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Influence of Aerodynamic Stability on the Design of Bridges

Influence de la stabilité aérodynamique sur le projet de ponts

Wirkung der aerodynamischen Stabilität auf den Entwurf von Brücken

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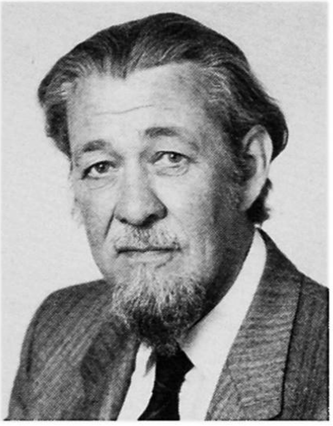

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SUMMARY

This article reviews past and present methods of preventing aerodynamic instabilities on long suspension bridges. The current trend in design philosophy is to improve the aerodynamic characteristics and control the inertia, instead of simply increasing the structural stiffness. This has led to some unconventional new forms of road deck, which will enable much greater spans to be built in the future.

RESUME

L'article présente une revue des méthodes anciennes et actuelles pour éviter les instabilités aérodynamiques dans des longs ponts suspendus. La tendance actuelle des projeteurs est d'améliorer les caractéristiques aérodynamiques et de contrôler l'inertie, plutôt que d'augmenter la rigidité structurale. Cette tendance conduit à quelques nouvelles formes de tablier, qui conduiront à l'avenir à des travées plus larges.

ZUSAMMENFASSUNG

Dies ist ein Beitrag über frühere und gegenwärtige Methoden der Verhinderung aerodynamischer Instabilität bei grossen Hängebrücken. Die heutige Planungstendenz geht dahin, die charakteristischen aerodynamischen Eigenschaften zu verbessern und die Trägheitskräfte zu kontrollieren, anstatt einfach die Steifigkeit zu erhöhen. Das hat zu einigen unkonventionellen neuen Formen von Fahrbahnträgern geführt, die in Zukunft das Bauen viel grösserer Spannweiten ermöglichen werden.

1. INTRODUCTION

The design philosphy for very long-span bridges has become increasingly influenced by the problem of aerodynamic stability. Past efforts to combat this problem by providing high torsional stiffness in the deck have become uneconomic. Long bridges are invariably cable supported, so that the resulting heavier deck increases the dead-load on the cables. Alternative solutions can, however, be achieved by a proper understanding of the problem.

There is an historic parallel between bridge and aircraft design during the past 40 years. Bridges were getting longer and aircraft were going faster. Stiffness was overtaking strength as the design criterion for both types of structure. In the aeronautical field a great deal of flutter research had already been done [1], but the Tacoma disaster in 1940 left bridge designers starting almost from scratch. Although research was quickly commissioned [2], this relied heavily upon aircraft experience.

Solutions to the aircraft flutter problem were invariably sought through changes of stiffness and inertia distribution, because the aerodynamic configuration was determined by its efficiency as a vehicle. Bridge design followed this route, although deck symmetry gave little scope for inertia changes, so that stiffness was the goal in practice. In recent years, however, more attention has been devoted to modifying the aerodynamic properties of the road deck in an effort to reduce the economic penalty of high stiffness.

2. AERODYNAMIC STABILITY

2.1 The Aeroelastic Triangle

Many years ago, Collar [1] gave an illuminating description of the nature of aeroelastic stability. His triangle (Fig.1) shows the three fundamental kinds of force - structural stiffness, aerodynamic and inertia - which can combine to give various phenomena. Those which involve only two kinds of force are the most easily understood. Stiffness and inertia combine to give structural vibrations. Stiffness and aerodynamics can lead to divergence - a kind of aerodynamic buckling. Finally inertia and aerodynamics determine the stability of a rigid aircraft - a problem irrelevant to bridges.

Flutter is more esoteric, being caused by a combination of all three forces. It is a growing oscillation which occurs above some critical wind speed, and it can easily destroy the structure. Below this speed the air forces damp each of the vibration modes.

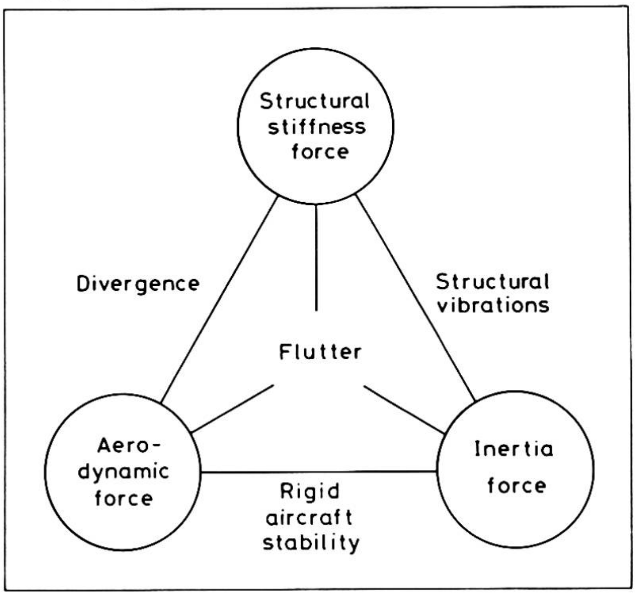

Fig.1 Aeroelastic triangle.

2.2 Types of Instability

In this paper we are concerned only with true instabilities, not with resonant vibrations due to forcing from shed vortices or turbulence. Two unstable phenomena can occur on bluff deck sections, such as those with plate stiffening girders. One is a motion in pure bending - called "galloping" - caused by negative aerodynamic damping at certain wind inclinations. The other, in pure torsion, is also due to negative aerodynamic damping. As will be shown, even a slender deck has little aerodynamic damping in torsion. However, since we intend to avoid such unstable deck sections, we will concentrate upon divergence and coupled flutter.

When the deck is twisted, the wind gives it both a lift force and a pitching moment. The latter tends to increase the angle of twist since the lift centre acts at the quarter point of the deck on the windward side. It is thus a negative torsional stiffness which increases with wind speed. At some critical wind speed it overcomes the torsional stiffness of the structure and buckles the deck statically. This is "divergence".

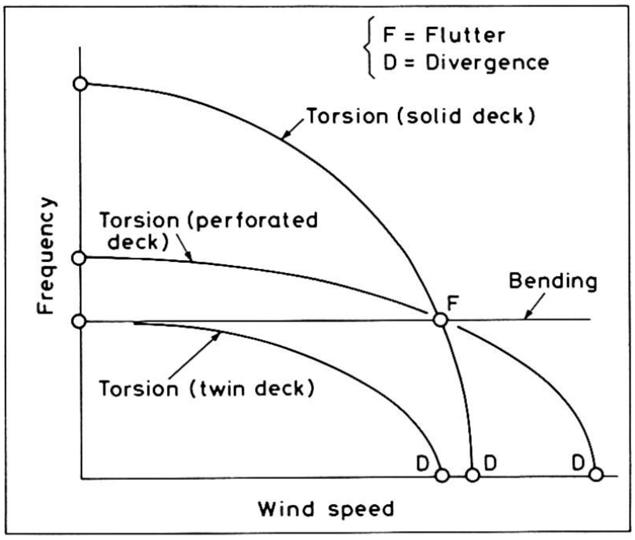

Fig.2 Flutter and divergence.

The same destabilising moment is responsible for "flutter". At wind speeds below divergence the torsion frequency is finite, but lower than that in still air (Fig.2). The bending frequency, on the other hand, remains sensibly constant because the aerodynamic forces give damping instead of stiffness forces in this mode. The two frequencies therefore coincide at a wind speed below that of divergence. Secondary forces then couple the bending and torsion modes to produce an unstable oscillation.

This simplified explanation ignores the effect of aerodynamic damping which, although a secondary force, can be significant in some circumstances.

2.3 Effect on Design

When the physical nature of the aerodynamic-structural-inertia interaction is understood, the designer has the opportunity to vary all three forces in an optimum manner to ensure bridge stability at minimum cost. First, however, practical ways of changing each kind of force must be considered.

3. STRUCTURAL STIFFNESS

3.1 Bending

Very long spans are invariably suspension bridges, whose bending stiffness and frequencies are determined naturally by gravity and the elastic properties of the cables. Secondary stiffness, provided by stay-cables or girder stiffness have a significant effect only for relatively short spans. Little opportunity thus exists to alter the bending characteristics.

3.2 Torsion

In conventional bridge design, flutter is avoided by increasing the torsional stiffness. This can be achieved in a variety of ways.

Girders attached to the deck extremities, in the manner of earlier bridges (Fig.3a), give resistance to twisting. This is obtained from warping of the deck - or differential bending of the girders - which is efficient only for very short spans. Furthermore the bending stiffness is increased in proportion, so that the frequency ratio remains essentially unchanged.

When a second lateral shear bracing, as pioneered by Steinmann, is added below the road deck, it forms a torsion truss with the side girders and the deck itself (Fig.3b). This dramatically increases the torsional stiffness, because shear rather than bending forces are involved. Since the bending stiffness is unaltered the frequency ratio is greatly improved.

Another type of lattice truss, the "monocable", has been proposed by Leonhardt (Fig.3c). In this design a triangular box is formed by a single suspension cable at the apex and the road deck at the base. The nearly vertical shear panels are provided by inclining the hangers in the manner of a Warren girder, so that they double as both strength and stiffness members. Although the "box" area increases towards the towers, the shear efficiency of the hangers is reduced in this region because they become nearly vertical to maintain a constant spanwise pitch. The torsion stiffness may therefore be lower at the towers than at mid-span.

A streamlined steel torsion box was first used by Freeman Fox and Partners on the Severn crossing (Fig.3d). It uses steel more efficiently than a truss, and owes much to aircraft practice. Nevertheless it has the same limitations as other box structures, because its depth must increase when greater spans are contemplated. Its limit-span may have been reached with the Humber bridge.

When, for other reasons, the need for torsional stiffness can be reduced, widely spaced cables present an alternative to torsion boxes (Fig.3e), as has been proposed by W C Brown of Freeman Fox & Partners. Although two towers are needed at each pier, and transverse beams to support the central road, this solution has much to commend it.

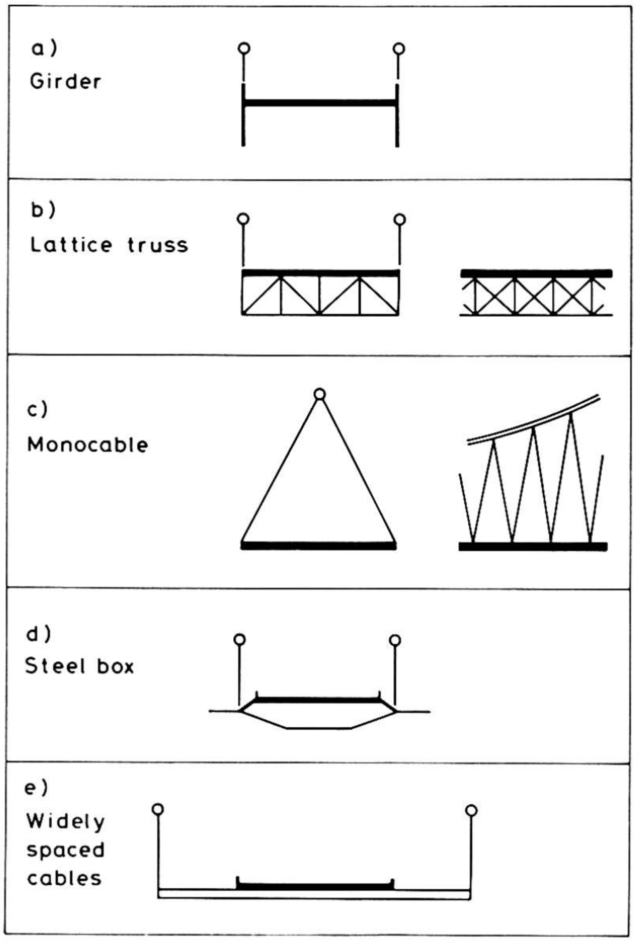

Fig.3 Types of torsional stiffening.

4. AERODYNAMIC FORCES

Since our purpose is to review the design implications of various deck configurations, we will consider only the steady or quasi-steady forces acting on the opaque segments of thin road decks. Unsteady aerodynamic effects, which reduce the lift and cause phase lags, and bluffness which causes separation of the flow will be largely ignored. Two types of force are involved. Aerodynamic stiffness is proportional to displacement and damping is proportional to velocity. The bending mode has no aerodynamic stiffness since the angle to the wind is unchanged. However, it has considerable damping, because its vertical velocity combines with the wind speed to give an effective angle of attack. The torsion mode has aerodynamic stiffness which is identical in form to that caused by bending velocity, since the deck is at an angle to the airstream. Its damping is more complex, however, because the vertical velocities increase linearly from the centre of the deck. These aerodynamic forces on various deck configurations will be described in turn.

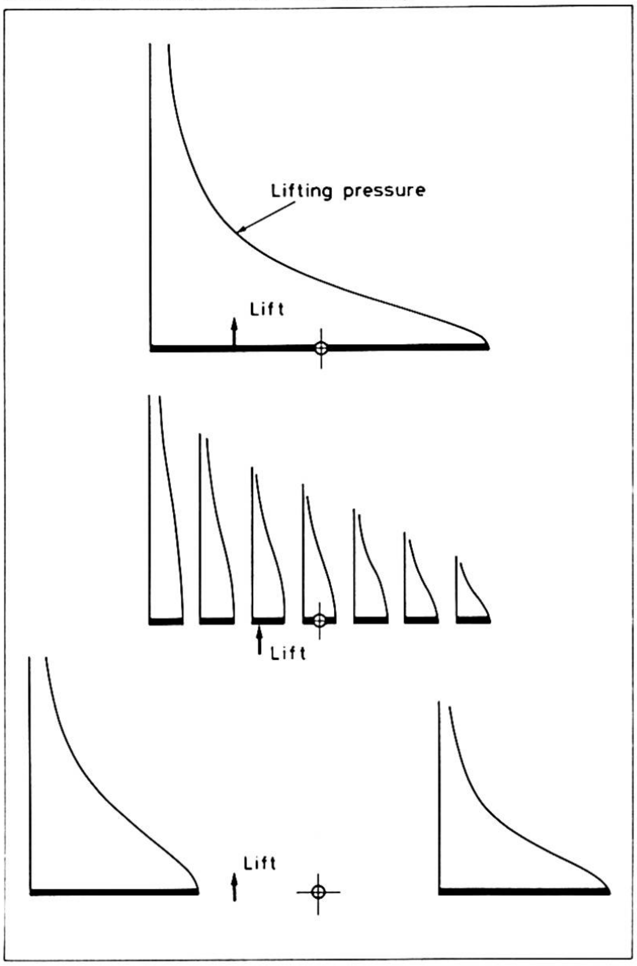

Fig.4 Lift due to pitch angle.

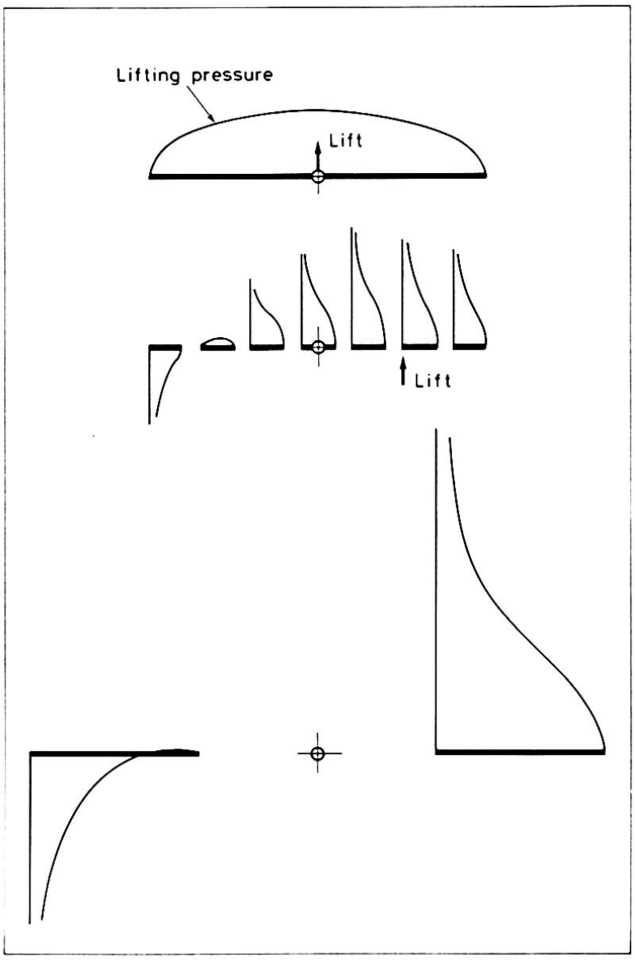

Fig.5 Lift due to pitch velocity.

4.1 Conventional Decks

A thin opaque road deck behaves like a wing. At an angle of twist, or when subjected to a vertical velocity, the wind causes lifting pressures which give both lift and pitching moment (Fig.4). The lift centre is at the quarter point of the deck and thus provides the destabilising moment discussed previously. Torsion velocity gives an elliptical lift distribution (Fig.5). This has a lift but no moment, so that the torsion damping is theoretically zero. Unsteady aerodynamic effects make this damping positive, but bluffness may have the opposite effect. The flutter speed of a conventional road deck can thus be sensitive to its aerodynamic shape.

4.2 Double Decks

On truss-stiffened bridges the lower shear bracing is often replaced by a second road deck. The aerodynamic forces on the two decks then resemble those on biplane wings. The total lift force, due to angle of twist, is reduced as the gap between the decks become less. The centre of lift, however, moves ahead of the quarter-chord so that the effect on the destabilising moment is less pronounced. Unfortunately the quasi-steady torsion damping is still theoretically zero because the lift distribution due to torsional velocity is still symmetric. This can be alleviated to some extent by separating the vertical position of the torsion and drag centres, so that horizontal velocities of the deck contribute to its torsional damping [3].

4.3 Perforated Decks

Although small aerodynamic slots have been used on many bridges, the idea of a true perforated deck is due to W C Brown. Experimental and theoretical work at NMI [4,5] has uncovered some important facts about this concept. When multiple slots are introduced in a thin road deck the lifting force due to wind inclination is reduced directly in proportion to the deck "solidity". Furthermore, the centre of lift is moved closer to the midchord so that the moment is proportional to the square of the solidity. Thus, with a typical solidity of 70%, the destabilising moment is reduced to 49% of that of a solid deck (Fig.4). This means that the torsional frequency can be reduced to maintain the same flutter speed (Fig.2).

An additional advantage of deck perforations is that positive damping occurs in the torsion mode. The lift distribution due to pitch velocity (Fig.5) is no longer symmetrical, having a downward force on the windward side.

4.4 Twin Decks

A logical extension of the perforated deck is the twin deck. When the two traffic carriageways are separated laterally, leaving a huge "slot" between them, some remarkable aerodynamic effects take place [6]. In an inclined wind the lift distribution gives exactly the same total lift and moment as the unseparated decks. The lift centre is unaffected by the separation (Fig.4).

Pitch velocity, however, results in a very different lift distribution to that of a solid deck (Fig.5). The windward deck has a large downward force on it, so that the aerodynamic damping in the torsion mode is highly positive.

The implications of these facts will be described in later sections of this paper.

5. INERTIA FORCES

Bridge decks are symmetrical and must be stable in winds blowing from either direction. The opportunity to shift the mass centre to the windward side, and thus prevent flutter by "mass balancing" as on aircraft, is therefore severely limited. During the construction phase of the Humber bridge, the author's suggestion of temporary water bags on each side of the deck, one of which could be drained when the direction of a high wind was known, proved successful. Such a measure for a completed bridge would, however, add to the dead load.

The radius of gyration of the mass in the torsion mode is therefore the only inertia parameter which can be varied by the designer. On a conventional bridge this is invariably less than half the distance between the cables, so that the still air torsion frequency is always higher than that of bending, even without a torsion box. If the radius of gyration could be increased to lower the torsion frequency to that of bending, flutter (but not divergence) could be eliminated. Unfortunately, this leads to nearly zero damping of the torsion mode on a conventional deck. However, a perforated or twin deck does not suffer from this problem when the still air frequencies coincide, because each has an inherent damping in torsion.

6. FUTURE DESIGN

A variety of means of controlling the aerodynamic, inertia and structural stiffness forces independently have been presented. When individual possibilities are combined together, a number of new forms for stable large-span bridges emerge. Three of these will be described.

6.1 The Proposed Tsing-Ma Bridge

The design of this bridge was recently completed by Mott, Hay and Anderson, as part of the system to join Lantau Island to the mainland in Hong Hong. Its deck structure is a conventional lattice-truss designed to carry motor traffic and commuter trains on two levels. Streamlined fairings cover the ends of the truss to reduce the drag and vortex excitation, and large aerodynamic slots are provided under the railway lines and between the carriageways on the upper deck (Fig.6). Its aerodynamic characteristics are thus a combination of the double and slotted decks. Tests at NMI Ltd [7] proved it to be stable in typhoon winds.

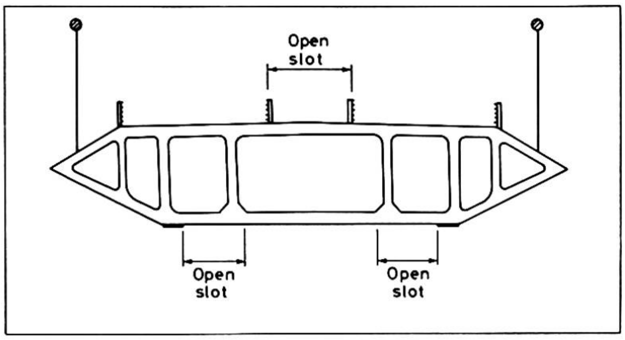

Fig.6 The Tsing-Ma design.

6.2 The Proposed Messina Bridge

Freeman, Fox and Partners have combined the principles of the perforated deck and widely spaced cables in a design for a bridge across the Messina Straits with a mainspan of 3300m (Fig.7). The central roadway contains multiple slots which are covered by grills, and is supported on transverse beams connected to the hangers. Twin railway tracks under the road are braced to the crossbeam extremities by stay cables. Since the deck has no significant torsional stiffness, twisting is resisted by the widely spaced suspension cables. Despite the the fact that its bending and torsion frequencies are much closer together than is usual, the bridge has been shown to be stable in high winds because the deck slots reduce the destabilising aerodynamic moment (Fig.2).

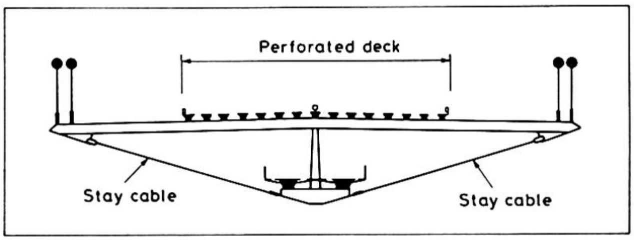

Fig.7 The Messina Straits design.

6.3 Twin Bridges

The twin-bridge (Fig.8), as yet only a design concept [6], uses the physical properties of all three types of force to give aerodynamic stability. Torsional stiffness is provided by widely spaced cables. The radius of gyration of the deck is raised by suspending each half under one of the (pairs of) cables, leaving a large gap between them which is traversed by crossbeams at intervals along the span. This equalises the bending and torsion frequencies. The separation of the deck halves does not increase the destabilising aerodynamic moment, so that the divergence speed is not affected. However, it provides considerable aerodynamic damping in torsion. Flutter is therefore completely eliminated by the frequency coincidence (Fig.2), without incurring the serious consequences of poor torsional damping.

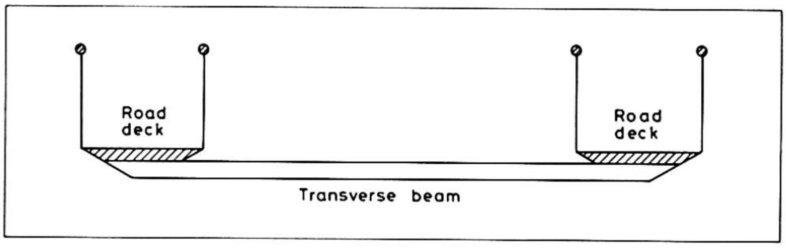

Fig.8 The twin-bridge concept.

The advantage of such a design is that the road decks can be shallow and light in weight, thus reducing the amount of steel required in the cables.

7. CONCLUDING REMARKS

A recent trend in bridge design is to seek better aerodynamic forms for the road deck, to avoid providing heavy torsion boxes which become increasingly uneconomic as longer spans are contemplated. Modifications to the inertia properties can also be used to advantage. Future bridges of much greater length are now possible, but they will look very different from current designs.

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