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# Innovative configurations for long-span suspension bridges

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## ABSTRACT

This paper reports the results of a piece of research about long-span suspension bridges with multiple-box girder steel deck characterized by low drag coefficient and high aeroelastic stability. For this type of bridges, by increasing the span length, the contribution to the stiffness of the suspension cables becomes dominant with respect to that of the deck, so that the ratio of the frequency of the first torsional mode to the frequency of the first vertical bending mode approaches unity, while they both decrease. As a consequence, if the deck cross-section geometry does not allow single-degree-of-freedom torsional flutter, one would observe the onset of two-degree-of-freedom classical flutter at a relatively low wind speed, depending on the dynamic and aerodynamic properties of the structure. The research presented herein, proposes an innovative approach to the design of long-span suspension bridges by studying deck configurations with frequency ratios of first torsional to vertical bending modes susceptible to couple lower than unity. The aim is to investigate, on the one hand, the possibility to obtain a total inhibition of the classical flutter instability mechanism in the wind speed range of interest and, on the other, the potentiality of such a design to allow significant savings in the costs of construction, which is an aspect of primary importance for this type of structures.

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## 1. INTRODUCTION

This paper reports the results of a piece of research about long-span road suspension bridges with steel deck, composed by longitudinal beams supporting the roadway and transversal beams connected to the hangers. Classical multiple-box girder decks, whose roadway is placed mainly internally with respect to the main suspension cables, are characterized by low drag coefficient and high aeroelastic stability. Therefore they represent a good solution for long-span suspension bridges. The most outstanding example is the design studied for the crossing of Messina Strait, Italy (Brancaleoni & Diana, 1993; Diana et al., 1995; D'Asdia & Sepe, 1998). For this type of bridge configurations by increasing the span length the contribution to the stiffness of the suspension cables becomes dominant with respect to that of the deck, so that the ratio of the frequency of the first torsional mode to the frequency of the first vertical bending mode approaches unity (for example 1.3 if the mass distribution is constant over the deck width, as shown in Bartoli et al., 2006b), while they both decrease. As a consequence, if the cross-section geometry does not allow single-degree-of-freedom torsional flutter, one would observe the onset of two-degree-of-freedom classical flutter at a relatively low wind speed, depending on the dynamic and aerodynamic properties of the structure (e.g. Simiu & Scanlan, 1996; Dyrbye & Hansen, 1997). In this case, to increase the frequency separation by means of particular structural solutions, such as crossed hangers (Bartoli et al., 2006b; Febo, 2007), can be effective up to large span lengths but it requires an ever improved aerodynamic performance of the deck and therefore a higher cost of the structure.

The ongoing research presented herein, limiting so far to road bridges only, proposes an innovative approach to the design of long-span suspension bridges by studying decks with frequency ratios of first torsional to vertical bending modes susceptible to couple lower than unity (Febo, 2007; Bartoli et al., 2007; D'Asdia & Febo, 2007). As a matter of fact, it is known that a two-degree-of-freedom linear oscillator with frequency ratio lower than one cannot undergo classical flutter instability (Dyrbye & Hansen, 1997; Bartoli et al., 2008). The main purpose of this paper is to investigate the potentiality of such a design to allow significant savings in the costs of construction, which is an aspect of primary importance for this type of structures.

In a first phase, starting from Messina Strait Bridge design and keeping unchanged the main span length (3300 m), the approaching span lengths (960 m on the Sicilian coast and 810 m on the Calabrian coast), the main suspension cable sag (300 m) and the height of the towers (about 380 m), twin-box girder decks with spacing between the main cables of 26 m (Figure 1), 39 m (Figure 2) and 52 m (Figure 3) have been taken into account (Bartoli et al., 2008). In the first case the transversal width is the same as in the reference bridge, whereas in the second and third cases it is increased in order to reduce the torsional rotations due to particularly unfavorable traffic load configurations (for instance, keeping unchanged the diameter of the suspension cables, the second deck presents torsional rotations equal to one half of those of the first deck).

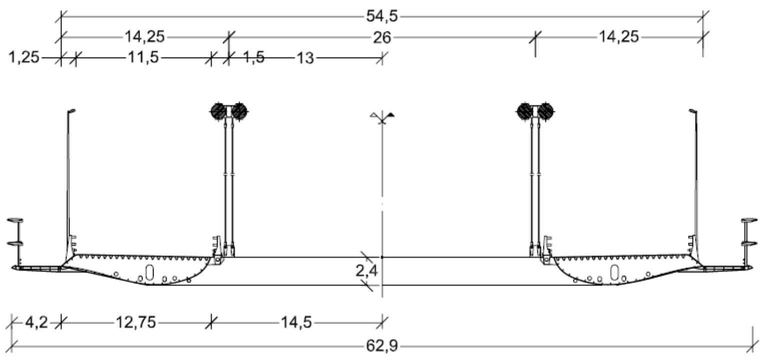


Figure 1: Cross-section of the deck with main suspension cables spaced 26 m apart.

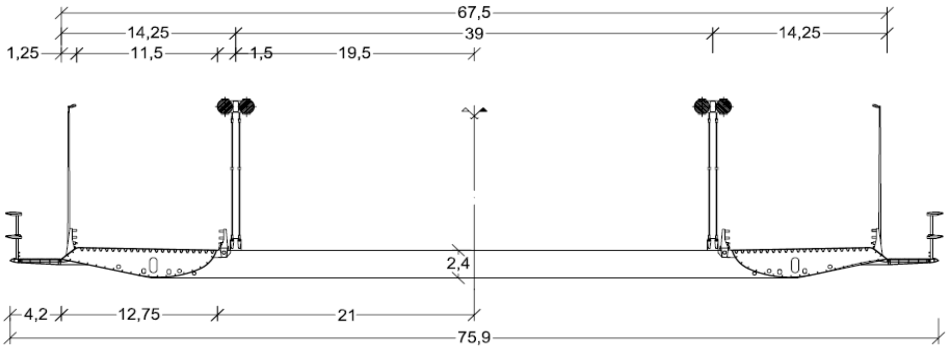


Figure 2: Cross-section of the deck with main suspension cables spaced 39 m apart.

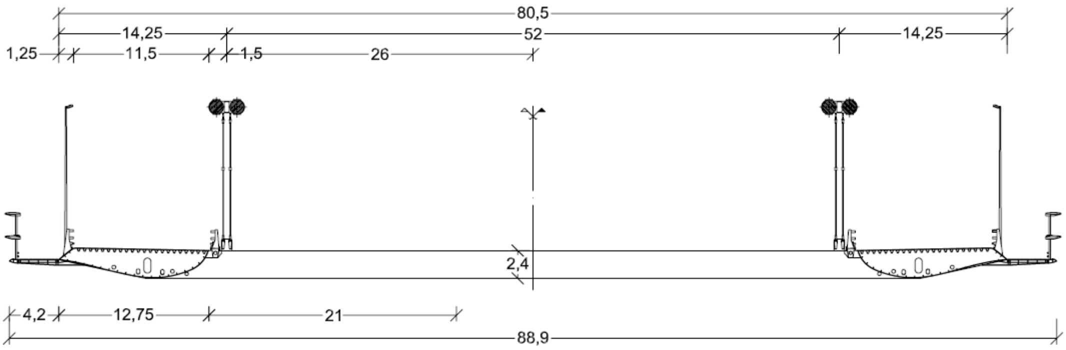


Figure 3: Cross-section of the deck with main suspension cables spaced 52 m apart.

It is also worth noting that the bending moment and the shear stress in the transversal beams is practically the same in the three cases and therefore their weight (and cost) increases only linearly with the spacing between the suspension cables, so that the difference in the total weight of the three decks is negligible. Obviously the new deck configurations have implied a modified design of the towers and suspension cables as well, according to the performance requirements of the 1992-original design of Messina Strait Bridge.

In addition, given the key role played by the aerodynamic and aeroelastic load in the design of this type of decks, a wind-tunnel test campaign has been performed in the CRIACIV laboratory in order to study the sensitivity of the structural response to the wind action. Static and aeroelastic tests have been performed on section models scaled of about 1:100 (Bartoli et al., 2008). Both the experimental investigation and the numerical aeroelastic simulations on a complete finite-element model of the bridge based on the aerodynamic coefficients measured in the wind tunnel confirmed that for the aforementioned bridge structures the lower modes of vibration cannot couple and therefore cannot give rise to classical flutter instability. However, the use of boxes similar to those of the design of the deck of Messina Strait Bridge, which require sophisticated metallic carpentries, leads to design of structures that are more expensive than those obtainable in a “traditional” way, at least for spans up to 3300 m.

In order to understand whether this type of deck with inverted frequencies can be economically advantageous for span lengths of the order of Messina Strait Bridge or lower, it is necessary to verify if the relaxation of the aerodynamic constraints on the longitudinal beams can allow a cost reduction by means of the use of solutions much simpler from the constructional point of view.

As a matter of fact in the structures with frequency ratios lower than unity the aerodynamic optimization of the deck is supposed to be much less enhanced, since only a reduction of the static (in particular the drag and moment coefficients) and dynamic wind loads due to buffeting and vortex shedding is required and not a substantial increment of the flutter critical wind speed.

In order to estimate the possible cost reduction with respect to aerodynamically more sophisticated solutions (such as the one of Messina Strait Bridge), some simple typologies have been taken into account, such as truss girders or steel boxes as transversal beams and orthotropic slabs supported by steel beams or steel boxes for the roadway. Each deck configuration has been pre-designed for various values of the longitudinal spacing between the hangers (in a range between 20 and 30 m). In these cases the minimal required aerodynamic performance can be guaranteed through more or less simple non-structural aerodynamic appendices and in particular fairings (e.g. De Miranda & Bartoli, 2001).

During this research campaign an analytical-experimental approach has been followed. Assuming reasonable values of the aerodynamic coefficients for the different deck solutions, pre-designs of the bridge have been obtained with a suspension scheme able to guarantee the inversion of the first pairs of modal frequencies (i.e. the torsional frequencies are lower than the corresponding vertical bending frequencies). Then the designs have been refined in order to limit the torsional rotations due to traffic loads.

The results obtained for one of those simplified deck configurations are summarized in the paper and seem to lead to the conclusion that the proposed solution is feasible and can imply a significant reduction of costs of deck construction, due to much more sophisticated metallic carpentries designed for Messina Bridge.

## 2. FEASIBILITY STUDY

Starting from the encouraging preliminary results obtained for the modified configurations of Messina bridge (Figures 1, 2 and 3), some simple deck configurations have been taken into account, in order to obtain the inversion of the first couples of modal frequencies and with respect to the original design criteria. The main span (3300 m), the side spans (960 m and 810 m), the maximum sag of the suspension cables (300 m) and the tower height (around 380 m) have not been changed, while the deck geometry, the distance between the main cables and the shape of the towers have been varied in order to obtain different bridge configurations. The deck configuration with the roadways supported by an orthotropic steel slab and four steel beams with double T section and with steel boxes as transversal beams is one of the investigated solutions (Figure 4). For this structural solution the distance between the main cables is 40 m and the steel mechanical characteristics of different structural elements of the deck are the same as for the original Messina Strait Bridge, in order to obtain realistic proposals of suspension bridges, in terms of design criteria.

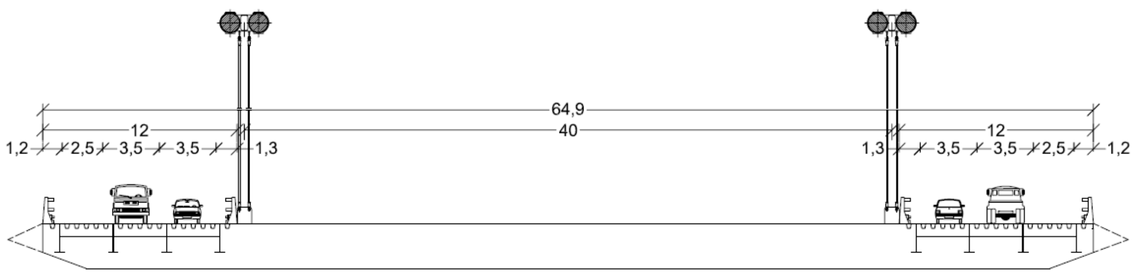


Figure 4: Cross-section (AA) of the simplified deck with main suspension cables spaced 40 m apart.

The geometric characteristics of the structural elements have been defined taking into account both the local and the global static response of the bridge under dead loads and different operating load conditions. In particular, once defined the number of lanes, the total amount of traffic loads and their position and referring to asymmetric traffic actions in serviceability limit state, the dimension of transversal boxes has been defined locally, accepting simultaneously a transversal slope just over 1%

and operating stresses well below the yield strength.

The longitudinal structures which support the roadways, have been stiffened with L-section steel elements, introduced to connect the main double T-section beams (Figure 5), according to the plan scheme showed in Figure 6.

The geometric and mechanical characteristics of the towers, cables and hangers have been evaluated taking into account the actual new permanent loads and mass distributions.

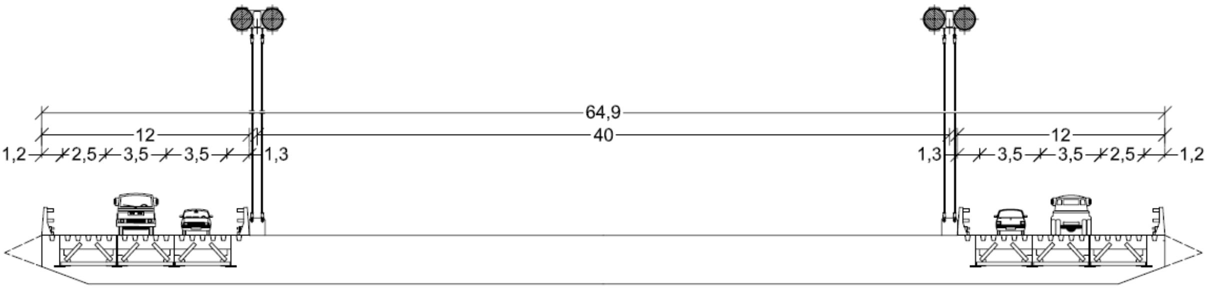


Figure 5: Cross-section (BB) of the simplified deck with main suspension cables spaced 40 m apart.

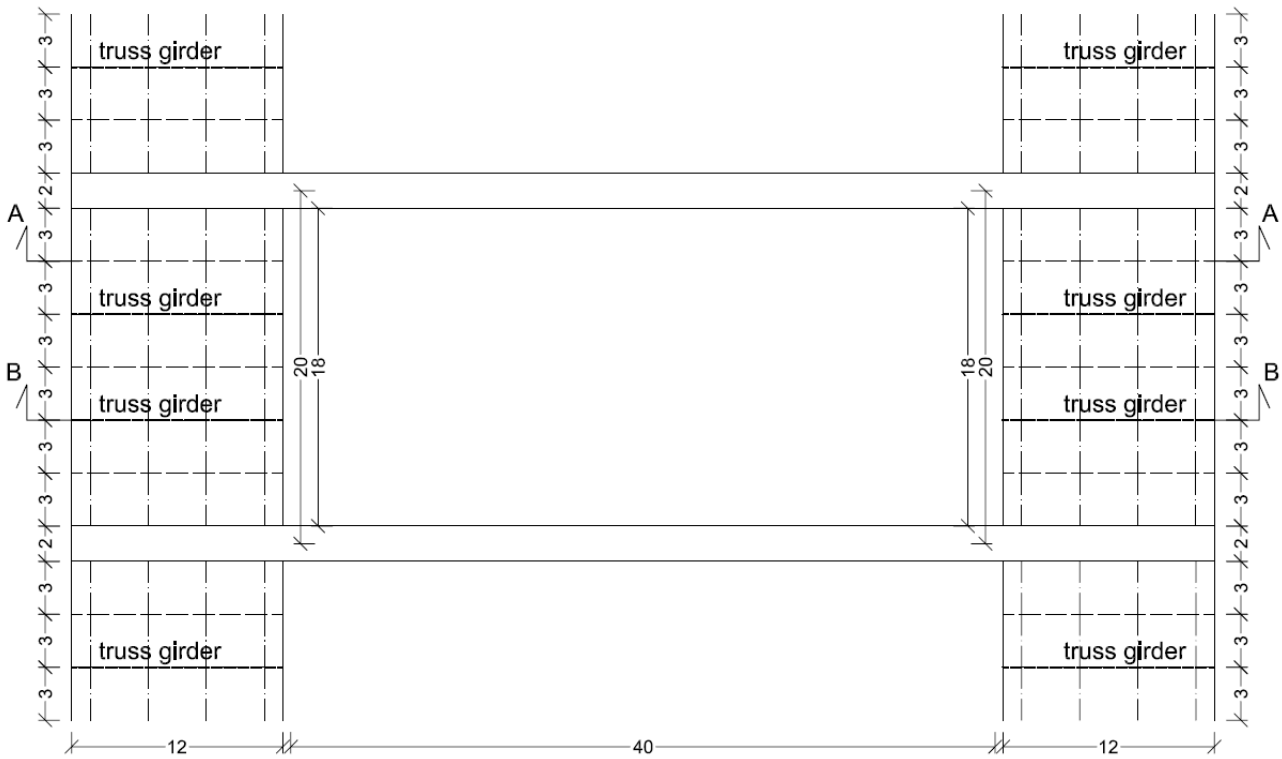


Figure 6: Plain of the simplified deck with main suspension cables spaced 40 m apart.

## 3. MODAL ANALISYS RESULTS

In order to evaluate the frequency ratio between vertical and torsional modes of the suspension bridge with the geometrical characteristics described in the previous section, finite element numerical models of deck sections and global structures have been set up. In particular, the global model consists of 1670 joints, 884 cable elements and 1360 frame elements.

Both numerical section model and global model results show that the examined configuration could be an effective solution to design long-span suspension bridges with frequency ratios lower than one. In particular, referring to numerical global model results (Figures 7-8 and Table 1), even if the 1st torsional-to-1st bending frequency ratio is about one in still air, the attainment of the aim against flutter instability is substantially obtained. In fact, under wind the mode frequencies tend to further separate instead of coupling (the torsional frequency tends to reduce and, at the same time, the vertical bending frequency tends to increase), thus not giving rise to classical flutter (Bartoli et al. 2008). The achievement of the aim against flutter instability is confirmed by the 2nd torsional-to-2nd bending frequency ratio, that is smaller than one too.

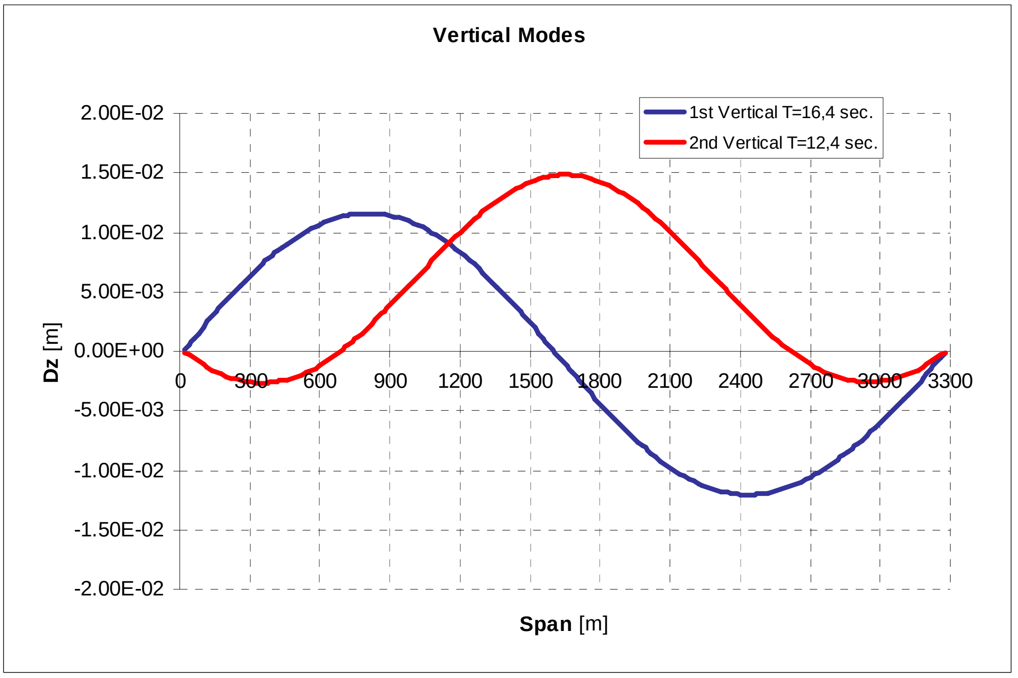


Figure 7: Shape of the first two vertical modes

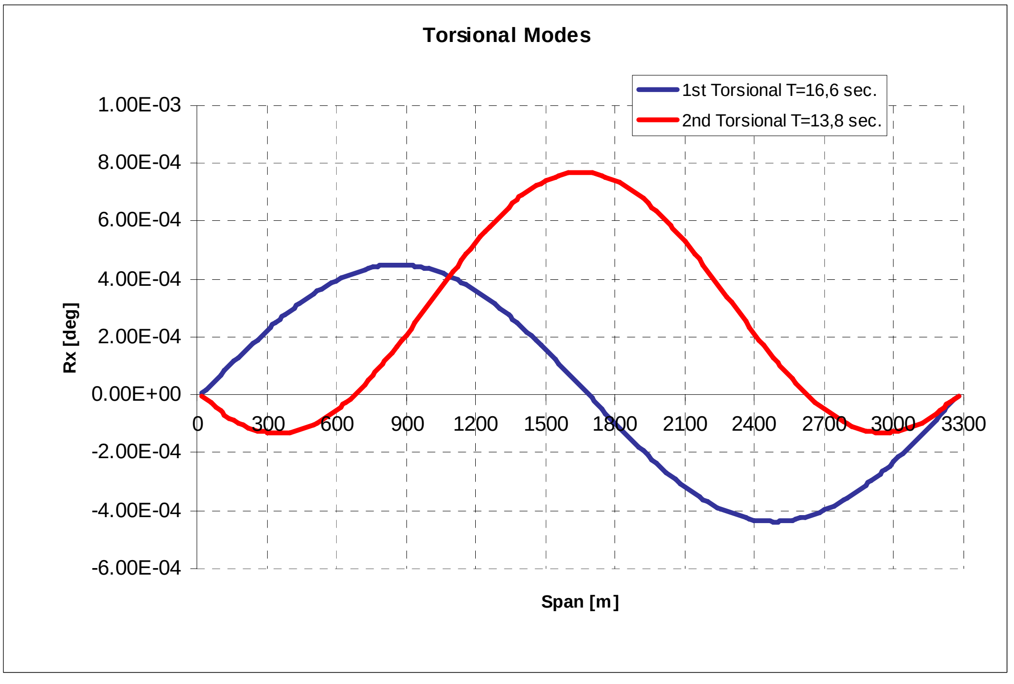


Figure 8: Shape of the first two torsional modes

| Mode shape | $f$ [Hz] |
|---|---|
| $1^{st}$ torsional | 0.0602 |
| $1^{st}$ vertical | 0.0608 |
| $2^{nd}$ torsional | 0.0725 |
| $2^{nd}$ vertical | 0.0804 |

Table 1: Modal frequencies for the examined configuration

## 4. WIND TUNNEL TEST RESULTS

Despite the fact that the conceived bridge structure is not prone to coupled flutter instability (at least for the first modes of vibration, i.e., those of major interest), a minimum aerodynamic performance of the deck has to be guaranteed with respect to the wind static load and to the dynamic response to vortex-shedding excitation and atmospheric turbulence. For this purpose simple non-structural elements have been added to the basic structural design discussed in the previous sections. In particular the lower side of the beams has been closed with non-structural panels in order to obtain two boxes, from the aerodynamic point of view, as elements supporting the roadways. In addition triangular fairings have been added at the external edges of the deck, as shown in Figure 9. In view of the limited literature available on the optimization of these aerodynamic devices and the very geometry-dependent results (e.g. Kawatani et al. 1999, De Miranda & Bartoli 2001, Ogawa et al. 2002), the simplest configuration has been chosen: therefore symmetric fairings with an angle of 60° have been tested.

A series of static wind tunnel tests have been performed and the mean aerodynamic coefficients for various angles of flow incidence have been measured by means of an aerodynamic balance composed by six load cells and a system of connecting rods (see e.g. Bartoli et al. 2007). A steel section model at the scale 1:180 has been manufactured and tested in the 2.40 × 1.60 m CRIACIV wind tunnel in Prato. The model is 378 mm wide and 1120 mm long (Figures 9-10). After a preliminary study of sensitivity to Reynolds number variation, aerodynamic coefficients were measured at a flow speed of about 22 m/s, corresponding to a Reynolds number of $5.5 \times 10^5$ (based on the deck width). Results for drag ($C_D$, positive downstream), lift ($C_L$, positive upward) and moment ($C_M$, positive nose-up) coefficients are shown in Figure 11. All force coefficients are normalized with respect to the total width of the model and the angle of flow incidence is considered as positive if nose-up. It is worth noting the low values of the aerodynamic coefficients near zero-angle of attack ($C_D$ = 0.033, $C_L$ = -0.001, $C_M$ = -0.010), as well as the limited slope of the lift coefficient ($dC_L/d\alpha$ = 2.77) and above all of the moment coefficient ($dC_M/d\alpha$ = 0.20), which imply limited wind static and buffeting loads. In Figure 12 the aerodynamic coefficients of the twin-box girder deck with longitudinal beams identical to the road boxes of Messina Strait Bridge are reported for comparison (Bartoli et al. 2008).

At this preliminary stage the obtained results have been considered as satisfactory without the necessity of aerodynamic optimization. However in the future a series of aeroelastic tests will also be needed to finally validate the proposed study case.

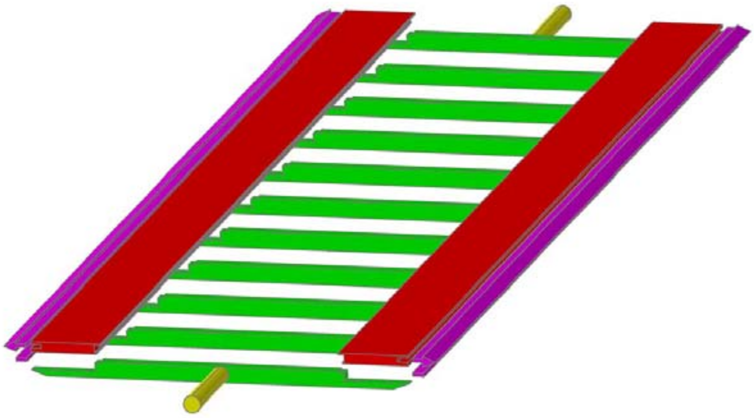

Figure 9: Render of the wind-tunnel section model

Figure 10: Section model in the CRIACIV wind tunnel

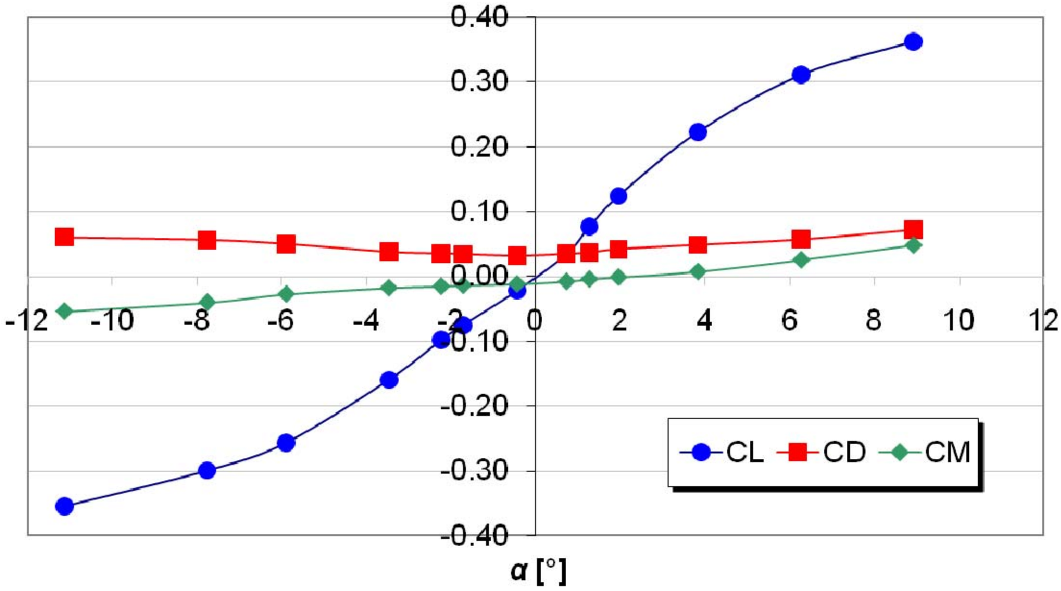


Figure 11: Aerodynamic force coefficients measured in the wind tunnel for the studied configuration

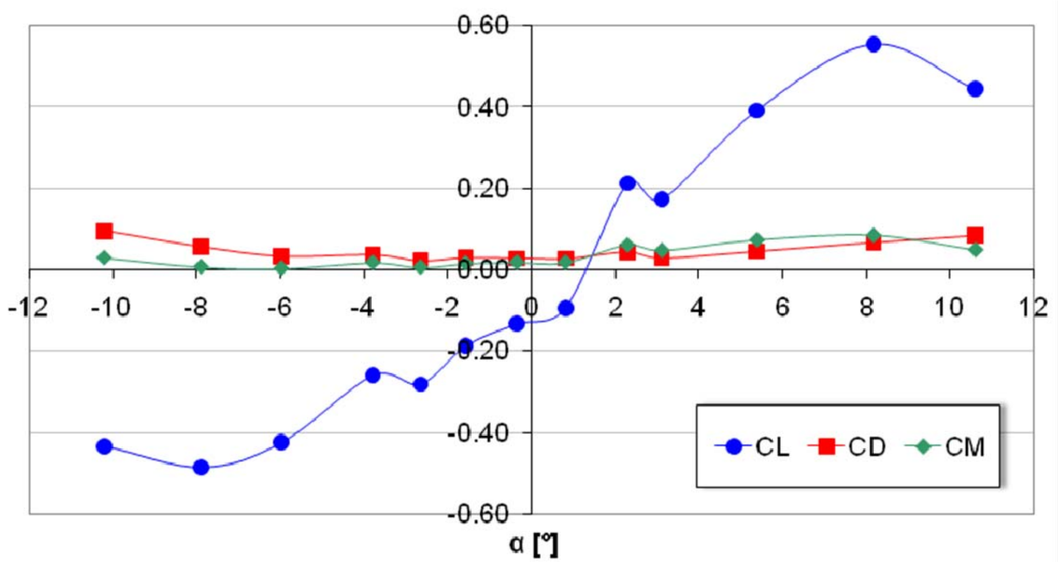


Figure 12: Aerodynamic force coefficients measured in the wind tunnel for the studied configuration

## 5. TIME HISTORY ANALYSIS RESULTS

In order to complete analytical and experimental studies, Time-History analyses have been performed on the global numerical model referring to the configuration described in Section 2. The self-excited forces acting on the deck are obtained from the static aerodynamic coefficients shown in Section 4 (Figure 11) following the Quasi-Steady analytical method (see Febo 2007).

For each numerical model the duration of the dynamical analysis is 1000 seconds and the duration of the linear ramp of increase of the wind speed up to the target value is 100 seconds.

The analysis results show that flutter instability does not occur up to high wind. In Figure 14, Time-History analysis results are shown for the examined configuration under a wind speed of 60 m/s, being **Fy** and **Fz** respectively the drag and lift self-excited forces on the bridge deck, **Mx** the self-excited moment with respect to the longitudinal x-axis of the deck, **Sz** the vertical displacement of the deck, **Vy** the horizontal velocity and **Rx** the rotation around the longitudinal axis, all referring to the sign convention of Figure 13.

Although static deflections and rotations are evident, no classical flutter instability occurs up to a wind speed of 60 m/s. Further numerical analysis with higher wind velocities show an increase of rotations due to the low torsional stiffness of longitudinal beams only when reaching wind speeds of about 70 m/s. However this phenomenon can be reduced after introducing few pairs of X-shaped structural elements to connect truss girders in longitudinal beams.

## 6. CONCLUSIONS

In this paper an innovative strategy to design long-span suspension bridges is proposed. The main idea is to conceive a structure with torsional to vertical bending frequency ratio lower than unity for the first pairs of modes of vibration, in order to prevent the occurrence of classical flutter instability in the range of wind speed of practical interest, that is one of the major sources of concern for this type of bridges. In this way a strongly enhanced aerodynamic optimization is no longer necessary, as it is necessary just to avoid bluff cross sections, which could be prone to single-degree-of-freedom torsional flutter, and to guarantee a good behavior with respect to the static response to mean wind and to the dynamic response to vortex-shedding excitation and to turbulent wind.

The aim to obtain frequency ratios lower than unity can be achieved by adopting a twin-box girder deck and moving most of the mass of the deck outside the planes of main cables and hangers. Since a strong aerodynamic optimization is no longer required, simpler and therefore more economical structural solutions can be sought, as discussed in the first part of the paper. It is shown that a solution with double-T steel beams supporting an orthotropic slab, stiffened by transversal beams, is feasible and respects the prescribed limitations concerning resistance and deformation under permanent and operating loads.

The aerodynamic force coefficients for the selected solution have been measured through wind-tunnel tests, showing that simple aerodynamic devices, such as external triangular fairings and non-structural panels to close the lower side of the deck, without any complex procedure of optimization, are sufficient to guarantee a fair behavior under wind load.

Finally, the static deflection and rotation of the deck under wind and the actual aeroelastic stability of the bridge have been verified by means of time-history numerical analyses on a global finite-element model of the structure.

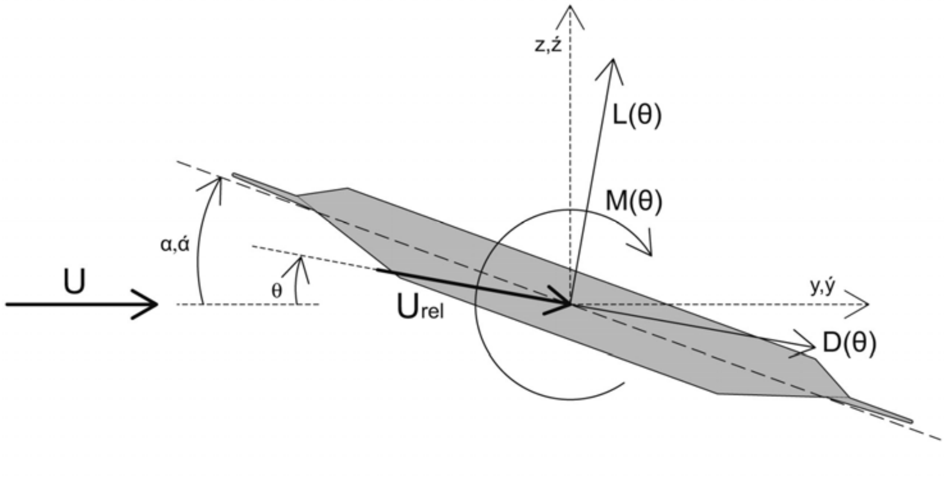


Figure 13: Sign convention for forces, displacements and velocities

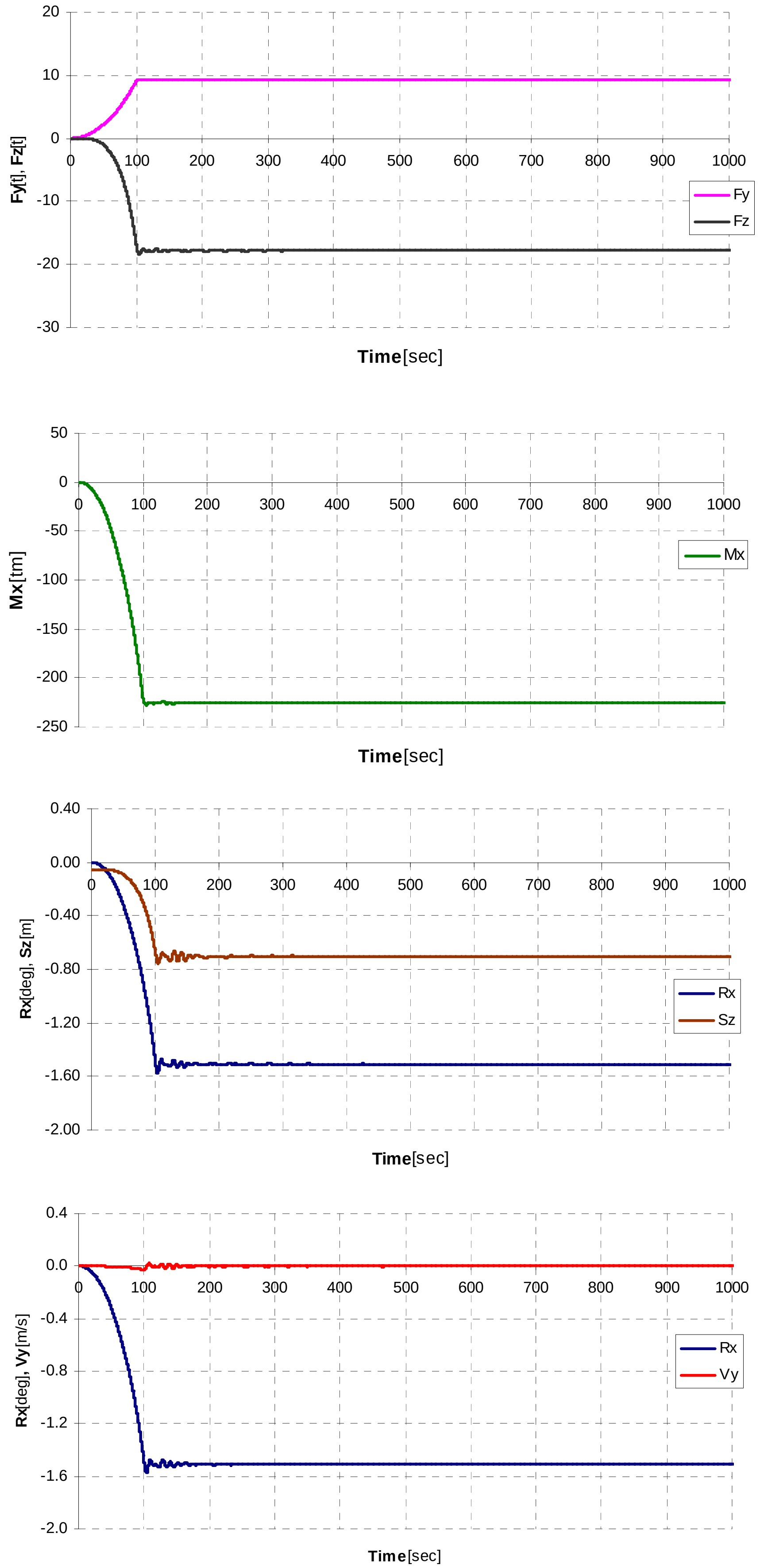


Figure 14: Time History results for the examined configuration at 60 m/s wind velocity

## 7. ACKNOWLEDGEMENT

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