Flutter stability of a suspension bridge during construction

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ABSTRACT: This work aims to infer some general considerations on flutter stability of long-span suspension bridges, considering both the completed configuration and the erection phase. A main span length that is expected to become soon not so exceptional (about 1600 m) and a common closed-box deck cross section have been taken into account in the analysis. The bridge planned for the crossing of the Julsundet Fjord in Norway has been assumed as a case study. The investigation revealed that stability against flutter is warranted without the need of particular optimizations except for the first phase of deck erection when this is started from the centre. In addition, the flutter calculations emphasize the key role of mode coupling coefficients both in service and during the construction stages.

1 INTRODUCTION

Nowadays the rapid increase in the number of long-span suspension bridges in the world emphasizes the importance of a reliable assessment of the stability of these amazing engineering structures against classical flutter. This holds true for the bridge completed and opened to traffic, but it seems particularly crucial for the construction phase, when the stiffness of the structure tends to be lower and the dynamical behavior is very different from that in service. Though the large majority of case studies on bridge flutter refer to the final configuration of the structure, a handful of research works address the stability of the construction phase, stressing its criticality (*e.g.* [1-4]).

Flutter assessment is usually carried out measuring aerodynamic derivatives in the wind tunnel and then calculating the critical wind speed at which the trivial oscillating solution loses stability. Several vibration modes are supposed to be included in this stability calculation (*e.g.* [5]), but in many cases a simple bimodal analysis is sufficient to accurately estimate the flutter stability threshold, provided that the vertical bending and torsional natural modes susceptible to couple are carefully selected, and the associated effective inertial properties are considered. In [6] all of the assumptions that theoretically need to be verified for a bimodal calculation to be accurate are examined. Among these, a key point is that the two natural modes that contribute to flutter instability present similar shapes. Otherwise, in order not to underestimate too much the critical wind speed, it is important to include in the bimodal calculation the effect of non-homothetic mode shapes through mode coupling coefficients [6-7]. This is particularly important for the construction phase, when mode shapes progressively change with advancement in deck erection, but this issue has not been thoroughly addressed in the literature.

In the present work, the project of a suspension bridge with a main span of about 1600 m is taken as a case study. The structure was preliminarily designed, assuming the same aerodynamic properties as the deck cross section of the Great Belt East Bridge. Two deck erection strategies, starting either from the centre or from the towers, were investigated since both are followed in the engineering practice (*e.g.* [4]). One of the goals of the study is a general understanding of the extent

to which flutter instability can be an issue for a suspension bridge with a main span that today cannot be considered super-long anymore, and with a deck cross section that is aerodynamically efficient, but without pursuing any multiple-deck or other highly-stable innovative solutions.

2 FLUTTER ASSESSMENT

The linearized self-excited forces that are responsible for flutter can be written in the classical semi-empirical form where the aerodynamic derivatives are the coefficients that relate the nondimensional forces and the motion components. For a two-degree-of-freedom linear oscillator, the flutter critical wind speed can be easily calculated assuming harmonic coupled oscillations and imposing the loss of stability of the trivial zero-amplitude solution. Nevertheless, when a deformable structure with several vibration modes is concerned, self-excited forces has to be projected onto these modes. During this operation, modal integrals and modal coupling coefficients appear:

$$G_{\xi_r \xi_j} = \int_D \xi_r(x)\xi_j(x)\frac{dx}{L} \qquad\qquad C_{\xi_r \xi_j} = \frac{G_{\xi_r \xi_j}}{G_{\xi_r \xi_r}} \qquad\qquad (1\text{-}2)$$

where $\xi_r(x)$ denotes a certain mode shape component (either bending or torsion) for the r-th mode. x is a coordinate that describes the bridge deck axis, while L is the main span length. The integrals are calculated over the deck. If one selects two modes, one with a dominant vertical bending component and the other with a large torsional component, the basic flutter equations usually obtained for pure vertical-bending and pure torsional homothetic modes are retrieved by defining some modified aerodynamic derivatives as follows:

$$\bar{H}_1^* = C_{h_1 h_1}H_1^* + C_{\alpha_1 h_1}H_2^* + C_{h_1 \alpha_1}A_1^* + C_{\alpha_1 \alpha_1}A_2^* \qquad\qquad (3)$$

$$\bar{H}_2^* = C_{h_2 h_1}H_1^* + C_{\alpha_2 h_1}H_2^* + C_{h_2 \alpha_1}A_1^* + C_{\alpha_2 \alpha_1}A_2^* \qquad\qquad (4)$$

$$\bar{H}_3^* = C_{\alpha_2 h_1}H_3^* + C_{h_2 h_1}H_4^* + C_{\alpha_2 \alpha_1}A_3^* + C_{h_2 \alpha_1}A_4^* \qquad\qquad (5)$$

$$\bar{H}_4^* = C_{\alpha_1 h_1}H_3^* + C_{h_1 h_1}H_4^* + C_{\alpha_1 \alpha_1}A_3^* + C_{h_1 \alpha_1}A_4^* \qquad\qquad (6)$$

$$\bar{A}_1^* = C_{h_1 h_2}H_1^* + C_{\alpha_1 h_2}H_2^* + C_{h_1 \alpha_2}A_1^* + C_{\alpha_1 \alpha_2}A_2^* \qquad\qquad (7)$$

$$\bar{A}_2^* = C_{h_2 h_2}H_1^* + C_{\alpha_2 h_2}H_2^* + C_{h_2 \alpha_2}A_1^* + C_{\alpha_2 \alpha_2}A_2^* \qquad\qquad (8)$$

$$\bar{A}_3^* = C_{\alpha_2 h_2}H_3^* + C_{h_2 h_2}H_4^* + C_{\alpha_2 \alpha_2}A_3^* + C_{h_2 \alpha_2}A_4^* \qquad\qquad (9)$$

$$\bar{A}_4^* = C_{\alpha_1 h_2}H_3^* + C_{h_1 h_2}H_4^* + C_{\alpha_1 \alpha_2}A_3^* + C_{h_1 \alpha_2}A_4^* \qquad\qquad (10)$$

where H_i^* and A_i^*, $i = 1, \dots, 4$, denote the aerodynamic derivatives usually measured in the wind tunnel. This approach accounts for the differences between the vertical bending and the torsional components of two modes susceptible to couple and give rise to flutter instability. It also takes into consideration that in some cases a mode can present both a vertical-bending and a torsional component due to asymmetries in the structure (especially non-conventional footbridges). It is worth noting that Eqs. (3)-(10) implicitly assume that self-excited drag force and horizontal bending of the deck do not contribute significantly to flutter instability. This is often true [6] although there are a few counter-examples in the literature.

3 CASE STUDY

The considered case study is the suspension bridge project to cross the Julsundet Fjord in Norway. The Norwegian Public Roads Administration provided us several constraints of the design, such as the characteristics of the access viaducts, the position of the foundations of the bridge towers (fixing the main span of the bridge to 1625 m), the navigation clearance (65 m), and the requirements for the roadway (two road lanes for each direction and a cycle lane on one side, leading to a small asymmetry of the deck). Based on these data, a preliminary design of the structure was carried out, paying particular attention to the optimization of the suspension system (Fig. 1).

The shape of the deck cross section was chosen as very close to the one of the Great Belt East Bridge, given the similarity with the design of the Julsundet Bridge and so to have information on the steady and unsteady aerodynamic coefficients of the deck. In particular, the same flutter derivatives as those reported in [3] were assumed.

The Norwegian Public Roads Administration also provided the wind speeds at 70-m height to be considered in the various calculations. In particular, for flutter stability a return period of 500 years was specified along with a safety factor of 1.6, leading to a design wind speed of 65.5 m/s. For the construction phase, we reduced the return period to 10 years, obtaining 50.0 m/s.
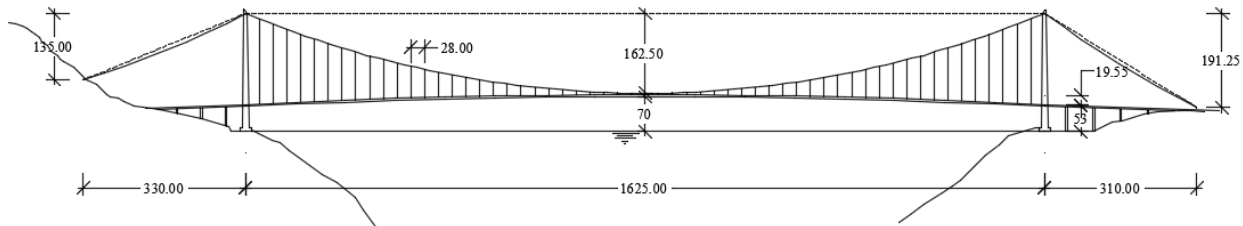

Figure 1. Frontal view of the preliminary design of the Julsundet Bridge.

4 RESULTS

In addition to the configuration of the bridge in service, two different erection sequences were studied: the first starting from the center and the second from the towers. For each stage of deck erection, a nonlinear analysis was carried out to determine the static deformed configuration of the bridge, and a modal analysis was conducted in its neighborhood. Effective mass and mass moment of inertia were then calculated. Results of the flutter calculations are reported in Fig. 2.

Considering the construction from the centre (Fig. 2(a)), critical wind speeds much lower than the design one were obtained until more than 30% of the deck is erected. Nevertheless, when about 50% of the deck is in place the coupling coefficients for the considered pair of symmetric modes reduce so much that the structure becomes stable all over the considered range of reduced wind speed. At this stage, flutter arises due to the coupling of antisymmetric modes, but the critical velocity becomes then much higher than the allowable limit. As for the construction from the towers (Fig. 2(b)), the flutter wind speed is always higher than the design threshold, in particular when less than 60% of the deck is erected. The critical modes are antisymmetric, but during the last stages of construction a second pair of antisymmetric modes brings to a lower critical flow speed. Finally, for the complete bridge the critical flutter mode is symmetric and the flutter stability request is generously satisfied, especially if one accounts for the mode coupling coefficients.
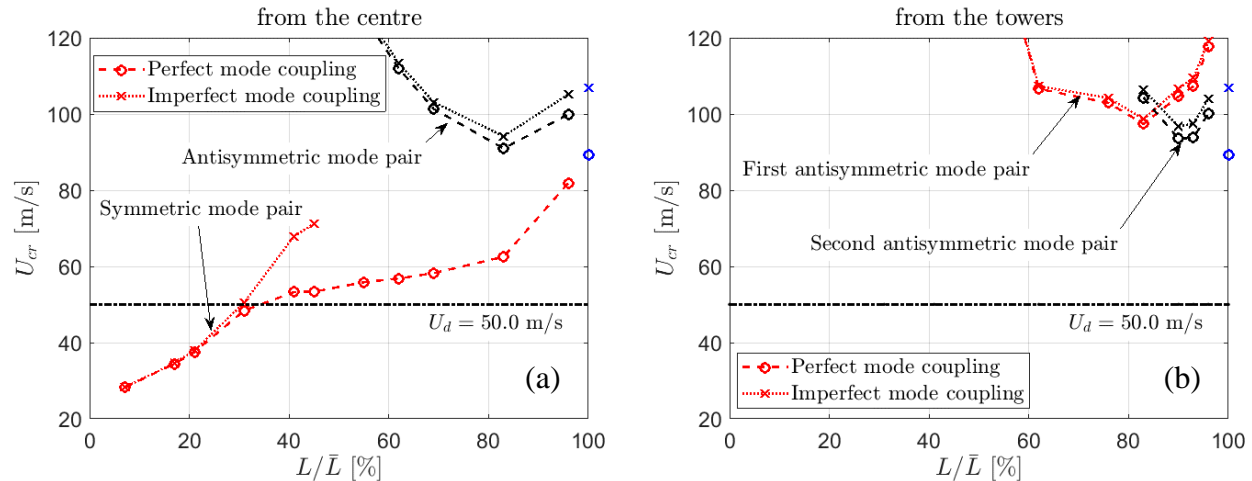
Figure 2. Flutter critical wind speed during the erection phase and in service. Where the critical velocity is not reported, it means that no flutter solution has been found in the considered range of reduced flow speed (up to a value of 20). U_d is the wind speed design during construction; $\bar{L}$ represents the total length of the span of the bridge.

5 CONCLUDING REMARKS

The extensive analysis conducted for the Julsundet bridge case study highlighted that, for a suspension bridge with a main span of about 1600 m and a streamlined closed-box deck cross section, the flutter stability in service can be guaranteed in a relatively easy way. The same can be claimed for the construction phase if the deck is erected from the towers toward the centre. In contrast, when the construction starts from the centre, flutter can be a serious issue until a sufficient portion of the deck is mounted. The analysis also revealed the crucial role in the flutter calculation of mode coupling coefficients, especially for some stages of construction and for the bridge in service.

6 ACKNOWLEDGEMENTS

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