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Wind stability of three-tower suspension bridges

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1. Introduction

Currently, the widely constructed suspension bridges are two-tower single or three-span system. As compared to the common two-tower suspension bridges with single main span, the main spans of three-tower suspension bridge can be greatly shortened, and the cables' tensional forces, the size of anchorages and also the cost are thus decreased significantly, and it becomes a competitive solution for long-span bridges under certain conditions (Gimsing 1997).

Due to the lack of effective longitudinal restraint for the center tower, the three-tower suspension bridge is a structural system with greater flexibility, and more susceptible to the wind action. In order to comprehensively investigate the wind stability of three-tower suspension bridges, in this work, by taking the Taizhou Highway Bridge over the Yangtze River with two main spans of 1080 m as example, structural dynamic characteristics, the aerostatic and aerodynamic stability are investigated numerically by 3D nonlinear aerostatic and aerodynamic analysis, and compared to those of the bridge with concrete center tower and two-tower suspension bridge with the same main span, and some conclusions are finally drawn.

2. Description of the sample bridge

The Taizhou Highway Bridge over the Yangtze River as shown in Fig. 1 is a three-tower suspension bridge with two main spans of 1080 m and two 390 m side spans(Chen 2006). The cable's sag to span ratio is 1/9, and the hangers are spaced at 16 m. A streamlined steel box girder with the fairings is adopted for the bridge deck with 3.5 m depth and 39.1 m width. The towers are door-shaped frames, the side towers are concrete structures with height of 178 m, and but the center tower is a steel structure of 182.5 m high and has an inverse Y-shaped side view. As compared to the side concrete towers, the steel center tower is much more slender, and can be recognized as a flexible tower. In order to investigate the effect of structural stiffness of the center tower on the wind stability of three-tower suspension bridges, two case bridges are assumed: Case bridge 1 has the same design parameters as the Taizhou Bridge, instead of steel center tower, the concrete center tower is adopted, and its material and cross-sectional properties are the same as the side towers; Case bridge 2 is a two-tower suspension bridge with a main span 1080 m and two side spans of 390 m, and the same design parameters as the Taizhou Bridge are adopted..

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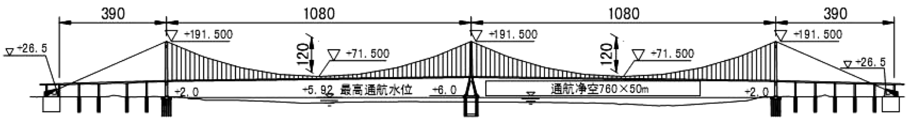

Fig. 1 General layout of the Taizhou Highway Bridge over the Yangtze River(unit: m)

3. Dynamic characteristics

On the computed equilibrium position of the bridge in completion, the first 20 modes of the entire bridge models described above are calculated by the dynamic characteristics finite element analysis (Zhang, *et al*. 2002). Table 1 shows the modal properties of the bridge deck.

Table 1 The modal properties of the bridge deck

Modes	Natural frequency(Hz)			Modal shape
	Taizhou Bridge	Case bridge 1	Case bridge 2	
Vertical bending	0.1155	0.1155	0.1483	1-S
	0.0625	0.0669	0.0874	1-AS
	0.1526	0.1526	0.2040	2-S
	0.0932	0.0936	0.1274	2-AS
	0.2231	0.2232	0.3073	3-S
	0.1301	0.1301	0.2310	3-AS
	0.2329	0.2329	0.4822	4-S
	0.1674	0.1671	0.3878	4-AS
Lateral bending	0.0980	0.0992	0.0731	1-S
	0.0733	0.0733	0.2321	1-AS
Torsion	0.3232	0.3261	0.3392	1-S
	0.2523	0.3046	0.3953	1-AS

Note: The number represents the modal order; S = Symmetric; AS = Anti-symmetric

In the case of concrete center tower, as compared to the Taizhou Bridge, the first anti-symmetric torsional frequency is increased significantly, and however the other frequencies are basically remained the same. As found in the analysis, the modal components of the center tower in the vertical and lateral bending modes of the bridge deck equal to approximately zero, the supporting effect of center tower for main cables seems to be a rigid support, and thus structural stiffness of the center tower has basically no influence on the natural frequencies of vertical and lateral bending modes of the bridge deck. But for anti-symmetric torsion mode, the center tower twists greatly. Due to the significant enhancement of structural stiffness of the center tower, the anti-symmetric torsional frequency is therefore increased greatly in the case of concrete center tower.

Due to the lack of effective longitudinal restraint for center tower, except the first symmetric lateral bending mode, the natural frequencies of the Taizhou bridge are all less than those of Case bridge 2. Therefore, it can be concluded that the longitudinal restraint of the center tower is an effective measure to improve structural stiffness of three-tower suspension bridges.

4. Aerostatic stability

Under the wind attack angle of 0^o, with increase of wind speed, aerostatic behaviors of the entire bridge models described previously are investigated numerically by three-dimensional nonlinear aerostatic analysis(Zhang, *et al*. 2002). Evolutions of the bridge deck's displacements at midpoint of main span with wind speed are plotted in Fig. 2.

As seen in Fig. 2, the deformation of the Taizhou Bridge is very identical to that of Case bridge 1, but for Case bridge 2, much greater deformation happens. Due to the symmetry of structure and the aerostatic loads applying on the bridge deck, the center tower does not bends longitudinaly, and only bends lateraly, as mentioned above, structural stiffness of the center tower therefore has basically no influence on the vertical and torsional deformations of the bridge deck. However for the lateral deformation, in the case of concrete center tower, due to the reinforcement of lateral bending stiffness of center tower, the lateral deformations of center tower and also the bridge deck are thus reduced. For three-tower suspension bridge, as a main span deforms, its deformation can reduce that of another main span, therefore the total deformation under the static wind action is much less than that of two-tower suspension bridge.

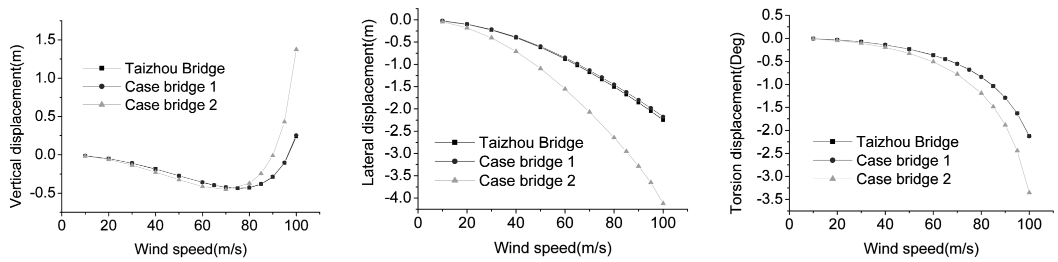

Fig. 2 Evolutions of the bridge deck's displacements at midpoint of main span with wind speed

For all the bridge models, the evolutions of aerostatic deformations of the bridge deck with wind speed are very similar. At the low wind speed, the bridge deck deforms little, with increase of wind speed, the bridge deck's deformation increases nonlinearly. At the beginning, the bridge deck deforms downward, as wind speed increases to 75 m/s(the Taizhou Bridge) or 70 m/s(Case bridge 2), the maximum downward deformation is achieved, and then the bridge deck deforms upward; as wind speed is over 80 m/s, the bridge deck deforms rapidly; as wind speed increases to 95 m/s(the Taizhou Bridge) or 90 m/s(Case bridge 2), the jumping phenomenon of the bridge deck's vertical deformation encounters, particularly for Case bridge 2, it means that the critical condition of aerostatic instability happens. The bridge deck's torsional deformations are always negative, and increase in a nonlinear manner, as wind speed increases to 95 m/s(the Taizhou Bridge) or 90 m/s(Case bridge 2), the jumping phenomenon also encounters. The bridge deck's lateral deformation increases with wind speed, but the jumping phenomenon does not encounter. Therefore, aerostatic instability of the Taizhou Bridge is a coupled vertical-torsional instability. The critical wind speed of aerostatic instability for all the bridge models are greater than 90 m/s, and also higher than the critical wind speed of the aerostatic torsional divergence 80.4 m/s, and therefore all the bridge models are stable aerostatically.

It can be concluded from the above analysis that structural stiffness of the center tower has basically no influence on the aerostatic instability of three-tower suspension bridges, due to the counteraction of the bridge deck's deformations of two main spans, the three-tower suspension bridge is more stable aerostatically than the two-tower suspension bridge.

5. Aerodynamic stability

As known from sectional-model wind tunnel test of the Taizhou Bridge, it is prone to aerodynamic instability under the positive wind attack angles(Chen 2006). Therefore under wind attack angles of 0^o and $+3^o$, aerodynamic stability of all the bridge models is investigated numerically by three-dimensional nonlinear aerodynamic stability analysis(Zhang, *et al*. 2002), and the critical wind speeds of aerodynamic instability are presented in Table 2.

As found in Table 2, the computed results are very identical to those of the sectional-model wind tunnel test, and the validity of the employed method is thus verified. Under wind attack angles of 0^o and $+3^o$, the critical wind speeds are all greater than the flutter checking wind speed 57.4 m/s, and therefore the bridge is stable aerodynamically. In the case of concrete center tower, the critical wind speeds are much greater than those of the Taizhou Bridge, and the increase amplitudes are greater than 14%. The aerodynamic instability of the bridge is the coupled oscillation of the first symmetric vertical bending and the first anti-symmetric torsion. As shown in Table 1, with increase of the first anti-symmetric torsional frequency, aerodynamic stability is consequently improved. Similarly, for the two-tower suspension bridge(Case bridge 2), the aerodynamic stability is further improved. It can be also mainly due to the increase of the first anti-symmetric torsional frequency. Therefore, increasing structural stiffness of the center tower is favorable aerodynamically for three-tower suspension bridges. Due to its lower structural stiffness, the three-tower suspension bridge is less stable aerodynamically than the two-tower suspension bridge.

Table 2 The critical wind speed of aerodynamic instability(m/s)

Wind attack angle	Taizhou Bridge	Case bridge 1	Case bridge 2
0^o	79.5 (79.0)[82.8]	90.6 (92.0)	109.1(92.0)
$+3^o$	59.3 [61.9]	72.9	76.0

Note: Values in square brackets are the sectional-model wind tunnel test results, values in brackets are the computed results using the aerodynamic derivatives of an ideal flat plate.

6. Conclusions

In this work, by taking a three-tower suspension bridge-the Taizhou Highway Bridge over Yangtze River with main spans of 1080 m as example, structural dynamic characteristics, the aerostatic and aerodynamic stability are investigated numerically by 3D nonlinear aerostatic and aerodynamic analysis, and compared to those of the bridge with concrete center tower and two-tower suspension bridge with the same main span. The results show that structural torsional frequency and wind stability are significantly improved by increasing structural stiffness of the center tower; Due to the lack of effective longitudinal restraint for center tower, as compared to two-tower suspension bridge, three-tower suspension bridge becomes more susceptible to aerodynamic instability, and but it becomes more stable aerostatically.

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