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# CFD practical application in conceptual design of a 425 m cable-stayed bridge

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**Abstract.** CFD techniques try to find their way in the bridge engineering realm nowadays. However, there are certain fields where they offer superior performance such as conceptual bridge design and bidding design. The CFD studies carried out for the conceptual design of a 425 m length cable-stayed bridge are presented. A CFD commercial package has been employed to obtain for a set of cross-sections the aerodynamic coefficients considering 2D steady state. Additionally, for those cross-sections which showed adequate force coefficients, unsteady 2D simulations were carried out to detect the risk of vortex shedding. Based upon these computations the effect on the aerodynamic behavior of the deck cross-section caused by a number of modifications has been evaluated. As a consequence, a new more feasible cross-section design has been proposed. Nevertheless, if the design process proceeds to a more detailed step a comprehensive set of studies, comprising extensive wind tunnel tests, are required to better find out the aerodynamic bridge behavior.

**Keywords:** CFD; RANS; conceptual structural design; cable-stayed bridges.

## 1. Introduction

Cable supported bridges are flexible, thus wind prone structures. As a matter of fact, the list of bridges which have collapsed, suffered substantial damage or present service problems due to wind action throughout history is long. Some examples are: the Brighton Chain Pier which collapsed in 1836 (Simiu and Scanlan 1996), the Menai Strait Bridge which suffered substantial damage by a storm in 1839 (Brown 1993), the Wheeling Suspension Bridge destroyed by a gale in 1854 (Brown 1993), the famous Tacoma Narrows Bridge blew down by a moderate wind in 1940 (Scott 2001), the Bronx-Whitestone Bridge where oscillations were observed entailing the use of correcting arrangements (Wardlaw 1992), the Longs Creek Bridge which shown oscillations due to vortex shedding thus fairings and a soffit plate were installed to mitigate them (Wardlaw 1992) or the Great Belt suspension Bridge who showed low frequency deck oscillations during the final phases of deck erection and surfacing caused also by vortex shedding (Larsen 1993).

Computational fluid dynamics (CFD) is finding its way in the wind engineering realm. Starting with the early works of researchers such as Son and Hanratty (1969), CFD has experienced a great development from the 1990 decade thanks to the contributions of a number of authors such as

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Murakami (Murakami and Mochida 1988, 1995, Murakami 1990a, b), Tamura (Tamura *et al*. 1993, 1995, 1998) or Larsen who focused on bridges (Larsen and Walther 1997, 1998, Walther and Larsen 1997, Selvam *et al*. 1998, Vejrum *et al*. 2000). Other authors responsible for significant contributions in bridges in recent years are Frandsen (2004), Morgenthal (2002), Bruno (Bruno *et al*. 1999, Bruno and Fransos 2008), Liaw (2005) or Ge and Xiang (2008). Therefore, the state of the art in CDF applications in bridge engineering shows a panorama where, in general, the aerodynamic coefficients for a bridge deck section can be accurately predicted, vortex shedding and the associated Strouhal number can be identified and even flutter derivatives and the flutter wind speed can be computed obtaining results close to the experimental ones. On the other hand, multiple challenging questions keep open such as precise turbulence modeling, limitations in the models size, anticipation of the reliability of the computational results or difficulties solving fluid structure interaction problems, amongst others. Thus, this research field is an extremely dynamic one.

There are two specific design activities where CFD techniques can nowadays provide overall superior performance compared with conventional wind tunnel experiments. Those are: conceptual design of new long-span bridges proposals and also definition of preliminary tender projects for design and construction competitions of cable supported bridges.

A long-span bridge is an infrastructure which in many cases requires years to cover the distance between the first sketch and the opening ceremony (Gimsing 1993). Often, the first step in this long-distance race is a conceptual design of the structure, but the usual situation at that stage is the lack of financial resources to develop a wind tunnel experimental campaign of the proposal. During the conceptual design phase a number of alternatives are considered. Therefore, it is a key issue for the designers to have a clear idea about the alternatives' behavior in order to dismiss the inadequate ones to focus just on those designs which show adequate performance. The set of requirements to be fulfilled in bridge design is always long and in cable-supported bridges the aerodynamic and aeroelastic issues are for sure at the top of the list. In that respect, just the computational evaluation of the aerodynamic coefficients of the deck offers valuable qualitative information about the aerodynamic performance of the proposed design while the costs can be easily assumed.

In fact, an even more unfriendly wind design environment can be found in competitive turnkey conventional long-span bridges biddings. This is a process in which several independent companies or joint ventures are invited to bid on a contract. Typically, the key points in these competitions are the economical budget and the preliminary technical proposal for the bridge which would be fully defined by the applicant company in case of being awarded with the contract. Thus companies during a few months do their best in order to produce a technically solvent tender preliminary design compatible with moderate construction and maintenance costs. Of course, only one of the bidders would be awarded with the contract, therefore the investment made by each company in the project of the preliminary tender design cannot be high. Consequently, in many cases there are not available time and-or financial resources to carry out experimental wind tunnel tests. The lack of aerodynamic studies represents in first place a technical drawback in the competitive bidding for the company but also could drive to a difficult situation in case of being awarded with the contract and afterwards, in the detailed design stage, finding the necessity of introducing mayor changes in the design due to aerodynamic and-or aeroelastic issues which would give place to unexpected increments in the construction costs not included in the contract budget. Again, CFD can be the right solution as nowadays, in the absence of wind tunnel tests, it is capable of giving qualitative information about the overall aerodynamic performance of a deck cross-section. Additionally, the required time for obtaining results is generally shorter than wind tunnel testing, circumstance which allows for a quick introduction and evaluation of design modifications. Also the economical costs of performing average CFD analysis by means of commercial software are usually lower than the equivalent wind tunnel tests.

In the following sections a CFD application to the aerodynamic analysis of the deck of a 425 m main span cable-stayed bridge at the conceptual design stage is going to be presented.

## 2. Initial design proposal and analysis strategy

An international competitive bidding was called to design a new highway parallel to a pre-existing one with the aim of improving traffic conditions. The main technical difficulty of the overall project was the construction of a new bridge, parallel to an actual arch bridge, spanning a wide river.

Nowadays bridge design is not an individual person's duty. The amount and diversity of requirements to be considered is so long that a multidisciplinary team must be in charge of the design project. It has been mentioned in the previous point that the first task in the design process must be the definition of the bridge conceptual design. In fact, at that stage a number of alternatives have to be considered and studied by the designers. The authors have taken part in the conceptual design of the aforementioned bridge, taking the responsibility of the aerodynamic design of the deck.

The engineers responsible for the conceptual design made at an early stage a decision concerning a number of project requirements. The bridge typology should be a cable-stayed bridge with a span, between pylons, of 425 m and the cross-section should consist in an unsymmetrical $\pi$ deck cross-section made with two longitudinal steel wide flange members and transversal secondary girders standing for a concrete slab. Figs. 1 and 2 depict the proposed bridge layout and the initial deck design. From the designers' point of view the key factors to be addressed in the conceptual design phase were: a moderate execution budget, a short construction schedule and a solid technical justification of the proposed solution. However, the short available time to present the design documents in conjunction with the moderate budget to be dedicated to structural engineering issues made unaffordable any wind tunnel study of the deck at this stage.

Nevertheless, it is well know that $\pi$ cross-sections show an inappropriate aerodynamic behavior

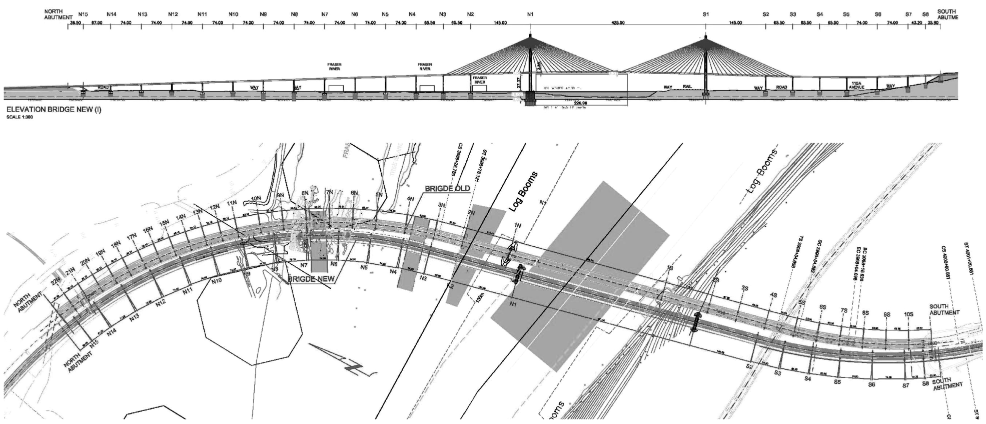


Fig. 1 Cable-stayed bridge elevation and plane views

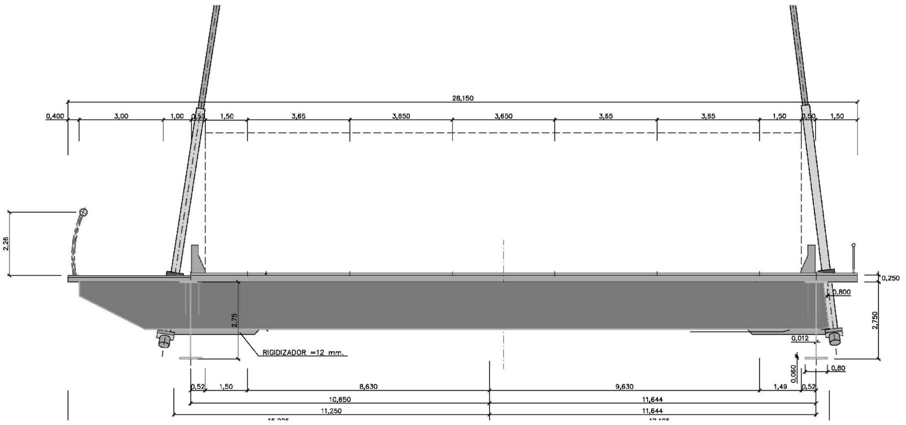


Fig. 2 Preliminary design deck cross-section

(Kubo *et al.* 2001) and also that already built cable-stayed bridges, as the 420 m central span Vasco da Gama Bridge (Mendes and Branco 1998, Branco *et al.* 2000) or the Kessock Bridge (Owen *et al.* 1996) were prone to wind instability problems and vortex shedding. Therefore, concerns could rise regarding the efficiency of the aerodynamic solution being initially considered.

The agreement between the project managers and the authors comprised in first place, the analysis of the initial design to assess its aerodynamic behaviour. Additionally, design modifications could be suggested in order to fulfil common aerodynamic design criteria. Nevertheless, any change in the design should be limited and scientifically justified as it would represent an increment in the construction budget. Due to the short time available for the presentation of the conceptual design, experimental wind tunnel tests were not taken into consideration due to the required time to build the models, thus a CFD approach focusing on the evaluation of the qualitative aerodynamic behaviour of the considered deck cross-section was chosen.

In order to speed up the analysis process, FLUENT by ANSYS was chosen as it is a standard general purpose commercial CFD software. With the aim of keeping computation times and costs bounded, 2D models were chosen as the focus was put on the overall behaviour instead of the detailed and precise evaluation of any particular magnitude.

The analysis strategy consisted in the evaluation of the aerodynamic coefficients of the cross-section assuming steady state condition. In fact, aerodynamic coefficients play a very significant role because to avoid one degree of freedom instability lift and moment coefficients first derivative must be positive according with the criteria of Fig. 3; additionally, the greater is the value of those derivatives the lower is the flutter critical wind speed of the structure (Larose and Livesey 1997, Diana *et al.* 2007).

Another crucial issue to be addressed in an initial study was the risk of vortex shedding excitation. The separated flow past bluff bodies is associated with periodic vortex shedding which is responsible for the fluctuation of pressure on the body surface (Lee and Bienkiewicz 1998). Typically, this phenomenon takes place at low reduced velocities and, although this kind of wind forcing usually does not cause instability by itself, it can interfere with other aeroelastic effects and be responsible for fatigue problems in the structure (Diana *et al.* 2006). Therefore, unsteady 2D CFD simulations were planned in order to detect the risk of vortex shedding for the initial design proposal. Again the focus has been put on detecting force fluctuations experienced by the

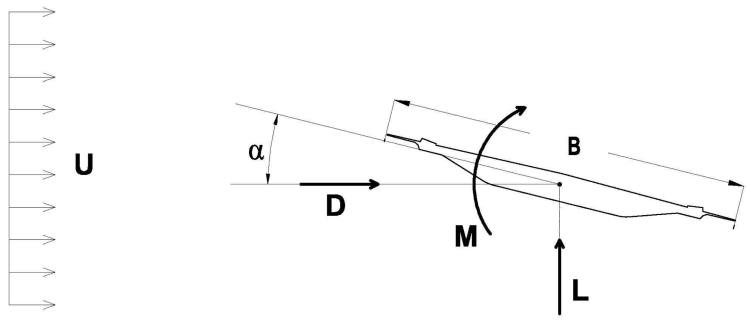


Fig. 3 Sign criteria for the aerodynamic coefficients

deck.

It has always been kept in mind that, in case of the final conceptual design being awarded with the contract to develop a formal construction project, extensive and comprehensive wind tunnel tests should be carried out to confirm the obtained CFD results but also address certain complex issues such as the effect of the parallel pre-existing arch bridge or the precise analysis of flutter and buffeting amongst others.

## 3. Flow modeling and computational approach

For both steady and unsteady simulations incompressible turbulent flow around the 2D analyzed sections has been modeled by the classical Navier-Stokes equations, along with the widely used two equations RANS (Reynolds Averaged Navier-Stokes) realizable $\kappa$-$\varepsilon$ model (Hasebe and Nomura 2009) with enhanced wall treatment. Dirichlet conditions have been imposed at inlet and outlet boundaries, moreover no-slip conditions have been imposed at the deck section surface. The turbulent characteristics of the flow have been defined in terms of intensity and length scale. Although $\kappa$-$\omega$ models according with some authors (Sun *et al.* 2005) perform more accurately for bridges, its bigger computational cost has suggested the use of the $\kappa$-$\varepsilon$ turbulence model in this study as the aim is the qualitative identification of the deck aerodynamic behavior. Moreover, it is well known that 3D models considering DES (Detached Eddy Simulation) or LES (Large Eddy Simulation) provide more accurate results than 2D or 3D unsteady RANS (Lübcke *et al.* 2001, Nishino *et al.* 2008). Again, the associated computational and time costs have suggested postponing the use of DES or LES turbulence models for a more advanced design stage.

The Finite Volume solver Fluent by ANSYS has been used to numerically evaluate the flow field. A quadrilateral mesh using the map scheme near walls and pave scheme in the main part of the flow domain has been employed. The total number of cells in the computational grids that are going to be presented is between 477126 for the initial design proposal and 599465 for one of the analyzed alternatives that will be presented later. Both steady and unsteady simulations have been carried out for a Reynolds number of 3.85E+5 considering the deck width of the initial design proposal as reference dimension. For the unsteady simulations the maximum non-dimensional time step chosen for advancement in time has been 0.0178, advancement in time is accomplished by a second-order implicit scheme and PISO algorithm is used for the pressure-velocity coupling. The unsteady simulations have been extended until a periodic behavior was reached.

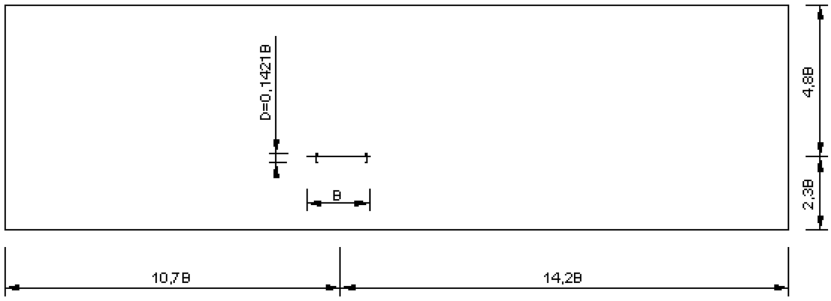


Fig. 4 Computational domain

Computations have been carried out on a cluster with 16 CPU's of 64 bits architecture and 64 GB of overall RAM memory.

## 4. Aerodynamic analysis of the initial design proposal

In the top left box of Fig. 5 the geometry of the deck cross-section computationally analyzed is depicted. It can be seen that the deck is formed by two wide flange section girders which support a concrete slab; additionally the two New Jersey type crash barriers have been modeled.

A distinctive characteristic of the cross-section is its asymmetry. In fact, a zone for pedestrians has been established on the left side of the deck (according with the top left box in Fig. 5), on the other hand, no pedestrian zone was established on the right side as there was no available space due to the pre-existing arch bridge which is located beside the bridge, at the right (according again with Fig. 5). No wind barriers have been considered at the tips of the cross-section as they were not designed at this stage of the project and the decision of the design team was to choose barriers as open as possible, thus with low effect on the flow. In the aerodynamic studies it has been assumed that the air flow was coming from the left to right (according with the top left image in Fig. 5) as that was the dominant direction for the wind according with the information supplied by the project managers and the current existence of a bridge at the right side of the projected bridge would have made unrealistic the analysis of undisturbed wind coming from the right side.

### *4.1 Aerodynamic coefficients*

The first step in the aerodynamic design verification has been the computational evaluation of the aerodynamic coefficients of the initial design deck by means of a 2D steady simulation. In Fig. 5 the aerodynamic coefficients are presented.

The analysis of the force coefficients presented in Fig. 5 makes clear the inadequacy of the initial aerodynamic design. Regarding the lift coefficient $C_l$, its negative slope between -6$^o$ and 2$^o$ shows the risk of one degree of freedom instability. Moreover, the negative slope of the moment coefficient $C_m$ from 4$^o$ to 8$^o$ denotes the possibility of one degree of freedom torsional instability. Additionally, another key characteristic of the deck cross-section is that the moment coefficient is positive along the interval of studied angles of attack (-8$^o$, 8$^o$).

With the aim of better understanding the aerodynamic behavior of the cross-section, the individual

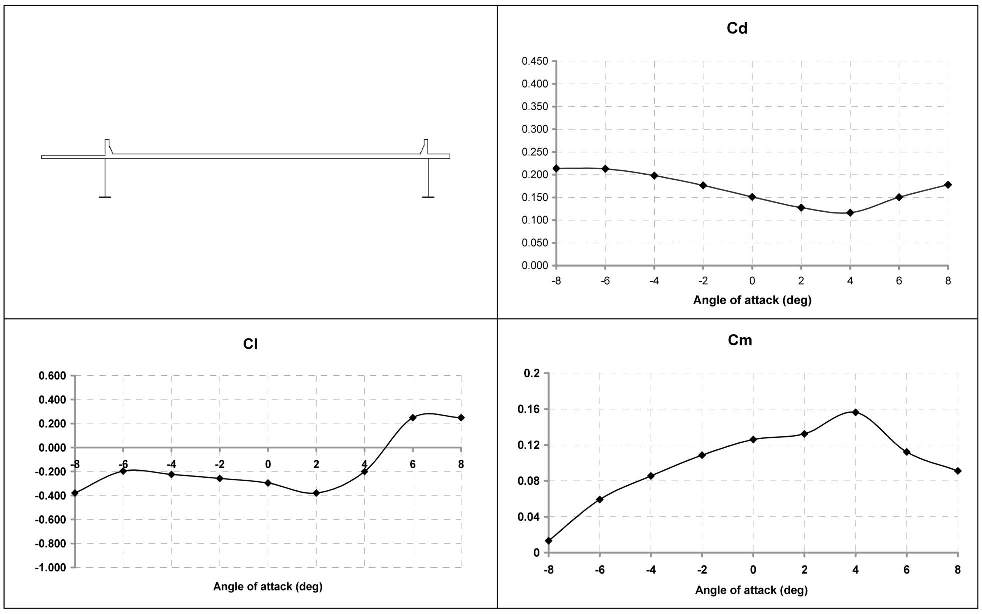


Fig. 5 Aerodynamic coefficients of the initial design proposal

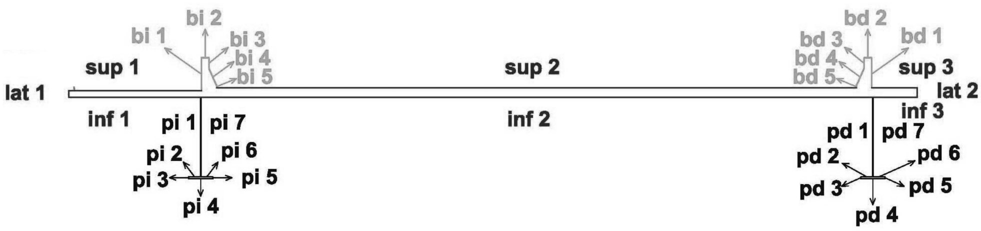


Fig. 6 Definition of individualized surfaces of the deck

contribution of the forces and moments acting on each surface of the deck has been analyzed. In Fig. 6 the name assigned for each surface is presented while in Figs. 7, 8 and 9 the obtained results are depicted. For the sake of clarity, the continuous black gross line represents the total drag, lift or moment acting on the deck while the gross dashed grey lines represent the main disaggregated forces and moments. On the other hand, the measurement of these magnitudes by means of wind tunnel tests would require non-standard equipments and specialized staff, therefore great costs in terms of both time and money.

From Fig. 7, it can be concluded that the forces acting on both faces of the wedge of the wide flange members are responsible for most of the overall deck behaviour concerning the drag force.

Some interesting conclusions can be driven from Fig. 8. The total lift force is due mainly to the forces acting on the central part of the concrete slab, although the force sign is different: negative lift force acting on the lower part of the concrete slab (surface inf2) but positive lift force on the upper part of the deck (surface sup2). Additionally, the force acting on the lower left part of the concrete slab (surface inf1) is nearly constant along the studied angle of attack interval. This fact is going to have a significant effect on the moment acting on the deck due to the important arm of this

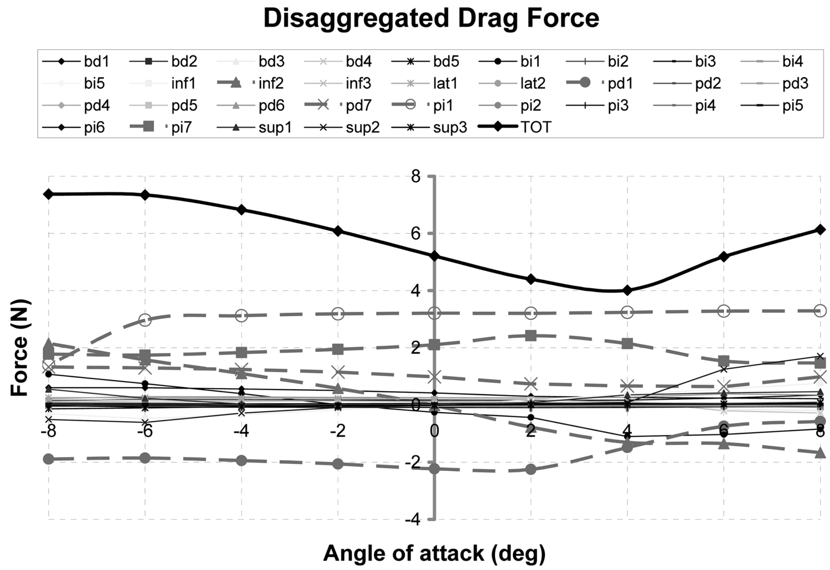


Fig. 7 Disaggregated drag forces on the initial design deck

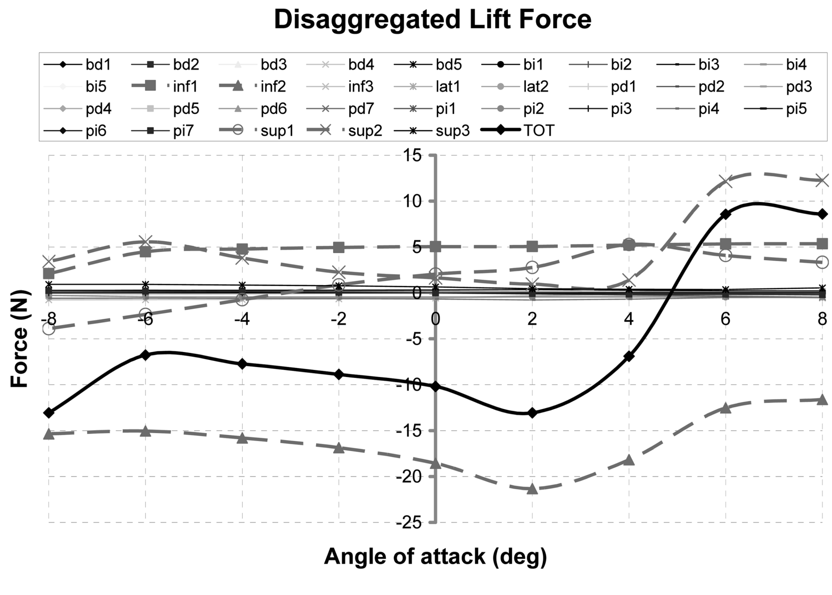


Fig. 8 Disaggregated lift forces on the initial design deck

force with regards to the centroid of the cross-section.

In Fig. 9, the disaggregated moments are perused. It can be seen how the total moment on the cross-section is caused mainly by the moment acting on the left upper part of the concrete slab (sup1) plus the nearly constant moment, for the studied angles of attack, caused by the lift force acting on the lower part of the left side of the slab (inf1). Thus, it is the left cantilever slab the one which controls the aerodynamic moment on the section. The moments caused by the pressure

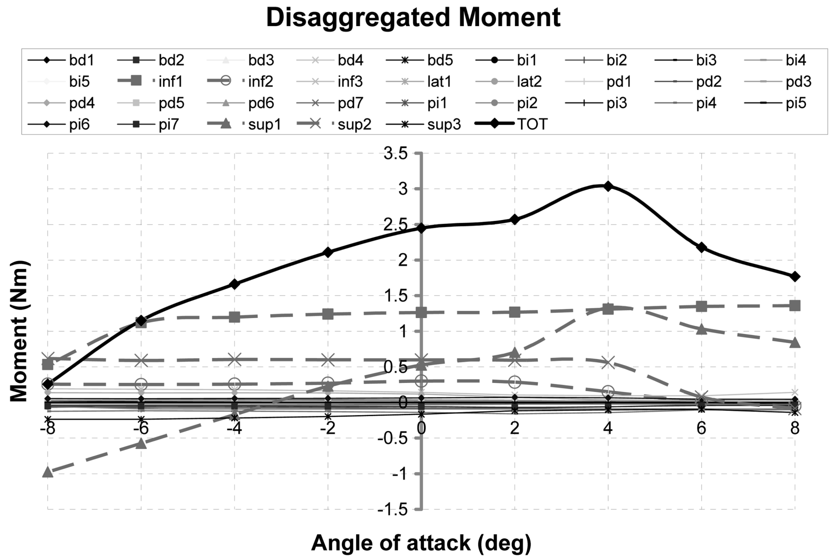


Fig. 9 Disaggregated moments on the initial design deck

distribution along the upper and lower central part of the concrete slab are not so important. Moreover, the contribution to the aerodynamic moment of the remaining surfaces is practically insignificant.

From the above information it can be concluded that the initial design proposal presents important drawbacks as lift and moment coefficients show negative slope intervals. Additionally, the asymmetrical configuration of the cross-section produces an aerodynamic behaviour greatly governed by the left long overhang slab, responsible for high values of the moment coefficient and the positive sign of this coefficient for the analyzed interval of angles of attack.

### *4.2 Vortex induced vibrations*

Another crucial concern regarding the aerodynamic behaviour of the proposed deck was the risk of vortex shedding excitation. In order to preliminarily assess this problem 2D unsteady simulations for velocities of 2 m/s, 4 m/s, 6 m/s, 8 m/s and 10 m/s have been carried out for a $0^o$ angle of attack. The focus has been put at this stage in the identification of a flow pattern corresponding with creation of vortices in the wake of the cross-section but also on the existence of periodic excitation acting on the deck. It has been put forward that vortex induced vibrations take place for wind speeds ranging from 4 m/s to 10 m/s while the cross-section shown a steady behaviour for 2 m/s wind speed. The Strouhal number associated to the oscillations of the lift force has been 0.11. The deck concrete slab provides significant structural damping, however at this design stage relying only on that structural property does not guarantee the efficient mitigation of vortex induced vibrations. In Fig. 10, the oscillations obtained for the lift coefficient under a wind flow of 10 m/s are shown. It can be seen the importance of the magnitude in the oscillations of the lift force. In Fig. 11, the instantaneous vorticity magnitude field is presented for values in the interval (-50, 50). Vortices are alternatively shed in the wake of the deck which denotes the risk of vortex shedding excitation.

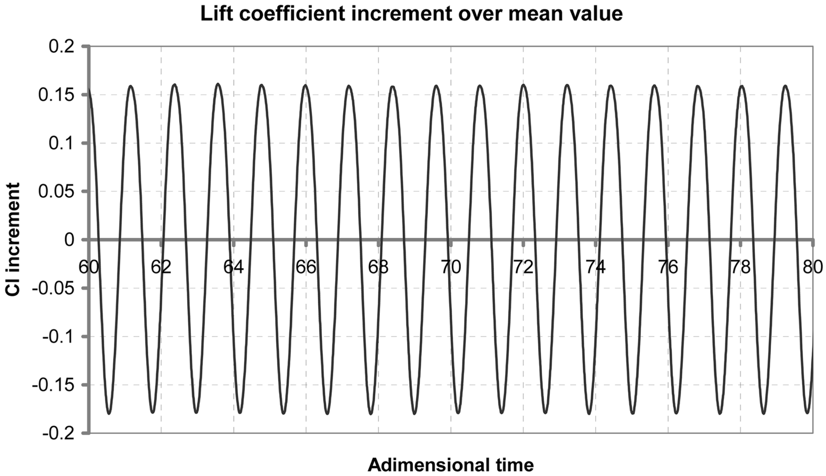


Fig. 10 Oscillations of the lift coefficient as a function of the adimensional time

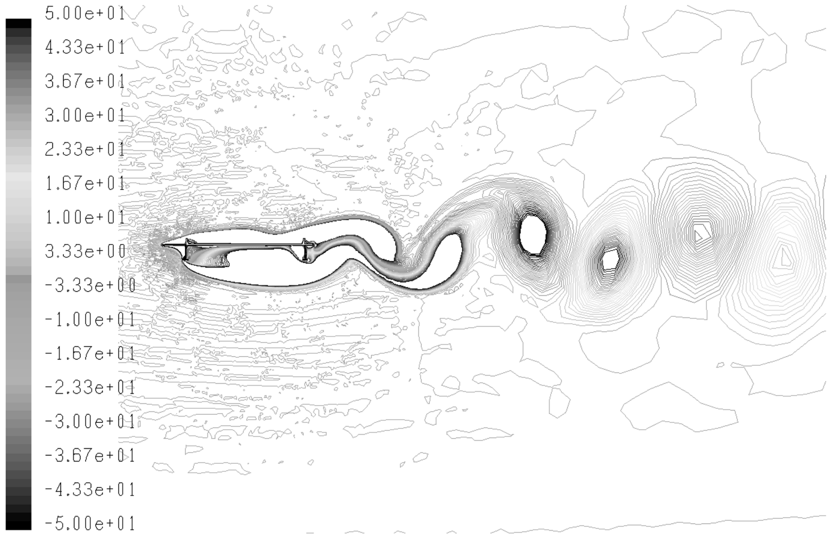


Fig. 11 Contours of instantaneous vorticity magnitude for adimensional time of 106.6

## 5. Modifications of the initial design proposal

From the results shown in the last section it has been concluded the unfeasibility of the deck cross-section initial design. Therefore, several changes in that initial proposal were considered in order to improve the aerodynamic performance while limiting the extent of the design modifications to avoid major changes in the project. Two were the tentative strategies: in first place the addition of a porous wind barrier at the tip of the left overhang which would act as a shelter for pedestrians and vehicles but also would change the flow pattern around the deck; in second place, due to the lack of symmetry of the deck, the windward overhang was responsible for the aerodynamic characteristics of the cross-section, thus several symmetric configurations were tested.

### *5.1 Initial design proposal + wind barrier*

A wind barrier located at the tip of the long left overhang with the geometry of Fig. 2 was considered. The characteristic values such as face permeability or pressure-jump coefficient were taken from previous cases studied by the authors. In Fig. 12, the aerodynamic coefficients obtained numerically for this modified cross-section are presented. The effect of the wind barrier is important. In fact, the drag coefficient is very high and nearly constant along the analyzed interval of angles of attack. Moreover, the change in the lift coefficient is dramatic as it changes its sign for angles of attack of -4$^o$, -2$^o$, 0$^o$, 6 and 8$^o$ compared with the initial design proposal. Finally, moment coefficient is nearly constant from -4$^o$ to 8$^o$ and its value is lower form -4$^o$ to 6$^o$.

From the aerodynamic coefficients it is clear the unfeasible performance of the cross-section due to the negative slope presented by the lift coefficient from -2$^o$ to 4$^o$. Additionally moment coefficient also shows negative slope from 0$^o$ to 8$^o$ angle of attack. Finally, an unsteady simulation was not carried out as the aerodynamic coefficients showed an inadequate aerodynamic behaviour.

### *5.2 Symmetric configurations*

The analysis of symmetric configurations has had mainly an academic interest as they would not satisfy functional requirements as pedestrian lanes or available space for stay anchorage to the deck. Additionally, the geometry of the New Jersey type crash barrier has been simplified in these draft designs. Two have been the symmetric configurations considered: deck with short overhangs (the length of the lateral overhangs is equal to the length of the right short overhang in the initial design proposal) and deck without overhangs. In Figs. 13 and 14, the aerodynamic coefficients obtained for both configurations are depicted.

Again, the aeroelastic performance of the cross-section in Fig. 13 can be anticipated as poor due

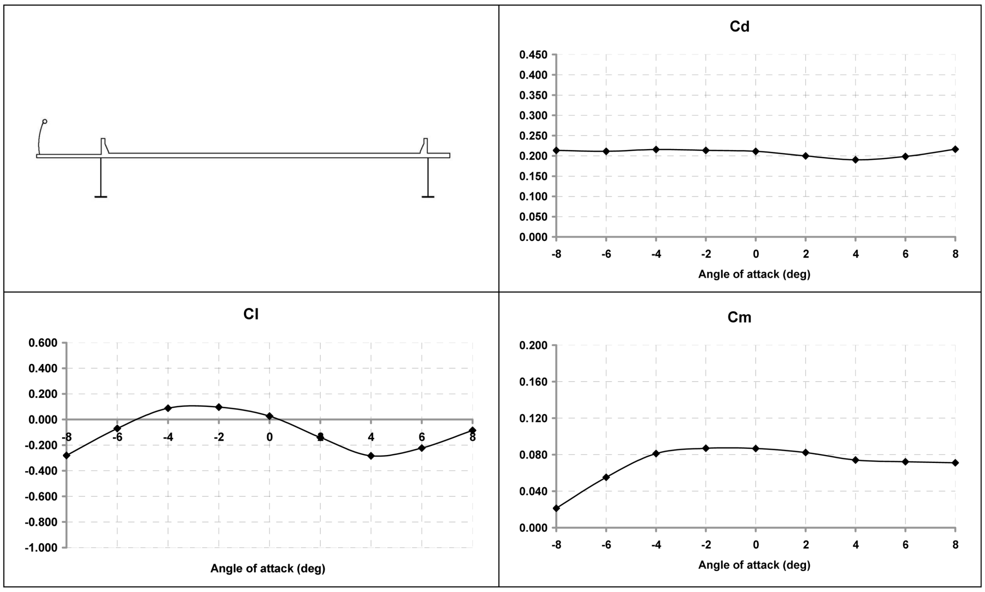


Fig. 12 Aerodynamic coefficients of the initial design proposal + wind barrier

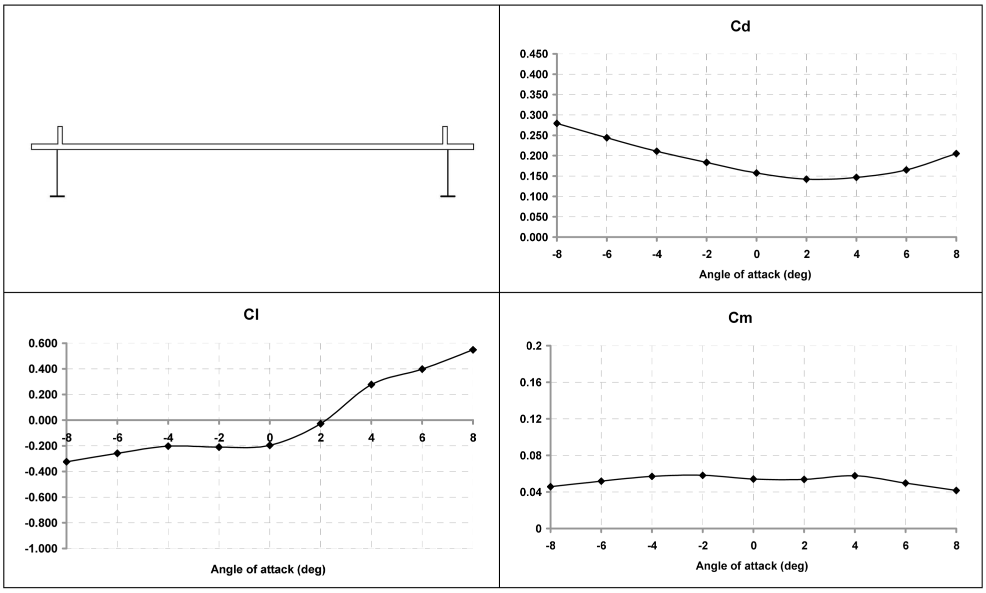


Fig. 13 Aerodynamic coefficients of the symmetric configuration with short overhangs

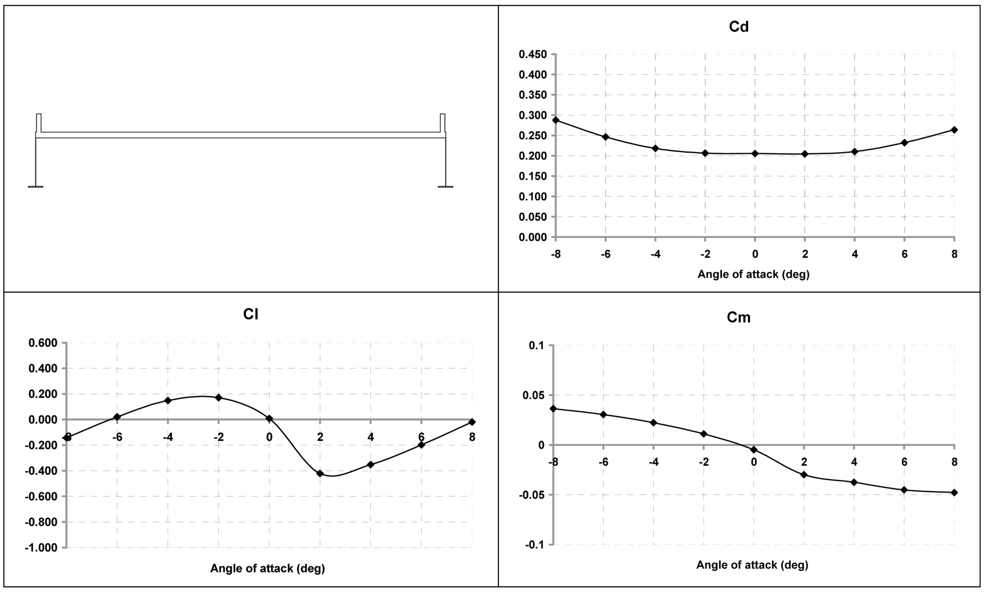


Fig. 14 Aerodynamic coefficients of the symmetric configuration without overhangs

to the negative slope in the moment coefficient form -2º to 2º and from 4º to 8º. Additionally, the lift coefficient also shows a slightly negative slope from -4º to -2º. Taking into account these results vortex shedding risk has not been analyzed for this configuration.

The aerodynamic coefficients of the previous charts (Fig. 14) show a clear potential instable behaviour. As a matter of fact, the step negative slope of the lift coefficient from -2º to 2º plus the negative slope of the moment coefficient for the whole range of considered angles of attack make clear the risk of one degree of freedom aeroelastic instability. This result is not surprising as the geometry of the analyzed deck cross-section is very close to the old Tacoma Narrows Bridge cross-section whose collapse is very well known by the engineering community. Nevertheless, this result gives another hint of the feasibility of the CFD approach employed in this research. Again, for a cross-section with such aerodynamic characteristics it is not worthy to devote resources to the vortex shedding issue as its appearance is almost certain.

Bearing in mind the results presented in this section it is clear that a significant improvement in the aerodynamic characteristics of the deck cannot be reached by means of adding a wind barrier to the initial design proposal neither adopting a symmetric configuration. A dramatic change in the wind separation and flowing around the cross-section has to be obtained and that should be achieved modifying the deck configuration by means of fairings and/or other aerodynamic devices such as baffles (Dunn and Irwin 2004).

## 6. Effect of fairings and baffles added to the initial design proposal

### *6.1 Initial design proposal + fairings*

The analyzed configuration has been the initial design proposal with fairings covering the space between the overhangs and the wide flange members as shown in the top left box of Fig. 15. In this way the strong static pressure acting on the lower part of the left overhang and the web of the left steel girder should be avoided.

The modifications introduced in the external shape of the cross-section have had dramatic consequences in the aerodynamic coefficients (see Fig. 15). It can be noted the important reduction

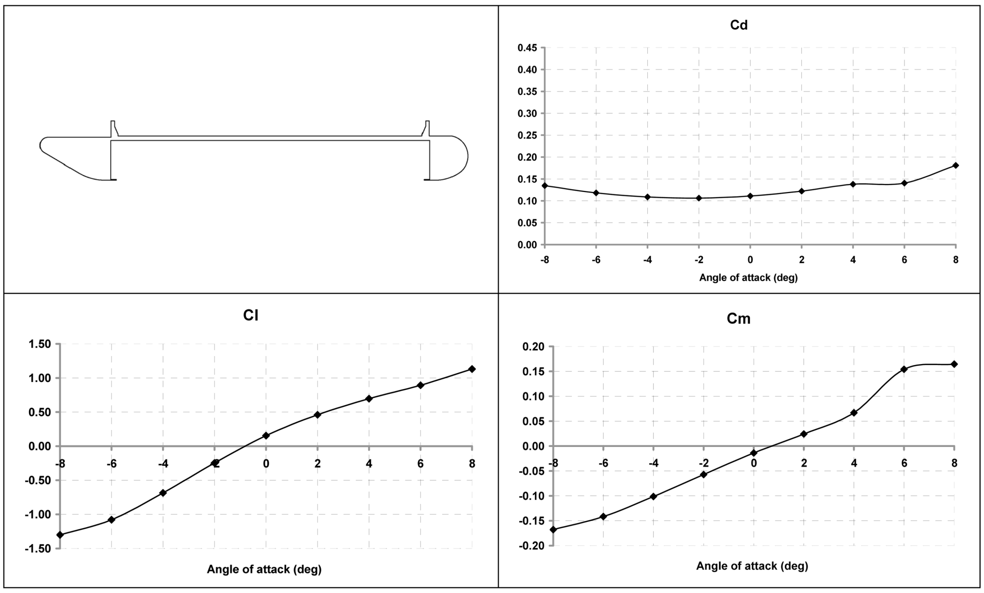


Fig. 15 Aerodynamic coefficients of the initial design proposal + fairings

in the values of the drag coefficient, as well as the improvement in the lift and moment coefficients whose slopes are positive. Thus, it can be concluded that the expected aeroelastic behaviour should be more efficient thanks to these changes introduced in the design.

The second step in the design process has been the verification of the vortex-induced motions risk. Again unsteady simulations considering this new configuration have been carried out for a set of wind speeds ranging from 2 m/s to 10 m/s. In Fig. 16, the evolution of the aerodynamic coefficients for 0º angle of attack as a function of the adimensional time is presented for flow speed of 10 m/s. It can be seen how the aerodynamic coefficients do not show oscillatory behaviour and their values are constant from 20 adimensional time. For all the analyzed flow speeds a non-oscillatory behaviour has been found.

Additionally in Fig. 17 the instantaneous vorticity field for values lower than 50 is shown under

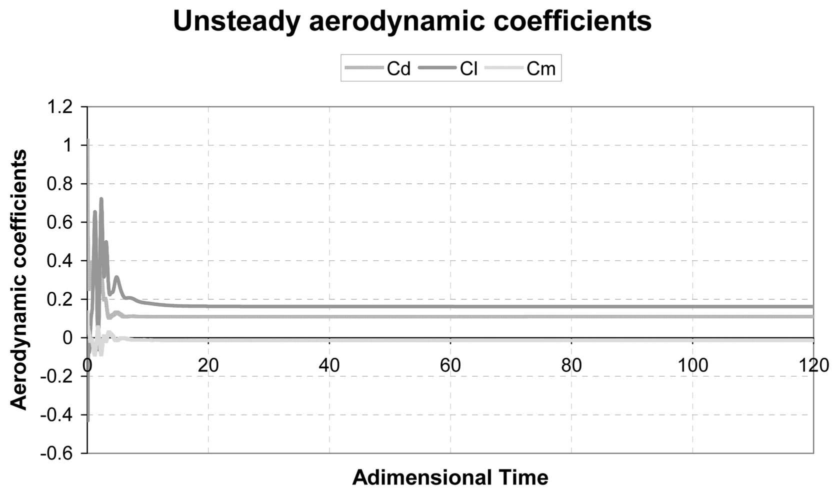


Fig. 16 Unsteady aerodynamic coefficients of the initial design proposal + fairings

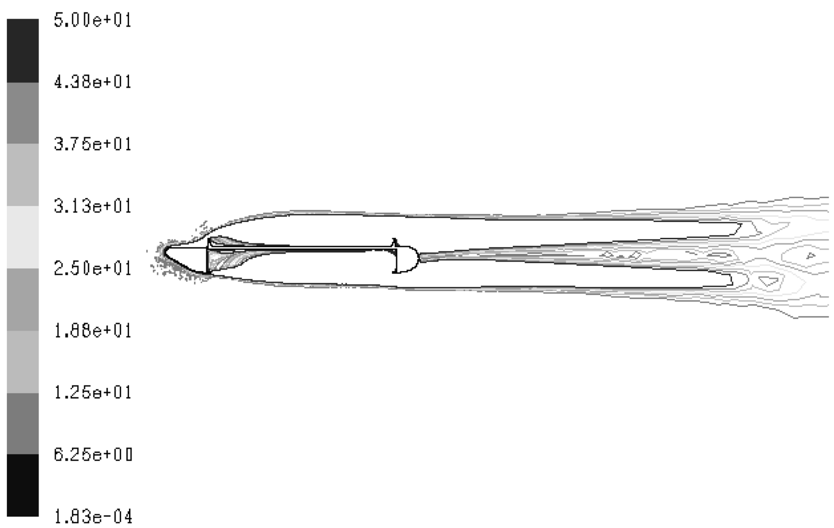


Fig. 17 Contours of instantaneous vorticity magnitude for adimensional time of 175.8. Initial design proposal + fairings

10 m/s air velocity. No vortex shedding presence has been detected.

However, the high value of the slope of the lift coefficient has made the authors think that there was room for further improvement in the aerodynamics of the cross-section. In fact a lower slope would represent a higher flutter speed, that is, a safer bridge. Thus, new configurations adding baffles have been studied.

### *6.2 Initial design proposal + fairings + baffles*

Two have been the analyzed configurations: firstly two rows of baffles at a third of the chord length location and finally baffles at a quarter of the chord length location. The results obtained for the aerodynamic coefficients have been very close, thus the latter configuration has been selected as the most feasible design as the slopes of the aerodynamic coefficients were slightly flatter than the former. In Fig. 18, the charts of the aerodynamic coefficients for the initial design proposal + fairings + two rows of baffles at a quarter of the chord location are presented.

This configuration offers superior aerodynamic performance as values for drag coefficient are lower than for the configuration without baffles and additionally the slope of the lift coefficient has decreased.

Regarding vortex shedding risk, unsteady simulations of this modified configuration for $0^o$ angle of attack has been carried out considering flow velocities ranging again from 2 m/s to 10 m/s. In Fig. 19, the evolution of the aerodynamic coefficients as a function of the adimensional time is presented for a 10 m/s speed. In Fig. 20, the vorticity field for values lower than 50 can also be perused. As in the latest case, no oscillation in forces has happened while no vortices has been detected in the flow pattern for any of the analyzed wind speeds.

Based upon the CFD analysis carried out, in the proposed conceptual design of the bridge fairings and two rows of baffles at a quarter of the chord location have been added to the initial design of

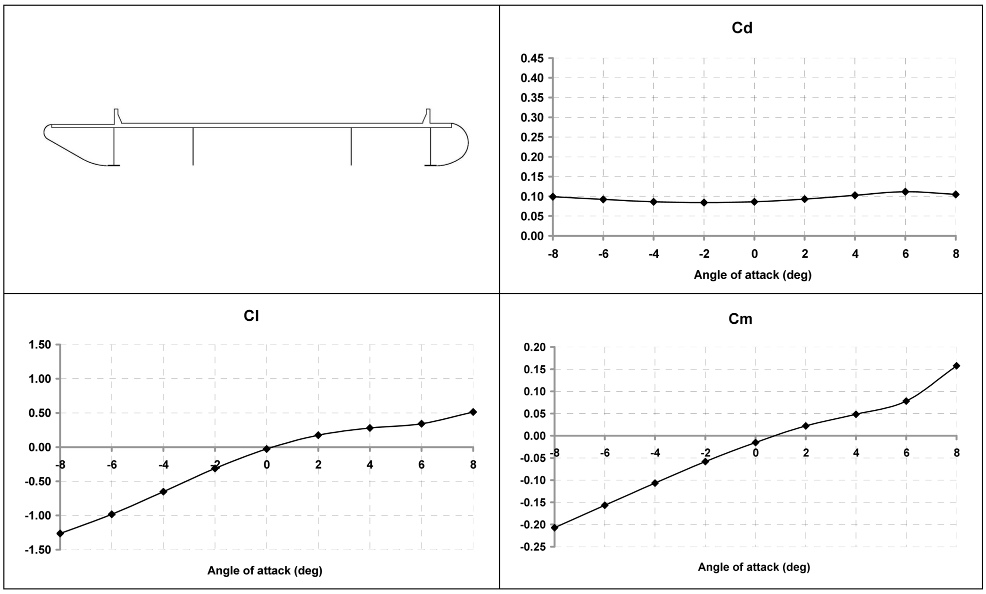


Fig. 18 Aerodynamic coefficients of the initial design proposal + fairings + baffles at quarter chord

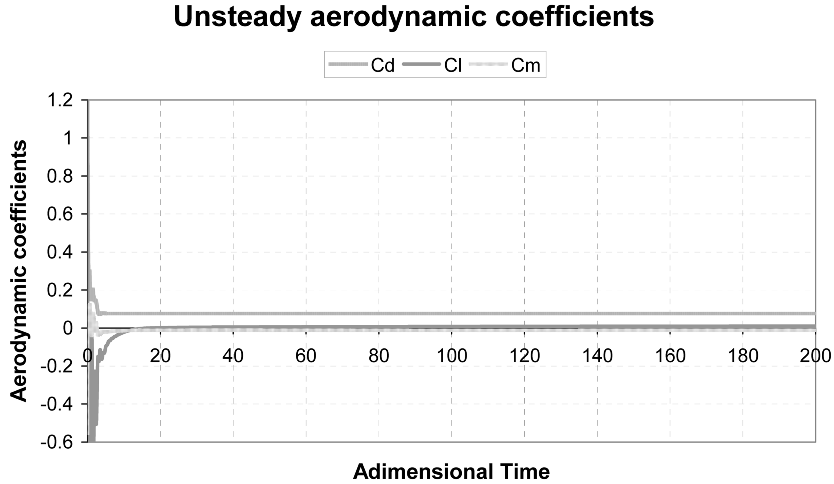


Fig. 19 Unsteady aerodynamic coefficients of the initial design proposal + fairings + baffles at quarter chord

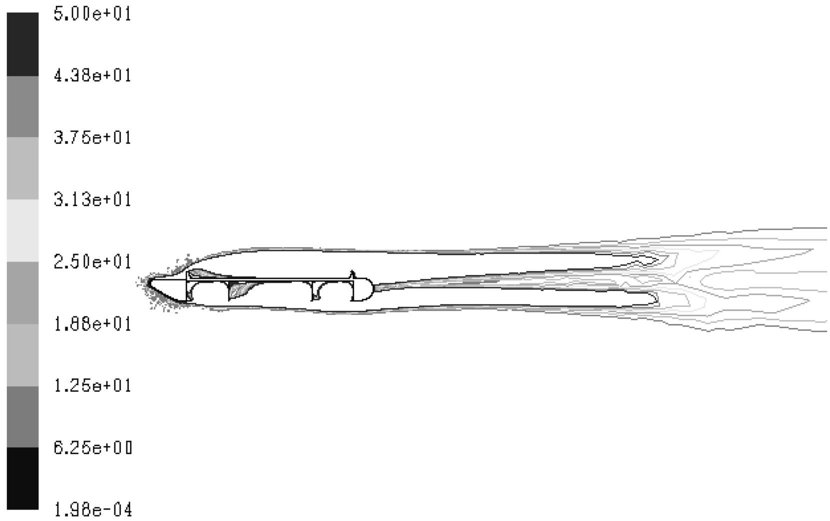


Fig. 20 Contours of instantaneous vorticity magnitude for adimensional time of 175.8. Initial design proposal + fairings + baffles at quarter chord

the deck cross-section. This would produce an important improvement in the aerodynamic and aeroelastic characteristics of the deck.

## 7. Conclusions

In the first place, brief review of the literature concerning CFD applications in bridges has been presented. It has been underlined the potential of CFD techniques in the conceptual design of long span bridges as well as in aerodynamic studies for competitive biddings. Nevertheless it has also been pointed out that extensive wind tunnel campaigns are nowadays mandatory to guarantee the safe and adequate performance against wind actions of this kind of structures.

Using a CFD package the aerodynamic coefficients of a number of deck cross-sections have been obtained assuming steady state. These results have been the main source of information in order to judge the aerodynamic and aeroelastic feasibility of the considered deck designs. Moreover, for certain designs, the cross-section vortex induced vibration sensitivity has been analyzed by means of 2D unsteady simulations for $0^o$ angle of attack considering flow speed ranging from 2 m/s to 10 m/s.

Along the analysis process the focus has always been put on the qualitative results offered by the numerical simulations. Thus, information such as the slope of the aerodynamic coefficients or the identification of periodic oscillations in the unsteady aerodynamic coefficients has been the valuable one.

Improvement in the aerodynamic design of the cross-section has been achieved based upon objective technical criteria which was the core goal of this research work.

The wind tunnel campaign to develop for the detailed project will address the uncertainties that have not been studied in this preliminary study but also it would provide an unplayable feedback to check the accuracy of the obtained numerical results.

A wide room is open for CFD techniques in the design of wind prone structures such as cable-supported bridges. Further developments in currently breakthrough studies like the determination of flutter derivatives or the generalization of 3D models to study the three-dimensional nature of vortex shedding would represent mayor steps towards numerically based wind design of bridges.

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