Computer-aided wind engineering of long-span bridges

Autor(en): **Larsen, Allan / Esdahl, Soren**

Objekttyp: **Article**

Zeitschrift: **IABSE reports = Rapports AIPC = IVBH Berichte**

Band (Jahr): **79 (1998)**

PDF erstellt am: **14.09.2024**

Persistenter Link: https://doi.org/10.5169/seals-59880

Computer-Aided Wind Engineering of Long-Span Bridges

Allan LARSEN
Dr Eng.
COWI AS
Lyngby, Denmark

Allan Larsen, born 1953, obtained his engineering degree in 1979, the von Karman Institute diploma in 1981 and a Ph.D. in flow induced vibrations in 1984. Mr Larsen joined COWI in 1989 working as a bridge engineer specialising in aeroelastic analyses, wind loads and structural dynamics.

Soren ESDAHL
Civil Eng.
COWI AS
Lyngby, Denmark

Soren Esdahl, born 1971, obtained his engineering degree in 1995 at the Technical University of Denmark. Mr. Esdahl is a bridge engineer working within Finite Element modelling analysis, structural dynamics, and aeroelasticity.

Summary

The design of long-span cable supported bridges often involves considerations of wind effects and aeroelastic stability. A new computational fluid dynamics code is combined with an existing in-house FEM code to form a computer-aided engineering system suitable for wind engineering analysis and assessment of bridges. This paper offers a brief discussion of two actual bridge designs analysed using this system. It is demonstrated how geometrical girder cross section details is significant to the aerodynamic performance of a long-span bridge.

1 Introduction

Wind engineering of long-span bridges most often focuses on the interaction of aerodynamic loads generated by the wind and the elastic response of the bridge structure. The related engineering discipline of aeroelasticity requires tools that will allow the engineering analyst to establish the effect of the over all structural lay-out as well as predict the influences of structural changes as they occur during the design process. Prior to the early 1970'ties most aerodynamic and structural dynamics analyses relied on physical model testing of the bridge in question. Needless to say, this approach was time consuming and did not allow for many design iterations. The advent of the computer based Finite Element Method rendered structural model testing superfluous and allowed the designer to explore the dynamics of a wide range of structural configurations, but aeroelastic analyses were still relying on experimental data obtained from wind tunnel testing. Recent advances in computer sciences have made numerical simulations of aerodynamic loads on bridge girder cross sections possible thus allowing the entire wind engineering process of long-span bridges to be aided by computers. This paper presents two examples of how computer-aided wind engineering analyses may influence the design and performance assessment of long-span bridges. Two design cases involving assessment of the critical wind speed for onset of flutter for cable-stayed bridges are discussed highlighting the influence of cross section geometry. The bridges discussed are a cable-stayed bicycle bridge to be build in Holland (Tuibrug in de Zuidtangent) and a cable-stayed motorway bridge (Sunningesund Bridge) now under construction in Sweden. Principal dimensions of the bridges discussed are shown in fig. 1.

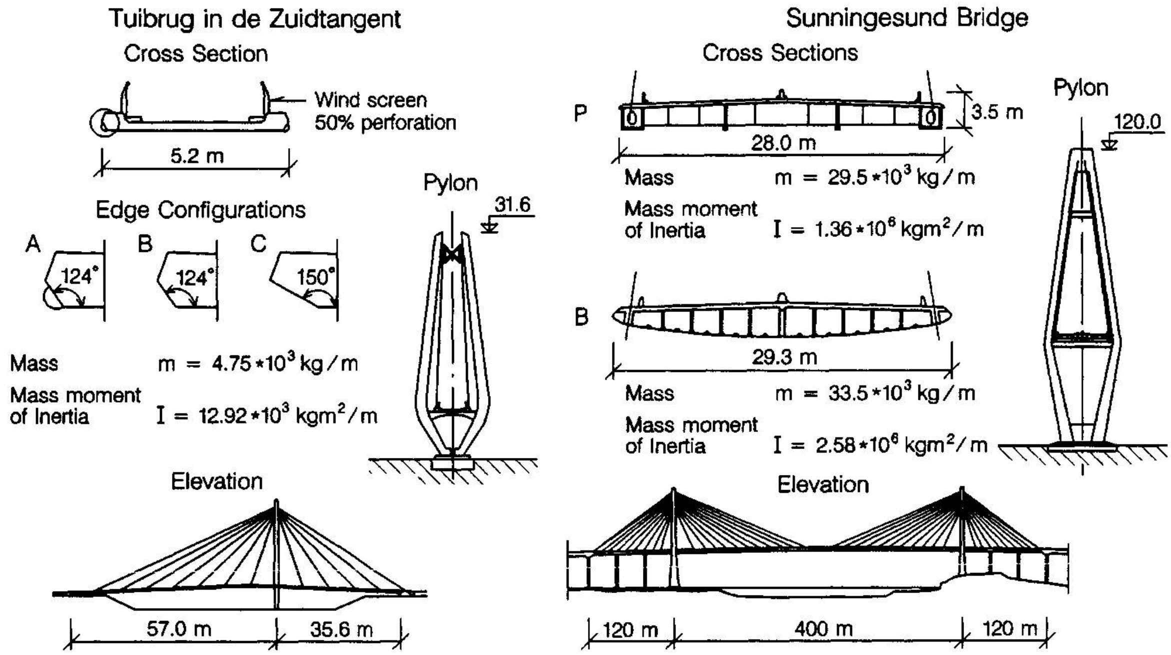


Fig. 1 Main particulars of cable-stayed bridges investigated

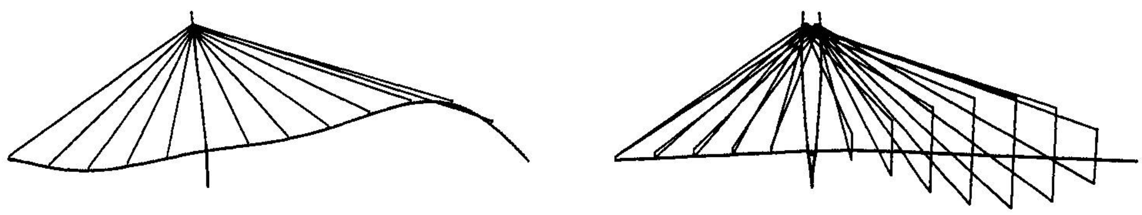
2 Computer-Aided Wind Engineering System

The aerodynamic back-bone of the computer-aided wind engineering system operated by COWI is the computer code DVMFLOW introduced to the IABSE community at the Copenhagen Congress 1996, Larsen and Walther [1]. The DVMFLOW code applies the discrete vortex method for simulation of aerodynamic loads on two-dimensional (2D) cross sections which are fixed or undergoing forced motion relative to the flow. Also the cross sections may be elastically suspended in the flow allowing simulation of non-linear flow induced response. Full three-dimensional (3D) dynamic analysis of a bridge structure is facilitated by the COWI CAE system IBDAS which makes a wide range of structural elements and a parametric representation of the turbulent wind available to the aeroelastic analyst, Sørensen, Andersen and Jacobsen [2]. Links between 2D simulations of the aerodynamic properties of the bridge girder and the dynamics of 3D pylon-cable-girder assemblies are provided by the modal analysis method developed by Scanlan [3] and co-workers. Specific details of the simulation and analysis procedures will not be detailed further. Interested readers are referred to Walther and Larsen [4], for a presentation of the discrete vortex method employed in DVMFLOW and to Larsen [5] for a general discussion of computer simulations of wind-structure interaction in bridge aerodynamics.

3 Cable-Stayed Bicycle Bridge

The infrastructure serving the Schiphol Airport, the Netherlands, is currently being expanded. One of the additions to the road system feeding the airport is a slender cable-stayed bicycle bridge designed by the Dutch engineers IBA / TauwMabeg. The bridge comprises a 92.6 m long and 5.2 m wide concrete girder carried by two fans of stay-cables anchored at the girder edges and at the top of a single central steel pylon, fig. 1. Preliminary aeroelastic analysis based on a plane (2D) structural model and wind tunnel data compiled in the bridge design literature [6], yielded an unacceptable low critical wind speed for onset of flutter and further investigations were recommended. At the request of IBA / TauwMabeg, COWI was entrusted a computational aeroelastic analysis of the bridge involving a three-dimensional structural dynamics analysis and assessments of the influence of modifications of the bridge girder cross section geometry.

The IBDAS model developed for structural dynamic analysis of the bridge reproduced the full 3D geometry of the structure and included supports and fixations at the landfalls and pylon. Mass and stiffness properties of the individual elements were based on the material specifications and dimensions given in the design drawings. Particular attention was given to modelling of the cross beam at the top of the pylon as details in this region is known to have significant effect on the torsion frequency of the bridge. Fig. 2 shows the lowest vertical (h) and torsional (α) eigenmodes for which the bridge is likely to encounter flutter. Comparison of vertical eigenfrequencies f_h obtained from 2D and 3D analysis yields good agreement. Analysis of torsion modes is, by definition, not possible in 2D modelling as the torsion stiffness of the girder and twist of the pylon structure around a vertical axis is not accounted for. Torsion frequencies f_α are, however, sometimes inferred from the vertical modes by scaling the vertical frequencies with the ratio of the semi-distance (b) between the cable planes to the cross section radius of gyration (r): $f_\alpha = f_h \cdot b/r$. This simplification, which borrows from the analysis of suspension bridges with stiffening girders composed of open and thin walled cross sections, leads to serious underestimation of f_α in the present case.



3D: f_h = 0.92 Hz 2D: f_h = 0.86 Hz 3D: f_α = 2.55 Hz 2D: f_α = 1.17 Hz

Fig. 2 Lowest vertical and torsion modes and frequencies obtained from 3D and 2D analysis

The main element of the DVMFLOW models developed for the three cross sections (A, B, C) investigated reproduced the external contour of the girders and featured approximately 200 vortex panels. The 50% perforated plate wind screens were modelled as assemblies of three equidistant spaced rectangles comprising 30 vortex panels each, covering a total of 50% of the frontal area of the wind screens. The circular hand rail was modelled by a ring assembly of 40 vortex panels. Aerodynamic derivatives computed for each of the cross sections by means of the forced oscillation technique, Larsen [5]. In case of cross sections A and B, the results revealed a change in sign (from - to +) of the A_2^* derivative at increasing non-dimensional wind speeds U/fB as shown in fig. 3. A behaviour indicating *one-degree-of-freedom* (1DOF) torsional flutter. The A_2^* and H_1^* derivatives of the C cross section displayed increasingly negative values at increasing non-dimensional wind speeds consistent with *two-degree-of-freedom* (2DOF) classical flutter.

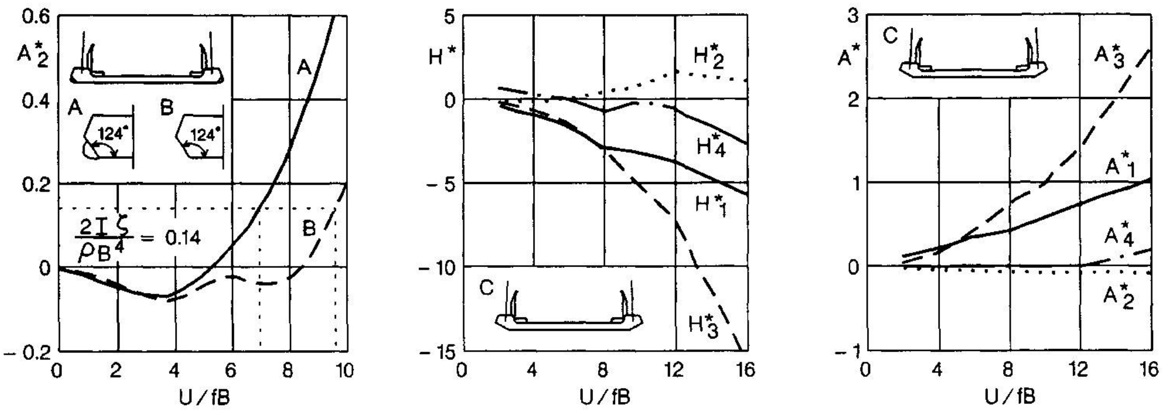
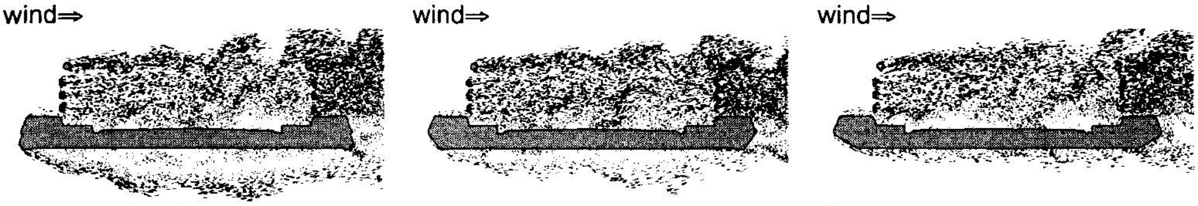


Fig. 3 Aerodynamic derivatives obtained from forced oscillation simulations of the flow about cross sections A, B and C.

Some insight into the flow conditions and cross section geometry responsible for the two flutter modes is offered in fig. 4. The flow about cross section A, which features a semi-circular edge profile, displays flow separation and formation of a vortex just downwind of the bottom plate / side panel joint. According to experience, Larsen [7], this type of vortex may create an aerodynamic moment which at a certain non-dimensional wind speed becomes in phase with structural twist of the girder thus amplifying the structural motion. This action is reflected in the change of sign of A_2* at U/fB ≈ 5.2. In cross section B the semi-circular edge profile is removed securing a more smooth flow around the bottom plate / side panel joint. The separation vortex is still formed leading to a cross-over of A_2*, but now at higher U/fB ≈ 9.5. The C cross section features a less steep bottom side panel as compared to cross section B. This detail prevents massive flow separation along the bottom plate and thus formation and drift of a large coherent vortex. The now "smooth" flow along the bottom plate is consistent with 2DOF flutter. Increase of the flutter wind speed is noted with increasing "streamlining" of the bottom portion of the cross section.

wind⇒ wind⇒ wind⇒



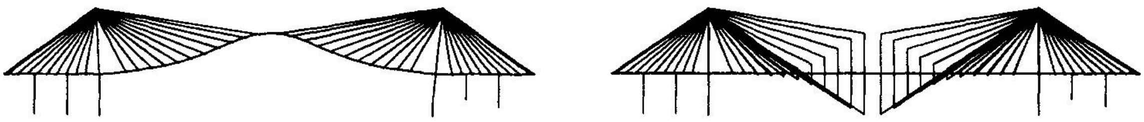
Cross section A: U_c = 90 m/s Cross section B: U_c = 121 m/s Cross section C: U_c = 198 m/s

Fig. 4 Visualisation of the flow about cross sections A, B and C and corresponding wind speeds U_c for onset of flutter assuming a structural damping ζ = 0.5% re-to-crit.

3 Cable-Stayed Motorway Bridge

The E6 motorway running along the east coast of Sweden is expanded north of Gothenburg to connect the Øresund region to the Oslo region in Norway. At Uddevalla the E6 will be carried across the Sunningesund fjord by a 3 span cable-stayed bridge drafted by Vägverket, the Swedish National Road Administration. The bridge comprises a 400 m composite girder in the main span, flanked by two 120 m concrete side spans carried by four fans of stay-cables anchored at the girder edges. Prior to tendering of the bridge COWI was entrusted with a computational aeroelastic analysis of two design alternatives involving plate (P) and closed box (B) section girders. The plate girder alternative incorporated two intermediate pier supports in the side spans (fig. 1) where as the box girder alternative featured three clear spans (no pier supports in the side spans) The analyses performed comprised a 3D structural analysis of the bridge and a 2D flow analysis for assessment of the influence of bridge girder cross section shape on the aeroelastic stability and buffeting response.

The structural dynamics effect of the girder / pier support configurations are demonstrated in fig. 5, which reproduces the lowest vertical and torsion mode shapes and eigenfrequencies of the bridge. It is noted that the torsion frequency of the box girder alternative is higher than the torsion frequency of the plate girder due to the increased torsion stiffness of the closed box compared to the open plate cross section. The vertical bending frequency of the box girder alternative is, however lower than the corresponding value of the plate girder bridge due to the absence of the intermediate piers in the side spans.



P: f_h = 0.307 Hz B: f_h = 0.243 Hz P: f_α = 0.753 Hz B: f_α = 0.801 Hz

Fig. 5 Lowest vertical and torsion modes and frequencies obtained from 3D analysis of Plate girder (P) and box girder (B) alternatives. Modeshapes for Plate girder alternative shown.

The 2D aerodynamic analysis of the cross sections targeted the effect of cross section shape on the critical wind speed for onset of flutter U_c and the cross section drag coefficient C_D. In the case of the plate cross section P the results revealed a change of sign (from - to +) of the A_2^* derivative at increasing U/fB indicating 1DOF flutter. The A_2^* and H_1^* derivatives of the box cross section B displayed increasingly negative values at increasing U/fB, consistent with 2DOF classical flutter, fig. 6.

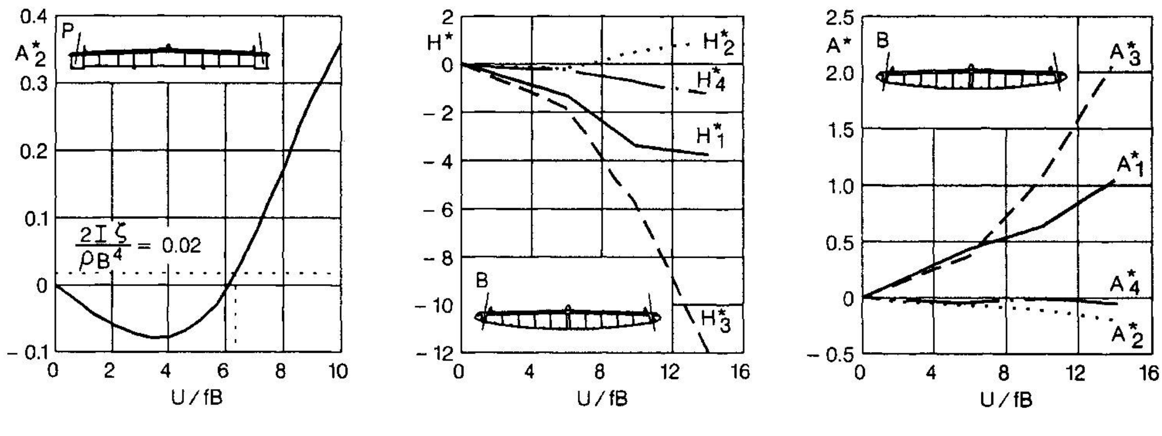
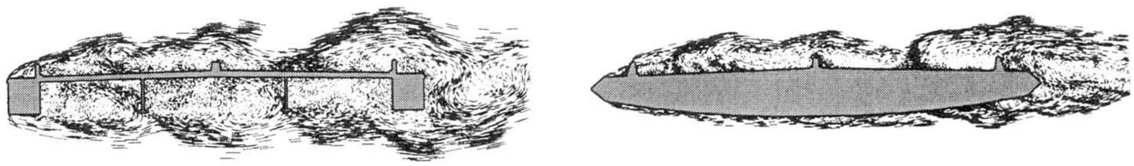


Fig. 6 Aerodynamic derivatives obtained from forced oscillation simulations of the flow about the plate and box cross sections alternatives for the Sunningesund bridge.

Fig. 7 offers a plot of the simulated flows and the predicted aerodynamic performance. The flow about the plate girder cross section forms large recirculating vortical structures below the deck in the compartments between the edge girders and the longitudinals. In contrast the flow about the box girder cross section is smooth along the slightly curved bottom plate.

wind⇒ wind⇒



Cross section P: $C_D = 0.12$, $U_c = 130$ m/s Cross section B: $C_D = 0.07$, $U_c = 210$ m/s

Fig. 7 Visualisation of the flow about the plate and box cross sections. Drag coefficients C_D and flutter wind speeds U_c assuming a structural damping $\zeta = 0.5\%$ rel-to-crit.

The differences in the respective flow fields carry over in the predicted aerodynamic properties. As in the previous example it is noted that increased "streamlining" of the cross section leads to better aerodynamic performance in terms a of higher flutter wind speed and a lower cross section drag coefficient. It should also be emphasised that the increased torsion stiffness of the box girder is beneficial for the aerodynamic stability.

4 Conclusion

A computer aided wind engineering system for analysis of long-span bridges is presented. This system allows the designer to explore the effect of cross section shape on aerodynamic performance of a given bridge structure without resorting to time consuming and costly wind tunnel tests. The cases discussed clearly demonstrate that the aerodynamic performance of a bridge may be significantly enhanced by "streamlining" of the bridge girder cross section. The importance of utilising a full three dimensional model for the structural dynamics input to aerodynamic analyses of long-span bridges is stressed.

5 References

[1] Larsen, A. and Walther, J.H.: A New Computational Method for Assessment of the Aeroelastic Stability of Long-Span Bridges, Proc. 15th IABSE Congress, Copenhagen, 1996

[2] Sørensen, K.A., Andersen, G.B and Jacobsen P.F.: Integrated Bridge Design and Analysis System. Proc. 13th IABSE Congress, Helsinki, 1988.

[3] Simiu, E. and Scanlan, R.H.: *Wind Effects on Structures*, 2. ed., Wiley Interscience, New York, 1986.

[4] Walther, J.H. and Larsen, A.: Two Dimensional Discrete Vortex Method for Application to Bluff Body Aerodynamics. Journal of Wind Engineering and Industrial Aerodynamics, vol. 67-68, pp 183-194, 1997.

[5] Larsen, A.: Computer Simulation of Wind-Structure Interaction in Bridge Aerodynamics, Structural Engineering International, Vol. 2, 1998.

[6] Walter, R., Houriet, B. et al. : *Ponts Haubané*, Presses Polytechniques Romandes, 1985.

[7] Larsen, A.: Aeroelastic Instability of an H-shaped Cross Section, Proc. ASCE Engineering Mechanics Conference, La Jolla, 1998.