COMPUTER AIDED WIND DESIGN FOR LONG BRIDGE CROSSINGS

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Abstract: *Dynamic wind analyses are increasingly becoming important in bridge engineering. Quite different critical aero-elastic phenomena have been observed, and solving all these problems within one software package considerably eases the design process. These phenomena include vortex shedding and the lock-in phenomenon, across-wind galloping and wake galloping, torsional divergence, flutter phenomena and wind buffeting.*

The solution of these problems within one comprehensive software tool considerably eases the design process. The required tasks range from the determination of the aerodynamic parameters to sophisticated buffeting analyses. The CFD function for determining the aerodynamic coefficients not only calculates the actually acting wind forces, but also allows for investigating the vortex shedding phenomenon.

The wind buffeting analysis is on the one hand based on the above-mentioned aerodynamic coefficients and their derivatives, and on the other hand on the wind profile parameters (speed, direction, turbulence intensity, power spectrum, coherence data).

1. WIND AS DESIGN CRITERION

1.1 General

Bridging large distances often requires using ultra long spans, especially in the context of crossing large rivers, estuaries, fjords or sounds in maritime and coastal areas. This is mainly due to shipping requirements on the one hand, and due to foundation problems in deep water on the other hand. The extraordinary slenderness of these structures yields indeed a considerable susceptibility for wind-induced vibrations.

Apparently, the effects of the wind loading on the bridge design become bigger with increasing span lengths. Therefore, sophisticated dynamic wind analyses are becoming more and more important in bridge engineering. Wind induced vibrations must often also be investigated for various construction stages during the erection, in addition to the final system after completion with and without traffic.

These investigations must cover all the different phenomena connected with dynamic wind impact, e.g. buffeting (gust response), vortex excitations, galloping and classical and torsional flutter as given below more in detail. They are also required for the total system (global vibration behaviour) as well as, if necessary, locally for certain structural parts such as the pylon, individual stay cables or suspension cables and hangers.

1.2 Wind Impact

The wind impact is generally described by static parameters describing the mean wind speed as a function of the height above ground, and respective dynamic parameters like the turbulence intensity describing the deviation of the actual wind speed from the mean value in size and direction. In addition, a power spectrum defines the energy content of these wind fluctuations as a function of the fluctuation frequency. Finally, appropriate coherence parameters define the spatial distribution of these fluctuations.

All these parameters are gathered in so-called wind profiles, which are assigned to the structural elements and evaluated in the static and dynamic wind analysis. Different wind profiles may be relevant for different mean wind directions. However, the actual excitation is not only governed by the wind profile parameters, but also by structural parameters describing the interaction between wind and the structure.

1.3 Wind - Structure Interaction Phenomena

With respect to wind–structure interaction, various quite different critical aero-elastic phenomena have been observed on existing bridges, ranging from local cable vibration to dramatic collapse of the whole structure as it was the case with the first Tacoma Narrows Bridge in 1940. These phenomena have been categorized with respect to the involved kinematical mechanisms and include

- Vortex shedding and lock-in phenomenon
- Across-wind galloping and wake galloping
- Torsional divergence

- Flutter
- Wind buffeting response

1.4 Mathematical Solution

Natural modes: Dynamic wind analyses are usually based on the modal method, and respective buffeting analyses have already been state of the art in leading structural analysis programs like RM2006 for several years. For applying this method, the determination of the structural eigenmodes and eigenvalues under the current total loading is an essential first step. The computation is generally based on the tangential stiffness matrix of the structure, allowing for including all prior non-linear effects. The usage of the structural “tangent stiffness” results in the best possible linearization for the subsequent dynamic analysis steps in the modal domain.

Cross-sectional investigations: The forces acting on the structural members are not only dependent on the wind profile parameters, but also and essentially by the aerodynamic coefficients of the structural parts and their derivatives with respect to the attack angle. These coefficients have usually been determined in wind tunnel tests. However, the great costs of these tests and the limited applicability due to physical model restrictions yielded the demand for a comprehensive computer solution covering the determination of the relevant drag, lift and moment coefficients in addition to the actual analysis module.

Therefore, a sophisticated CFD code, based on the vortex particle method, has been developed in the last 2 years, and implemented in the analysis program RM2006. Extensive investigations have been performed for the validation of this code and for the optimisation of the required computer time and quality of results. The validation work included comparisons with previous research work results documented in the scientific literature, with available results of investigations for previously built long span bridges, and with the results of wind tunnel tests performed within the project.

The code also calculates the Strouhal number of the investigated cross-sections and thus determines the vortex shedding frequency as a function of the wind speed. Comparing it with the natural frequencies yields the critical wind speed values. Furthermore, any torsional divergence behaviour is detected by evaluating the interplay between the different coefficients. In addition, the derivatives of the aero-dynamic coefficients describe the flutter behaviour of the cross-section.

Buffeting (gust response): Structural vibrations due to gusty wind will occur in any natural turbulent wind events. Aerodynamic drag forces will create random vibrations of lateral bending. Lifting forces yield vertical bending and pitching moments yield torsion moments around the bridge axis. Based on the wind-profile data and cross-sectional aero-dynamic and aero-elastic parameters, sophisticated buffeting analyses can be easily performed within the structural analysis procedure. This analysis yields root mean square values and/or peak values of displacements and/or internal forces arising in addition to the static deformation and stressing state.

2. INTEGRATED DESIGN PROCEDURE

It is essential, that the used software product support all required special analysis tasks arising in the bridge design process on the basis of the same structural model database. Data transfer between different special purpose programs would cause much additional work and involves the persistent danger that serious errors might occur.

In addition, the software must grant the possibility of easily enhancing and extending the mathematical model of the structure throughout the design process. This allows for very fast getting tentative answers in the preliminary design phase, and to get additional and enhanced the answers by gradually refining the model in lockstep with the requirements.

TDV's program suite RM is one of the commercial packages available for supporting the bridge design and erection process from the very first beginning to the completed structure. With implementing a sophisticated CFD code (based on the vortex particle method) for supporting dynamic wind analyses from the very beginning onwards, TDV stepped beyond the limits of solving traditional structural analysis tasks and fluid dynamics tasks separately

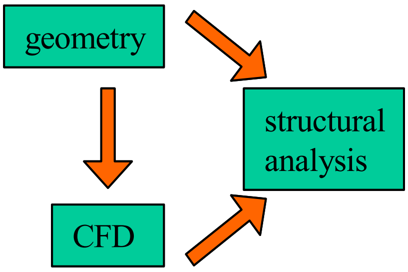

Figure 1: Flow chart of non-integrated solution

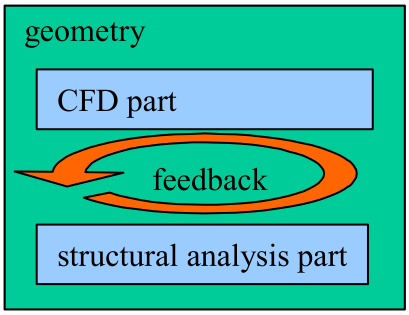

Figure 2:Flow chart of integrated solution

Within RM, the geometric preprocessor GP allows for easily defining the structural model of any bridge structure. Complicated geometric conditions can easily be recorded by defining "axes" in plan and elevation view, with using all geometric elements (straight, circular, parabolic, spiral, etc) commonly known in road construction. Extensive graphic input facilities allow for efficiently constructing any type of bridge cross-section on the screen. The superstructure segments are allocated by placing the different cross-sections along these axes. These "segments" relate the physical model to the structural model (elements, nodes).

Special types of segments define cross-girders of truss models (link segments), temporary support conditions in incremental launching processes (ILM-segments) or substructure entities like abutments, piers or pile groups. A very interesting recent development aims at analyzing bascule bridges and allows for arranging model parts in different positions and directions within the different construction stages.

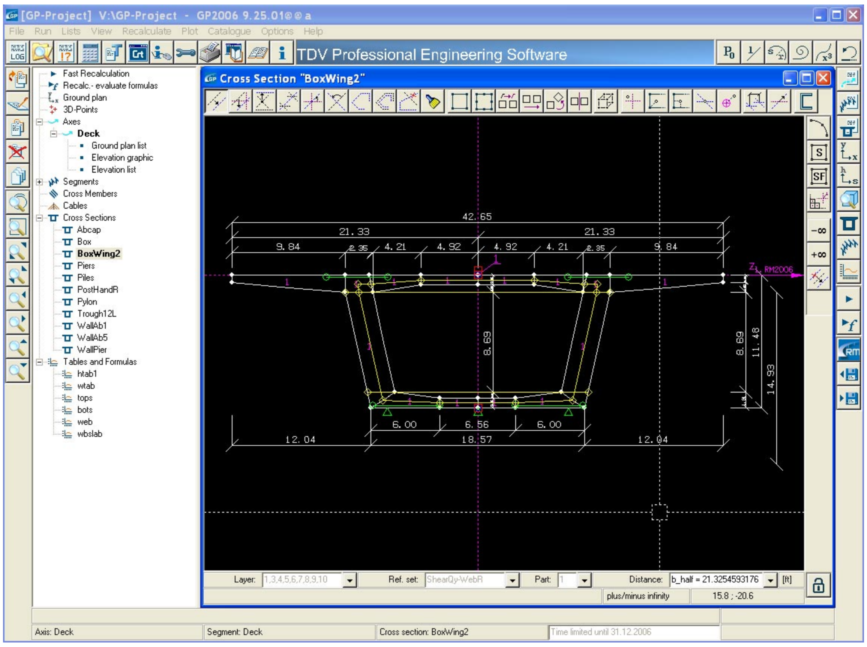

Figure 3 Graphical input of the cross-section geometry

The analysis part not only allows fully non-linear analyses for all types of bridge structures, but also contains special design check modules for proof-checking stability and serviceability in accordance with most national design codes worldwide. The *construction schedule* as central database objects contains all loadings being applied during and after the erection phase, and the information about the erection of the different structural part in time.

Modifying the respective data in the database and recalculating the whole job can easily account for any deviations of the actual construction schedule from regular one. The construction schedule also contains the information on the time dependent behaviour of the material, and therefore allows for properly taking into account all creep and shrinkage effects as well as prestressing steel relaxation in accordance with the relevant design codes or proposals of international institutes like **CEB-FIP**.

The wind related functions match nearly all needs for the design of long-span bridges. Arbitrary complicated wind profiles with varying wind speed and turbulence intensity in accordance with different national design codes can be easily defined. The different aspects of the aerodynamic excitation can be easily calculated with the inbuilt CFD-code. Together with the cross-section related shape factor diagrams defining the dependency of the drag-lift- and moment coefficients on the attack angle of the wind impact, these wind profiles allow for performing comprehensive wind buffeting analyses.

3. EXAMPLES

Different aspects of the integrated design procedure are shown on practical examples of major bridges having been recently built or being currently under or shortly before construction. Results of buffeting analyses are shown for two major cable-stayed bridges, the Shenzen Western Corridor and the Stonecutters Bridge in Hongkong. Sophisticated vortex shedding investigations have been performed for the deck and the pylons of the Hardanger Bridge in Norway.

Stonecutters Bridge, Hong Kong: The Stonecutters Bridge is a cable-stayed bridge with a main span of 1018 m, side spans of 298 m, and two single pylon towers of a height of 290 m. The bridge will straddle the Rambler Channel at the entrance to the busy Kwai Chung container port and its northern end will be located on reclaimed land that forms part of the Container Terminal 8 at the eastern side of Stonecutters Island.

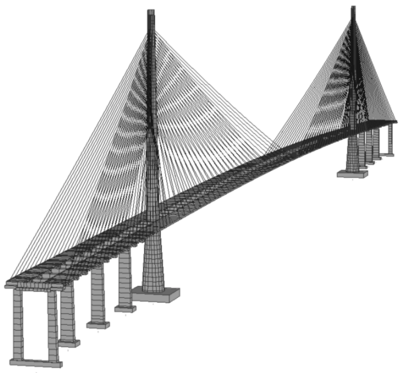

Figure 4: Structural RM2006 model

The deck of the main span is a twin girder steel deck, whilst the side spans are concrete. The side spans will be built in advance of the stay cable erection in order to counterbalance and stabilise the slender lightweight main span deck.

Prefabricated cable stays are arranged in a laterally inclined fan arrangement to maximize the transverse and torsional stability of the main span. They include the world's longest bridge stay to date. Wind buffeting responses are shown in the below figures.

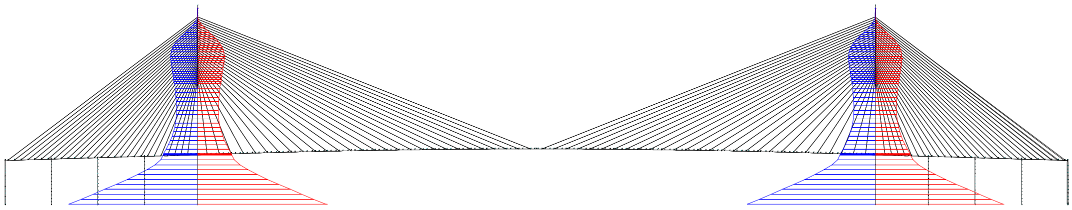

Figure 5: Bending moments in the pylon

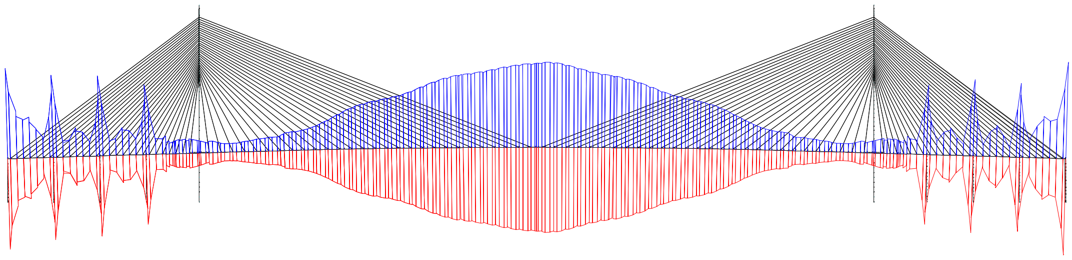

Figure 6: Bending moments of the bridge deck

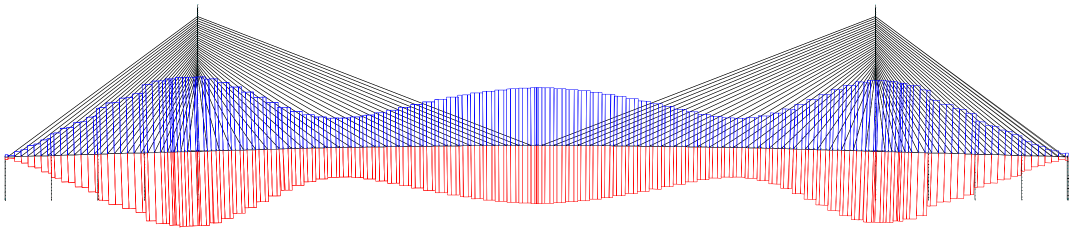

Figure 7: Normal forces in the bridge deck

Shenzhen Western Corridor: An other remarkable cable stayed bridge has been erected on the Hong-Kong side of the Shenzhen Western Corridor. It is an unsymmetrical bridge with an inclined pylon and a main span of 210 m. The deck is a steel girder, and the height of the inclined pylon is 158 m. The wind buffeting response has also been calculated for this bridge and the below sketches show the model and the internal force envelopes due to dynamic wind impact respectively.

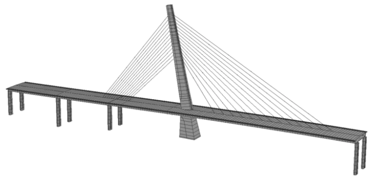

Figure 8: Structural RM2006 model

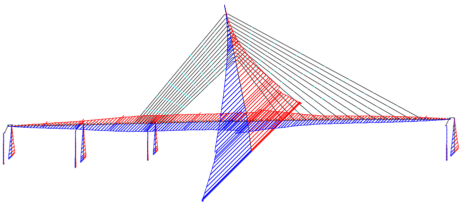

Figure 9: Lateral bending moments

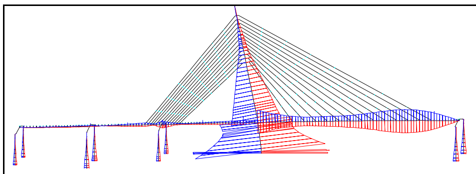

Figure 10: Vertical bending moments

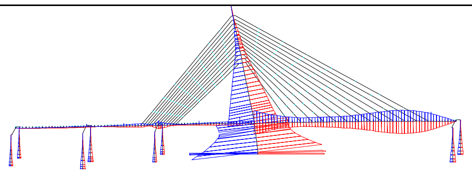

Figure 11: Normal forces

Hardanger Bridge: The Hardanger bridge in Norway will cross the Hardanger fjord to replace the ferry transport (Figure 12). The main span length will be 1310 m at a total length of 1380 m. The bridge will be the longest suspension bridge in Norway and no 7 worldwide. A *RM2006* structural model of the bridge is shown in Figure 13.

Figure 12: Location of Hardanger Bridge.

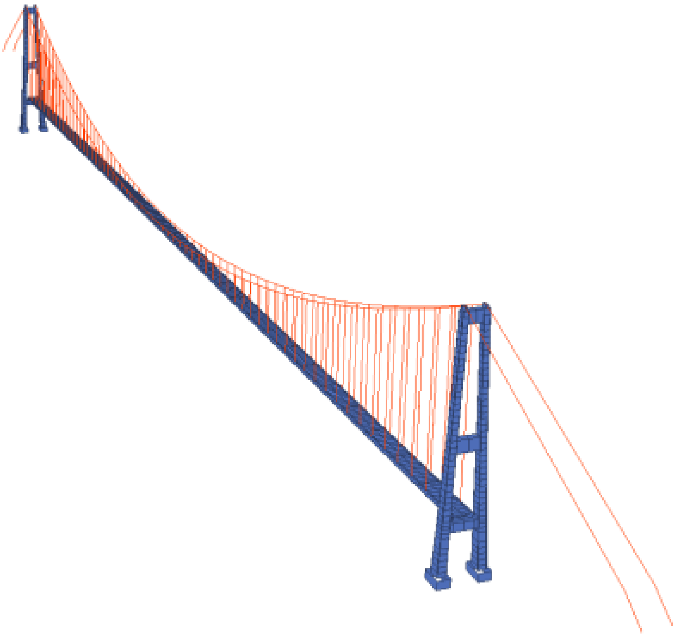

Figure 13: Structural model of Hardanger Bridge.

Some aspects of the wind leated investigations of the pylon are shown below. Similar investigations have also been performed for the bridge deck. The pylon legs are modeled by two rectangles with an aspect ratio of the sides H:B = 4:3 and a reference length H = 6 m. The distance S between the centres of the legs depends on the height above ground. Considered distances are approximately 15 m, 20 m and 25 m. A sketch of the geometry is shown in Figure 14. Although the basic elements of the cross section haven been intensively reported in the literature, a detailed insight into the aerodynamic behaviour of a dual bluff body is usually not given. In the present study, wind directions from 0° to 90° at Reynolds numbers above 10^7 were considered.

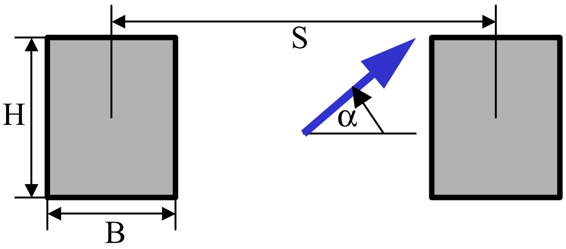

Figure 14: Considered pylon geometry

For low attack angles α ≈ 0°, the right leg lies in the wind shadow of the left one. Consequently a significantly reduced drag coefficient can be expected for transversal wind. For longitudinal wind direction, α ≈ 90°, it is not clear a priori, if the distance between the legs is small enough to cause interactions between the two legs. As expected, strong wind shadow effects of the drag coefficient can be observed for lateral wind directions as shown in Figure 15.

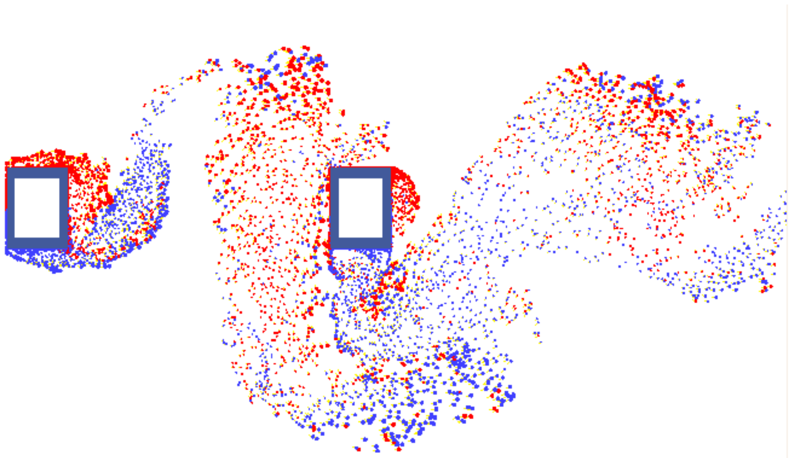

Figure 15: Flow pattern of lateral wind

For longitudinal wind, the pylon geometry is symmetric with respect to the wind direction, which is also reflected by the drag coefficient. In general, for angles α > 45°, the coefficients for both legs show a good agreement, i.e. they do not influence each other.

SUMMARY

The numerical procedures for investigating the bridge behaviour due to dynamic wind impact as outlined in this paper are implemented in the computer package RM2006. They allow for completely replacing wind tunnel tests in the preliminary design phase, and for complementing the physical tests in the detailed design, with considerably enhancing the design basis by evaluating, validating and calibrating the physical test results. The described methods for the numerical analysis can handle satisfactorily all static and dynamic bridge behavior problems.

The presented wind related algorithms predicts wind-buffeting response with non-linear analysis .The wind related functions of RM2006 match nearly all needs for the design of long-span bridges. Arbitrary complicated wind profiles with varying wind speed and turbulence intensity are easily defined. Together with the shape factor diagrams defining the dependency of the drag- lift- and moment coefficients on the attack angle, these wind profiles allow a comprehensive wind buffeting analysis taking into account the varying along-wind and lateral forces of gusty wind events.

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