Engineering Structures 120 (2016) 82–91

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Aerodynamic stability of long span suspension bridges with low torsional natural frequencies

Michael Styrk Andersen [a,*], Jens Johansson [a], Anders Brandt [a], Svend Ole Hansen [a,b]

[a] Dept. of Technology and Innovation, University of Southern Denmark, Campusvej 55, Odense, Denmark
[b] Svend Ole Hansen ApS, Skt. Jørgens Allé 5c, 1615 København V, Denmark

ARTICLE INFO

Article history:
Received 5 July 2015
Revised 7 April 2016
Accepted 11 April 2016
Available online 3 May 2016

Keywords:
Long-span bridge
Flutter
Torsional divergence
Aerodynamics
Wind–structure interaction
Aeroelasticity
Wind tunnel experiments
Non-flutter design principle

ABSTRACT

Classical flutter of suspended bridge decks can be avoided if the torsional frequencies are lower than the vertical. Wind tunnel tests of single boxes and twin box section models with torsional natural frequencies above and below the vertical frequency has been conducted. Flutter was avoided in all tests where the torsional frequency was lower than the vertical. But too low torsional stiffness caused large static displacements of the girder at medium–high wind speeds and steady state oscillations driven by a combination of torsional divergence and stalling behavior at the critical wind seed. In order to design aerodynamically stable suspension bridges with low torsional natural frequencies it is suggested to increase the mass moment of inertia and provide adequate torsional stiffness by the main cables spacing.

1. Introduction

The aerodynamic stability of the bridge deck has been a major issue in the design of long span bridges since the disastrous collapse of the first Tacoma Narrows in 1940. During the last two decades, 3 world records in main span lengths have been broken each using different approaches to obtain aerodynamic stability. The Akashi Kaikyo Bridge in Japan has a main span of 1991 m where a slotted deck is supported on a truss girder. The slots improve the aerodynamic stability.

The Xihoumen Bridge in China spans 1650 m and has a twin box girder with a central gap of 6 m. The central gap was introduced to increase the critical flutter wind speed. The Great Belt Bridge in Denmark has a main span of 1624 m and is constructed with a single box shaped girder with fairings at the windward and leeward edges.

The possibility of longer spans is related to the implementation of stronger and lighter materials. At the moment, new world record breaking spans are being considered for e.g. fjord crossings along the Coastal Highway Route 39 in Norway from Kristiansand to Trondheim.

In traditional bridge design where the torsional-to-vertical frequency ratio, $\gamma_\omega = \omega_\alpha/\omega_h$, is above 1 both mass, stiffness and frequency ratio must be increased in order to raise the critical flutter wind speed. A pure increase in mass seems less favorable than an increase in stiffness. However, increased stiffness tends to require an increase in mass. Furthermore, for long span bridges, the torsional rigidity of the girder declines and the mass moment of inertia in the main cables increases with increased span length. This naturally leads to a reduction of the frequency ratio γ_ω.

Thin airfoil theory [1] was previously used to estimate an upper limit for the flutter wind speed for single box shaped girder suspension bridges. But after the introduction of the twin box girder, critical flutter wind speeds may exceed the thin airfoil flutter speed by as much as 200% [2]. This may however not be sufficient for all super long span bridges.

There is no theoretical solution to the critical flutter wind speed for airfoils having $\gamma_\omega < 1$. Therefore, a lighter and more economical suspension bridge design may thus be developed based on the principle that the frequency of the fundamental torsional mode of the bridge deck deliberately should be lower than the frequency of the corresponding vertical mode. Similarly this can be obtained by either an increase in the mass moment of inertia in the torsional motion or a decrease in the torsional stiffness. A decrease in torsional stiffness does however lead to a reduction of the critical wind speed for torsional divergence.

* Corresponding author.
E-mail addresses: mian@iti.sdu.dk (M.S. Andersen), jensj@iti.sdu.dk (J. Johansson), abra@iti.sdu.dk (A. Brandt).

http://dx.doi.org/10.1016/j.engstruct.2016.04.025
0141-0296/

The slope of the time mean aerodynamic moment $dC_m/d\alpha$ acting on airfoils at different angles of attack is considerable larger than corresponding values of streamlined bridge deck girders and especially twin box girders. Therefore, the critical wind speed for torsional divergence is larger for bridge decks than for thin airfoils. Adequate torsional stiffness may be provided by the cable plane spacing alone and might thus not need to be obtained through the deck girder as in traditional design.

The self-excited forces on the bridge deck occurring from the motion of the bridge deck itself is expressed in terms of Aerodynamic Derivatives (AD's) introduced for bridge decks by Scanlan and Tomko in [3].

The idea of designing a suspension bridge with $\gamma_\omega < 1$ was originally proposed by [4] with the introduction of the twin bridge. Walshe and Wyatt [5] mentioned the idea and stated that the needed gap width between the twin boxes also depends on the static rotations under eccentric traffic load.

Bartoli et al. [6,7] tested section models of a twin box with a large gap width having $\gamma_\omega < 1$ and reported the sections to be aerodynamically stable. Torsional divergence did occur, but only at wind tunnel speeds corresponding to full scale values above the required critical wind speed. Wind tunnel results of aerodynamically stable flat plate section models with $\gamma_\omega < 1$ were reported by [8]. However, torsional flutter of bluff bridge sections occurred. Larsen and Larose [9] wrote that classical flutter may be prevented if $\gamma_\omega < 1$, but that issues with e.g. eccentricities due to traffic loads, buffeting response, vortex shedding and torsional divergence need to be resolved before this design principle has matured.

The present paper aims to explain why the critical flutter wind speed tends to decline as the span width increases in traditional bridge design. Wind tunnel tests of single boxes and twin boxes with different width-to-depth ratios, B/D, and gap-to-width ratios, Z/B, has been tested at torsional-to-vertical frequency ratios, γ_ω, above and below unity. The observed critical wind speeds are presented in Section 4 and compared with the corresponding thin airfoil critical wind speeds.

2. Background

Cable supported bridges are flexible structures that respond to the wind in a dynamic manner. Therefore structural dynamics plays a vital role within bridge aerodynamics. It is important to correctly estimate the vertical and torsional still air natural frequencies during the design phase because their ratio are crucial for the determination of the flutter wind speed. An "exact solution" to the fundamental symmetric frequencies is given in [10,11].

2.1. Declining torsional-to-vertical frequency ratio with increasing span length

The change in torsional-to-vertical frequency ratio with span-length will here be illustrated with four simplified cases. Table 1 presents the four cases with different torsional girder constants K_t and mass moment of inertia I_d, each of which is considered at different main span lengths. No suspended side spans are included. The cable sag is equal to 10% of the span. The distance from the shear center of the bridge deck to the main cable planes are $a = 7.5$ m and the Young modulus of the cables is 205 GPa. The bridge deck width is a constant $B = 18.3$ m and has a shear modulus of 66.7 GPa. Its mass is $m_d = 12.5 \times 10^3$ kg/m.

The area of the main cables obviously depends on the span length. In the present the necessary cable area is estimated following [12]. Assuming a distributed liveload on the bridge deck $p = 46.58$ kN/m and a concentrated liveload representing special vehicles $P = 675$ kN the cable area A_c is calculated by the equation

$$A_c = \frac{[(g_d + p)l_m + 2P]\sqrt{l_m^2 + 16k_m^2}}{8f_{cbd}k_m - \gamma_{cb}l_m\sqrt{l_m^2 + 16k_m^2}} \tag{1}$$

The design stress and the equivalent density of the main cable are $f_{cbd} = 800$ MPa and $\gamma_{cb} = 84$ kN/m^3, respectively. The span length and the sag is denoted l_m and k_m respectively. The deadload of the bridge deck per unit length is $g_d = m_d * 9.81$ m/s^2. The cable mass per unit length depends on the cable area and is given by $\mu = 8560$ kg/m^3 A_c. The mass and mass moment of inertia per unit length of the deck and the cables are $m = (m_d + 2\mu)$ and $I = (I_d + 2\mu a^2)$ respectively. The weight of hangers has been neglected. Fig. 2 shows the relationship between the span-to-width ratios and γ_ω, as well as the critical flutter wind speed in m/s. The calculations of the critical flutter wind speed have been simplified by assuming that the flutter derivatives corresponds to thin airfoil derivatives and that the vertical and torsional modes are shape wise similar. The calculation routine is given in Section 2.2. Case 1 has a high torsional stiffness and thus a high frequency ratio at low span-to-width ratios. Increase in span-to-width ratio causes a relatively rapid decrease in frequency ratio. This rate of change decreases when the torsional stiffness of the deck is reduced, as illustrated with cases 2 and 3. Hence, the effect of the torsional stiffness in the girder on γ_ω is seen to decline as the span length increases. No critical flutter wind speeds were found for

Table 1
Torsional girder constant K_t and mass moment of inertia I_d.

Case		1	2	3	4
K_t	m^4	5	0.5	0	0.15
I_d	10^3 kg m^2/m	250	250	250	1250

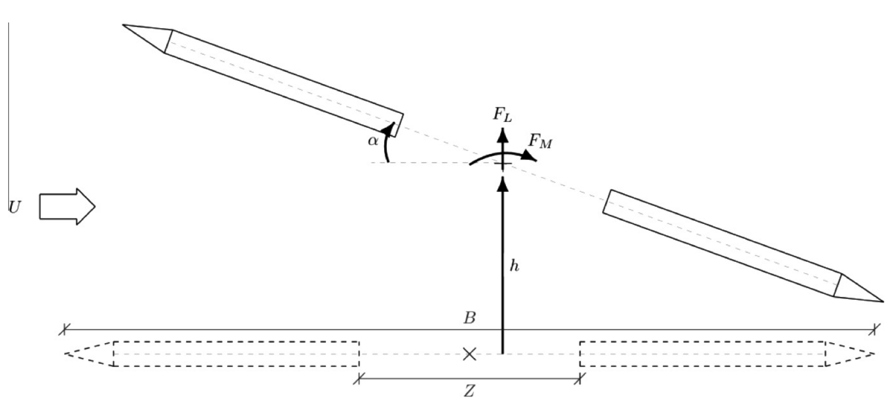

Fig. 1. Two degrees of freedom section model of a thin plate with a central gap.