Review on the Service Safety Assessment of Main Cable of Long Span Multi-Tower Suspension Bridge

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Abstract: The long-span multi-tower suspension bridge is widely used in the construction of river and sea crossing bridges. The load-bearing safety and anti-sliding safety of its main cable are directly related to the structural safety of a suspension bridge. Failure mechanisms of the main cable of a long-span multi-tower suspension bridge are discussed. Meanwhile, the tribo-corrosion-fatigue of main cable, contact, and slip behaviors of the saddle and service safety assessment of the main cable are reviewed. Finally, research trends in service safety assessment of main cable are proposed. It is of great significance to improve the service safety of the main cable and thereby to ensure the structural safety of long-span multi-tower suspension bridges.

Keywords: long-span multi-tower suspension bridge; main cable; load-bearing safety; anti-sliding safety

1. Introduction

In China, bridge construction has entered the river and sea crossing era [1,2]. The multi-tower multi-span suspension bridge (Figure 1) realizes the super long span capacity by adding middle cable tower based on the traditional two tower suspension bridge, and has advantages in terms of reductions of main cable tension, anchorage scale, main span length, and total cost as compared to other typologies of bridges [3,4]. With the continuous improvement of the expressway network and high-speed railway network constructions, and according to resource-saving, environment-friendly, and sustainable development concepts, the suspension bridge share by highways and railways has become a resource-saving bridge type for river and sea crossing channels, such as Qingma suspension bridge in Hong Kong and Wufengshan Yangtze River Bridge in Jiangsu under construction. Therefore, it is of great importance to explore the construction technology of long-span multi-tower suspension bridges across the river and sea, shared by highways and railways.

The long-span multi-tower suspension bridge consists of a main cable, cable tower, main cable saddle, splay saddle, hanger, stiffening beam, and anchorage (Figure 1). The main cable is a flexible load-bearing component suspended on the cable tower through the main cable saddle composed of saddle groove and diaphragm, and anchored in the anchorages at both ends through the splay saddle [5]. The main cable, with the characteristics of high cost and difficult replacement, is the “lifeline” of suspension bridge. Once it fails, it will seriously endanger the structural safety of suspension bridge, even cause great economic losses and endanger safety of people’s lives. The main cables of George Washington Bridge, built in 1931 with a main span of 1067 m, exhibit severe corrosion and a large number of fractured wires [6], which causes a maintenance cost of approximately 500 million US dollars. The main cable wires of Forsyth bridge present severe wear and...
corrosion [6], which induces a maintenance cost of approximately 200 million pounds. The main cable and saddle of the middle tower of a multi-tower suspension bridge are prone to skidding accidents, which causes the structural instability and even collapse of suspension bridge [7]. Therefore, the service safety of main cable of long-span multi-tower suspension bridge is directly related to the structural safety of suspension bridge.

Figure 1. Schematic diagram of long-span multi-tower suspension bridge.

The main cable of long-span multi-tower suspension bridge across the river and sea is subjected to the wind loads with distinct directions attributed to the effect of strong wind [8]. The roles of changing environment temperature and sunlight radiation cause the obvious temperature gradient of internal and surface temperature fields of main cable (attributed to the hysteresis of internal temperature change of main cable), and thereby induce changes of internal forces and line shape of main cable [9]. In addition, the main cable of a suspension bridge shared by highway and railway is subjected to the dead load (bridge deck system, stiffening beam, main cable, hanger) and live load (automobile, railway train) through hanger and cable clamp. The railway train has the characteristics of high speed and heavy load. The long-span multi-tower suspension bridge across the river and sea exhibits the large flexibility [4]. Ref. [4] indicates that the up and down deflection deformations of main beam of a three-tower suspension bridge are 7.65 and 2.44 times of those of a two-tower suspension bridge, respectively, under the action of the vehicle attributed to the weak restraint of main cable at the top of middle tower of three tower suspension bridge. The suspension bridge with very low natural frequency is very sensitive to wind loads, which easily induces the coupled vibration of wind-vehicle-bridge system; the lateral displacement, lateral acceleration and vertical acceleration of the vehicle attributed to the weak restraint of main cable at the top of middle tower of three tower suspension bridge. 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corrosion solutions with different salt concentrations and PH values are easily formed. However, the electrolyte corrosion solution can invade and stay in the main cable during the erection period of main cable (usually more than one year). Meanwhile, the electrolyte corrosion solution easily invades and gathers at clearances among steel wires in the main cable [16]. Therefore, the main cable of a long-span multi-tower suspension bridge across the river and sea is always subjected to electrolyte corrosion. It was reported that electrolyte corrosion is one of main failure modes of existing bridges [17,18].

As the main cable of long-span multi-tower suspension bridge is bent around the main cable saddle, average axial and bending stresses of the main cable at the saddle and near both sides exhibit the largest values, which indicates easier failure locations of main cable [19,20]. The main cable is composed of parallel strands, and the strand is composed of parallel high-strength galvanized steel wires. As the main cable is bent around the saddle groove of main cable saddle, time-varying dynamic loads of main cable at both sides of the saddle easily cause dynamic contacts and “layered sliding” between strands and between steel wires in the main cable as well as the fatigue stresses of cable strands and wires. Meanwhile, dynamic contact and slip characteristics between the main cable strand and saddle groove/diaphragm easily occur.

Therefore, those will cause the friction and wear between steel wires in the main cable, friction and wear between external steel wires of main cable and saddle groove/diaphragm, and fatigue stresses of cable strands and wires. As the difference of time-varying dynamic loads of the main cable at both sides of the saddle is enough to overcome the total friction force between main cable and saddle during dynamic slipping, the gross slip phenomenon occurs between main cable and saddle [7]. Skidding accidents between main cable and saddle easily occur at the middle cable tower, attributed to weak constraints of main cables on both sides [21], which leads to the structural instability and even collapse of the suspension bridge.

Therefore, coupled effects of temperature, electrolyte corrosion solution, internal and external friction and wear of main cable, and fatigue stress cause the tribo-corrosion-fatigue damage of main cable under the temperature effect. The tribo-corrosion-fatigue induces the friction and wear, electrochemical corrosion, fatigue crack propagation and fracture of steel wires in the main cable, which reduces the effective cross-sectional area and thereby affects the load-bearing safety of main cable. In addition, the corrosion and scratch of steel wire during transportation and erection lead to the crack initiation of steel wire. Meanwhile, coupled effects of temperature, electrolyte corrosion solution, and time-varying dynamic loads induce dynamic contact and slip characteristics between the main cable and saddle under effects of temperature and electrochemical corrosion, and thus affect the anti-sliding safety between main cable and the saddle. Therefore, load-bearing safety and anti-sliding safety are two key issues in service safety assessment of main cable of long-span multi-tower suspension bridge. Lots of scholars have carried out relevant researches on tribo-corrosion-fatigue of the main cable, contact and slip behaviors of the saddle, and service safety assessment of the main cable as follows.

2. The Tribo-Corrosion-Fatigue

In the aspect of environmental conditions of main cable, Que et al. [22] presented the corrosion status of main cable in the humid corrosive marine environment (Figure 1 in Ref. [22]) and analyzed anti-corrosion measures. Que et al. [22] and Tian et al. [23] measured the in-situ temperature and humidity at the saddle and anchor chamber locations (Figures 2 and 3 in Ref. [23]), and indicated the good heat insulation effect of anchor chamber and sharp variations of temperature and humidity at the saddle location greatly affected by solar radiation and air convection. Meanwhile, they proposed that the change and distribution of humidity in the main cable was mainly influenced by the temperature field, and in turn affected the temperature distribution [22].

Considering friction behaviors of main cable, Montoya et al. [24] found the friction between parallel steel wires, redistributions of stresses of steel wires adjacent to the frac-
tured wire, and the fractured wire far away from the fracture location restoring part of load-bearing capacity. Zhang et al. [25] established the balance equation of friction force between main cable strand and saddle at any longitudinal contact locations (Equation (1)) and basic theoretical equation of frictional characteristics between main cable strand and saddle in the parallel model of sub saddle (Equation (2)). They also proposed the total friction force between the main cable strand and saddle mainly composed of friction forces between the main cable strand and bottom surface/side wall of cable groove. However, the friction force between main cable strand and bottom surface accounted for 70% of total friction force. Cheng et al. [26] established the friction resistance model between main cable and saddle of multi-tower suspension bridge, and found the friction resistance between main cable and saddle composed of friction resistances between main cable and saddle groove/diaphragm (Figures 1, 2, and 7 in Ref. [26]). It was revealed that using one horizontal friction plate was more effective in enhancing friction resistance than using one vertical friction plate. However, the total number of vertical friction plate could be much greater than that of horizontal friction plates in engineering practice. Using one horizontal friction plate in the saddle could increase the frictional resistance by up to 107% and the nominal coefficient of friction by up to 78%. Using 12 vertical friction plates in the saddle could increase the frictional resistance by up to 187% and the nominal coefficient of friction by up to 128%.

\[
2 \cdot \mu_0 \cdot f_{H} + \mu_0 \cdot \sum_{i=1}^{n_{cum}} f_{c}^i - \mu_n \cdot \sum_{i=1}^{n_{cum}} f_{b}^i = 0 \quad (1)
\]

\[
f(\mu_0) = \left(2 \cdot f_{H}^c + 4 \cdot f_{H}^b + f_{c}^b + 2f_{c}^b\right) \cdot \mu_0 - \left(f_{c}^b + 2f_{c}^b\right) \cdot \mu_n \quad (2)
\]

where \(f_{H}^c\) and \(f_{H}^b\) are total lateral forces in height ranges of central strands and side strands, respectively, while \(f_{c}^b\) and \(f_{c}^b\) are radial pressure of central and side strands, respectively.

According to corrosion behaviors of main cable, Nakamura and Suzumura [27] studied the effect of corrosion level on the tensile strength of galvanized steel wire of main cable. Tian [28] and Chen [29] discussed corrosion mechanisms and corrosion protection strategies of main cables of long-span suspension bridge. They proposed that water, harmful gas, and fatigue stress were main reasons of chemical corrosion and stress corrosion of steel wires and thus greatly affected the endurance of main cable. Meanwhile, they suggested the applications of galvanized steel wires to increase the corrosion resistance of steel wires and sealing measures to cut off the contacts between steel wires and external corrosive media. Hong [30] discussed corrosion mechanisms of steel wires and their galvanized layers, and presented reaction mechanisms of galvanized steel wires in the acid solution (Figure 3-1 in Ref. [30]). It was revealed that the corrosion rate of steel wire was affected by the temperature, relative humidity, electrolyte solution concentration, type and pH value of corrosive medium, corrosion potential difference, crack depth, external load and other impurities. He proposed that the tensile strength of steel wire of main cable decreased with the increasing loss rate of steel wire cross-section and the larger tensile strength loss rate of steel wire as compared to its yielding strength loss rate. Miao et al. [31] studied the effects of temperature, salt content and pH value on corrosion rates of high strength steel wires of long-span suspension bridge through electrochemical tests (Figures 3–5 in Ref. [31]). They indicated that environmental conditions affecting the corrosion rate of steel wire descended with the order of NaCl concentration, temperature, interaction between temperature and pH, and pH value and temperature. Sun [32] analyzed corrosion conditions of steel wires and distribution laws of corrosion degree in the main cable (Figures 3–14 in Ref. [32]). Statistics of corrosion dimensions of galvanized steel wires indicated that the actual and average corrosion depths satisfied generalized extreme value distributions, and corrosion width and length satisfied lognormal distributions. He also proposed comparisons of tensile curves of steel wires with distinct corrosion degrees (Figure 4-3 in Ref. [32]).

Referring to fatigue and fracture behaviors of main cable, Xiu [33] indicated the main cable near the tower of long-span suspension bridge presented a larger stress amplitude and was more prone to fatigue failure. He estimated fatigue crack initiation and propa-
gation lives of main cable employing the local stress–strain method and Paris equation, respectively. Meanwhile, he proposed recommended material parameters for the estimation equation of crack propagation of steel wire in the main cable, i.e., $m = 3$ and $C = 1.592 \times 10^{-13}$. Zeng et al. [34] proposed the fitting formula of stress intensity factor (Equation (3)) based on propagation laws of “first round and then flat” crack profiles of steel wire, and calculated the residual strength of steel wire based on fracture toughness. Sih et al. [35] studied the effects of crack shape and dimension on the fracture strength and crack propagation life of steel wire. Li et al. [36] analyzed the crack propagation laws of steel wires employing the multi-scale modeling and micro fracture mechanics. Zejli et al. [37] dynamically monitored fractured steel wires of main cable employing the acoustic emission technology. Roffey [38] analyzed fracture mechanisms of steel wires of main cable and found that possible mechanisms of crack initiation and propagation were considered to be pitting corrosion, hydrogen assisted cracking, branched cracking, and corrosion-fatigue (Figures 1, 6, and 7 in Ref. [38]).

$$K_I = Y(a)\sigma(\pi a)^{1/2}$$  \hfill (3)

where $\sigma$ is the stress of specimen, $a$ is the surface crack depth, and $y(a)$ is the geometric correction factor.

In conclusion, the researchers analyzed wet corrosion environment and distribution characteristics of temperature and humidity, studied tribological characteristics between steel wires in the main cable and between main cable and saddle in the atmospheric environment, discussed the effects of temperature, salt content, and pH value on corrosion behaviors of main cable, and investigated the fatigue life of main cable, crack propagation, and fracture characteristics of steel wire.

### 3. The Contact and Slip Behaviors of the Saddle

In the aspect of contact between main cable and saddle, Qi et al. [39] developed three nodes space saddle element (Figure 1 in Ref. [39]), and obtained the cable force at the tangent point between main cable and saddle during the contact process. Yan et al. [19,20] and Zhang [40] calculated the secondary stress of main cable bent around the saddle under dead and live loads of suspension bridge, respectively. Meanwhile, they found the separation and slip behaviors between steel wires and between strands in the main cable during the bending deformation of main cable, and proposed calculation methods of a layered element model of bent main cable and limited friction force between layers. Xiao et al. [41] proposed a cable saddle modeling method in order to finely simulate the separation, contact and slip behaviors between main cable and saddle. He found that, in the case of unbalanced cable force loading, the radial pressure and friction force of the saddle both increase with increasing cable force and increase from the non-loading side to the loading side. Ji [42] established the refined contact model to discuss the lateral force distribution, layered sliding, force transfer mechanism and anti-sliding measures between main cable and saddle groove. He found that the lateral force of cable strand presented a negative exponential convergence curve distribution and the lateral force was the direct factor affecting layered sliding. According to the layered sliding, he proposed that the upper steel wire slipped easily as compared to the lower steel wire. As the bottom steel wire exhibited the gross slip, the cable strand would skid as a whole. It was revealed that settings of vertical and horizontal friction plates could effectively improve the anti-sliding ability of main cable but the application of horizontal friction plate was relatively limited.

Considering the micro slip between main cable and saddle, Chung et al. [43] established the three-dimensional elastic catenary elements based on micro slip between main cable and saddle (Figure 3 in Ref. [43]). Zhang and Li [44] proposed the criterion of slip time and showed that testing results of relative slip between main cable and saddle at the non-loading side of saddle groove were most sensitive to the slip and could be used as the slip criterion. Meanwhile, they measured the coefficient of friction between main cable and saddle with two or without diaphragms, i.e., 0.473 and 0.552, respectively. Ji [42]
explored effects of coefficient of friction, vertical or horizontal diaphragms, cable strand arrangement in the saddle groove on slip characteristics between main cable and saddle through numerical simulation.

In conclusion, lots of scholars calculated the lateral force and secondary stress of main cable on the saddle, studied the separation, contact and slip behaviors between main cable and saddle, explored separation and slip characteristics of strands and steel wires in main cable during the contact between main cable and saddle, and investigated the effects of coefficient of friction, diaphragm, and cable strand arrangement on static slip characteristics and criteria between main cable and saddle.

4. The Service Safety Assessment

Considering the load-bearing safety of main cable, Cheng and Xiao [45] evaluated the safety factor of main cable of long-span suspension bridge based on the inverse reliability method. Xu [46] calculated relevant parameters of main cable at typical locations according to standards in different countries (Table 2 in Ref. [46]) and suggested the safety factor of 2.3 of main cables for Chinese long-span suspension bridges. Meanwhile, he proposed the calculation method for the safety factor of main cable considering secondary stress and verified the enough safety reserve of main cable when selecting the safety factor of 2.3. Chen et al. [47] proposed the factors affecting the bearing capacity of main cable at stages of cable design, cable construction, operation phase of bridge and maintenance phase of main cable. During the stage of cable design, the safety factor was introduced to ensure the cable safety, while the safety factor is based on the suspension bridge model and designer’s experience, and the actual safety degree of main cable is undetermined. During the cable construction stage, he indicated considerations of the control of main cable shape, the wire fracture caused by construction process, damages of outer steel wires of main cable attributed to the excessive clamping force of cable clamp, and secondary stresses of main cable caused by constraints of cable clamp and saddle. During the operation phase of a bridge, corrosion, fracture of steel wires, and moment of inertia of the bending section of the main cable at bending segment greatly affected the loading conditions of main cable. Da [48] proposed that the wrapping angle of main cable around the saddle greatly affected the performance of main cable at the saddle; it was found that maximum equivalent stresses of main cable and clamp with the clamping force was greater than that without clamping force (Table 5.1 in Ref. [48]). Deng et al. [49] dynamically monitored tension forces of separate cable strands of main cable of the long-span suspension bridge, derived the overall tension force of a main cable, and conducted the load bearing capacity assessment using concept of safety factor. With long-term monitoring data, monitoring-based evaluation methods could provide critical information to assess safety and serviceability performance of main cables.

In the aspect of anti-sliding safety of main cable, Jiang et al. [7] studied the effect of middle tower stiffness on the critical span of sliding instability between main cable and saddle of multi-tower suspension bridge, and found that the anti-sliding safety coefficient was related to the span and ratio of dead load to live load. Xiao [21], Chai et al. [50], and Wang et al. [51] proposed analytical calculation methods for anti-sliding safety factor between main cable and saddle of middle tower of multi-tower suspension bridge, studied effects of sag-span ratio, span, middle tower stiffness and ratio of dead load to live load on the anti-sliding safety factor of main cable. It was found that an increase of the ratio of tower stiffness to cable stiffness caused a decrease in the anti-slip factor. The effect of sag-span ratio on the anti-sliding factor depended on the tower stiffness. Increases of span length and ratio of dead load to live load induced an increase in the anti-sliding factor. Zhang et al. [52] proposed that the anti-sliding safety factor was equal to the ratio of friction force between main cable and saddle to the tension difference of main cable at both sides of saddle, and discussed the effects of saddle design parameters on anti-sliding safety factor. Ruan et al. [53] evaluated anti-sliding safety between main cable and saddle of middle tower of long-span suspension bridge. He found that the assessment of anti-sliding safety of saddle was more conservative when geometric nonlinearity of live load was not included.
The comparison between deterministic approaches in codes and reliability-based approach indicated that the selection of friction coefficient, traffic load modeling, and assessment approaches are important to results. Besides, lots of researchers conducted tests to obtain the coefficient of friction between main cable and saddle in cases of distinct suspension bridges (Table 1).

| Bridges                          | Tested Coefficients of Friction | Brief Introduction                                                                 |
|----------------------------------|---------------------------------|------------------------------------------------------------------------------------|
| George Washington Bridge and Forth Road Bridge [54] | 0.30                           | Measured value of real bridge                                                      |
| Delaware River Bridge [54]      | 0.19–0.21                      | During loading and measuring processes of the three bridges, the slip time is not clear enough and the error is large |
| Kan-mon Bridge [54]             | 0.15–0.21                      | Testing results corresponding to the saddles with inorganic zinc rich paint and zinc coating, respectively |
| Honshu-Shikoku Bridge [54]      | 0.16–0.44                      | The contact stress between cable strand and saddle during the test is smaller as compared to the real bridge |
| Tokyo Port Link Bridge [54,55]  | 0.31/0.60                      | Mean value of test results of a strand                                            |
| Yangluo Bridge in Wuhan [56]    | 0.14–0.33                      | Sliding tests between main cable and saddle with different diaphragms              |
| Yingwu River Bridge [25]        | 0.27–0.33                      | Mean value of test results of 10 strands                                           |
| Taizhou Yangtze River Bridge [57,58] | 0.31                           | Mean value of test results of a strand                                            |

According to the monitoring technology of service safety status of main cable, Tian [59] employed acoustic detection system to detect fractured steel wires in order to dynamically monitor the service safety of main cable. Yu [60] studied the service safety of main cable under coupled roles of corrosion and fatigue load based on the probability analysis method. Yue [61] developed a strain and temperature monitoring system for steel wires of main cable based on the remote on-line fiber grating technology. Sloane et al. [62] and Betti et al. [63] developed a nondestructive corrosion monitoring system which can dynamically monitor the temperature, humidity, and corrosion level of main cable in order to explore the main cable degradation.

In conclusion, lots of scholars introduced calculation methods of load-bearing safety factor of main cable based on the inverse reliability method and considering the secondary stress, studied the effects of corrosion induced fractured steel wire, secondary stress, and wrapping angle on the load-bearing capacity of main cable. Meanwhile, the effects of design parameters of suspension bridge on the anti-sliding safety factor based on Euler’s formula were analyzed. The anti-sliding safety factor was calculated using the reliability method and ratio of friction force to static tension difference method. The anti-sliding safety between main cable and main cable saddle was evaluated. The service safety of main cable was monitored dynamically based on acoustic detection and probability analysis. The fiber grating technology and corrosion monitoring system were combined to dynamically monitor the temperature and corrosion degradation of main cable.

5. Research Trends in Service Safety Assessment of Main Cable

Load-bearing safety and anti-sliding safety of main cable are evaluated by the load-bearing safety factor and anti-sliding safety factor, respectively. At present, the load-bearing safety factor of main cable is mostly based on the determined suspension bridge model and designer experience, which causes the unknown actual safety degree of main cable, uneconomic design, and difficulty in maintenance decision-making [47]. The formula of anti-sliding safety factor is based on Euler’s formula of friction transmission of flexible body, which only considers the dry friction between main cable and the bottom surface of saddle groove of the saddle [42]. Therefore, the calculated value is difficult to evaluate the anti-sliding safety between main cable and saddle accurately. In fact, the load-bearing and anti-sliding safety factors of main cable of long-span multi-tower suspension bridge over the sea and river are both affected by design parameters of suspension bridge and environmental conditions such as temperature, wind (wind load, wind speed, wind attack angle), and electrolyte corrosion solution (salt concentration and pH value). At present,
we are not clear about the relationships between loading-bearing capacity/safety factor and tribo-corrosion-fatigue damage of main cable. Meanwhile, dynamic contact and micro slip mechanisms between main cable and saddle and the anti-sliding safety factor under coupled roles of temperature, electrochemical corrosion and time-varying dynamic load have not been reported yet. Besides, main factors affecting the service safety of the main cable are still not clear. Therefore, it is of great importance to obtain relationships between load-bearing/anti-sliding safety factors of main cable and influencing factors of temperature, time-varying dynamic loads and tribo-corrosion-fatigue damage. Moreover, we have to associate the load-bearing capacity and anti-sliding safety factor with environmental conditions and design parameters of suspension bridge. Finally, optimized design parameters of a suspension bridge are proposed to improve the service safety of the main cable of long-span multi-tower suspension bridges. This is of great theoretical significance to improve the service safety of main cable and to ensure the structural safety of long-span multi-tower suspension bridge.

6. Conclusions

The long-span multi-tower suspension bridge is widely used in the construction of river and sea crossing bridges. Loading bearing and anti-sliding safeties of the main cable directly affect the service safety of long-span multi-tower suspension bridge. Previous researches indicated that the loading bearing safety of main cable was affected by the temperature, electrochemical corrosion, friction wear, and fatigue stress, and the anti-skidding safety of main cable was influenced by the temperature, electrochemical corrosion, and time-varying dynamic load. The anti-sliding safety factor of main cable considering environmental conditions (temperature, wind and electrolyte solution), time-varying load, as well as main saddle structural parameters and materials was not proposed. In the present study, we proposed the research idea of predicting the load bearing safety factor of main cable based on tribo-corrosion-fatigue damage, and establishing the anti-sliding safety factor model of main cable considering environmental conditions, time-varying load, saddle structural parameters, and saddle materials. Meanwhile, it is intended to reveal relationships between load-bearing/anti-sliding safety factor, environmental conditions, and the design parameters of suspension bridges, respectively. Therefore, optimized design parameters can be obtained, which can be used to conduct the optimized structural design of suspension bridges.

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