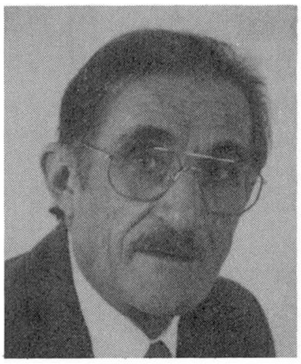
Comparative Investigations of Suspension Bridges and Cable-Stayed Bridges for Spans Exceeding 1000 m

Mehdi ASCHRAFI
Senior Eng.
DSD GmbH
Saarlouis, Germany



Mehedi Aschrafi, born 1941, received his structural eng. degree from Techn. Univ. Aachen in 1969. From 1969 to 1983 he worked in the Bridge Constr. Dept as structural eng. and since 1984 he is Senior Eng. for Bridge and Heavy Industries with the company DSD Germany.

Summary

The author has studied the possibility of building long-span cable-stayed bridges with spans of 1000 m and more. This is possible based on the present high standard of theory and calculation methods and additionally due to the tendency to use lightweight structures (super-structure, orthotropic plates) including optimum welding techniques as well as high admissible stresses in cables. The use of lightweight structures is also important in seismic areas. Finally, the vibration of complex long cables is controllable.

1. Introduction

As F. Leonhardt (1972) showed , cable-stayed bridges with a maximum span of approximately 400 m are possible. From the engineering point of view, only the erection stage is critical due to wind excitations [1].

In 1972, this problem was investigated by full-scale tests on the cable-stayed motorway bridge over the Rhine near Speyer, Germany.The paper deals with the results and the conclusions of passive control. Furthermore, the passive control of cable vibrations, especially rain-induced oscillations, is illustrated.

First results regarding long-span cable-stayed bridges were presented by the author in the International Wind-Engineering Congress in 1983 Australia [2] and the International Conference IABSE, FIP in Deauville, France.[3], where he pointed out that even with long spans, cable-stayed bridges are by far superior to other bridge types not only technically and economically but particularly with regard to aerodynamic stability. Meanwhile, numerous cable-stayed bridges with spans up to 856 m (Normandy bridge) have been built all over the world. At present, the Tatara bridge with a span of 890 m is under construction. The most common opinion is that the conventional suspension bridge is still the best solution for long-span bridges. In specialist literature one can also read that the so-called Hybrid [4] or the bi-stayed bridges [5] are the bridge types of the future.

This paper presents comparisons of the behaviour of suspension and cable-stayed bridges under critical conditions.

This paper will discuss the optimum shape of the superstructure selected for pylons, the type of cable suspensions and details of cable connections including passive control, temporary control of vibration during erection stages and studies of active control devices.

2. Comparative Investigation of Suspension and Cable-Stayed Bridges

Fig. 1 shows the development of the suspension and cable-stayed bridges. It illustrates the rapid development of the spans of cable-stayed bridges over the past few years. Since the 1980s, the cable-stayed bridge has become a standard system for spans up to 600 m.

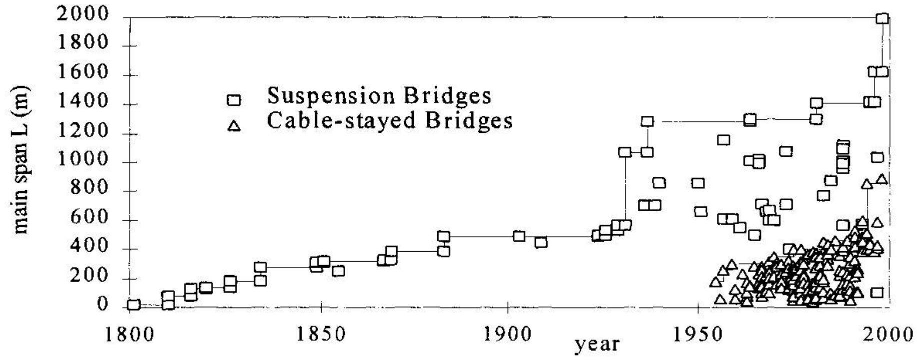


Fig. 1 : Development of the construction of suspension and cable-stayed bridges

To find out the optimum solution for bridges with spans between 1000 m and 2000 m, various 3D systems were calculated - in intervals of 200 m - acc. to the 2nd order theory. These calculations were carried out for the bridge widths 22.0 m, 30.0 m, 38.0 m. (Fig. 2).

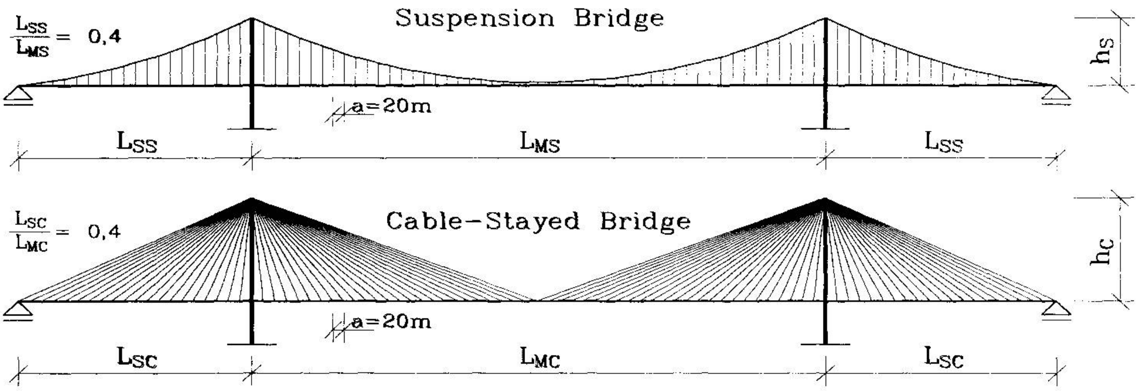


Fig. 2 : Suspension and cable-stayed bridge systems with fan-shaped cables

2.1 Bridge Deck Cross-Sections

Meanwhile, numerous wind tunnel tests and practical experience have shown which cross-section designs of the bridge deck must be chosen in order to avoid the occurrence of wind vortices. Furthermore, lift and pitching moment should to be reduced to a minimum to avoid flutter- and torsion-induced vibrations.

The development of the cross-section design of the bridge deck shows that the conventional truss design to achieve stability against wind is out-dated. The flat cross-section design as shown in Fig. 2 will replace the truss-type cross-sections in future. In the intervening period, several bridges have been built with these new cross-section types.

It has been proved by now that aerodynamic stability can be achieved even in suspension bridges which are susceptible to vibrations by using these aerodynamically shaped cross-sections, if the bridge deck is sufficiently wide in relation to the span and is continuous at the pylons.

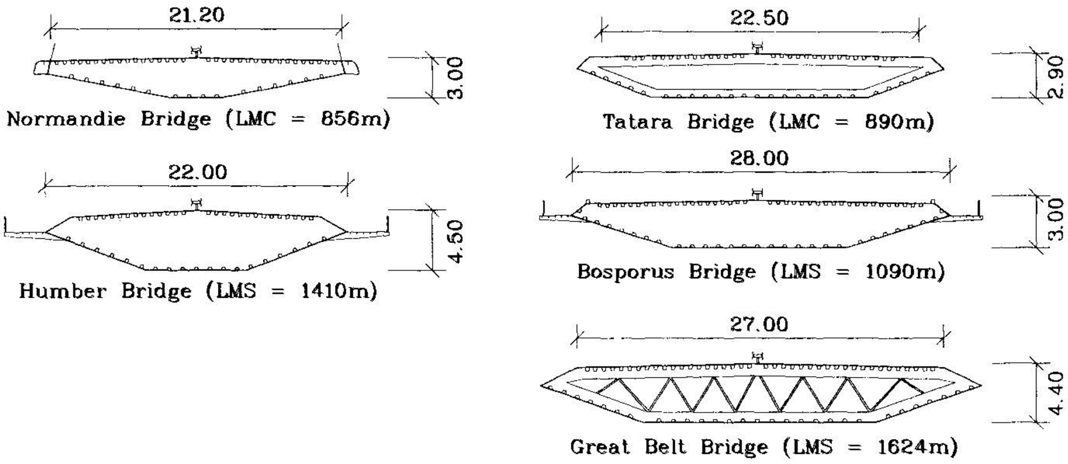


Fig. 3 : Cross-sections of bridge decks

The aerostatic coefficients measured for these cross-sections show that the coefficient is low both for lift and for pitching moment, so that the forces inducing bending and torsional vibrations remain very small, but the coefficient for the horizontal wind resistance is also exceptionally small, too [3], [6], [7].

The investigation shows that for spans of more than 1000 m, an overall construction height of such flat bridge cross-sections of 3.0 to 3.6 m is sufficient for cable-stayed bridges.

If we consider the quantity of steel required for the superstructure, we see firstly that the orthotropic plate is the same in both cases. The suspension bridge needs a bridge deck with higher bending strength and torsional stiffness than the cable-stayed bridges, on the other hand, the latter requires additional steel to resist the axial compression forces which result from the cables anchored in the deck. The resulting requirement of steel is however. relatvely small.

2.2 Pylons

The investigation shows that the cable forces and also the required steel quantities for the cables are influenced by the height of the pylons above the road in relation to the span (Fig. 4).

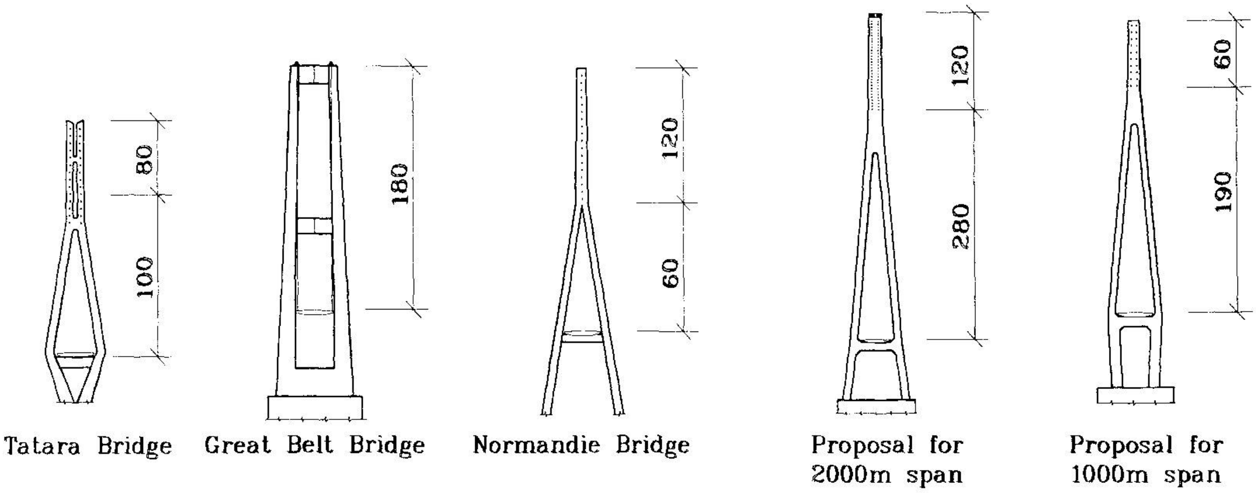


Fig. 4 Types of pylons

Regarding the steel required for the pylons (cable-stayed bridge in composite construction), the bridge deck and the fact that for a sufficient stiffness of the bridge, the pylons must not be too high, a good relation for cable-stayed bridges (fan-shaped cable arrangement) would be h/l = 1/5 and for suspension bridges h/l = 1/9. Furthermore the investigations show that bringing the cables together in a pylon saddle above the bridge axis on an A-shaped pylon is an excellent solution for spans up to 2000 m.

2.3 Cables

The deflections of cable-stayed bridges depend to a great extent on the changes in the length of the cables under increasing loads. The changes in length depend on the change in the sagging of the cables, which occurs with the 3rd power of the stresses.
This shows to what extent it is necessary, especially with long spans, to use cables which can bear great stresses, with the strength of the cable anchorage playing an important role.
Of course it is possible to reduce the sagging changes of very long cables by means of bracing cables, so that the loss of stiffness of the cables due to sagging changes can be limited to 20 % of horizontal cable lengths of more than 1000 m.
The cable-stayed bridges with fan-shaped cable arrangement require about 50 % less steel for the cables than suspension bridges (1000 m span) under the same admissible stresses.
With long spans, the cables already have a considerable dead weight with a span of 1000 m, i.e. 15 %, compared to only 4 % for the fan-shape solution. With a span of 2000 m, a suspension bridge requires nearly half the weight of the cables to support itself.
In contrast to the cables and hangers of suspension bridges, the vibrations of the stay cables of cable-stayed bridges are significant in particular. Because of the potentially large amplitudes of cables, there is a risk of fatigue failures, and the ensuing possible traffic risk (Bangkok bridge for example) due to excessive deck vibrations. Although the cable vibrations will not cause failures of cable-stayed bridges immediately, the capacity or fatigue resistance will be diminished, leading finally to a reduction in service life and the occurrence of failures.
At present, the passive control method is most commonly applied in the control of cable vibrations [3], [8].
As we know, the cable damping is very small. The logarithmic decrement of structural damping will be approximately 0.003. Using a simple damper (e.g. hydraulic or rubber damper), the generalized equivalent damping ratio can be increased considerably. Thus, vortex-induced oscillations, galloping, rain-induced vibrations and also parameter instability (caused by bridge deck and / or pylon movement) may be controlled completely.
Aerodynamic control methods are uneconomical in comparison to simple mechanical devices.

3. Erection Stages, Temporary Control of Vibrations

The investigations show that under construction with a 1000 m long cantilever, the width of the bridge should be 38 m minimum.
During erection stages, the detached pylons of cable-stayed and suspension bridges present a special kind of tower structure. Steel pylons are low-damped and therefore particulary susceptible to vibrations.
The nature of vibrations depends on the form of the pylon. Apart from their response to stochastic gust effects, bridge pylons show a tendency both to forced vibrations due to vortex excitation and also to self-induced movements (galloping).
In the first place, optimum tuned vibration absorbers should be considered. Figure 5 shows a sketch of such a system in use.

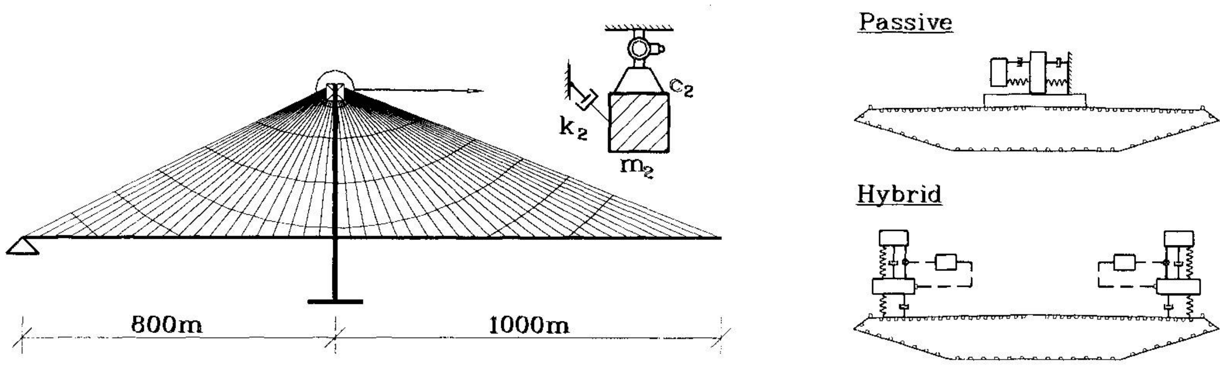


Fig. 5 : Cable-stayed bridge under construction (main span 2000m)

If the natural frequencies in both principal directions are different, the pendulum system could also have different natural frequencies in the two directions by means of connections in series of torsional-springs pendulum suspensions. After completion of the bridge, the damping system can be alive but tuned to the changed natural frequencies.
Tuned mass dampers (Fig. 6) should be considered also to avoid vibrations of the bridge deck in the erection stage [9], [11].

Fig. 6 : Tuned mass dampers

4. Studies of Active Control Devices

For ultra-long-span bridges, other means than maximizing the torsional stiffness and possible redistribution of the torsional inertia may be achieved. If properly arranged, additional damping will reduce the amplitudes of response due to wind (buffeting, vortex shedding, galloping and wake-galloping). However, by means of passive devices, the critical flutter speed (separated flow torsional flutter) cannot be increasead considerably. Active control measures will be necessary for this. The active control can be carried out by means of aerodynamic and/or mechanical systems. From an economical point of view the mechanical hybrid system (combination of passive and active control) will be the best. As the governing equation shows [11] by means of active/passive control both an increasing of the total damping and or stiffness will be attainable. In the case of a bridge, the control of the acceleration (mass influence) will be unrealistic.
To avoid forced and self-induced vibrations, including bending and/or torsional vibrations, both in the erection stage and after completion of the bridge, mechanical hybrid systems at the bridge deck corners are proposed as follows.
Active control systems acc. to [10] are - though very interesting technically - not economical. Since traffic induced vibrations will act on the bridge, in addition to the wind, those mechanical control systems will not be able to fully control the vibrations.
This phenomenon was experienced during the reconstruction of the Lisbon Tagus bridge [12].

5. Conclusions

The comparative investigations showed that the cable-stayed bridge with fan-type cables is superior to the suspension bridge both technically and economically and with regard to aerodynamic stability despite taller pylons. That applies also to spans up to 2000 m.
The structural and aerodynamic stability will also be safe during construction with a 1000 m cantilever. The cross-section of the bridge deck should be flat and wide and of slender box girder type. Preferably, an A-shaped pylon with inclined cable ends should be used.
Further investigations should deal with particular solutions concerning hybrid dampers.
For total bridge length of 3600m or more, the multispan cable-stayed bridge should be used.

References

[1] LEONHARDT, F.-ZELLNER , W.: Comparative Investigations Between Suspension Bridges and Cable-Stayed Bridges for Spans Exceeding 600 m, Publications 32-1, 1972 IABSE, p.126-165.

[2] ASCHRAFI, M.-HIRSCH,G. : Control of Wind-Induced Vibrations of Cable-Stayed Bridges. J. of Wind Eng. and Ind. Aerodyn., 1983, Vol 14 , P. 235-246

[3] ASCHRAFI, M. : Control of Wind-Induced Vibrations of Cable-Stayed Bridges International Conference A.I.P.C.-F.I.P. Deauville, France, Oct. 1994, Volume 2, p. 45-52

[4] WALTHER, R.-AMSLER, D.: Hybrid Suspension System for Very Long-Span Bridges: Aerodynamic Analysis and Cost Estimates Cable-Stayed and Suspension Bridges. International Conference A.I.P.C.-F.I.P. Deauville, France, Oct. 1994, Volume 1, p. 529-536

[5] MULLER, J.: The Bi-Stayed Bridge Concept : Overview of Wind Engineering Problems. Aerodynamics of Large Bridges, A. A. Balkema / Rotterdam / Brokfield / 1992 p. 237-245

[6] VIRLOGEUX, M.: Wind Design and Analysis for the Normandy Bridge. Aerodynamics of Large Bridges, A. A. Balkema / Rotterdam / Brokfield / 1992p. 183-216

[7] LARSEN, A.-JACOBSEN, A.-S.: Aerodynamic Design of Great Belt East Bridge. Aerodynamics of Large Bridges , A. A. Balkema / Rotterdam / Brokfield / 1992 p. 269-283

[8] HIRSCH, G. : Cable Vibration Overview. International Conference A.I.P.C.-F.I.P. Deauville, France, Oct. 1994 Volume 2, p. 453-464

[9] CONTI, E. - GRILLAUD, G. - JACOB, J.- COHEN, N.: Wind Effects on the Normandy Cable-Stayed Bridge: Comparison between Full Aeroelastic Model Test and Quasi-Steady Analytical Approach. International Conference A.I.P.C.-F.I.P. Deauville, France, Oct. 1994 Volume 2, p. 81-90

[10] OSTENFELD, K.H. - LARSEN,A. : Elements of Active Flutter Control of Bridges. New Technologies in Structural Engineering, 1997. Lisbon, Portugal, p. 683-694 volume 2

[11] ASCHRAFI, M. - HIRSCH, G.:Vibration Control of Assembly Stands during Bridge Extension. Technologies in Structural Engineering, 1997, Lisbon. Portugal, p. 543-550

[12] ASCHRAFI, M. - HIRSCH, G.:Vibration Control of Tejo Bridge during Extension - to be published shortly