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Optimization of aerodynamic measures for rain wind induced vibration and its effect on engineering design of stay cables

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SUMMARY:
Rain wind induce vibration can cause large amplitude vibration of cables of cable-stayed bridges. Currently, aerodynamic measures such as dimples and helical ridges are often used as vibration suppression measures with additional wind load of cables. It is found that the proportion of the static wind load of the cable to the whole bridge increases approximately linearly with the bridge span. A recent mechanism research shows that, the excitation and development of RWIV has a certain randomness, and requires a long time of accumulation of rivulet mass and energy. The adhesion of water droplets on the cable surface can be greatly reduced by hydrophobic coating surface. Polyurea coating is experimentally proved to hinder the formation of rivulet, and prevent large RWIV. By adopting polyurea coating cables, nearly half of cable wind load can be reduced. Under these circumstances, the design optimization of a 1160m-span cable-stayed bridge under construction is carried out. The results show that under the condition of optimizing the cable wind load, the size of bridge tower and foundation can be reduced by 6%`8%, and the total investment can hence be saved by 6%-8%, which is about 100 million RMB (14 million USD) for this project.

Keywords: Rain wind induced vibration, wind load optimization, hydrophobic coating

1. INTRODUCTION

The cable-stayed bridge relies on stay cables to support the main beam elastically at multiple points. With its good mechanical characteristics and stability, it has obvious advantages in the span of 300m to 1000m, and can even be a favorable competitor of suspension bridge in the field of bridge spanned more than 1 kilometer. The stay cable is an important part of cable stayed bridge. With the increase of the cable length, the cable vibration problem becomes more prominent. Rain-wind-induced vibration (RWIV) is one of the most harmful cable vibrations. Since RWIV was first measured by Hikami and Shiraishi (1988), it has been observed on cable-stayed bridges around the world. The mechanism of RWIV has not been fully clarified. However, it has been agreed that rivulet is the key factor causing wind and rain excitation. On the other hand, the aerodynamic measures such as helical ridges and dimples are widely applied in engineering applications. Their principle is to interfere with the formation and development of the rivulet. However, for different cable types and diameters, aerodynamic measures need to be tested to verify their effectiveness. Moreover, almost all cables with surface treatment will bring additional wind load, which affects the economy of cable-stayed bridges.

In order to evaluate the importance of wind load on stay cables, this paper estimates the proportion of equivalent static wind load of cable-stayed bridges with different spans, and verifies an economical and effective aerodynamic measure to replace the current aerodynamic measure through theoretical derivation and experimental verification. On this basis, the effect of aerodynamic measures optimization is investigated through an actual engineering design case.

2. STATIC WIND LOAD OF STAY CABLES

Drag coefficient C_D directly affects the static wind load. Figure1 shows the wind tunnel test results of stay cables with aerodynamic measures at different Reynolds numbers Re (Chang et al., 2019). C_D of a smooth cylinder varies greatly with Reynolds number. In the critical and super critical regimes with Re varying from 2×10^6 to 8×10^6, C_D drops to 0.3-0.5. On the other hand, the Re effect on helical surface and dimpled cable is small. C_D mainly drops in the range of 0.6-0.8 in the critical and supercritical regimes. In most bridges, stay cables with surface treatments are in the critical or super-critical regime for extreme wind speeds. Therefore, C_D=0.8, 0.7, 0.7 is adopted for Chinese code (JTG/T 3360-01-2018), PTI recommendations (2018) and CIP recommendations (2002), respectively in order to cover changes in the surface treatments of aerodynamic measures.

Figure 2 shows the equivalent static gust loads of 6 cable-stayed bridges with different span based on Chinese code (JTG/T 3360-01-2018). With the increase of the span, the static gust load of the main beam and the tower gradually decrease from 20.7%, 53.3% to 18.0% and 40%, respectively. Only the proportion of the stay cables gradually increases, from 26% to 42%. This is mainly due to the continuous non linearly increase of the total length of cables. The fitting curve of cable proportion is also shown in Figure 2, and the fitting goodness R2 is 0.98. The wind load proportion of stay cables is approximately linearly increasing with bridge spans. When the central span of cable-stayed bridges exceeds 1000m, the wind load proportion of stay cables will account for more than 35%.

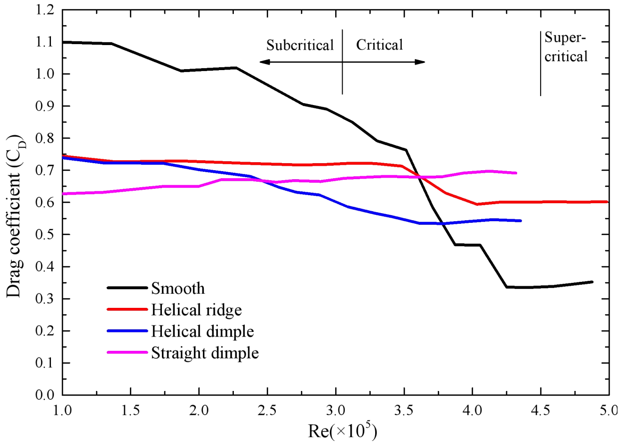

Figure 1. Drag coefficient of stay cables versus Re

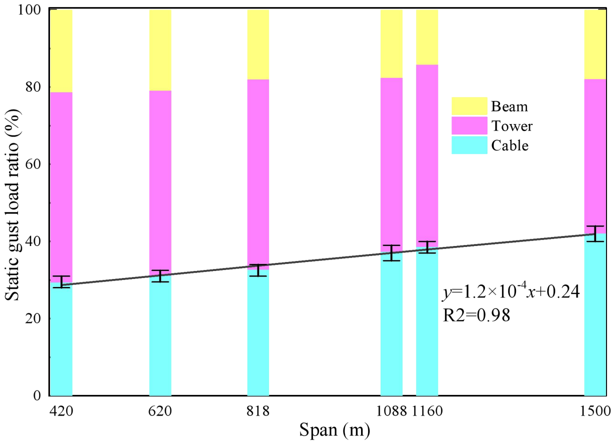

Figure 2. Proportion of equivalent static gust load of each part and fitting curve of the stay cable

3. OPTIMIZATION OF AERODYNAMIC MEASURES

According to our previous work (Chang et al., 2022), it is found that RWIV is a slow and random process, as shown in Figure 3. There is a critical state in the development of RWIV. In this critical stage, enough kinetic energy at cables’ frequency must be provided by the large-amplitude cable vibration and transfer to full and long rivulet to generate rivulet regular oscillation, or the whole system will return to the initial stage of forced random vibration. If the cable surface lacks formed water film and rivulets when the cable vibrates with large amplitude, the energy of the system will be gradually consumed by the random aerodynamic force, rather than transferring to the rivulet. Hence, the RWIV development can be blocked. The self-cleaning and water-drainage hydrophobic and superhydrophobic coatings are consistent with the vibration suppression requirements of RWIV, and no additional aerodynamic drag will be added with the coating. Figure 4 shows the wind tunnel test results of a PE and a polyurea cables. Polyurea has a ordinary hydrophobicity. But compared with PE cable, the maximum amplitude decreases by more than 80%. Therefore, hydrophobic coating measures are feasible.

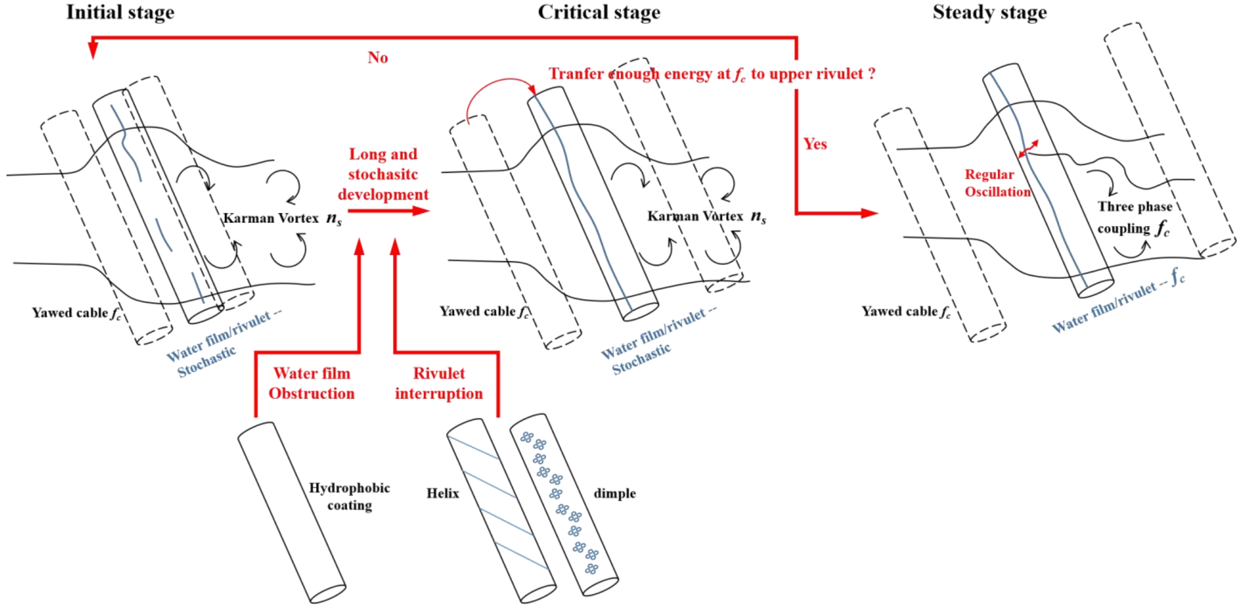

Figure 3. Development processes and suppression measures of RWIV

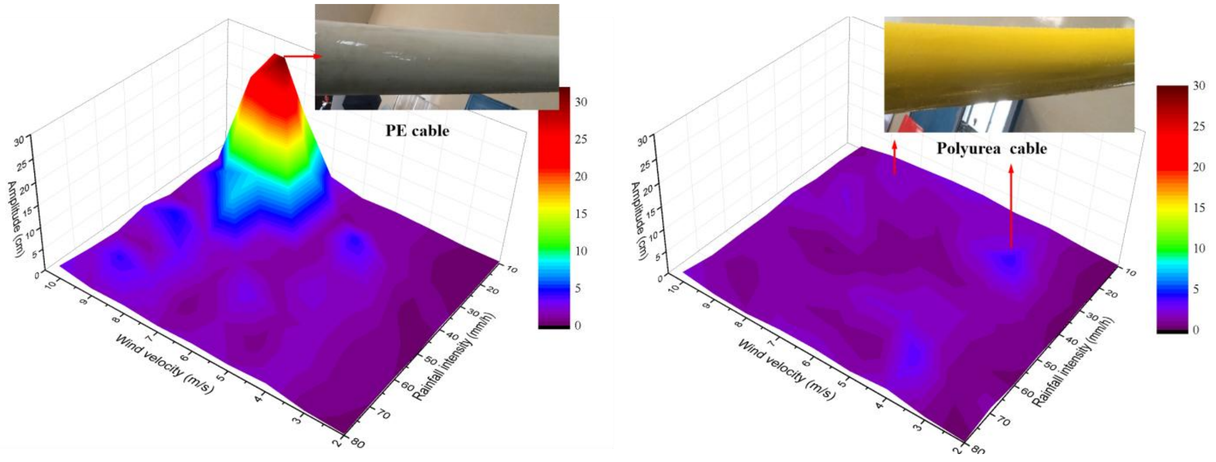

Figure 4. Vibration amplitude and water film for PE and Polyurea cables

4. EFFECT OF CABLE WIND LOAD REDUCTION ON ENGINEERING DESIGN

The drag coefficient of polyurea coating cable is equivalent to that of PE cable. Under this condition, the substructure of a actual bridge under construction is optimized in MIDAS/CIVIL with halved cable wind load. The load and size optimization of the bridge tower and foundation are mainly considered, and the bottom sections of the middle tower column and the lower tower column are selected as the control sections. The reduction of the cable wind load will reduce the bending moments of the control sections and optimize the size of the bridge tower. The reduction of the tower section size will then reduce the tower wind load, and the tower section size can be further reduced. The final convergent tower size after iteration is shown in Table 1. The section size of the final bridge tower and foundation can be reduced by 6~8%. The actual substructure investment (including the main towers and foundations) is about 1.5 billion RMB (225 million USD). So, about 100 million RMB (14 million USD) can be saved, which is a very appreciable economic benefit.

Table 1. The tower section sizes for 2 cases, unit: m

Case	Middle tower bottom				Lower tower bottom			
	W_t	t_W	L_t	t_L	W_t	t_W	L_t	t_L
Original	15 (100%)	3 (100%)	11.3 (100%)	3.2 (100%)	17 (100%)	3 (100%)	11.5 (100%)	3.2 (100%)
Halved cable wind load	14.05 (93.7%)	2.9 (96.7%)	11.3 (100%)	3 (93.8%)	16.5 (97.1%)	2.9 (96.7%)	11.5 (100%)	3 (93.8%)

W_t represents longitudinal width, t_w represents longitudinal wall thickness, L_t represents transverse width, and t_L represents transverse wall thickness

5. CONCLUSIONS

With the increase of the cable-stayed bridge span, the cable wind load problem becomes more and more serious. Hydrophobic coating can effectively suppress RWIV without additional wind load. According to the results of cable wind load optimization of a cable-stayed bridge under construction, 6% - 8% of the construction cost can be saved, about 100 million yuan.

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