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Flutter performance and improvement for a suspension bridge with central-slotted box girder during erection

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ABSTRACT

Aerodynamic instabilities of super long-span bridges have always been the essential issue in design and construction, especially during the deck erection process. Based on the Xihoumen Bridge, this paper presents a particular insight into the flutter performance of a mega-bridge with a central-slotted box girder while in construction. Numerical analyses and full-model wind tunnel tests are conducted to explore the evolution of dynamic properties and flutter limits as erection proceeds. It is shown that favorable effects on aeroelastic stability are guaranteed following a symmetric deck erection sequence, but appropriate improvements are still required to ensure the safety of the structure under construction. The efficacy of different improvement methods, both structural and aerodynamic, are systematically examined, among which individual and conjoint applications of storm ropes are elaborated. The results indicate that single storm rope outperforms the combined application. In particular, one with 10% of the cross-section area of the main cable anchored at 1/8 of the midspan is especially effectual in improving the aerodynamic stability during erection.

1. Introduction

Suspension bridges have astonished the world with ever-growing spans due to the advanced capability both in design and construction. As they become longer and slenderer, the remarkable reduction in rigidity is one of the major concerns accompanying impressive improvement in span, which makes suspension bridges be more susceptible to wind-induced instabilities, the flutter particularly. Not until the notorious collapse of the original Tacoma Narrow Bridge in 1940 did the aerodynamic instabilities of long-span bridges truly attract the attention of bridge engineers. And a scaled model of that bridge was then first tested in wind tunnels to investigate its aerodynamic performance.

However, the overall stiffness of a suspension bridge at its erection stage is significantly smaller than that when it's in service condition, primarily due to the lack of overall torsional continuity of the deck. Therefore, the general conditions against the aerodynamic instability are far less favorable. It was not until the 1960s that due attention was finally paid upon the wind resistance issues of suspension bridges during construction, among which the Severn Bridge in England (Walsh, 1965) and the Thomas Mackay Bridge of Halifax in Canada (Davenport et al., 1969) were the earliest to employ wind tunnel tests to examine the aerodynamic stability during erection.

Brancaleoni (1992) first provided a comprehensive view of this subject and later supplemented by Tanaka et al. (1998), which enumerated several essential factors governing aerodynamic stabilities of suspension bridges during erection, including dynamic properties, structural rigidity and damping, the deck length and provision of eccentric mass and artificial dampers. Since then, a large number of scholars have conducted extensive researches on this subject and contributed to a profound understanding of this problem. Svensson and Kovacs (1992) investigated the effect of vibration mode shapes; Larsen (1995) analyzed how the mass eccentricity influences the erection of the Humber Bridge and the Great Belt Bridge. Cobo del Arco (1998) then examined the effect of erection sequences on aerodynamic stability of the Höga Kusten Bridge. Similar researches have also been conducted by Tanaka and Gimsing (1999) and Ge and Tanaka (2000).

Generally, wind-induced instabilities of suspension bridges under erection can be precluded by avoiding extreme weathers, as adopted in construction of the Tigergate suspension bridge in China (Chen et al., 1997). Besides, other practical measures taken to strengthen aerodynamic stability of suspension bridges during construction can be divided into three categories: (1) deck erection sequences; (2) structural approaches including installing storm ropes to increase natural frequencies of the overall bridge by restricting the motion of main cables,

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and providing a windward eccentric mass (water ballast) to reduce the aerodynamic moment by cutting the lever arm; (3) aerodynamic approaches to ameliorate the aerodynamic performance by changing section characteristics.

This paper focuses on the aerodynamic stability of suspension bridges during deck erection process and great effort is put into evaluating the effectiveness of various improvements on flutter performance. First, full model wind-tunnel tests of the bridge at its deck erection stage are performed to investigated the influence of deck erection sequence on flutter stability limits experimentally. Then, the effects of storm ropes in varied configurations on natural frequencies was discussed through numerical analysis, followed by comparisons of storm ropes' efficacy in improving aerodynamic stability.

2. Deck erection sequences

2.1. Wind-tunnel test setup

With a main span of 1650 m, the Xihoumen Bridge is currently the longest three-span continuous box-girder suspension bridge around the world. The streamlined box deck is 3.5 m in depth and 36.0 m in width, containing a 6-m-wide slot, as Figs. 1 and 2 illustrate. A 1:208 full model of the Xihoumen Bridge was designed for detailed investigations, of which the structural parameters including geometric dimensions, mass characteristics and fundamental frequencies were listed in Table 1. The wind-tunnel tests were conducted in the TJ-3 boundary layer wind tunnel of the State Key Laboratory of Disaster Reduction in Civil Engineering at Tongji University, which could replicate the wind velocity up to 17.6 m/s. The testing section of the TJ-3 wind tunnel is 15 m in width, 2 m in

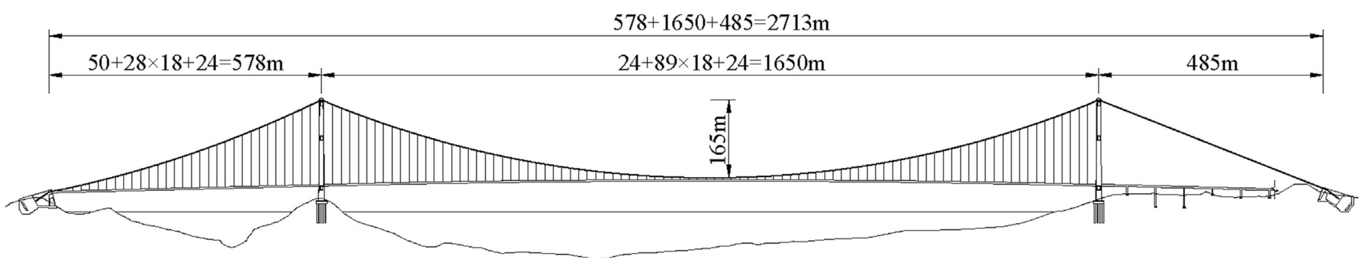

Fig. 1. Elevation of the Xihoumen bridge.

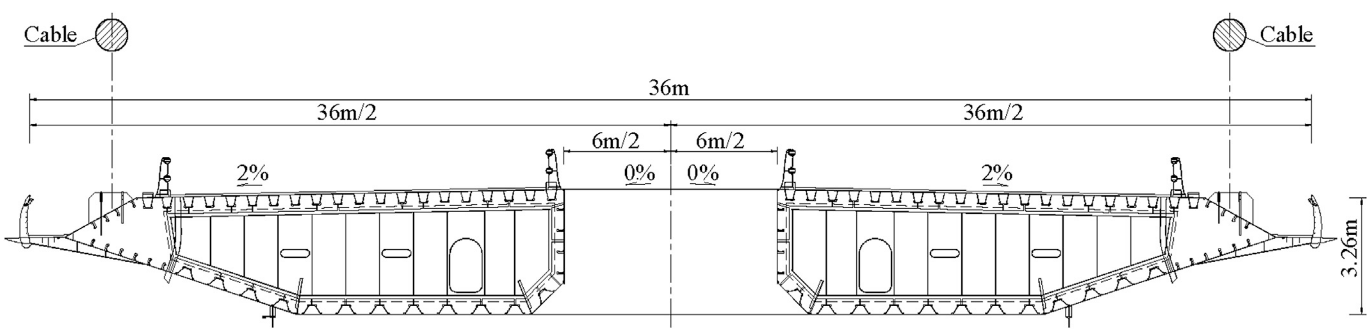

Fig. 2. Central-slotted box girder of Xihoumen Bridge.

Table 1
Structural parameters of objective model.

Parameter	Unit	Prototype		Scaling	Model
Length (L)	m	Deck	$578+1650+485$	$\lambda_L = 1:208$	$2.779+7.933+2.332$
Width (B)	m	Deck	36.000	$\lambda_L = 1:208$	0.173
Depth (H)	m	Deck	3.538	$\lambda_L = 1:208$	0.017
Mass (m)	kg/m	Deck	1.691×10^4 ~1.731×10^4	$\lambda_m = 1:208^2$	0.391~0.400
		Main cables	3.879×10^3 ~4.017×10^3		8.967×10^{-2} ~9.285×10^{-2}
Mass moment (J_m)	$kg \cdot m^2/m$	Deck	1.936×10^6 ~2.036×10^6	$\lambda_L = 1:208^4$	1.034×10^{-3} ~1.088×10^{-3}
Cross-section area (A)	m^2	Main cables	0.46460 ~0.48110	$\lambda_A = 1:208^2$	1.112×10^{-5} ~1.074×10^{-5}
		Hangers	0.00726		1.678×10^{-7}
Tensile stiffness (EA)	N	Main cables	9.292×10^{10} ~9.622×10^{10}	$\lambda_{EA} = 1:208^3$	1.033×10^4 ~1.069×10^4
		Hangers	1.016×10^9		1.129×10^2
Vertical bending stiffness (EI_z)	$N \cdot m^2$	Deck	2.101×10^{12}	$\lambda_{EI} = 1:208^5$	5.397
Lateral bending stiffness (EI_y)	$N \cdot m^2$	Deck	1.190×10^{14}	$\lambda_{EI} = 1:208^5$	3.057×10^2
Torsional stiffness (GJ_d)	$N \cdot m^2$	Deck	4.628×10^{12}	$\lambda_{GJ} = 1:208^5$	11.887
Vertical bending frequency (f_h)	Hz	0.1005		$\lambda_f = \sqrt{208}:1$	1.4491
Lateral bending frequency (f_p)	Hz	0.0485		$\lambda_f = \sqrt{208}:1$	0.7001
Torsional frequency (f_t)	Hz	0.2321		$\lambda_f = \sqrt{208}:1$	3.3478