Research on Wind-induced Vibration of Long-span Cable-stayed Bridges

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Abstract. With the development of mechanical theories and bridge construction technologies, there are increasing number of long-span cable-stayed (LSCS) bridges crossing bays or oceans, which can shorten the distance between two places and facilitate the travel of people. However, with the increase of bridge length, the damping ratio decreases at the same time, making the bridge structure more sensitive to wind-induced vibration (WIV). The vibration can cause safety problems and even the deformation of the bridge. Therefore, it is of great significance to research on the WIV of LSCS bridges. In this paper, common types of WIV of LSCS bridges are firstly introduced from their common definitions and present studies. Then, the mechanical performances under typhoon events and daily average wind conditions are analyzed, respectively. Finally, the solution methods of eliminating WIV of these bridges are discussed, involving strengthening structural stiffness, increasing damping ratio as well as changing the section form of the bridge.

Keywords: Long-span cable-stayed bridge; wind-induced vibration; aerodynamic behavior.

1. Introduction

Cable-stayed bridge is a structure composed of pylons that bear compression, the girder that bears bending moment, and cables that bears tension. By reducing the bending inside the girder, using the style of cable-stayed bridge can save the material and reduce the weight, thus lower the total project cost. The cable-stayed bridge contains beautiful aesthetic forms as well. And cable-stayed bridge has stronger crossing capacity compared with other bridges so that it is the main bridge style for long span bridge. Stromsund Bridge is the earliest modernized cable-stayed bridge that was constructed by a German company DEMAG in 1955 in Sweden. Its main span is 182.6 m. Up to now, the longest cable-stayed bridge is Russky Island Bridge which is 1104 m long. And there are also many other famous cable-stayed bridges in the world, such as Tatara Bridge in Japan and Sutong Bridge in China.

However, with the increase of the length of main span, the cable-stayed bridge becomes lighter and stiffer as well. As a result, the bridge will be more sensitive to the influence of wind that leads to the WIV. Hence, the stability and the wind resistance of LSCS bridge should be taken into account from design to construction more carefully. There were several bridges being destroyed because of insufficient design of wind influence. One example is Tacoma Bridge in Washington, which was destroyed by the fresh gale after four months of service. During construction, the Forth Bridge in Britain also experienced WIV, which led to the damage of tower column joint. These cases led designers to think about promoting wind resistance of bridges.

To strengthen the wind-resistant performance of LSCS bridge, relevant researchers and scholars have already done many studies, put forward relevant theories or formulas, and put them into practice. In 1990s, linear method was developed to be used in wind resistance analysis. And later, non-linear method was established as well. Boonyapinyo et al. [1] combined eigenvalue analysis with algorithms to calculate wind-induced buckling of the bridge. Moreover, Scanlan and Tomko put forward a half experience and half theory method by introducing the concept of aerodynamic derivative. This idea was successfully used to explain the failure of Tacoma Bridge [2]. Recently, Zhao et al. [3] stated that because of decreasing stiffness caused by viscous excitation of wind load, systematic stiffness and torsion, the bridge would be in wind-induced instability. Although many complex problems in this field have not been solved yet, the study of wind resistance is going deeper and wider.

This essay firstly discusses the definition of WIV. Then the performance of the bridge under two typical conditions is analyzed, one is during typhoon events, the other one is during daily average wind conditions. Finally, this essay covers the solutions to improving the wind resistance caused by WIV of the LSCS bridge.

2. Wind-induced Vibration

WIV means horizontal or vertical vibration of bridge because of the flowing wind. There are mainly four types of common vibration: vortex-induced vibration (VIV), flutter, buffeting and galloping. These types of vibration together affect the stress state of LSCS bridge and contribute to the service time of a bridge, especially the bridge located in strong wind areas. If the bridge lacks wind resistance design, the bridge will be destroyed during service time so that pedestrians and moving vehicles on the bridge will be in unsafe situations and cause economic loss. This section will introduce each type of WIV by introducing its definition and the study advancement.

2.1. Vortex-induced Vibration and Galloping

VIV is a finite amplitude vibration with forced self-excited vibration properties under the action of average wind. It is induced by the periodic shedding vortex near the bridge structure surface. Long term VIV will negatively influence driving safety, fatigue life and durability of structure components [4].

However, there has not been a complete theory of VIV at home and abroad to quantify the value. Scholars mainly use a half-theory and half-experience way to estimate the vibration amplitude. Some commonly used mathematical models are simple harmonic oscillator model, wake oscillator model as well as the empirical linear and non-linear model. After that, researchers will usually do some wind tunnel simulation experiments by changing the wind attack angle and damping ratio to get some data or graphs for optimizing VIV performance. And wind tunnel experiment plays an important role in simulating the actual wind environment.

Galloping is a self-excited vibration with large amplitude and low frequency caused by flowing air under the action of average wind. This happens most frequently to bending member in the state of single degree freedom. Galloping is relatively rare in bridges so that few researchers paid attention to it. Li et al. [5] found that the damping ratio contributes little to the critical wind speed for galloping of bridge tower.

2.2. Flutter

Flutter is another type of vibration. Under the action of daily average wind, the bridge system, as a special structure, continuously absorbs divergent aerodynamic self-excited vibration from the flowing air, which is greater than the damping dissipation capacity of the structure. Tacoma Bridge was just destroyed by flutter.

There are two genres of bridge flutter: classic coupled flutter and separated-flow torsional flutter. Based on flutter types, there are generally three corresponding solutions. As for classic coupled flutter theory, Kloppel [6] programmed a software based on classic coupled flutter theory for calculation convenience. Moreover, Scanlan and Tomko [2] firstly introduced aerodynamic derivative into this field, established six equations to present unstable self-excited aerodynamic force, and used them in bridge sections. As for advantages, these frequency-domain (FD) algorithm methods are simple and efficient. However, the disadvantages of FD algorithm are obvious as well. It’s very difficult to predict the vibration in strong wind conditions owing to non-uniform large deformation [7]. As a result, time-domain (TD) algorithm was gradually created. Scanlan et al. [8] presented the self-excited aerodynamic force of arbitrary bridge cross-section through applying step functions. Later, rational functions were applied to express the aerodynamic force and used them for relevant studies [9,10].

2.3. Buffeting

The buffeting of bridge is a finite amplitude vibration with forced vibration characteristics. It is also a random vibration induced by pulsating wind spectrum under turbulence field [11]. Buffeting is induced when the turbulent wind existed in the natural wind flows around the bluff body structure [12]. Although buffeting will not lead to aerodynamic instability, it will produce local fatigue of supports and joints for the reason that the wind speed of buffeting is low and the wind efficiency is high. Excessive buffeting will make the driving of vehicles on bridge unsafe. Because of these reasons, buffeting is very essential phenomenon and needs careful prediction about it.

Up to now, there are mainly three commonly-acknowledged theories toward the calculation of buffeting. Scanlan's flutter-buffeting theory is one of them. Lin produced TD buffeting analysis method. Davenport also put forward his own analysis approach.

3. Influence of LSCS Bridge under Different Wind Forces

Different types of wind will influence the mechanical behavior of the bridge differently, and this section discusses two common occasions for LSCS bridge: vibration during typhoon events and the fatigue performance under average wind.

3.1. Typhoon Events

Typhoon is one of the tropical cyclones, and it will cause strong wind and raining in the area where it passes. For those LSCS bridges located in areas with frequent typhoons, it is of great importance to make them be wind-resistant and take proper preparations before typhoon comes.

The strong wind, especially the crosswind caused by typhoon will greatly challenge the wind resistance of a bridge. If the bridge is designed insufficiently, the bridge will tend to be deformed under the action of strong winds. Wang et al. [13] researched on Sutong Bridge that experiences typhoon events frequently. They used the health monitoring system to get information such as horizontal displacement and torsional acceleration for buffeting analysis. According to the statics and graphs, Wang et al. [13] stated that there are close connections downstream and upstream as well as great randomness for buffeting. However, generally, as the increase of wind speed, the buffeting increases at the same time. They also concluded that for one specific cable, buffeting has big difference between the windward and the leeward sides [13]. Tao et al. [14] carried out the experiment by simulating the non-stationary TD aerodynamic model of wind field of typhoon. From the two-dimensional step function, they [14] claimed that it is very hard to accurately estimate the influence of typhoon from traditional methods because they do not take time-varying effect into consideration. Therefore, considering average wind load and pulsating wind for typhoon is very important [14].

3.2. Daily Average Wind

Except for strong wind in a short time, daily average wind can also influence the service time of a bridge due to the fatigue under the action of stress cycle change of bridge components caused by WIV [15]. Rychlik [16] put forward a Rayleigh distribution model to estimate the structural fatigue. However, Yang et al. [17] claimed that Rychlik's method overestimates the structural fatigue of a LSCS bridge. Bishop theory has similar results to the actual value but has big difference in low-frequency domain. Based on these disadvantages, Yang et al. [17] proposed a FD analysis method to compute the fatigue using Markov process.

4. Solutions to Reduce Wind-induced Vibration

There are several ways to decrease the influence of vibration caused by the wind during service stage. Among different methods, engineers mainly work on three directions: improving the stiffness, increasing structural damping and choosing cross-section form of main beam properly. For the reason that buffeting and flutter are the most common vibration types in bridges, and VIV is paid attention gradually these years, this essay will mainly talk about their performances of LSCS bridge for each method.

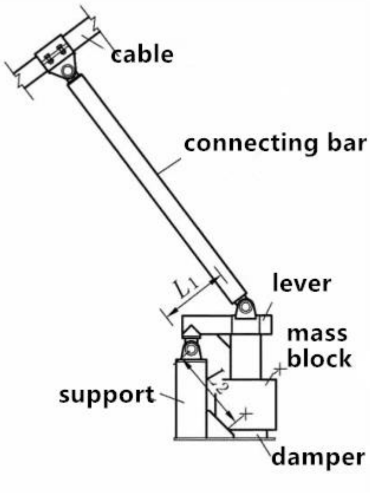
4.1. Stiffness Method

Increasing the stiffness of the total bridge is one way to reduce the influence of WIV to LSCS bridge, and by increasing the stiffness of each component of the LSCS bridge, like pylons, girder and cables, the bridge tends to be more wind resistant. Li et al. [18] studied a bridge in Yunnan Province using a finite element analysis software. The bridge shows better stiffness by using the composite beam structure of concrete and rebar. They concluded that compared with steel structure cable-stayed bridge, the composite structure bridge shows good wind resistance according to the buffeting and flutter analysis [18]. They said that the calculated flutter wind speed is smaller than the critical wind speed. Ni [19] said that the vertical WIV of bridge is closely associated with the stiffness of cables and the vertical stiffness of main girder. Therefore, by using much stiffer material to construct main beams and cables, the vertical stiffness of the bridge can be promoted, leading to better wind-resistant performance of the bridge. However, improving the horizontal stiffness cannot reduce the horizontal vibration amplitude.

4.2. Damping Method

Due to the lighter weight of bridges, the damping of bridge becomes smaller at the same time, which makes the bridge more sensitive to WIV. Through increasing the damping of cables and girder, the bridge will become less alert to WIV.

Zhang et al. [20] stated that the bridge will be more stable in terms of VIV by improving its structural damping ratio. Using dampers to reduce vibration is the most common method, among which decreasing the WIV of cables is paid most attention, because cables are usually light in weight, high in flexibility and low in internal damping, and these properties assist to form vibration caused by incentive effect of wind, especially for the LSCS bridges which are more flexible [21]. Liang et al. [22] found that connecting dampers to cables can greatly decrease the horizontal WIV of cables. For LSCS bridge, internal dampers and external dampers are both necessary to control WIV of cables [23]. However, it is very important to choose damper types properly based on the temperature, wind environment also the length of the cable. Commonly-used types are high damping rubber damper, oil damper, lever mass damper (Fig.1 & Fig.2) and viscous shear damper [23]. There are other aerodynamic measures that optimizes the cross-section form to increase damping ratio by specific design as well. Hu and Zhan [24] found that setting pneumatic wing plates can dissipate the surrounding air, thus improving the flutter stability. Moreover, according to a wind tunnel simulation experiment carried out by Zhang et al. [20], streamlined closed steel box girder section is a good form to resist VIV.



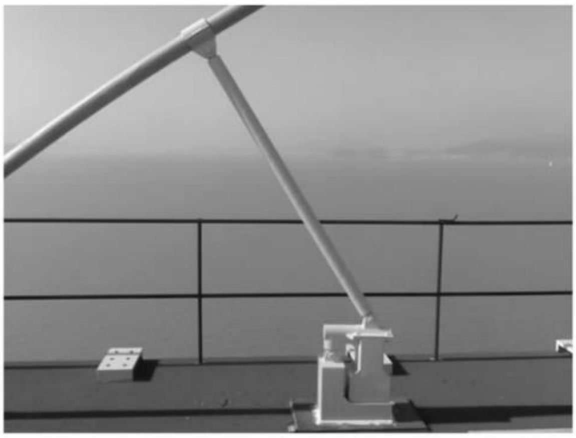


Fig.1 Model of lever mass damper [26] **Fig.2** Application of lever mass damper [26]

4.3. Section Form Method

Researchers usually examine the aerodynamic properties of cross-section of the main beam. And small changes of the bridge can reduce the vibration economically and effectively. There are several aerodynamic methods during design and construction process that change the section form to lower or eliminate WIV under common wind action. Central slotting, central stabilizer plate (Fig.3), air nozzle (Fig.4) and deflector (Fig.5) are frequently used for this purpose [25]. Central slotting is most effective for closed box girder section to improve its flutter stability by improving critical flutter wind speed up to 27% [25]. And it was found [24, 25] that setting central stabilizer plate can improve flutter performance if the plate dimension is appropriately chosen. To decrease the influence of flutter, engineers would set air nozzles and optimize their shapes so that the wind can get through the bridge easier and the vortex shedding can be decreased [24]. Yang et al. [25] added that air nozzle is most adaptable to the occasion when there is a passivated girder in terms of aerodynamic profile, where the critical flutter wind speed can be promoted by 30%. More recently, Liu et al. [26] promoted a combined form of lower stabilizer plate + lateral vertical skirt plate + upper stabilizer plate to restrain VIV and got satisfying result.

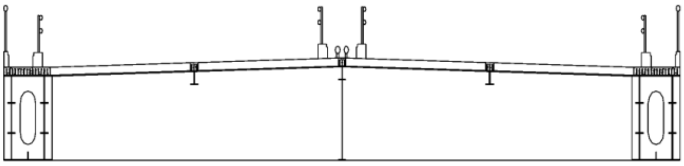


Fig. 3 Central stabilizer [30]

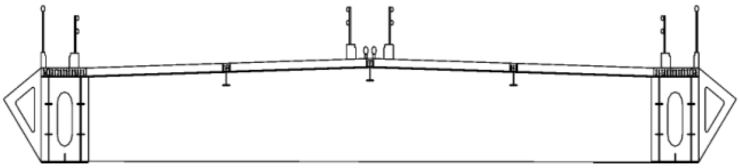


Fig.4 Air nozzle [30]

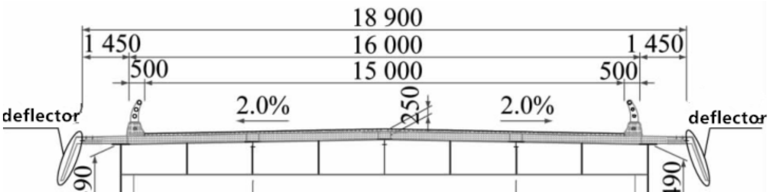


Fig.5 Deflector [30]

5. Conclusion

This essay studies on the WIV of LSCS bridge from the introduction of vibration to the solutions used in construction sites. There are mainly four conclusions from this essay:

(1) Due to the increasing length of LSCS bridge, it is shown that bridges become more sensitive to the vibration caused by wind. Therefore, it is vital to take wind resistance into account during design and construction processes for safety concern. For LSCS bridge, the vibration of the main girder, pylons and cables are the main focuses.

(2) VIV, buffeting, flutter and galloping are the fundamental types of WIV. Among them, scholars pay most attention to buffeting and flutter, while VIV and galloping rarely happens in the field.

(3) To abate the influence of WIV acting on the bridge during service time, it is suggested to think from three perspectives: increasing the stiffness of LSCS bridge, increasing the damping ratio of the structure and optimizing the section form from aerodynamic characteristics.

(4) Setting damping devices and changing the section form of the bridge are two frequently used methods. For damping devices, engineers usually install them to prevent the vibration of cables. To change the shape of the section, engineers usually set up central stabilizer plates, central slots and air nozzles.

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