Wind Stability Analysis of 4000m-Span Suspension Bridge with Carbon Fiber Spatial Cable System

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Abstract. In order to solve problems of the low utilization ratio of the material of main cable and wind instability of suspension bridges with super-long-span steel main cables, ANSYS is used in this paper to establish models of a spatial cable suspension bridge and a parallel cable suspension bridge respectively. The dynamic mode, static wind stability and flutter stability of the models are compared by the software. The results show that the spatial suspension bridge has tensional vibration appearing much later, a higher frequency of the cable system, and a higher critical wind speed for the flutter, compared with the parallel cable suspension bridge. Therefore, the spatial suspension bridge has better wind stability.

1. Introduction

At present, there is an upsurge in the construction of sea-crossing island bridges in the world. In order to meet the 500,000-ton ship navigation requirements and avoid the construction of huge water foundations, it is necessary to build 3000-5000m span bridges [1-3].

As the span of a suspension bridge increases, the weight of the main cable increases. The main cable is mainly used to overcome its own weight. The live load proportion of cable stress of the 1991 m Japan Akashi Channel Bridge is as low as only about 8\%. If the span further increases, the utilization ratio and economic efficiency of the material of the main cable will be extremely low, making the suspension bridge with long-span steel main cables infeasible [4-7]. Compared with traditional steel, carbon fiber has advantages of high strength, high rigidity, corrosion resistance, fatigue resistance and a low linear expansion coefficient. It is especially suitable for use as a cable material with high strength and light weight. Accordingly, it is the best choice and technical measure to improve the utilization ratio of the material of main cables of long-span suspension bridges.

With the increase of the span of suspension bridges, the torsional frequency and the bending frequency of traditional suspension bridges with a parallel cable system are close to each other, and the critical wind speed is low. The 2000m-span seems to be the insurmountable limit for the traditional suspension bridges with parallel cable systems. There are 3 main ways to improve the wind resistance of the structure: improving the overall stiffness of the structure, controlling the vibration characteristics of the structure and improving the aerodynamic characteristics of the section [8-11].

The structural rigidity of the long-span suspension bridge mainly comes from the main cable, and therefore, to improve the overall stiffness of the structure, the focus should be on the main cable. By changing the cable system, torsional vibration and lateral horizontal vibration of the suspension bridge are coupled to improve the dynamic stability of the cable system and the wind stability of the whole bridge, and greatly improve the torsional rigidity and lateral stiffness of the suspension bridge.
structure. It is expected to break through the current span limit for suspension bridges, making possible the construction of 3000-5000 m span bridges.

Taking advantage of ruled characteristics of the single-leaf hyperboloid, the traditional suspension bridge with a parallel cable system is reformed. The single-leaf hyperboloid cable suspension structure is formed by changing a single cable into a dispersed spatial cable and arranging an oval ring beam to fix the spatial cable. The new suspension bridge has advantages of good integrity, which can effectively improve the torsional frequency and the torsional-bending frequency ratio of the long-span suspension bridge, and thus can fundamentally solve the wind instability problem of super-long-span suspension bridges (as shown in Figure.1).

![Figure 1. Single-leaf hyperboloid cable suspension bridge.](image)

With Qiongzhou Strait Bridge as the background, analyses of mechanical characteristics of the 4000m long-span spatial carbon fiber cable suspension bridge are carried out. By exploring the wind stability of the hyperboloid spatial cable suspension bridge, the rationality of the application of high strength fiber in main cables of super-long-span suspension bridges is verified. This study will open up a new way for the construction of super-long-span suspension bridges in future.

2. Finite Element Model
A comparative analysis model of spatial suspension bridges and parallel suspension bridges is established to verify the superiority of single-leaf hyperboloid carbon fiber cable suspension bridges. The 4000m main span spatial suspension bridge and the parallel suspension bridge only have different layout styles of main cables, and have the same total area of the main cables. The basic data are listed as follows: the ratio of rise to span is l/10, the sling spacing is 40m, stiffening beams are separated by hollow flat steel box girders, the bridge has 8 lanes and a width of 60m, and the tower is about 587 meters high.

The parallel cable suspension bridge has 2 cables, and the suspension bridge with a hyperboloid spatial cable system adopts a triangle cable method, with a total of 24 cables. Therefore each cable of the parallel cable suspension bridge has a section area 12 times that of the suspension bridge with the new cable system, and other parameters are kept the same. The new material of the main cable is carbon fiber, with a standard strength of 3500 Mpa, an elastic modulus of 2.5*10^5 N/m², a weight of 17.65 kN/m³, and a Poisson's ratio of 0.3. The basic parameters of suspension bridge model are shown in table 1.

| Component           | E (Gpa) | Γ (kN/m³) | A (m²) | Ix (m⁴) | Iy (m⁴) | Iy (m⁴) |
|---------------------|---------|-----------|--------|---------|---------|---------|
| Parallel Cable      | 250     | 17.65     | 6.0    | 0       | 0       | 0       |
| Spatial Cable       | 250     | 17.65     | 0.5    | 0       | 0       | 0       |
| Sling               | 250     | 17.65     | 0.03   | 0       | 0       | 0       |
| Stiffening beam     | 210     | 78.5      | 2.52   | 22.65   | 693.84  | 8.25    |
| Tower               | 210     | 78.5      | 69.23  | 2533.0  | 1095.2  | 2844.0  |
| Tower crossbeam     | 210     | 78.5      | 51     | 1015.0  | 633.25  | 633.25  |
The top ring beam of the spatial cable suspension bridge has an elliptical form, a long axis of 100m, and a short shaft of 50m. The middle ring beam consists of a series of elliptical steel ring beams of different sizes, where the waist ellipse has a long axis of 50m and a short axis of 25m, and the single-leaf hyperboloid spatial cable and the middle ring beam are firmly connected through a special clamp to form a structure system of the spatial cable suspension bridge. The finite element model of space cable suspension bridge is shown in figure 2 and figure 3.

**Figure 2.** FEM of spatial cable suspension bridge.

**Figure 3.** FEM of parallel cable suspension bridge.

### 3. Dynamic Modal Analysis

After the model is established, the modal analysis is carried out by finite element software ANSYS, and the natural vibration characteristics and the vibration frequency of the two types of cable suspension bridges are analyzed and compared. Some typical vibration modes of the spatial suspension bridge and the parallel suspension bridge are given in figures 4 and 5 respectively. The typical frequencies and modal characteristics of the bridges are described in tables 2 and 3.

**Figure 4.** Vibration mode of spatial suspension bridges.
By comparing the results of the natural vibration characteristics of the above two types of bridges, we can find that:

1. The two types of bridges belong to super-long-span flexible structures, so the basic cycles are long. The vibration modes of the two bridges are symmetrical, anti-symmetric lateral bending and symmetrical, anti-symmetric vertical bending. These are the same as those of short-span suspension bridges.
(2) Compared with parallel suspension bridges, the spatial suspension bridges are improved in the basic frequency of the lateral bending and vertical bending indicative of the rigidity of the suspension bridge, but the improvement is not great. From the view of modes, the cable vibration of the parallel suspension bridge appears at the sixth order. However, the 24 cables of the single-leaf hyperboloid spatial cable suspension bridge are formed as a whole under the action of the steel ring beam.

(3) The torsional vibration of the parallel suspension bridge appears at the fourteenth order and the twenty-first order. In comparison, the torsional vibration appears in the spatial suspension bridge much later, at the forty-fifth order and the forty-second order respectively, and the torsional-bending frequency ratio (the ratio of the first order torsional frequency to the first order vertical frequency) is: 4.04 for the spatial suspension bridge and 1.35 for the parallel suspension bridge. Previous studies have shown that greater the frequency ratio is, the more favorable to the wind stability of the suspension bridge. It can be seen that, compared with parallel suspension bridges, the wind stability of the spatial suspension bridges has been greatly improved.

4. Analysis of Static Wind Stability

The static wind instability of suspension bridges is classified into roll instability and torsional divergence instability. In general, long-span suspension bridges are controlled by torsional divergence instability. The torsional divergence refers to an unstable torsional divergence phenomenon making the main beam unstable under the action of the static torsional moment, which occurs when the wind speed exceeds a critical value and thus the air moment generated by the additional angle of attack of the torsion of the main beam of the bridge exceeds the increment of the resistance moment of the structure.

The equation for calculating the critical wind speed for torsion divergence is:

\[ V_{td} = K_{td} \times f_t \times B \]

Where,

\[ K_{td} = \sqrt{\frac{\pi^3}{2 \times \frac{\mu}{b} \times \frac{1}{C_M}}} \]

\[ \mu = \frac{m}{\pi \rho b^2} \; ; \; b = \frac{B}{2} \; ; \; \epsilon = \frac{f_t}{f_b} \; ; \; and \; \; r = \frac{I_m}{m} \]

In the above model, \( V_{td} \) is the critical wind speed for torsional divergence, and CM is the torsional moment coefficient of the main beam at the \( 0^\circ \) wind attack angle.

\( V_{td} \) represents the critical wind speed for torsional divergence of the suspension bridge with a single-leaf hyperboloid spatial cable system, and \( V_{td}^{pl} \) represents the critical wind speed for torsional divergence of the suspension bridge with a parallel cable system.

From equation 1, we can come to: \( \frac{V_{td}^{pl}}{V_{th}} = \frac{r_{td}^{pl}}{r_{td}^{pl}} = \frac{0.307379}{0.101633} = 3.024 \).

Compared with the parallel cable suspension bridge, the critical wind speed for torsional divergence of the suspension bridge with the single-leaf hyperboloid spatial cable system is greatly improved by 202.4%.

Referring to the design of the Messina Bridge, according to the results of the wind tunnel test on the suspension bridge, the analysis reveals that: \( r = 16.21, \mu = 17.41, \) and \( CM = 2.244 \).

Then, the critical wind speed for torsional divergence is 110.53m/s for the suspension bridge with a single-leaf hyperboloid spatial cable system, and 36.55m/s for the parallel cable suspension bridge.

5. Analysis of Flutter Stability

Flutter is self-excited divergent instability of structures under the action of wind. In practical engineering, the cross section of a suspension bridge is mostly non-streamline, so the critical wind speed for flutter of the separated flow is widely used. In this paper, the flutter stability of suspension
bridges is analyzed with the Selberg formula\cite{4}, which is used to calculate the critical wind speed for flutter of the separated flow.

Selberg equation:

\[
V_{cr} = \eta_s \eta_\alpha b_1 \sqrt{r \mu \left[ 1 - \left( \frac{\omega_t}{\omega_\alpha} \right)^2 \right]}
\]

In the equation (2), \(\eta_s\) is main beam section shape coefficient, \(\eta_\alpha\) is the attack angle effect coefficient of the wind, and \(\eta_s\) and \(\eta_\alpha\) are taken as 1 for the flat section at 0° wind attack angle. \(r\) is the radius of gyration of the bridge section (the stiffening beam and the main cable), \(b_1\) is the half bridge width of the stiffening beam section, \(\mu\) is the ratio of bridge density to air density, and \(\omega_t\) and \(\omega_\alpha\) stand for the lowest order torsional frequency and vertical circle frequency, respectively.

\(V_{cr}^d\) and \(V_{cr}^p\) denote the critical wind speed for flutter of the suspension bridge with a hyperboloid spatial cable system and the suspension bridge with a parallel cable system, respectively; \(\omega_t^d\) and \(\omega_\alpha^d\) denote the lowest order torsional frequency and vertical bending frequency respectively, of the suspension bridge with a single-leaf hyperboloid spatial cable system; and \(\omega_t^p\) and \(\omega_\alpha^p\) denote the lowest order torsional frequency and vertical bending frequency respectively, of the suspension bridge with a parallel cable system. According to equation (3):

\[
\frac{V_{cr}^d}{V_{cr}^p} = \frac{\omega_t^d}{\omega_t^p} \frac{1 - \left( \frac{\omega_t^d}{\omega_\alpha^d} \right)^2}{1 - \left( \frac{\omega_t^p}{\omega_\alpha^p} \right)^2} = \frac{0.307379 \times 0.076047}{0.101633 \times 0.075078} = 4.42
\]

Therefore, compared with the suspension bridge with the parallel cable system, the critical wind speed for flutter of the single-leaf hyperboloid spatial cable suspension bridge has greatly improved by 342%.

Referring to the design of the Messina Bridge, according to results of the wind tunnel test, \(r=16.21\) m, and \(\mu=17.41\) can be obtained.

Therefore, the critical wind speed for flutter of the single-leaf hyperboloid spatial cable suspension bridges and parallel cable suspension bridges is \(V_{cr}^d=150.5\) m/s and \(V_{cr}^p=34.2\) m/s, respectively.

Compared with the parallel cable suspension bridge, the hyperboloid spatial cable suspension bridge has dynamic wind stability greatly improved. The new spatial cable suspension bridge has the potential to become a viable solution for future construction of super-long-span 3000-5000 m suspension bridges.

6. Conclusions
With the Qiongzhou Strait Bridge as the background, models of the 4000 m single-leaf hyperboloid spatial cable suspension bridge with carbon fiber as the main material for the cable, and a traditional parallel suspension bridge are established with the ANSYS finite element software. Through the analysis and comparison of the dynamic modes, static wind stability and flutter stability of the two bridges, the following main conclusions are obtained:

1) The 4000m carbon fiber spatial cable suspension bridge design proposed in this paper has good mechanical properties, with large stress reserve under the vertical load and good wind stability under the horizontal wind load.

2) Compared with the parallel suspension bridge, the spatial suspension bridge has slightly improved lateral and vertical bending frequencies, a torsion mode coming much later, a greatly improved torsional frequency, and a ratio of torsional frequency favorable to wind stability improved by about twice.
(3) Compared with the parallel suspension bridge, the static wind resistance of the spatial suspension bridges is higher. The critical wind speed for static wind torsion and divergence is $V_{td}^d=110.5$ m/s for the suspension bridge with a single-leaf hyperboloid carbon fiber system, increased by nearly 3 times, as compared with $V_{td}^p=36.5$ m/s for the suspension bridge with a parallel cable system.

(4) The critical wind speed for flutter is $V_{cr}^d=150.5$ m/s for the suspension bridge with a carbon fiber hyperboloid spatial cable system, and $V_{cr}^p=34.2$ m/s for the suspension bridge with a parallel cable system. The single-leaf hyperboloid spatial cable has a significant effect on the improvement of the flutter stability of super-long-span suspension bridges.

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