Probabilistic Criteria for Assessment of Aerodynamic Instability of Long-Span Bridges

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1. Introduction

With the rapid increase of bridge span length, bridge structures are becoming lighter and more flexible, which have resulted in an increasing importance in aerodynamic study and design related to wind actions, in particular aerodynamic instability. Deterministic approaches for evaluation of aerodynamic instability for long-span bridges has had a long history since the collapse of the original Tacoma Narrows Bridge in 1940, and the assessment of critical condition for destructive flutter in a probabilistic aspect began quite recently. In this paper, the probabilistic analysis model formulated by four independent random variables was adopted to carry out the probabilistic reassessment and calibration for flutter instability of ten cable-supported bridges including six cable-stayed bridges and four suspension bridges in China.

2. Limit State Function

The probabilistic reassessment for flutter instability is based on an established reliability model, in which the expression of the critical flutter speed U_{cr} minus the extreme wind speed U_e is defined as the limit state of flutter instability occurrence as follows:

$$M = g(x_1, x_2, \ldots, x_n) = g(C_w, U_f, G_s, U_b) = C_w U_f - G_s U_b = 0 \tag{1}$$

in which U_b is the annual maximum wind speed value at the bridge deck level; G_s is the gust speed factor on account of the influence of wind fluctuation and its horizontal correlation; U_f is the experimentally determined basic flutter speed through an aeroelastic full model with some uncertainties of the structural properties; and C_w is the conversion factor from a scaled model to the prototype structure.

3. Extended Design Point Approach

Although the failure probability from the safety margin may be efficiently calculated by some approximate reliability methods or by applying simulation techniques such as Monte Carlo method, the first-order reliability method, in particular extended design point approach (EDP), is applied here.

4. Probabilistic Reassessment

The cable-supported bridges investigated in this paper include six cable-stayed bridges and four suspension bridges, whose wind-tunnel tests with aeroelastic models were carried out in State Key Lab for Disaster Reduction in Civil Engineering at Tongji University. The structural characteristics of these bridges are listed in Table 1.

With the probabilistic analysis model introduced in the previous section, the parameters of the

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random variables U_b, G_s, C_w and U_f of each bridge are computed. On the basis of the EDP approach, a program was developed to carry out the reliability analysis on these ten cable supported bridges. The numerical results of reliability index β and failure probability P_F are listed in Table 2 and compared to the traditional safety factor.

Table 1 *Structural characteristics of investigated bridges*

Bridge Type	No.	Bridge Name	Span (m)	Girder Material	Girder Section	Natural Frequency (Hz) Symmetric		Anti-symmetric		Damping Ratio (%)
						f_{h_1}	f_{α_2}	f_{h_2}	f_{α_2}	
Cable Stayed bridges	1	2nd Nanjing	628	Steel	Box	0.2426	0.7275	0.3233	---	0.5
	2	Qingzhou	605	Composite	Π Shape	0.2075	0.5346	0.3571	0.6572	1.5
	3	Yangpu	602	Composite	Boxes	0.2733	0.5093	0.3327	0.6040	1.0
	4	Jingsha	500	Concrete	Π Shape	0.1987	0.3983	0.2739	0.5428	2.0
	5	Nanpu	423	Composite	Π Shape	0.3518	0.4498			2.0
	6	Haikou	340	Concrete	Π Shape	0.2728	0.6248	0.3669		0.5
Suspension bridges	1	Jiangyin	1385	Steel	Box	0.1334	0.2612	0.0890	0.2581	1.2
	2	Yichang	960	Steel	Box	0.1650	0.3580	0.1050	0.4260	0.5
	3	Humen	888	Steel	Box	0.1715	0.3612	0.1117	0.4260	0.9
	4	Hongguang	380	Steel	Π Shape	0.2768	0.3744	0.1915	0.3591	0.5

Table 2 *Reliability index and failure probability of investigated bridges due to flutter*

Bridge Type	No.	Bridge Name	Reliability Index β	Failure Probability P_F	Safety Factor K
Cable stayed bridges	1	2nd Nanjing	5.496	1.9×10^{-8}	3.27
	2	Qingzhou	2.579	5.0×10^{-3}	1.40
	3	Yangpu	3.138	8.5×10^{-4}	1.68
	4	Jingsha	5.230	7.1×10^{-8}	3.06
	5	Nanpu	2.571	5.1×10^{-3}	1.39
	6	Haikou	4.199	1.3×10^{-5}	2.31
Suspension bridges	1	Jiangyin	3.289	5.0×10^{-4}	1.76
	2	Yichang	4.299	8.6×10^{-6}	2.38
	3	Humen	3.000	1.4×10^{-3}	1.61
	4	Hongguang	3.737	9.5×10^{-5}	2.02

The failure probabilities of the investigated bridges due to aerodynamics flutter are quite different from one another, and can be broadly classified into three grades in accordance with the magnitudes of their failure probabilities. The top grade bridges including the 2nd Nanjing Bridge and the Jingsha Bridge, has the smallest failure probabilities at the order of 10^{-8}, while the bottom grade bridges are the Nanpu Bridge, the Qingzhou Bridge and the Humen Bridge, whose values of failure probabilities are quite large and at the order of 10^{-3}. The remaining bridges have the moderate magnitudes of the failure probabilities, ranging from 8.5×10^{-4} to 8.6×10^{-6}.

5. Conclusions

Formulated by four independent random variables, including annual maximum wind speed, gust speed factor, basic flutter speed and conversion factor, a proposed reliability analysis model was adopted to carry out the probabilistic reassessment and calibration for flutter instability of ten cable-supported bridges including six cable-stayed bridges and four suspension bridges in China. The failure probabilities of the investigated bridges due to aerodynamics flutter are quite different from 1.9×10^{-8} to 5.1×10^{-3}, whose corresponding values of the safety factors are from 1.39 to 3.27. It can be calibrated and concluded that probabilistic criteria for assessment of aerodynamic instability of long-span bridges should be less than the order of 10^{-3}.

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