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Damage Inspection and Analysis of an Expressway Partial Cable-stayed Bridge

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Abstract: Damage inspection and cable force test were discussed for an expressway partial cable-stayed bridge in a practical project in this study. Furthermore, the causes of damage were analyzed. The results showed that the repair and maintenance measures should be taken. Finally, the repair and maintenance measures were proposed for the damage of the expressway partial cable-stayed bridge. The cable forces were tested at 2 year (or less) intervals. And the health records of cable forces should be established to provide reliable scientific basis for the analysis of stay cable distribution, structural condition assessment, as well as maintenance and management of the bridge. The box girder of the bridge should be repaired, reinforced and the degree of inclination of the pylons be regularly measured. Anti-corrosion measures should be taken on the various components of stay cable systems. Grease should be filled in the anchorage components. The change in the relative position between the HDPE pipes and the guide pipes should be focused on. These results could also provide a reliable reference for the damage inspection and maintenance of similar bridge structures.

Key words: Cable-stayed bridge, partial cable-stayed bridge, stay cable, cable force test, repair, damage inspection

INTRODUCTION

A partial cable-stayed bridge is a new type of bridge structure. It was first developed in 1988 known as an Extra-dosed PC bridge. Yan (1995) first described extra dosed cable-stayed bridge as a partial cable-stayed bridge in China. The partial cable-stayed bridge is a structure form between a cable-stayed bridge and a continuous beam bridge. It is composed of both compressive and flexural girders, stay cables under tension and compressive pylons. A partial cable-stayed bridge has large stiffness and lower pylons. Each continuous stay cable through a pylon is anchored at both ends of a girder. Cable forces need no adjustment in the construction process. Due to its structural efficiency, economical construction and aesthetic shape, a partial cable-stayed bridge has become a competitive bridge structure within the range of 100~300 m span.

Currently, a wide research on a partial cable-stayed bridge focuses on design theory, parameter analysis, mechanical properties, cable force calculation (Chen, 2012; Huang *et al*., 2012; Lin *et al*., 2007; Liu *et al*., 2004) while very little research work is done in inspection, maintenance and repair of the bridge structure. Due to the defects of the materials itself, construction quality, environmental corrosion, lack of maintenance and management, damage occurs in a bridge structure during the use phase. The damage not only affects the normal use of a bridge structure but also endangers its safety. Cable-stayed bridge accidents in the world have occurred many times, causing huge economic losses and adverse consequences. Therefore, it is necessary to inspect damage of a partial cable-stayed bridge regularly in order to investigate and assessment working performance of components and subsidiary structures, timely find problems and implement corresponding repair or replacement, reinforcement (Zongbao *et al*., 2012; Park *et al*., 2010). Furthermore, damage inspection, corresponding maintenance and repair can ensure the bearing capacity and use function of the partial cable-stayed bridge, maintain its durability and lower its long-time maintenance cost.

So in this study, based on the technical conditions of the superstructure and substructure of an expressway partial cable-stayed bridge in China, the stay cable force of the bridge are determined by vibration-based measurements method. Then damage inspections are performed on the superstructure, substructure and miscellaneous elements of the expressway partial cable-stayed bridge. Furthermore, the causes of damage are found out according to the inspection results. Finally, the repair and reinforcement measures are proposed for the damage of the expressway partial cable-stayed bridge. All the results can provide a reliable reference for the damage inspection, maintenance and reinforcement of a similar bridge.

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BRIDGE OVERVIEWS

The Lishi Expressway Viaduct concerned in this study is a bridge on Fen-Li Expressway in Shanxi Province, China. The bridge is a partial cable-stayed bridge with a main span of 135 m and side spans of 85 m on each side, as shown in Fig. 1. The total deck width is 26 m. The three-way prestressed concrete girder with box section is adopted in the partial cable-stayed bridge. A total of 44 cables, arranged in single cable plane are used to support the bridge deck with the help of two pylons. Each continuous stay cable is anchored at both ends of a girder through a pylon. Single cable plane are arranged in the center of the expressway median strip. Stay cables from upstream to downstream are arranged in two rows. Each cable is comprised of 31 epoxy-coated strands. Multiple anti-corrosion measures are taken for the stay cables. HDPE pipes are used for the cable sheathings. Each pylon with solid rectangular cross-section is 18 m in calculation height.

CABLE FORCE TEST

Estimating cable tension in cable-stayed bridges is essential for regular inspection and assessment of those structures. Vibration measurements provide a solution (Li and Wang, 2012; Fang *et al*., 2007). The deviation rate in tension at both ends of each stay cable is the ratio of the tensions difference at both ends to the tension at one end of each stay cable and is required not to exceed ±3% during construction. The deviation rates of the corresponding tensions of two rows of stay cables from upstream to downstream are the ratios of the differences between the corresponding tensions of the first row of cables and of the second row of cables to the tensions of the second row of cables and must be within the allowable range. For a partial stayed-cable bridge, each continuous stay cable is anchored at both ends of a girder through a pylon. In the use stage, to ensure the stay cables on both pylons are relatively fixed, cables with HPDE sheathing have to be grouted at the saddles. However, grouting quality problems during construction may lead to the inclination of the pylons and a force change at both ends of a stay cable. Hence, the tension of each stay cable should be estimated.

A dynamic testing instrument is employed to measure cable forces by ambient vibration. Cable force tests are shown in Fig. 2.

Both ends of each cable through Pylon 1, in the first row from upstream to downstream, is numbered L0~L10

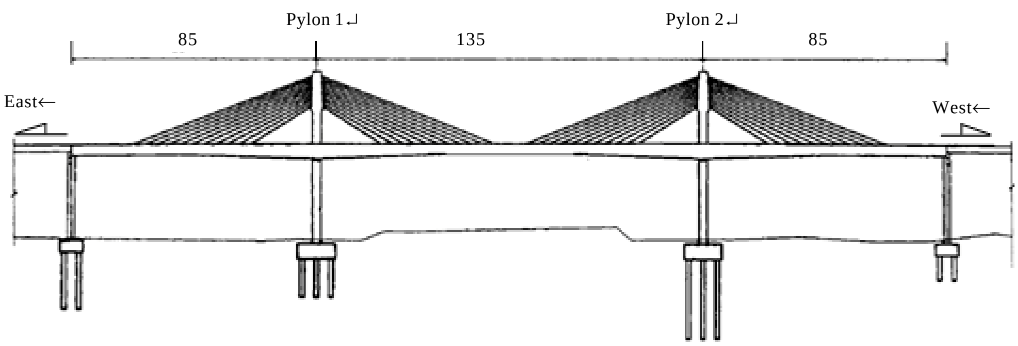

Fig. 1: Layout of lishi expressway viaduct

Fig. 2(a-b): Cable force test (a) Cable force measurement and (b) Layout of test probes

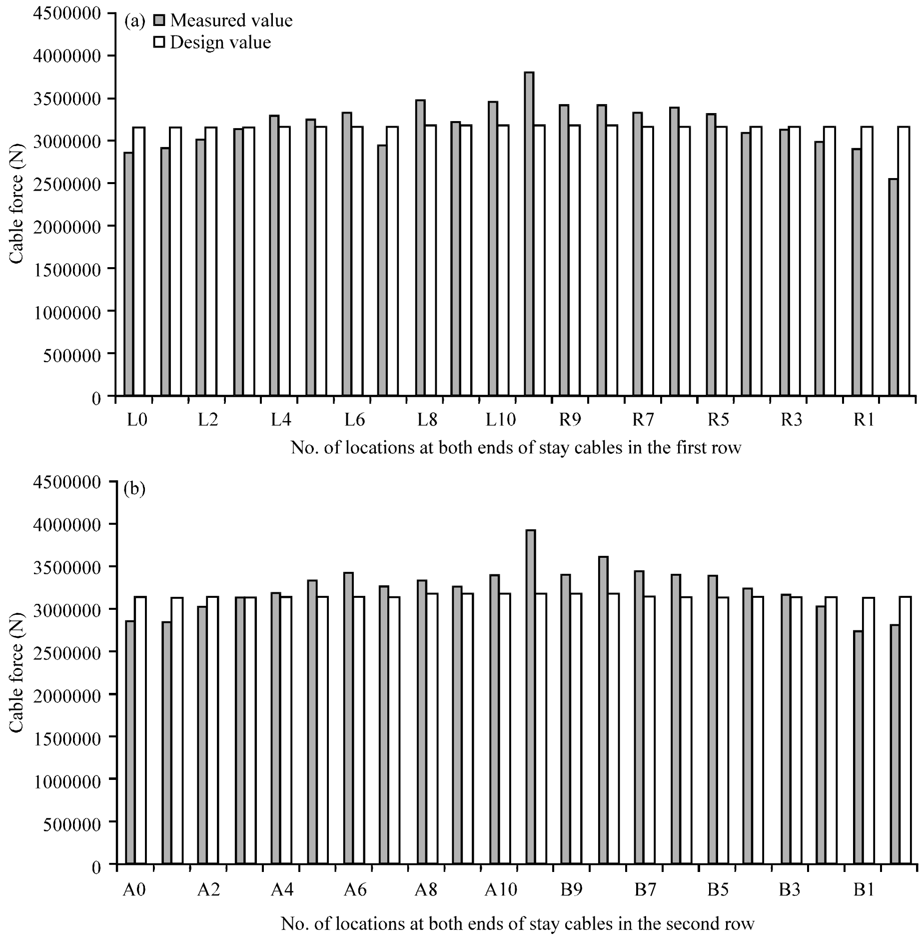

Fig. 3(a-b): Comparison of the measured values with design values of tensions for the cables through pylon 1 (a) Cables in the first row and (b) Cables in the second row

and R10~R0 from East to West. Both ends of each cable, in the second row, are numbered A0~A10 and B10~B0 from East to West.

Both ends of each cable through Pylon 2 which is in the first row from upstream to downstream, is numbered C0~C10 and D10~D0 from East to West. Both ends of each cable, in the second row, are numbered E0~E10 and F10~F0 from East to West.

Based on the results of measuring cable forces, the comparison of the measured values with the design values of cable forces are plotted in Fig. 3 and 4.

Figure 3 and 4 show that most of errors between measured and design values of cable forces vary between 1 and 10%.

For the corresponding cable forces at both ends of the first row of cables and of the second row of cables through Pylon 1, it is indicated that most of deviation rates of the measured values are less than ±3% from Fig. 3a-b. The maximum cable force deviation is 9.61%.

Comparing the measured values for the corresponding cable forces at both ends of the first row of cables with those of the second row of cables through Pylon 2, it can be found that most of deviation rates are less than ±3% from Fig. 4a-b. The maximum cable force deviation is 11.33%.

Locations of the larger tension deviations are presented in Table 1.

DAMAGE INSPECTION OF LISHI EXPRESSWAY VIADUCT

According to the technical conditions of the superstructure, substructure and accessory structures of Lishi Expressway Viaduct, the damage inspection focused on the inclination of pylon 1 and 2, cable-stayed system, the main girder, piers and accessory structures of the expressway partial cable-stayed bridge.

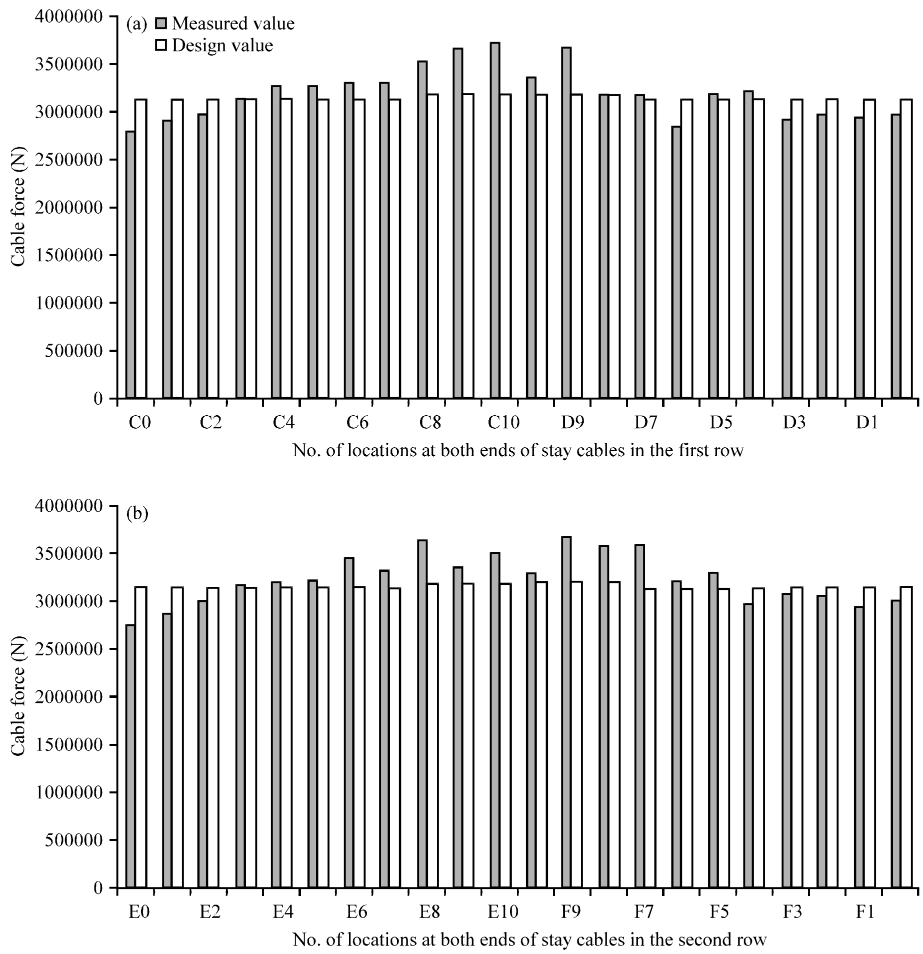

Fig. 4(a-b): Comparison of the measured values with design values of tensions for the cables through pylon 2 (a) Cables in the first row and (b) Cables in the second row

Table 1: Larger cable force deviations in two rows of cables

	Pylon 1			Pylon 2			
Location	Frequency (Hz)	Cable force (×103N)	Deviation rate (%)	Location	Frequency (Hz)	Cable force (×103N)	Deviation rate (%)
L7	4.228	2963.5	-9.61	C9	4.228	2963.5	-9.61
A7	4.447	3278.5		E9	4.447	3278.5	
L8	5.135	3437.3	-5.63	C10	5.135	3437.3	-5.63
A8	5.286	3642.5		E10	5.286	3642.5	
R7	4.484	3333.3	-4.11	D8	4.484	3333.3	-4.11
B7	4.579	3476.0		E8	4.579	3476.0	
R4	3.219	3100.5	-5.20	D7	3.219	3100.5	-5.20
B4	3.306	3270.4		E7	3.306	3270.4	
R1	2.467	2885.2	5.75	D6	2.467	2885.2	5.75
B1	2.399	2728.4		E6	2.399	2728.4	
R0	2.172	2555.5	-8.85	D4	2.172	2555.5	-8.85
B0	2.275	2803.6		E4	2.275	2803.6	

Tilt of pylon: From the measured results of the tilts of pylon 1, it can be estimated that the top of pylon 1 northward tilts 13 mm along the transverse direction of Lishi Expressway Viaduct, eastward 18 mm along the longitudinal direction.

The measured results of the tilts of pylon 2 show that the top of pylon 2 southward tilts 20 mm along the transverse direction, westward 21 mm along the longitudinal direction.

Based on the design requirements, the axis inclination of pylon is required to be less than or equal to H/3000 (H represents the height of a pylon height) and not more than 10 mm.

The calculation height of the pylon is 18 m. Consequently, In accordance with the above requirements, the top tilt of pylons of the partial cable-stayed bridge is required not to exceed 6 mm. So, it is concluded that the tilt of the two pylons is much more than design and specification requirements from the above inspection results. And the two main pylons irregularly tilt. This can be caused by construction errors, concrete crack development of main span structure and the concrete creep of the main girders.

Stay cable system: A lot of literature shows that the damage of stay cable system mainly appears in anchorage systems, cables themselves, guide pipes, cable sheathings (Tang *et al*., 2006). Therefore, the anchorage systems, cables themselves, cable sheathings and guide pipes are inspected for damage:

- **Guide pipes:** In view of the actual installation, the damage of the guide pipes can be inspected through random selection. Four stay cables, respectively chose from both ends of each pylon for the damage inspection. From the inspection results, it can be found no stagnant water within the selected guide pipes but rusty spots on the outer surface of the guide pipes, as shown in Fig. 5. The rust-resisting paint falling off causes rust

Fig. 5: Rusty spots on the outer surface of guide pipe

- **Anchorage systems and the end strands:** By random selection, anchorage systems and the end strands are examined for damage. Eight stay cables, respectively selected from both ends of each pylon for the damage inspection. Typical damage of anchorage systems is shown in Fig. 6. The examination results show that the seals of the grouting mouths have been broken, not playing a role in sealing. Grease exiting in the anchorage components seepages, as shown in Fig. 6a. But the end stands are wrapped by grease and have not suffered any significant damage (such as corrosion). Water exists in the end cap of the anchorages, as shown in Fig. 6b. It is founded that there is rust in all steel anchorage plates of the examined stay cables. And rust water is found to outflow from the anchorage plates and rings, shown in Fig. 6c
- **HDPE pipe:** Guide pipes of the selected stay cables inspected, the HDPE sheathings of the cables are simultaneously examined for bulging. No HDPE sheathings are found bulging. However, there are the following problems: sliding of the stay cables obviously in the anchorage areas at the top of pylon 1 and 2, rust of the guide pipes, deterioration of neoprene rings, grease seepage, as shown in Fig. 7. Due to vehicles and concrete creep, the change take places in the relative position between the HDPE pipes and the guide pipes, causing the HDPE pipes sliding. Damage of neoprene washers, gaps between the neoprene rings and the cables along the perimeter, result in seepage of grease

Fig. 6(a-c): Typical damage of anchorage systems (a) Ends of the anchorage, (b) End cap and (c) Corrosion of the bearing plates

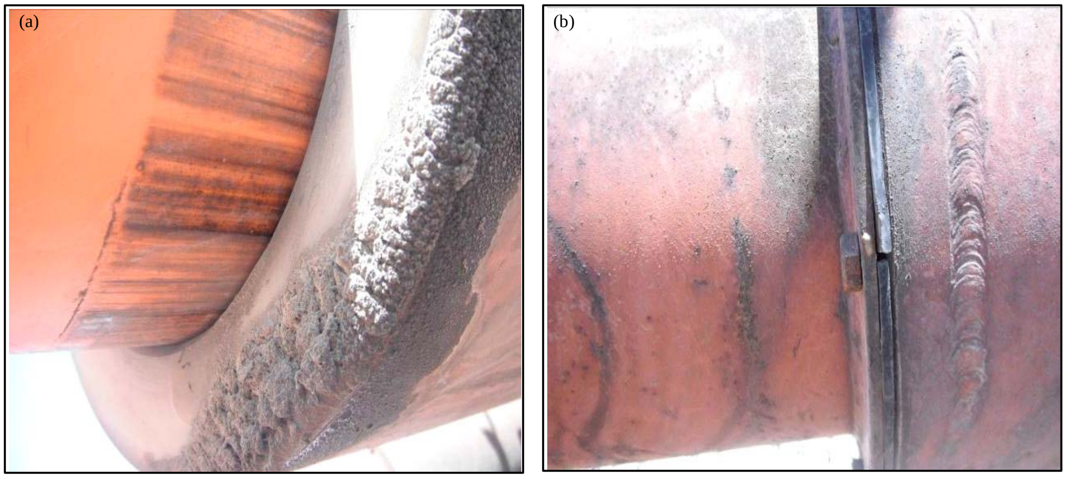

Fig. 7(a-b): Damage of HDPE pipe (a) Skid marks of a guide pipe and seepage of grease and (b) Damage of neoprene washer

Fig. 8(a-b): Damage of girders (a) Girder roof and (b) Water erosion in the anchorage of girder roof

Girders and piers: The girder and piers of the partial cable-stayed are inspected for cracking, carbonation depth of concrete, as well as local damage of concrete:

- Cracks in girders and local damage of concrete of girders. The inside of box girders is examined for damage through manholes. Based on this field inspection, no cracking is found in the anchorage areas of both longitudinal prestressed strands inside the box girder and the stay cables. But there is water seepage in the roof of the box girder, stagnant water inside and water erosion in the anchorages, as shown in Fig. 8. Construction holes not being closed, the inside of the box girders suffers from the damage. By inspecting the whole box girder, there are some transverse cracks in the top and bottom slabs, longitudinal cracks in the bottom slabs. The maximum width of transverse crack is 0.29 mm. The maximum width of longitudinal crack is 0.27 mm. Moreover, the box girders suffer from spalling and scaling exposed tendons. The main causes of damage of the whole box girder are overloaded vehicles, corrosion of embedded reinforcements, concrete shrinkage, poor maintenance and management

- Cracks in piers and local damage of concrete of piers. The situations of piers are good but there are only vertical cracks on the surface of pier caps due to temperature change and shrinkage. The pier caps suffer from spalling and scaling due to the flow of water erosion
- Inspection for depth of carbonation concrete is performed on the girders and pier caps of Lishi Expressway Viaduct. The inspection results indicate that the maximum depths of carbonation concrete, respectively 4.32 and 5.2 mm for the girders and pier caps. The maximum depths of carbonation concrete do not exceed the thickness of the concrete cover

Accessory structures: Excepting parts of drainage facilities, the conditions of the other accessory structures are good. Parts of drainage facilities are blocked by dust.

CONCLUSION

In this study, damage inspection process and cable force test are discussed for Lishi Expressway Viaduct, an expressway partial cable-stayed bridge in a practical project in China. The causes of damage are further analyzed. The analytical results indicate that the corresponding measures should be taken to repair and maintain the partial cable-stayed bridge so that the bridge meets the requirements of carrying capacity and normal use.

In order to prevent ploys from further tilting, the box girder of the bridge should be repaired, reinforced and the degree of inclination of the pylons be regularly measured. With respect to the stay cables, the health records of cable forces should be established. The cable forces are tested at 2 year (or less) intervals to monitor the development of the stay cable tension. On the basis of the monitoring results, the cables internal force can be adjusted to meet the use requirements.

In view of the damage of the inspected stay cable systems, the other stay cable systems should be inspected for damage. And rust removal is performed on the rusty guider pipes and bearing plates of the anchorage systems. Then rust-preventing paint is repainted. The broken seals of the grouting mouths should be replaced. Grease should be filled in the anchorage components. Replace all missing nuts in the end caps of the anchorages. Because sliding of the stay cables may relate to the loads acting on the partial cable-stayed bridge, regular observations should be made to monitor its damage development after the repair and reinforcement of the main girder.

The cracks in concrete, of width beyond limit requirements, can be sealed by high-pressure injection of epoxy resin. The cracks in concrete, of width in the allowable range, can be bonded by injection of epoxy resin. The concrete components with spall are patched by epoxy resin mortar after removing the deteriorated concrete and cleaning the steel reinforcements.

Dust in the parts of drainage facilities should be timely cleaned up.

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