64. The aerodynamic advantages of a double-effect large-span suspension bridge under wind loading

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SYNOPSIS. In the paper, some recent advances in the design of large span suspension bridges are reviewed and a solution based on a design of S. Musmeci is finally investigated. This solution, based on a double effect cable system, has many advantages, outlined here, mainly in providing stiffness and, possibly, damping "reserve", that can face effectively many design uncertainties.

INTRODUCTION

1. In the design of large suspension bridges there is today a clear dichotomy in design choices between aerodynamically transparent decking on the one hand and very rigid deck structures providing a high degree of resistance to wind action on the other. These solutions have been dictated by the need to provide decking with a high degree of torsional rigidity and at the same time minimise the effect of drag, a crucial factor on large bridges.

2. The complete contrast between these two design approaches was clearly evident at the ISLAB 92 Symposium on the Aerodynamics of Large Bridges (Copenhagen 1992) (ref. 1), widely considered to reflect the state of the art and current tendencies in large bridge aerodynamics, and confirmed at the recent IASS congress (Toronto, July 1992) (ref. 2); the differences can clearly be seen in the contrasting design concepts of two impressive large span bridges currently under construction:

- the Stoere Baelt suspension bridge in Denmark with a 1624 m central span and highly efficient aerodynamic decking, and
- the Akashi Kaikyo suspension bridge in Japan with a 1990 m central span and a very rigid deck framework.

3. We appear therefore to have arrived at a true parting of the ways as regards design criteria (Fig. 1): on the one hand there is a tendency to reduce the pressures acting on a structure and on the other an attempt to increase structural resistance.

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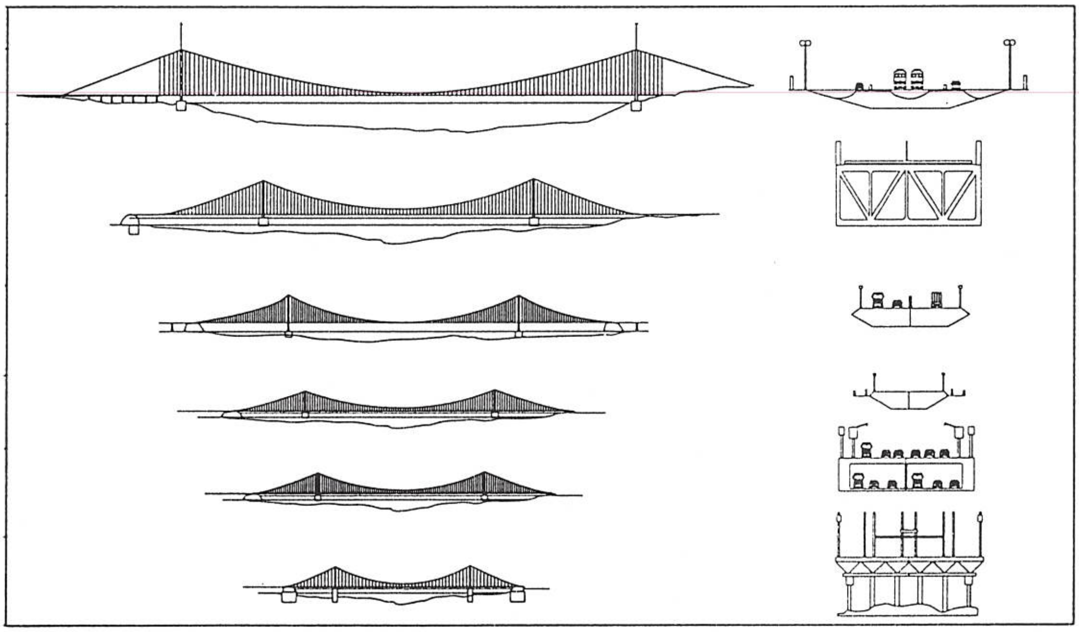


Fig. 1. Evolution of large span bridges.

4. It seems reasonable to ask therefore: can we continue to use the classical suspension bridge design with twin load-bearing cables and vertical hangers for very large spans without introducing structural innovations? N.J. Gimsing (ref. 3) has shown, in a series of interesting proposals, how considerable modifications to the classical vertical layout of cables and stays enables control of static and dynamic behaviour over spans far exceeding those currently possible (up to 5 kilometres using today's steels and theoretically up to 20 kilometres using carbon-fibre reinforced material). An equally stimulating contribution in this debate has been made by T.Y. Lin and P. Chow (ref. 4) in a proposal for bridging the Straits of Gibraltar.

THE EVOLUTION OF DESIGN ASPECTS OF LONG SPAN SUSPENSION BRIDGES

5. The two large suspension bridges mentioned earlier and currently under construction, both share the same main structural system, i.e. a classical suspension bridge design with decking on vertically parallel planes suspended on vertical hangers of variable length from two load-bearing cables. Given the well-known problems of aerodynamic stability in this type of bridge, recent theoretical and experimental research has been directed mainly towards the definition of aerodynamically efficient decking.

6. After the historic failure of the Tacoma Narrows bridge in 1940, caused by aerodynamic instability, most research analyses up until the 1960s concentrated on deck design .

7. An initial tendency was to provide suspension bridges with a high degree of torsional rigidity (see for example the heavy, stiff deck structures of the Verrazzano Narrows, Tago and Firth of Forth Road bridges). Rigid decking provides satisfactory aerodynamic resistance and stability but increases decking weight, construction costs, wind drag and lateral deflection (up to 14 meters on the Akashi Kaikyo (ref. 5). Not to be forgotten are the maintenance and inspection problems of this type of construction.

8. The end of the 1960s saw the introduction of a second approach to the problem: the basic strategy employed was to reduce the effects of wind action by concerning exclusively on the aerodynamics of deck profile. Because of their shape and behaviour under wind action, decks designed according to such criteria are defined as streamlined or aerodynamically transparent. Streamlined decks usually have a single- or multi-box girder construction with single or multiple cells and with an orthotropic decking plate to support and transmit loads. This type of construction reduces wind action, especially drag (either pseudo static or turbulent), and significantly contributes to overall torsional rigidity.

9. The single box girder solution does not, however, provide sufficient reliability on very large spans. A comparative study of some streamlined decks during preliminary design work for the Akashi Kaikyo bridge showed that the maximum span for a single box girder deck is 1700m. For this reason the height of the deck section, on two recent bridges the Stoere Baelt (1624 m) and the Humber (1100 m), has been increased in order to provide the torsional rigidity needed to counteract aeroelastic instability.

10. Another question currently debated is about the deck type that should be used for spans of over 2000m. An initial reply has been given by the Japanese designers of the Akashi Kaikyo bridge who ensure aerodynamic stability by means of a rigid deck framework despite the high price to be paid in terms of drag resistance and turbulence (buffeting and vortex shedding).

11. At 1624m the Stoere Baelt bridge was the longest of its type until the arrival of the Akashi Kaikyo at 1990m. The adoption of a rigid deck on the Akashi Kaikyo at the same time as this marked "jump" in scale from 1624m to 1990m, represents a historical departure in the development of suspension bridge design and raises a considerable number of questions for future applications. Even greater "jumps" in length are foreseen for the future: 3300m for the Straits of Messina, 5000m for a multi-span bridge over the Straits of Gibraltar.

12. The solution put forward by the designers of the Messina bridge (ref. 6) involves the use of a ventilated deck, i.e. a deck of three box sections separated by grill sections which permit the vertical passage of air. This drastically reduces the quasi-static coefficients of aerodynamic resistance to lifting and torque (moment).

13. Innovations in overall structural design can also be found in the large scale of the feasibility studies for bridging the Straits of Gibraltar (Fig. 3) (ref. 4). In this case attention is no longer exclusively concentrated on the aerodynamic performance of the deck but rather is mainly directed towards the use of purely

structural methods for increasing the resistance of a classic suspension bridge design so as to enable the large increase involved in this project.

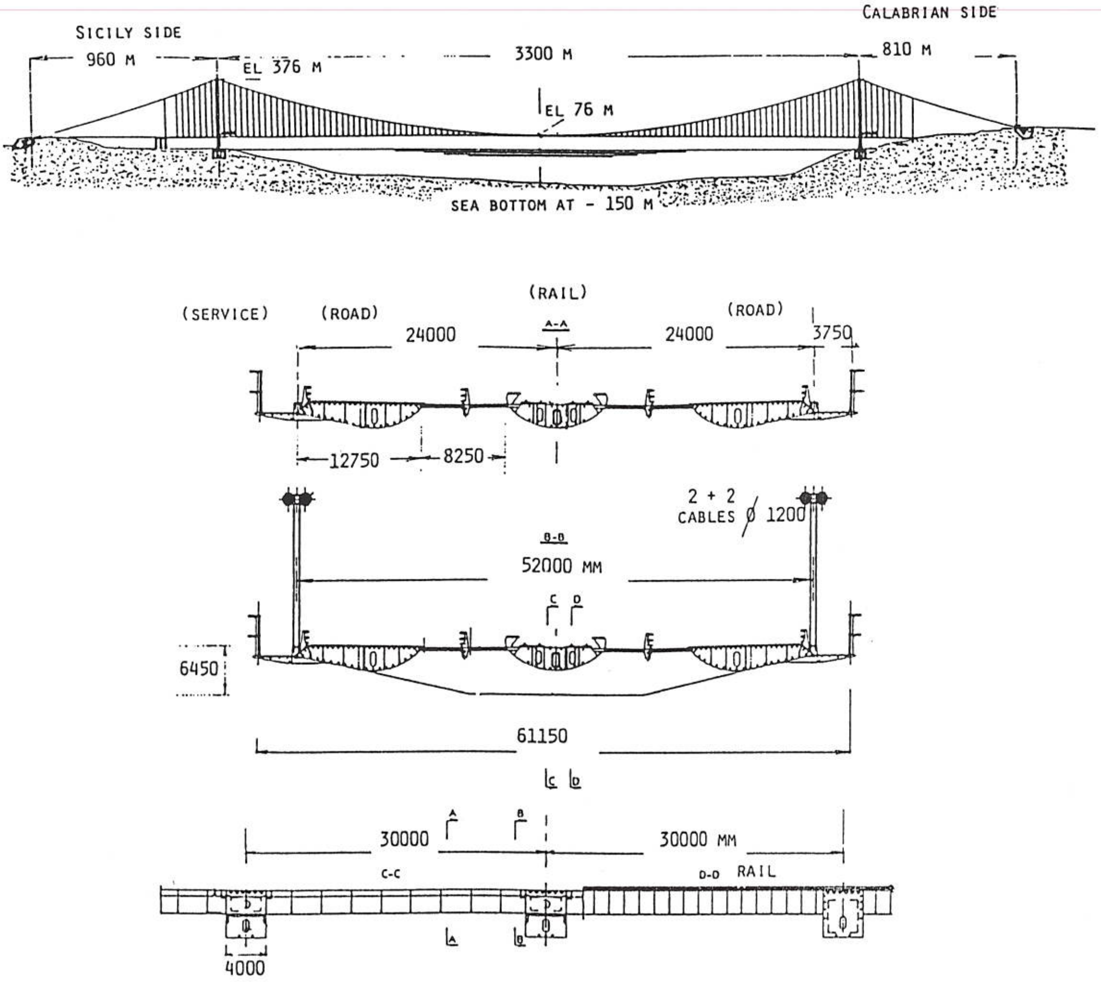
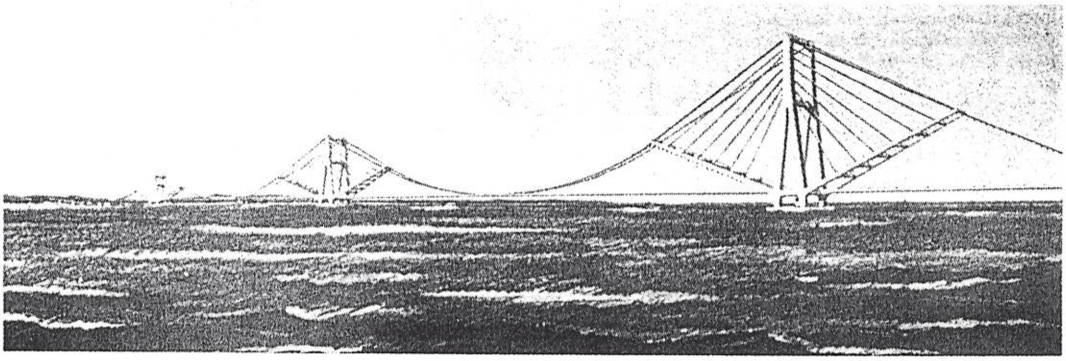


Fig. 2. Design of the Messina Bridge (ref. 6).

14. The discussion above will have made it clear that bridge designers are faced with two choices: a rigid deck or an aerodynamically transparent deck. Rigid decks can provide the aerodynamic characteristics needed to ensure efficiency and stability but entail increases in weight and therefore increases in the costs of structural works. Transparent decks reduce transverse pressures but are limited to use on spans of less than 1700m (as shown by Japanese studies) in those cases where considerable increases in length are not matched by corresponding increases width.



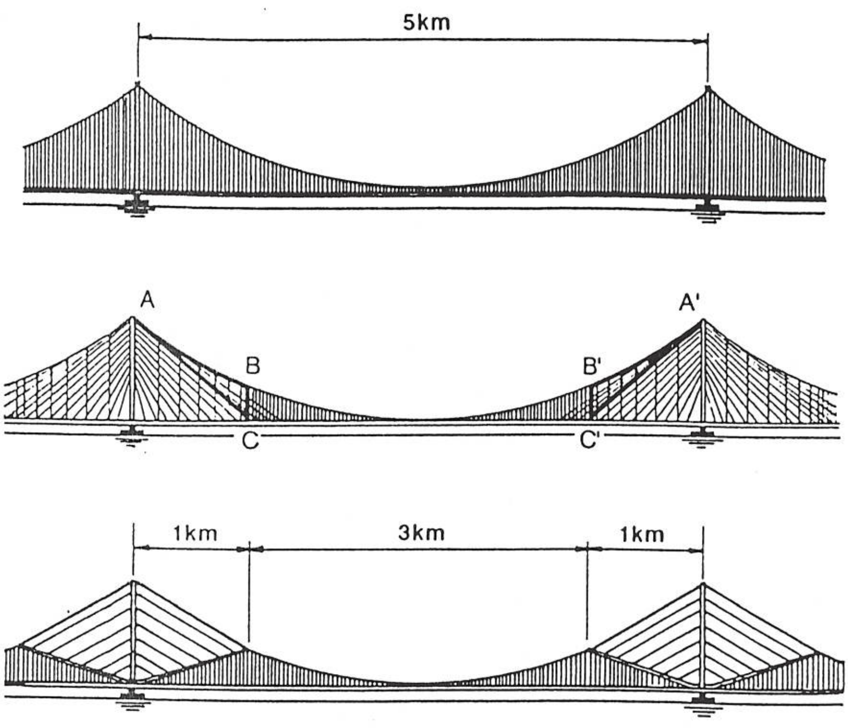


Fig. 3. Design of the Gibraltar bridge (ref. 4).

15. The lack of a synthetic solution combining these two design approaches is due mainly to the uncertainties in physical system modelling and more especially in the modelling of actions. Physical modelling does not yet make it possible to evaluate the sensitivity and degree of reliability of the overall design process, especially in the analysis of large bridges where wind action is undoubtedly a dominant factor.

16. Uncertainties arise from our incomplete knowledge of the stochastic properties of actions, the modelling and behaviour of materials, mathematic modelling and the modelling of structural properties such as mass, damping and rigidity. All these uncertainties mean that the whole design and construction process must be subject to general reliability testing (ref. 7). In a study of the Humber bridge (ref. 8), the uncertainties of the mathematical aeroelastic model were checked on the basis of structural parameter and aerodynamic uncertainties. For bridges of a similar type this study provides general indications concerning analytical model uncertainties through the use of critical flutter speed definitions. Maximum variation in this case is ± 10%.

17. An interesting debate during the ISALB 92 symposium gave the impression that from an engineering point of view the overall design process and structural system testing is reliable only on simple, classical suspension bridges of spans up to 2000 m. In order to remove some of these uncertainties, special wind tunnels have been constructed which are wide enough to take 1:100 aeroelastic bridge models complete with access viaducts. The wind tunnel for the Japanese project, for example, has a test width of 43 m. This was the only way of decreasing the degree of uncertainty when studying structural characteristics and wind-structure interaction (frequency, damping and inertial scaling) and the only way of faithfully modelling towers, decks and cable systems.

18. A second method for solving the problem is to deal with the "action" side of the equation. That is, by designing a deck section that is aerodynamically transparent or ventilated and which, as a consequence, drastically reduces the "actions" operating on the structure. To be applicable, however, this method presupposes that the methods for extrapolating from models to the finished project are reliable, i.e. that the uncertainties have been estimated on the basis of comparisons with existing constructions. In the case of large bridges, however, such a comparison is not practicable and extrapolation is not immediately possible. It should also be said that theoretical numeric methods for extrapolating from models to reality are also affected by numerous uncertainties which cannot be ignored.

19. A first series of uncertainties concerns the significance of the wind tunnel testing of models. According to Scanlan (ref. 9),"...the Reynolds number of the test will generally speaking be two to three orders of magnitude less... The common argument that the effects of the Reynolds number are negligible for structural elements with sharp edges still has to be fully demonstrated...".

20. Scanlan himself draws attention to some of the limits of his theory of aeroelastic instability: "... in the discussion reported above it is supposed that flutter and buffeting forces can be separated and do not interact... But given that physical phenomena and their interaction around bluff bodies are not linear effects, then this analytical separation, made for engineering analysis, is convenient but does not, in principle, include certain complexities of the fluid-structure interaction...".

21. Here it should also be emphasised that, even though model analyses and treatment might be exact, numeric extrapolation using algorithms to stimulate wind storms over time can itself lead to further uncertainties.

22. Firstly, a simulation must comprise at least 20 or 30 case histories of suitable duration (10-20 minutes) if it is to be statistically significant.

23. Secondly, all the algorithms used to generate histories in time do not take into account the quadrature components of the cross spectrum. This means that the phases cannot be simulated correctly. The same applies to the lee eddies caused by the shape of the object hit by wind currents or by the presence of transversal elements and roughnesses. The same is also true of cross winds and the eddy shedding running the entire length of a bridge which can trigger oscillations. These phenomenon cannot be correctly simulated given the current stage of development of generation methods.

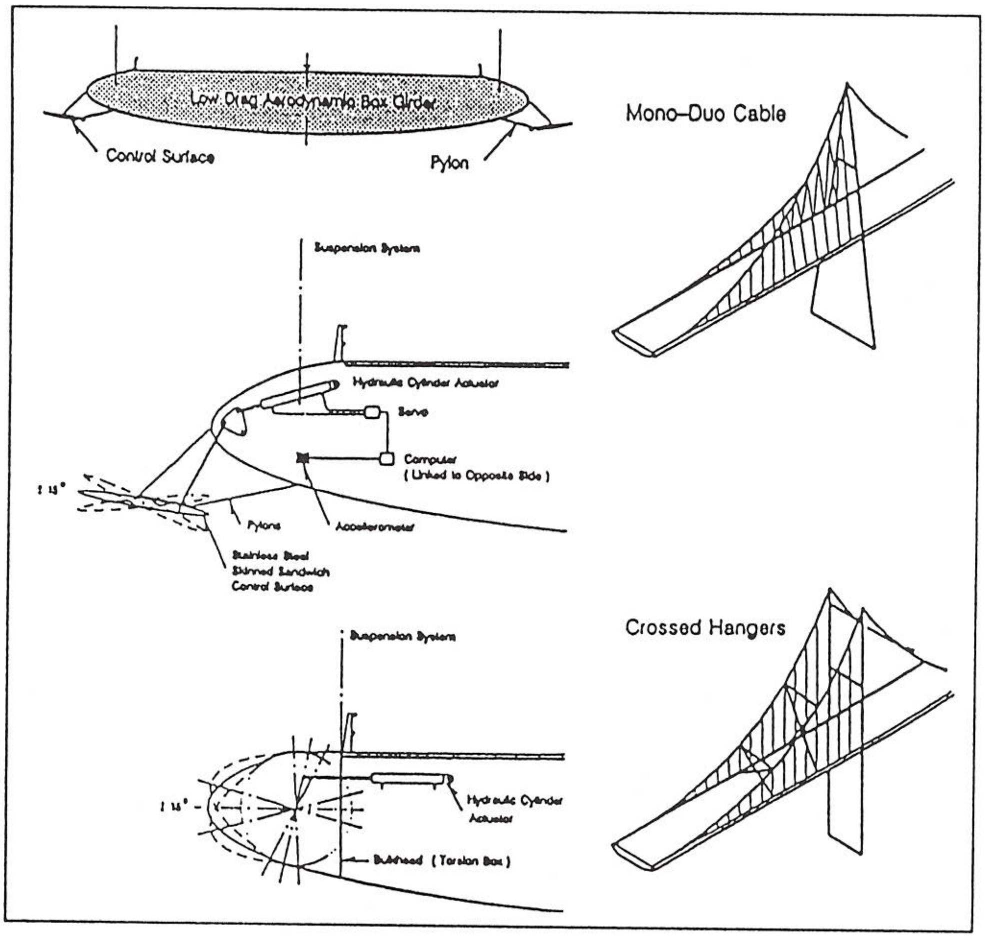


Fig. 4. (ref. 10).

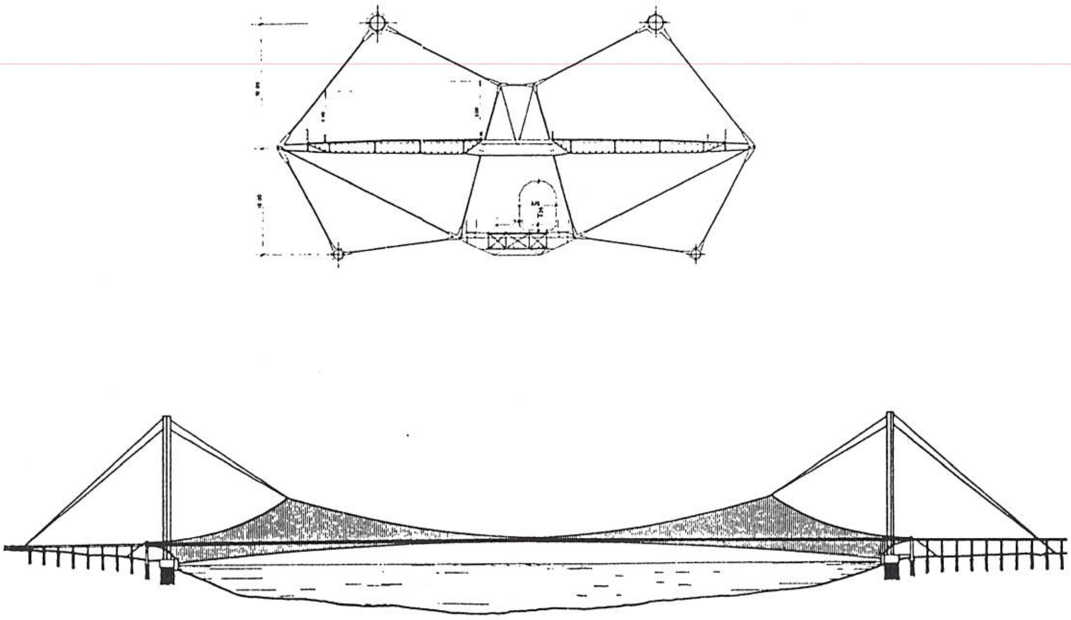


Fig. 5.

24. The considerations raised in the discussion above make it reasonable to ask the question: can we continue to propose the classical layout of a simple suspension bridge for large spans without introducing some structural innovations? In other words, can we hope to dominate all the problems which might arise through the zealous application of analyses to what is, in effect, an "old" layout without at the same time implementing an overall synthesis of structural concepts? Working along these lines, Lin and Chow (ref. 4), suggest increasing the deflection/ span ratio from 1/10 to 1/5 so as to reduce the stresses on the load-bearing cables. According to these authors, the increase in cost due to the higher towers required in their hypothesis would be offset by the reduction in cable diameter.

25. N.J. Gimsing (ref. 3) has shown, in a series of interesting proposals, how considerable modifications to the classical vertical arrangement of cables and stays enables control of static and dynamic behaviour over spans far exceeding those currently possible. K. Ostenfeld and A. Larsen (ref. 10) have proposed the introduction of a system of horizontal cables in order to control and limit lateral movement of the deck.

26. We are firmly convinced that theoretical and experimental analyses, the production, construction and maintenance of free spans greater than 2000m must

all be based on clear design concepts which remove, or at least substantially reduce, the uncertainties indicated by many leading authorities on the subject.

SOME REMARKS ABOUT A PROPOSED DOUBLE EFFECT TENSILE STRUCTURE

27. The aim of this paper is, therefore, to study the behaviour of a double-effect suspension bridge under the effect of wind action. To do this we will use a model inspired by S. Musmeci's design for the Straits of Messina bridge and we will be studying the reduction in aeroelastic instability provided by this model.

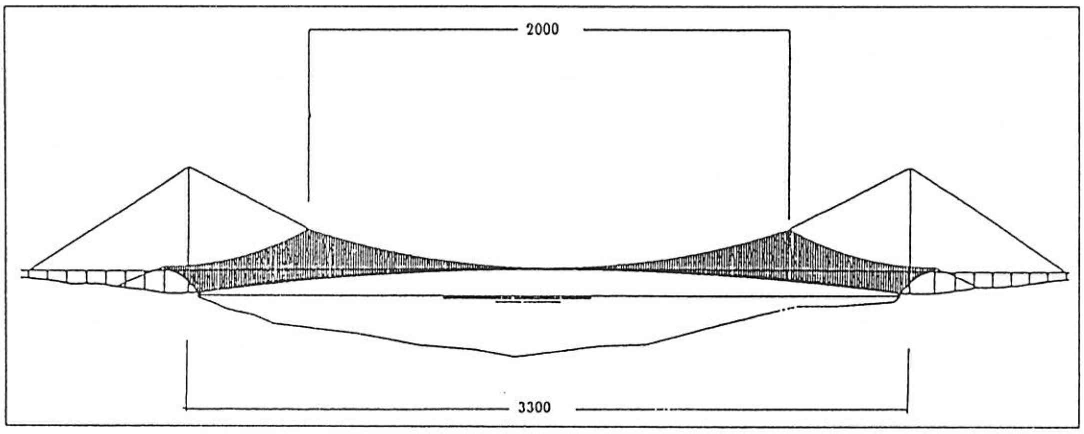


Fig. 6.

28. The model is based on four guidelines:

a) Reduction of bridge weight by means of a streamlined deck with high flutter stability.

b) Considerable increase in torsional rigidity (even though the deck is not torsionally rigid) by means of the double-effect produced by pull (or stabilising) cables with counter opposing curvature.

c) Increase in drag resistance through the adoption of multiple decks and the effect of second order rigidity produced by a spatial system of load-bearing and pull cables.

d) Increase in resistance to lift forces due to the double-effect in c above.

29. The aim of returning to the Musmeci project was to prove that it is possible to construct a large span suspension bridge through the introduction of certain structural innovations rather than by simply attempting to reduce the effects of actions to a minimum. Using the Musmeci structural layout means, in effect, giving a bridge design "structural reserves" in the form of pull cable rigidity, a rigidity which can be regulated. Structural reserves can also be provided in this layout by means of mechanical (but not aerodynamic) damping whereby the anchor points of the pull cables are fitted with viscous or hysteretic dampers. Put

in other terms, the structure in this case is no longer unprotected against external actions and we are no longer obliged to predict actions precisely (something which is in any case not possible). Rather, the structure is equipped with a rigidity and resistance which constitute the structural reserves needed to cope with the large increases in scale involved in this type of construction.

30. Therefore, the main advantages can be summarised as follows.

31. Increase of torsional and lateral stiffness: the increment of torsional stiffness leads, for bridges of about 3000 m span, to a reduction of the rotation at the mid-span to 80% of that computed for a classical suspension system (see Table 1).

Table 1. Input data of the example.

Central span of the bridge	3300m
Main cable's sag	300m A_f (main) $5.6m^2$
Stabilising cable's sag	80m A_f (stabilising) $0.8m^2$
Initial slope of the lower cable	30°
Vertical rigidity	$1.40m^4$
Lateral flexural rigidity	$276.1m^4$
$\lvert C_M \rvert \alpha = 0$	0.007
$dC_M/d\alpha \lvert \alpha = 0$	0.1 rad ÷ 1 rad
Mean wind velocity at the deck of the bridge	60 m/s

32. This amount becomes significantly higher if one considers the variation of C_M (aerodynamic moment coefficient). Table 2 shows the percentile differences for some values of the initial C_M derivative.

Table 2. Results.

$dC_M/d\alpha \lvert \alpha = 0$	0.1	0.5	1
$\Delta\alpha$ (%)	20.36	25.78	36.21
Δd(%)			27.37

$\Delta\alpha = (R_c - R_d)/R_c \times 100$

R_c quasi static rotation at mid-span (classical layout)
R_d quasi static rotation at mid-span (double effect layout)
$\Delta d = (D_c - D_d)/D_c \times 100$

D_c quasi static displacement at mid span (classical layout)
D_d quasi static displacement at mid span (double effect layout)

33. The stiffness increase has also an advantageous influence on the dynamic behaviour; in fact, the higher eigen frequency interacts with the lower spectral intensity of the wind turbulence. This will lead to a reduced dynamic response. Numerical tests on a 3D model are ongoing, whose results confirm substantially this effect.

34. Improvement of structural resource: the double effect suspension system allows the attribution of an additional design parameter for controlling the structural behaviour. This is given by the control one can activate on the pretension of the lower cables. This force is, primarily, an independent parameter, which can be easily changed. On the contrary, in the classical suspension layout the force in the cables is given by the equilibrium condition for given geometry and loads.

35. One should also stress the further advantage given by dampers, which can be easily installed at the extremities of the tower, stabilising cables, giving therefore a decisive contribution to the structural and aerodynamic damping.

36. Removing of the hangers at the extremities of the mid-span: as confirmed by the preliminary design of Gibraltar Strait Bridge by Lin and Chow, Musmeci's proposal allows the increase in the rigidity of the vertical hangers, which would become extremely low in the classical solution.

37. The factors listed above appear therefore to provide the hope for synthesis of the two approaches in suspension bridge construction. The solution proposed seems to satisfy all the primary requirements of large suspension bridges thus reconciling the two, previously opposing, design approaches. We can draw some comfort from the opinion expressed by R.H. Scanlan who believes that with the current design tendency towards high stability profiles, "instability due to pure and simple flutter is less and less probable... while the action of buffeting is attracting increasing attention as the main problem caused by wind on large bridges".

CONCLUDING REMARKS

38. Reproposing the concepts of the design of S. Musmeci, the authors tried to show an alternative way to face the design problems of long span suspension bridges, through the introduction of appropriate improvements in the structural layout. This concept is innovative with respect to the "classical" strategy of only reducing the loads due to the wind.

39. The double effect suspension bridge can provide some additional structural resources to the designer, consisting in the control of the stabilising cable rigidity as well as in the increased structural damping.

40. Comparative analyses into aeroelastic behaviour are still in progress, via numerical simulations on a 3D model. However, any worsening of the characteristic studied can be ruled out given that the proposal made does not influence deck aerodynamics.

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