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Flutter stabilization of 5000m spanned suspension bridge with widely slotted twin-box girder

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SUMMARY:
Based on a designed 5,000m spanned suspension bridge with widely slotted twin-box girder, flutter stability has been investigated through 1:250 scaled sectional model testing with amplitude nonlinearity, 2D numerical simulation for amplitude-independent nonlinearity and 1:620 scaled full bridge aeroelastic model testing for critical flutter speeds.

Keywords: flutter stability, suspension bridge, twin-box girder

1. INTRODUCTION

In order to aerodynamically stabilize long-span suspension bridges, centrally slotted twin-box stiffening girder has been studied and proposed since 1970s (Walshe et al., 1977), and applied in the 1,650m spanned Xihoumen Bridge in China in 2009 (Ge and Xiang, 2009), the 1,545m Yi Sun-sin Bridge in Korea in 2012 and the 2023m 1915 Canakkale Bridge in Turkey in 2022.

Based on steel main cables, Xiang and Ge (2003) firstly proposed the ultimate main span of suspension bridges is around 5,000m and 5,900m, and conceptually designed a 5,000m spanned suspension bridge in Figure 1 with widely slotted twin-box girder in Figure 2. Four main cables were adopted for reducing the diameters of each cable and the stiffness of cross beams connecting two boxes. Two pylons were designed in longitudinally A-shaped and transversely double-A-shaped with the height of 657m in Figure 3. Flutter stability has been investigated through sectional model testing, 2D numerical simulation and full aeroelastic model testing (Xia, 2020).

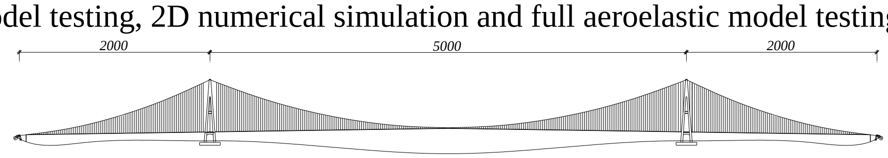


Figure 1. Layout of the 5,000m suspension bridge (unit: meter).

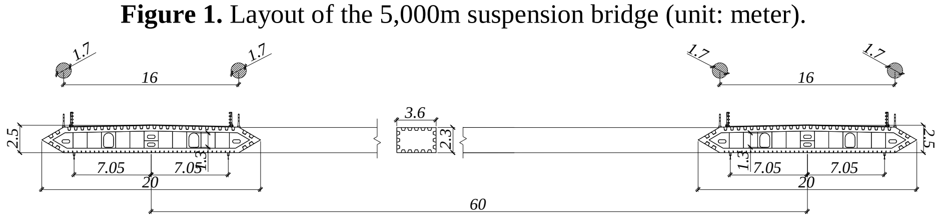


Figure 2. Cross section of twin-box girder (unit: meter).

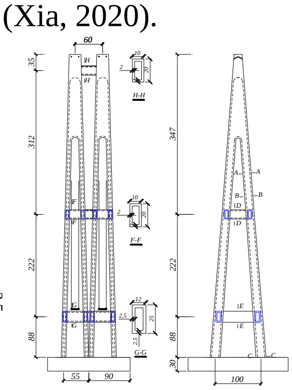


Fig. 3. Elevation of pylon

2. SECTIONAL MODEL TESTING WITH NONLINEARITY

With the main elements of the prototype bridge shown in Table 1, the finite element model was established and the dynamic characteristic analysis was conducted. A 1:250 scaled sectional model was designed and manufactured based on the main parameters in Table 2 and with the damping ratios of 0.2% in vertical and 1.0% in torsional vibration. The sectional model wind tunnel testing was carried out at the 0° angle of attack (AoA) in the University of Western Ontario (Xia, 2020).

Table 1. Main elements of prototype bridge.

Element	Parameter	Unit	Value
Cables (1 cable)	Sag ratio	-	1/10
	Area	m^2	1.872
	Modulus	MPa	2.00E+05
Girder (1 box)	Vertical stiff.	$MN.m^2$	2.12E+04
	Lateral stiff.	$MN.m^2$	6.03E+05
	Torsion stiff.	$MN.m^2$	2.36E+04
Pylon (1 column)	Height	m	657
	Section	m×m	20×15

Table 2. Main parameters of sectional model.

Parameter	Unit	Prototype	Scale ratio	Model
Slot	m	40	250	0.16
Girder width		80		0.32
Girder depth		2.5		0.01
Mass	kg/m	1.08E+05	250^2	1.72E+00
Mass moment of inertia	$kg.m^2/m$	8.33E+07	250^4	2.13E-02
Wind speed	m/s	-	8.1	-
Vertical frequency	Hz	0.067	30.86	2.05
Torsional frequency		0.082	30.86	2.50

Under the actual wind speed of 77.5m/s, limited amplitude oscillation begins at the dominant frequency of 2.32Hz shown in Figure 4. This limited amplitude increases with the increase of wind speeds from 77.5m/s to 98.5m/s shown in Figure 5, which represents amplitude independent nonlinearity. Flutter derivatives identification results also show this nonlinearity in Figure 6.

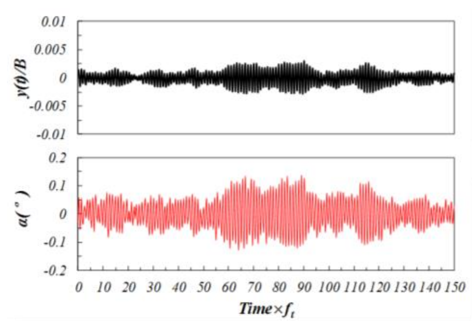


Figure 4. Vibration under actual wind speed of 77.5m/s.

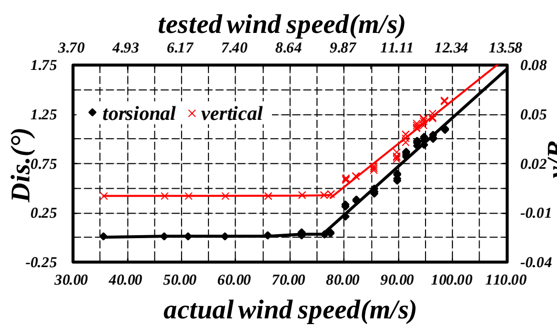


Figure 5. Amplitude RMS values vs wind speeds.

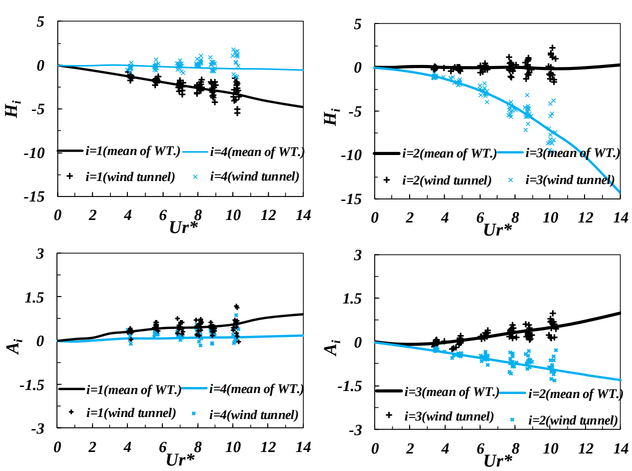


Figure 6. Flutter derivatives by sectional model testing.

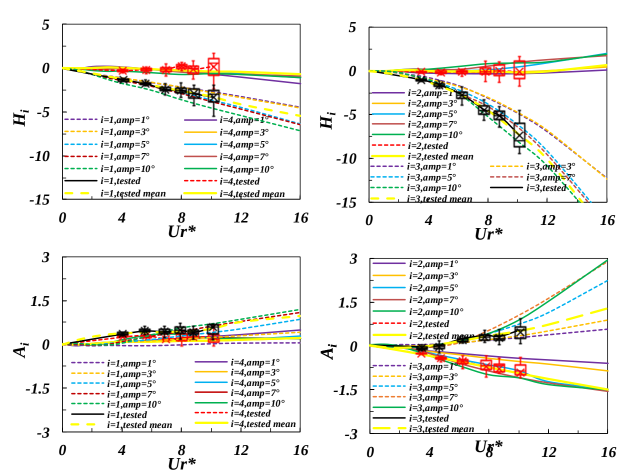


Figure 7. Flutter derivatives by numerical simulation.

3. 2D NUMERICAL SIMULATION FOR AMPLITUDE NONLINEARITY

In order to analyse the amplitude independent nonlinearity, 2D numerical simulation method has been developed to identify flutter derivatives under different forced vibration amplitudes shown in Figure 7. With the numerically identified flutter derivatives at the torsional amplitudes (amp.) of 2°, 4°, 6° and 8°, frequency domain method (M1), time domain iterative method (M2) and time domain assignment method (M3) have been applied to determine critical flutter speeds described in Figure 8. These three flutter analysis methods have almost the same results, and the maximum and minimum torsional amplitudes of 8° and 2° result in the critical flutter speeds of 69.0m/s and 100m/s, respectively. The critical flutter speed of 77.5m/s based on the sectional model testing corresponds to about the torsional amplitude of amp. 6°.

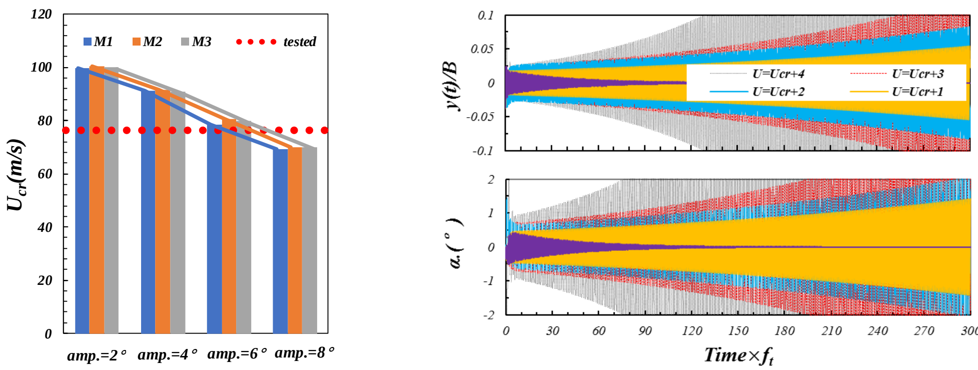


Figure 8. Comparison of linear flutter analysis methods with different amplitudes.

4. FULL AEROELASTIC MODEL TESTING FOR CRITICAL FLUTTER SPEED

As a more comprehensive and precise study in flutter stability, full aeroelastic model testing has been carried out to examine wind-induced vibrations of the 5,000m suspension bridge. The full bridge aeroelastic model was designed and manufactured with a geometrical scale of 1:620, and wind tunnel testing was performed under uniform flow and turbulent flow at the AoAs of -3°, 0° and 3° in TJ-3 Boundary Layer Wind Tunnel of Tongji University shown in Figure 9.

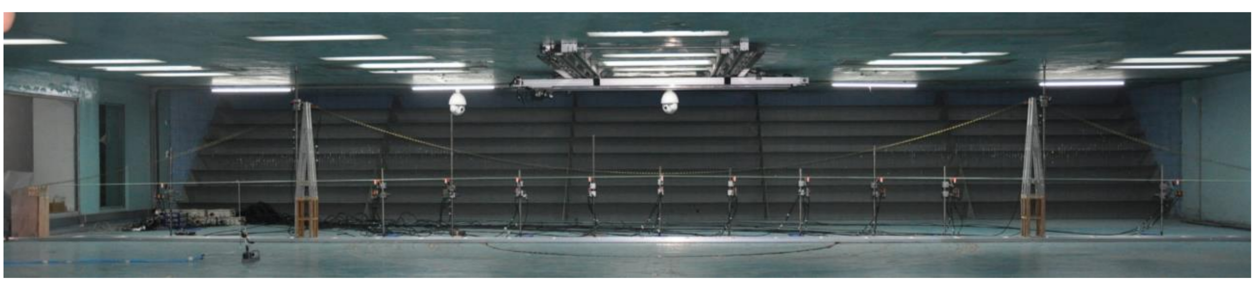
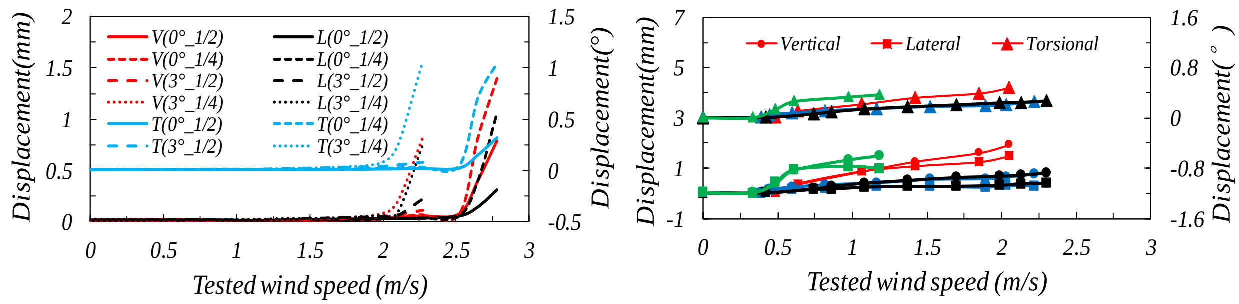


Figure 9. Overall of full bridge aeroelastic model.

The dynamic characteristics of the full aeroelastic model was checked before testing, and the damping ratios of the first two-mode vertical bending and torsional vibration were measured as between 0.3% and 0.5%. Under the tested wind speed, the root-mean-square (RMS) values of the wind induced vibration amplitudes at the mid span (L/2) and quarter span (L/4) were recorded in vertical, lateral and torsional modes in Figure 10. Figure 10a shows very clear flutter trend and shape (Figure 11) under uniform flow while turbulent flow has not so clear trend in Figure 10b.



(a) Uniform flow (b) Turbulence (black 10%, blue 11%, red 14%, green 24%)

Figure 10. Amplitude RMS values of vertical, lateral and torsional vibration modes

The critical flutter speeds were tested under uniform flow and 10% turbulence flow listed in Table 3, and the maximum and minimum values are >80.9m/s under uniform flow and >74.7m/s under the turbulent flow at the -3° AoA and 51.5m/s and 46.1m/s at the 3° AoA, respectively. At the 0° AoA, both uniform flow and turbulent flow have very similar critical flutter speeds, 69.2m/s and 69.7m/s, but the flutter speed reduces to 31.9m/s under uniform flow if the slot is sealed.

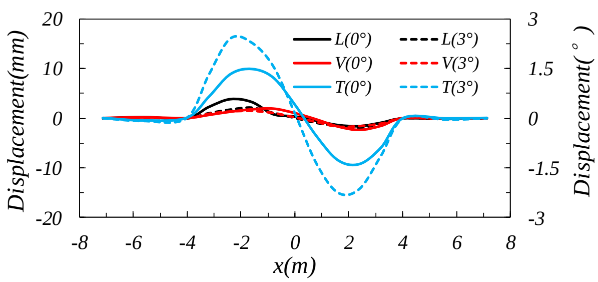


Figure 11. Flutter shape under smooth flow

Table 3. Critical flutter speeds of full model testing

Case	AoA (°)	Tested speed (m/s)	Actual speed (m/s)
Uniform flow (twin-box)	-3	>3.25	>80.9
	0	2.78	69.2
	3	2.07	51.5
Turbulent flow (10%, twin-box)	-3	>3.00	>74.7
	0	2.80	69.7
	3	1.85	46.1
Uniform flow (slot sealed)	0	1.28	31.9

5. CONCLUSIONS

Flutter stability of a 5,000m suspension bridge with twin-box girder has been systematically studied through 1:250 scaled sectional model testing, 2D numerical simulation and 1:620 scaled full aeroelastic model testing. The maximum and minimum critical flutter speeds are >80.9m/s under uniform flow at the -3° AoA and 46.1m/s under 10% turbulent flow at the 3° AoA.

ACKNOWLEDGEMENTS

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