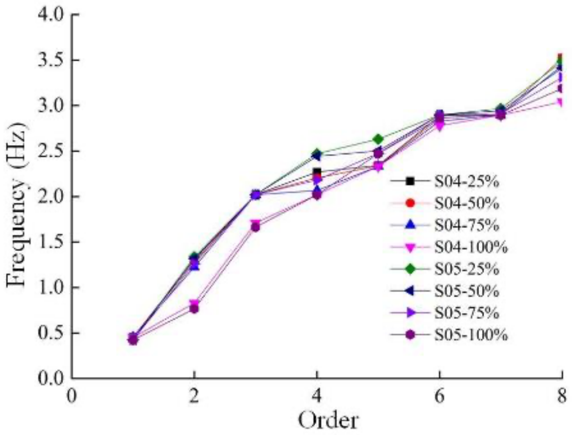


Fig. 9 - Different damage frequency of cables S04 and S05

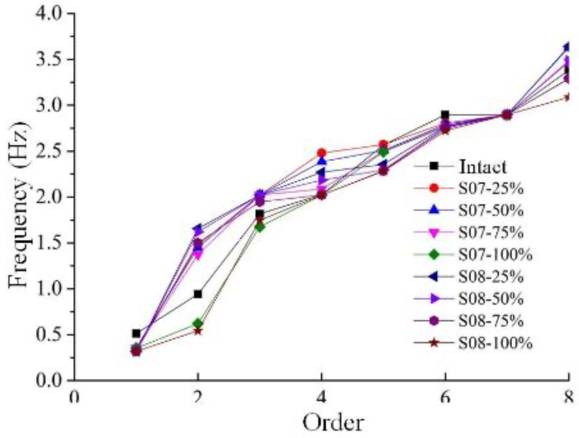


Fig.10 - Different damage frequency of cables S07 and S08

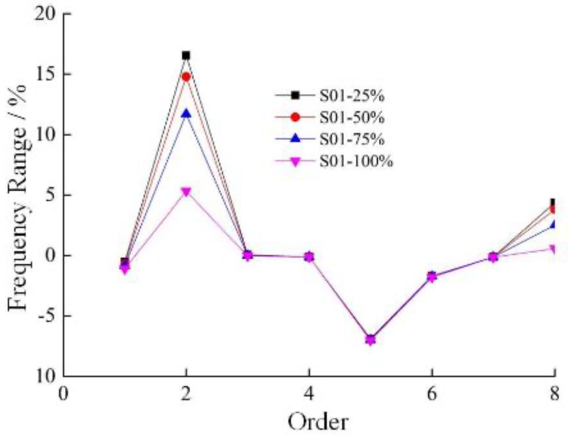


Fig.11 - Frequency variation of cable S01 with different damage degree

It can be seen from Figure 9 and Figure 12, the frequency of medium and long stay cables varies regularly under different damages. The damages are mainly reflected in the first--order vertical bending mode of the tower, the first--order transverse bending mode of the arch and the second-order transverse bending mode of the arch. It has little effect on other modes.

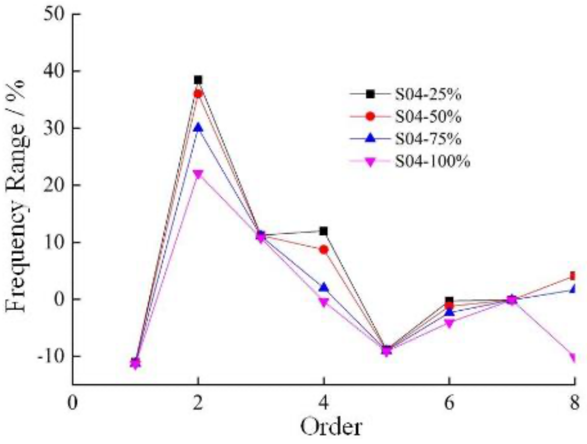


Fig.12 - Frequency variation of cable S04 with different damage degree

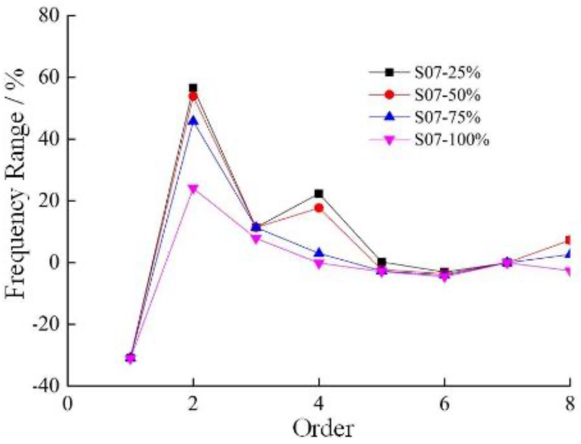


Fig.13 - Frequency variation of cable S07 with different damage degree

It can be seen from Figure 10 and Figure 13; the frequency of the long stay cables varies regularly under different damages. The damages are mainly reflected in the one-order vertical bending mode of the tower and the one-order transverse bending mode of the arch, which have little influence on the beam bending mode and the tower transverse bending mode.

The bridge has 17 pairs of slings, which are numbered from the bridge tower to the abutment, and are D1 ~ D17 respectively. The elastic modulus of 1×10^{-5} MPa was used to simulate D1-D3, D4-D6, D7-D9, D10-D12, D13-D15 sling damage, and the frequency amplitude after the sling damage was calculated. The frequency amplitude of the sling was = (the value of the natural vibration frequency after the damage - the value of the natural vibration frequency without damage)/the value of the natural vibration frequency without damage. As shown in Figure 14, the frequency variation amplitude of the boom sling after injury shows a linear increase under different sling injuries. It can be seen from the figure that sling damage has almost no effect on the first-order transverse bending natural vibration frequency of the main tower of cable-stayed arch bridge.

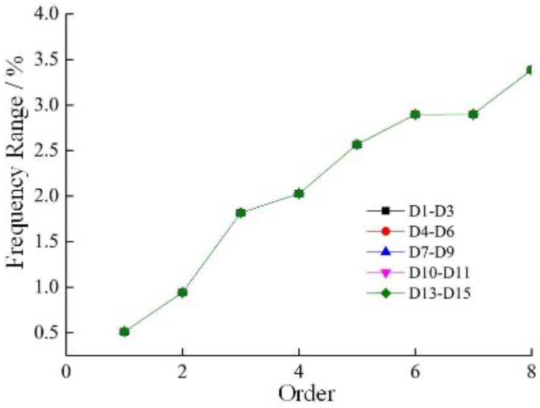


Fig.14 - Frequency variation under different sling damage

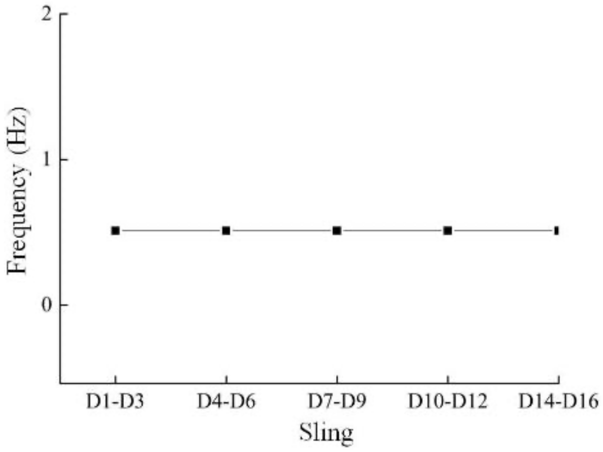


Fig.15 - First order transverse bending frequency of main tower under different cable damage

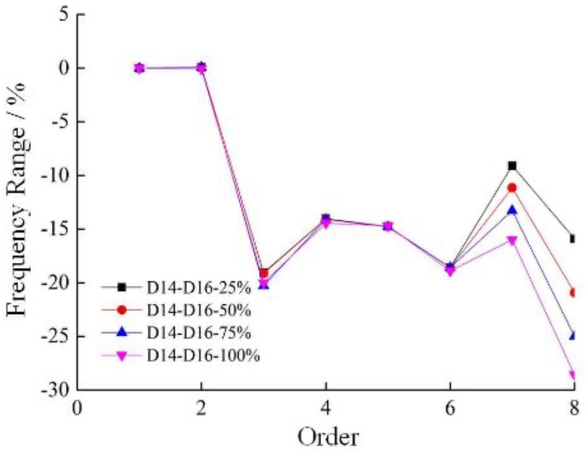


Fig.16- Different damage frequency variation of slings D1-D3

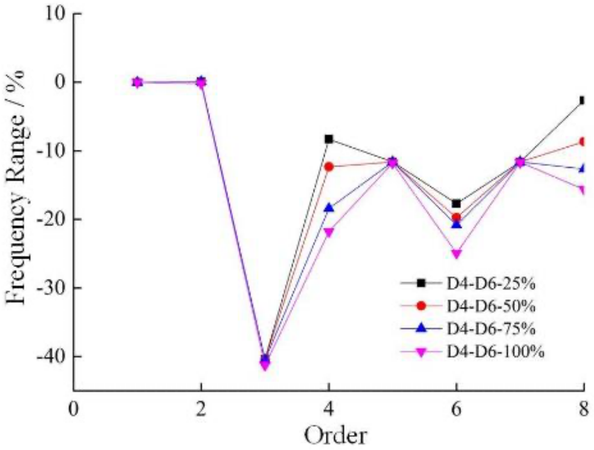


Fig.17- Different damage frequency variation of slings D4-D6

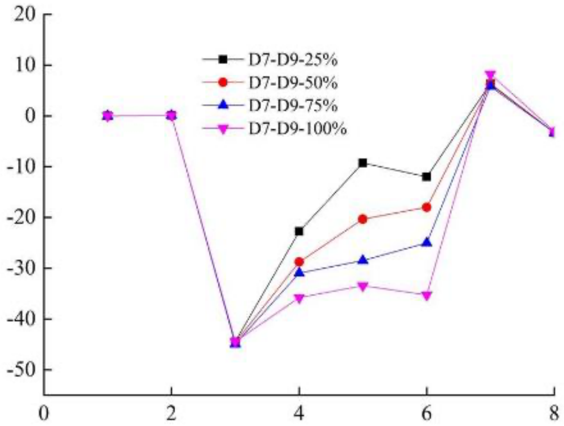


Fig.18 - Different damage frequency variation of slings D7-D9

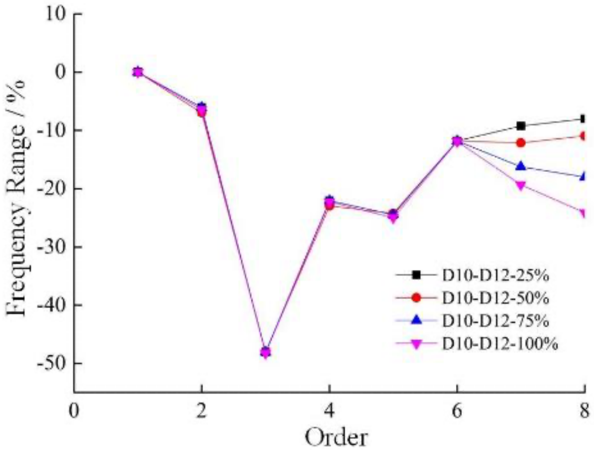


Fig.19 - Different damage frequency variation of slings D10-D12

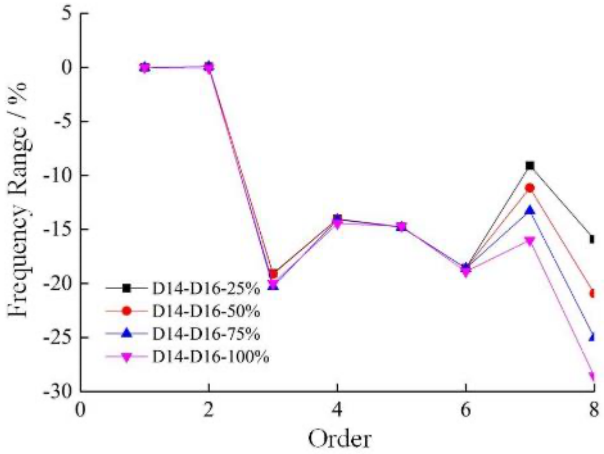


Fig.20 - Different damage frequency variation of slings D14-D16

In order to explore the influence of different damage degrees of cables on the bridge's natural vibration frequency, D1-D3, D4-D6, D7-D9, D10-D12 and D14-D16 for short cables, middle short cables, middle cables, middle long cables and long cables were taken to analyze the natural vibration characteristics under different damage degrees respectively. When the damage degree are 25%, 50%, 75% and 100% respectively, the elastic modulus are taken as 1.5×10^5 MPa, 1×10^5 MPa, 0.5×10^5 MPa and 1×10^{-5} MPa respectively.

After the short cables D1-D3 damage, the frequency variation of three pairs of cables under different damage degree is shown in Figure 16. After the middle long cables D4-D6 damage near the cable tower, the frequency of three pairs of cables D4-D6 under different damage degrees is shown in Figure 17. When the middle arch rib long cables D7-D9 are damaged, the frequency of three pairs of cables D7-D9 under different damage degrees is shown in Figure 18. The frequency of long cables D10-D12 in the far tower under different damage degrees is shown in Figure 19. The frequency variation of short cables D14-D16 under different damage degrees is shown in Figure 20. As it can be seen from Figure 16, under the condition of short cable damage near the tower, the frequency variation amplitude presents a parabolic change of the upper opening. Under different damage degrees, the variation effect is mainly reflected in that the transverse bending mode of the arch (the 4th mode) and the transverse bending mode of the tower (the 5th mode) have almost no effect on the beam mode. As it can be seen from Figure 17, when the long cables D4-D6 near the tower are damaged, the frequency changes irregularly. Under different damage degrees, the variation effect is mainly reflected in the transverse and flexural modes of the arch (the fourth and fifth modes), and it has almost no effect on the beam mode and tower mode. As it can be seen from Figure 18, when the long cables D7-D9 near the tower are damaged, the variation of frequency presents a parabolic change of the upper opening. Under different damage degrees, the influence of variation is mainly reflected in the transverse bending mode of the tower and the transverse bending mode of the arch. As can be seen from Figure 19 and Figure 20, under the condition of damage to the long cable away from the tower and the short cable away from the tower, the frequency variation amplitude presents irregular changes. Under different damage degrees, the variation effect is mainly reflected in the beam tower vertical bending mode (mode 7 and mode 8), and it has almost no effect on the arch mode.

CONCLUSION

In this paper, the self-vibration characteristics of the cable/sling under the damage of the cable-stayed arch bridge without back cable are analysed. The natural vibration frequency and its variation rule of bridges with different cable/sling damage and different cable damage degree are studied. The results of the study are as follows:

（1） There is no torsional mode in the first several modes of the bridge. It is shown that the special-shaped arch boom ensures the transverse mechanical performance of the broad section main beam, and makes the main beam of the cable-stayed arch bridge have a large torsional rigidity and a good ability to resist torsional deformation.

（2） With the increase of damage cable number, the frequency of 1st order vertical bending of main beam and the frequency of 1st order vertical bending of main tower are linearly decreasing, and the natural vibration frequency of bridge is the smallest when S9 cable is damaged. With the increase of the number of the damage sling, the frequency of the 1st order vertical bending of the main beam and the frequency of the 1st order vertical bending of the main tower are linearly increasing.

（3） The frequency of the short cable varies regularly under different damage conditions, and the damage is mainly reflected in the vertical bending mode of the low-order main beam (the second mode). Under the different damage of the middle length cable, the damage is mainly reflected in the 1st order vertical bending mode of the tower, the 1st order transverse bending mode of the arch and the 2nd order transverse bending mode of the arch. The damage of long stay cable is mainly reflected in the first order vertical bending mode of the tower and the first order transverse bending mode of the arch. With the increase of damage degree, the frequency variation amplitude becomes larger and larger, which has little effect on the beam bending mode and the tower transverse bending mode.

（4） The vertical stiffness of the main tower and the transverse stiffness of the wide main beam should be taken into account in the design of the bridge with no back cable and arch combination structure. Special attention should be paid to the construction and maintenance of long stay cables, which will affect the performance of the whole bridge. It is better to scatter the suspends of the arch to increase the transverse stability of the main beam.

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