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Wind Tunnel Tests of Long Span Bridges

Essais en soufflerie sur des ponts de longue portée

Windkanalversuche an Brücken mit grosser Spannweite

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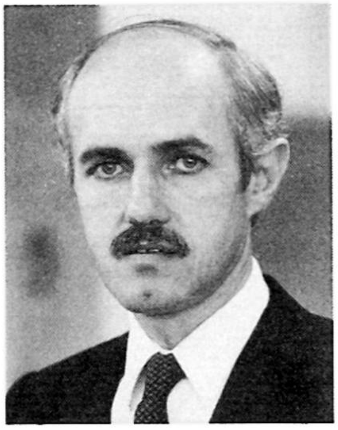

Peter Irwin was born in 1945, obtained his aeronautical engineering degree at the University of Southampton, U.K. and his Ph.D. from McGill University, Montreal, Quebec. Since 1974 he has been involved in research and consulting in wind engineering, first at the National Research Council, Ottawa, and, since 1980, at the wind tunnel laboratories of Morrison Hershfield Limited.

SUMMARY
Recent experiences in wind tunnel testing a number of long span bridge projects are described. These experiences include the aerodynamic stability of plate girder decks, the use of baffle plates and other methods to eliminate vortex excitation, the effects of wind turbulence, the effect on flutter of offset centre of rotation for torsional oscillations, the use of part-span fairings, and the effectiveness of tuned-mass dampers.

RESUME
Des expériences récentes lors d'essais en soufflerie sur des ponts de longue portée sont décrites. Ces expériences concernent la stabilité aérodynamique des tabliers, l'emploi de revêtements insonorisants et d'autres façons de lutter contre les effets des tourbillons, l'effet sur la stabilité aérodynamique d'un centre de rotation compensé pour les oscillations de torsion, l'emploi de profilés de travée partielle, et l'effet des amortisseurs de vibration.

ZUSAMMENFASSUNG
Die neuesten Erfahrungen aus den Windkanalversuchen mit einer Anzahl Brücken grosser Spannweite werden beschrieben. Die Erkenntnisse umfassen die aerodynamische Stabilität der Fahrbahnplatten von Balkenbrücken, die Verwendung von Prallplatten und anderer Vorkehrungen für das Vermeiden von Resonanzschwingungen, den Einfluss von Turbulenzen, die Auswirkung einer Verschiebung des Drehpunktes auf die Torsions- und Biegeschwingungen, die Wirkung einer strömungsgünstigen Verkleidung und die Wirksamkeit einer abgestimmten Dämpfungsvorrichtung.

1. INTRODUCTION

The object of this paper is to record some of the more interesting findings that have emerged from various wind tunnel tests that the author has been involved with including the new Annacis Island cable-stayed bridge near Vancouver[1]. The wind tunnel tests have ranged from simple sectional model tests in smooth uniform flow to full aeroelastic model investigations with wind turbulence simulated. One general observation is that the behaviour of a particular bridge in strong winds is influenced by many factors: overall deck shape; edge details; natural frequencies; deflection shapes of the modes of vibration; structural damping; the mass distribution of the deck and other major components; wind turbulence; height above the water; local topography; adjacent bridges; snow and ice accumulations; and alignment of the bridge relative to the most probable strong wind directions. The following selected experiences illustrate how some of the above mentioned factors have come into play in particular cases.

2. NOTATION

b	= width of deck	r	= offset of centre of rotation
I	= moment of inertia per unit length	r_G	= radius of gyration
U	= mean wind speed	R	= r for sectional model
u'	= rms value of wind speed	m	= mass per unit length
ζ	= damping ratio	N_V	= vertical frequency
ρ	= air density	N_T	= torsional frequency

3. USE OF PLATE GIRDERS ON ANNACIS ISLAND BRIDGE, VANCOUVER

Some bridge decks with plate girders have experienced serious aerodynamic instabilities. However, in the right circumstances they can have more than an adequate stability. Data on plate girder sections indicate that shallow girders and a girder location inboard of the deck edge are preferable aerodynamically and these concepts were applied to the new cable-stayed, 465 main span, Annacis Island Bridge [1,2]. Figure 1 shows the torsional response for three of the various cross-sections tested in Morrison Hershfield Limited's Guelph wind tunnel using 1:60 scale sectional models [1]. Cross-section 1 possessed the best aerodynamic stability but was less efficient structurally than cross-section 2 on which the cables could be directly attached to the girders. As can be seen in Figure 1 the torsional stability of cross-section 2 was not as good as for 1. However, by increasing the depth of the vertical plate at the extreme edge of the deck, as in cross-section 3, the torsional stability was significantly improved. This was attributed to the edge plate acting as a wind deflector that assisted the smooth passage of the flow around the bottom of the girder. The onset of torsional instability for cross-section 3 began at a nondimensional wind speed of 3.0 but was limited to an amplitude of less than 1 degree. This initial instability was attributed to vortex excitation. The strong flutter type of instability did not begin until a non-dimensional speed of 4.5. Both cross-sections 1 and 3 had sufficient aerodynamic stability for the site. Tests in turbulent wind indicated the torsional instability was not greatly altered by turbulence. The optimum shape, cross section 3, thus resulted from simultaneous considerations of structural economy and the aerodynamics of both the overall deck shape and edge details. In another paper in this conference, Taylor [2] describes the evolution of the Annacis design in more depth.

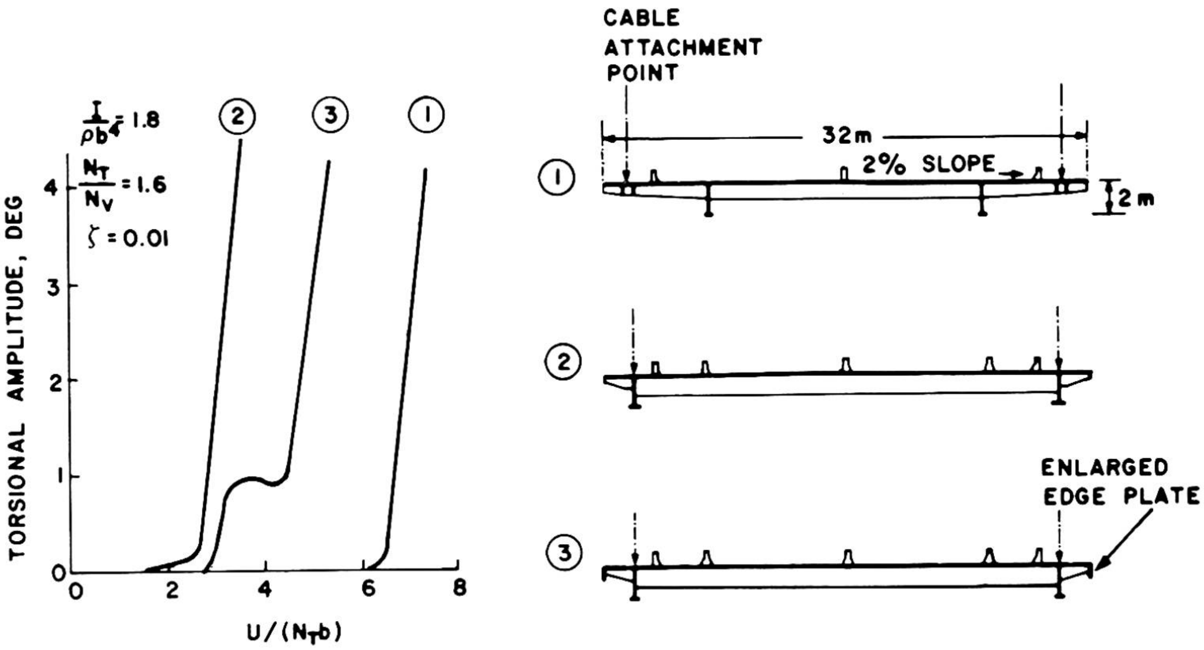

FIGURE 1 - TORSIONAL RESPONSE OF ANNACIS ISLAND BRIDGE

4. USE OF BAFFLE PLATES ON THE PROPOSED DAMES POINT STEEL BRIDGE

The evolution of the final steel version of Dames Point Bridge, Jacksonville, Florida, in Figure 2 took place in the course of sectional model tests in smooth flow at the National Research Council, Ottawa [3]. Although a number of details of the cross-section contributed towards providing good aerodynamic stability, the most important were the vertical baffle plates at approximately the 1/4-chord position under the road deck. These broke up vortices that otherwise tended to form under the deck on the original cross-section, as illustrated in Figure 2, and greatly reduced vortex excitation. Furthermore they provided a 40% increase in the critical wind speed for the onset of flutter. The baffle plate principle has subsequently been tested in other investigations for the Annacis Island bridge [1] and the Thousand Islands Bridge [4], and again found to be very beneficial for aerodynamic stability.

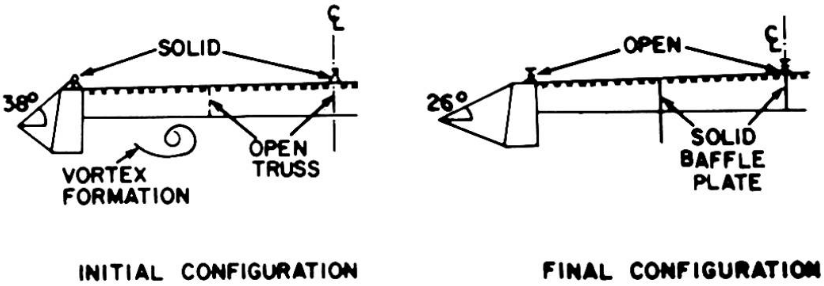

FIGURE 2 - DAMES POINT BRIDGE CROSS-SECTIONS

5. EXAMPLES OF THE EFFECTS OF WIND TURBULENCE

The importance of wind turbulence for aerodynamic stability was first brought to the fore by Davenport, Isyumov and Miyata [5] and then was strikingly illustrated on a 1:110 scale full aeroelastic model of Lions Gate Bridge, Vancouver [6]. Figure 3 shows the torsional response of the model which represented a modified version of this existing truss-stiffened bridge. Two experimental curves are shown, one for smooth wind and one for an accurately simulated natural wind with turbulence intensity $u'/U = 0.11$. It can be seen that the torsional response in smooth wind exhibited a sudden flutter instability at a nondimensional wind speed of $U/(N_t b) = 6.5$, similar to that observed in smooth flow sectional tests [7], whereas in the turbulent wind the instability was not evident. Clearly, in this case the neglect of turbulence would have led to overly pessimistic results for the torsional stability.

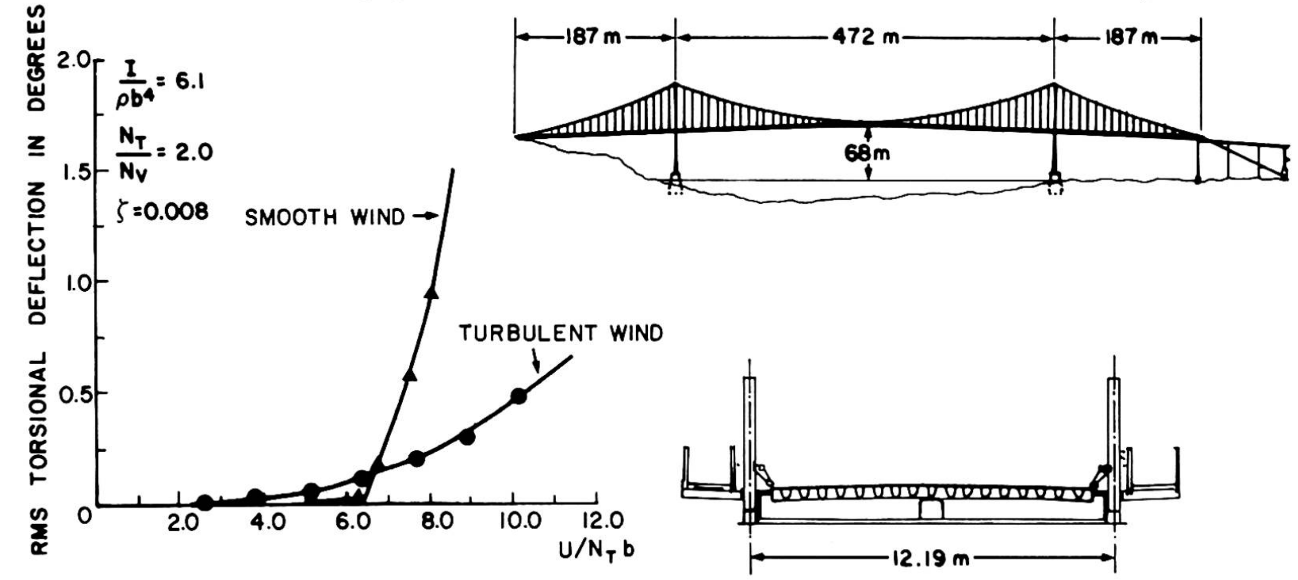

FIGURE 3 - EFFECT OF WIND TURBULENCE ON LIONS GATE BRIDGE

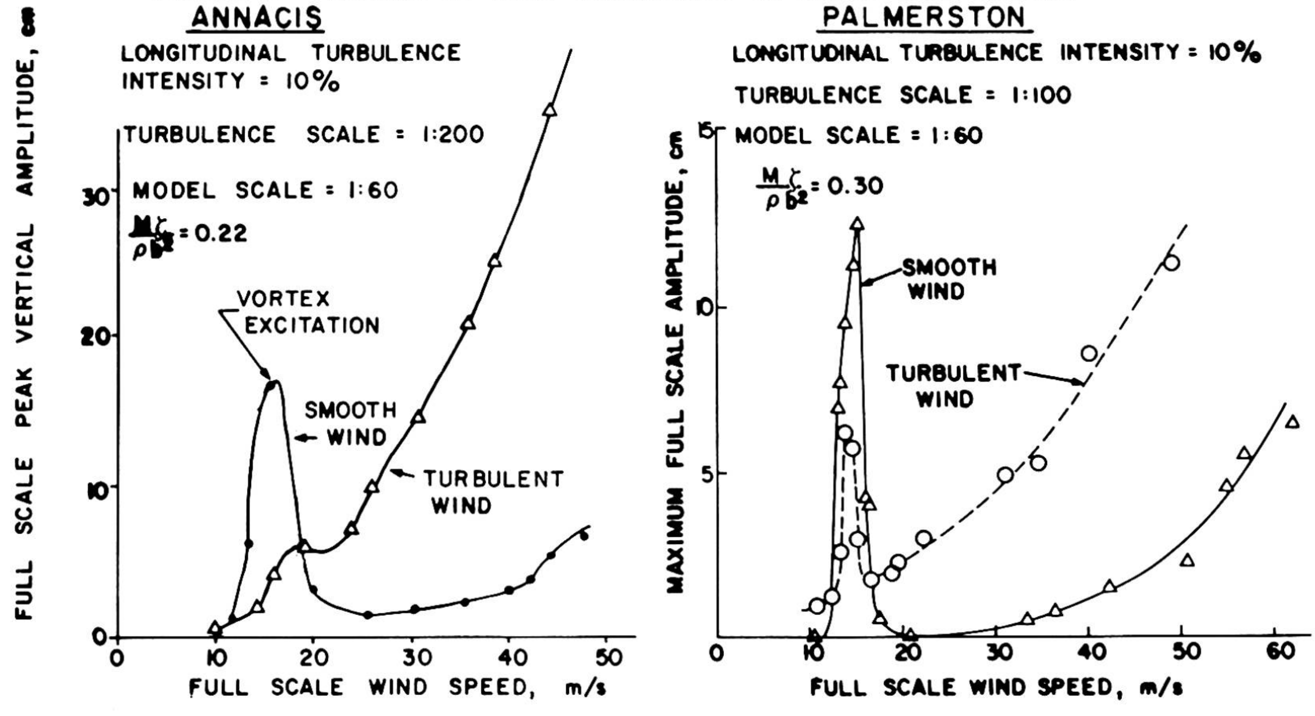

FIGURE 4 - EFFECT OF TURBULENCE ON VORTEX EXCITATION

Examples of the effect of turbulence on vortex induced vertical oscillations of models of the Palmerston girder bridge, Pugwash, Nova Scotia [8] and the Annacis Island bridge [1] are shown in Figure 4. The cross-section of the former bridge is shown in Figure 5. It is evident that turbulence has a significant mitigating effect on the vertical excitation of these decks. However, the Longs Creek bridge [9], which has a plate girder deck with similar overall dimensions to the Palmerston Bridge, is an example of serious vortex excitation actually occurring at full scale, indicating turbulence cannot be relied upon to quell vortex excitation in all cases. One contributing factor for Longs Creek may well have been the light weight and low damping of the steel deck. Figure 5 includes additional results from the Palmerston Bridge tests where the effect of varying the mass damping parameter, $m\zeta/\rho b^2$, was investigated. It is clear that the effect of turbulence is far less pronounced for low mass damping parameters and the Longs Greek value of m / b^2 would not have provided a very significant alleviation of vortex-induced oscillations. It is worth noting that both these decks were significantly affected by the proximity of the water surface.

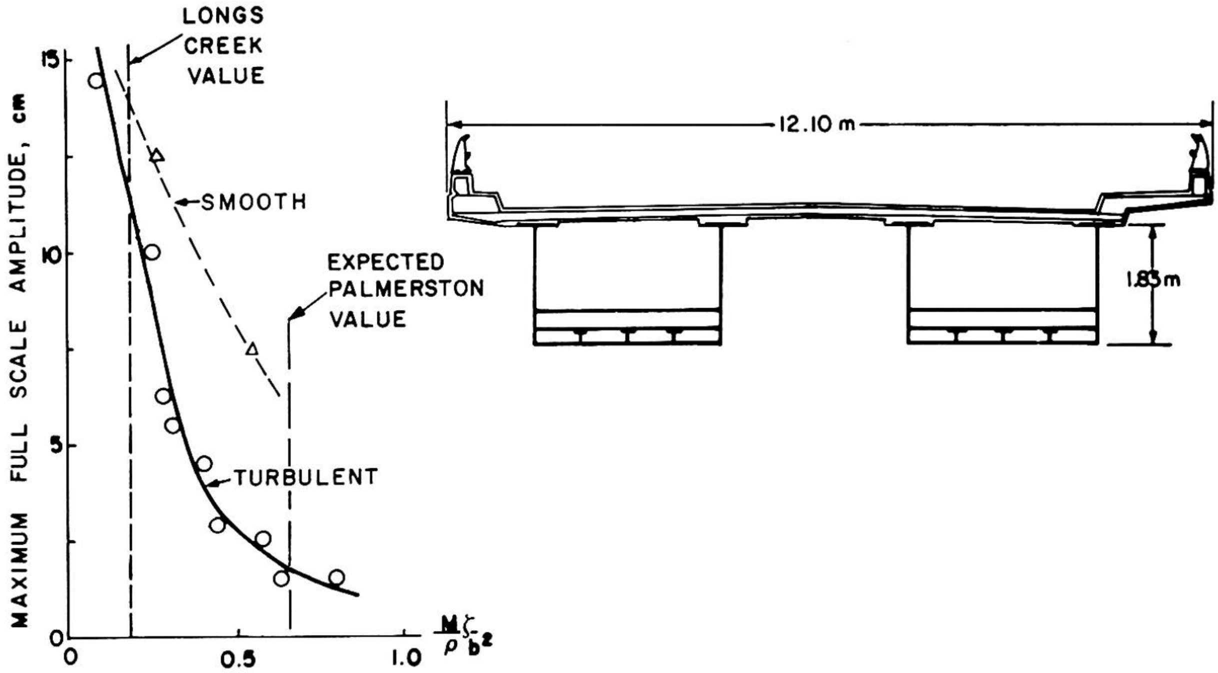

FIGURE 5 - PALMERSTON BRIDGE CROSS-SECTION AND EFFECT OF MASS-DAMPING PARAMETER

This section has discussed the effect of wind turbulence on stability. However, in high winds even a stable bridge is excited to large motions by the buffeting action of wind turbulence. Theoretical methods for computing the dynamic loads induced by buffeting are described in References 6 and 10. They involve a number of empirical assumptions and are therefore best used in conjunction with a wind tunnel investigation.

6. SIMILKAMEEN ORE CONVEYOR BRIDGE

Figure 6 illustrates this 396m span conveyor bridge. Sectional model tests [11] in smooth wind indicated that the bridge would experience vertical oscillations due to vortex excitation. These were eliminated on the model by cutting slots in the conveyor cover walls and removing short sections of the cover roof at line-stands as illustrated in Figure 6. The effect of various width wall slots on the response is shown in Figure 7. The ratio of open area to total cover area, as seen in elevation normal to the span, was 42% in the final configuration. The object of the cover was to prevent the conveyor belt being blown off its runners. It was verified in the tests that even with the openings in the cover it would still perform this function satisfactorily. An important factor for this structure was the large contribution to the overall oscillating mass that came from the cables and towers. This helped to reduce vertical oscillations and for torsional motion eliminated all forms of instability.

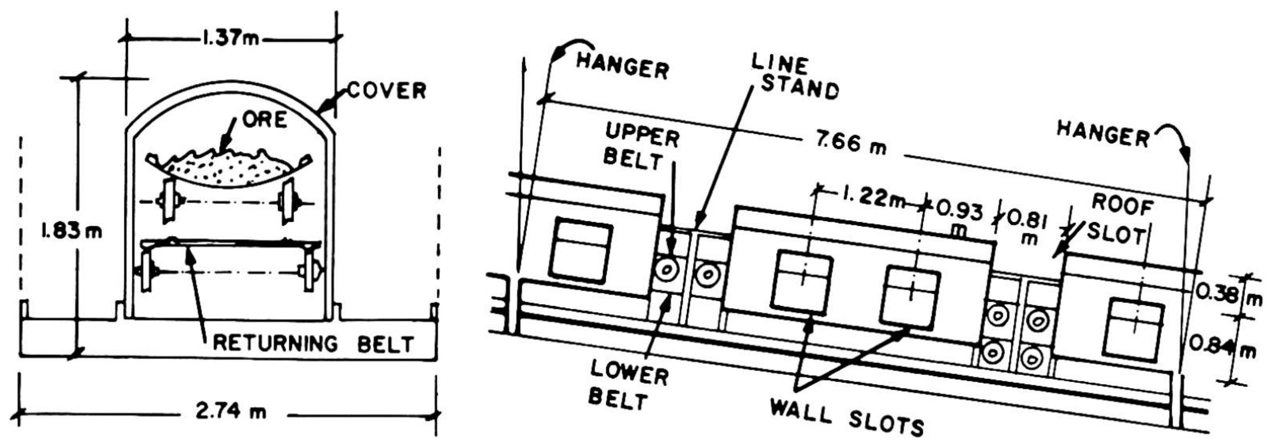

FIGURE 6 - 396m SIMILKAMEEN SUSPENDED ORE CONVEYOR BRIDGE

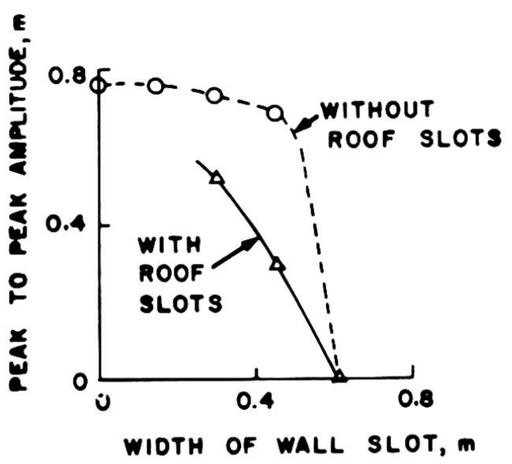

FIGURE 7 - EFFECT OF SLOTS ON SIMILKAMEEN BRIDGE

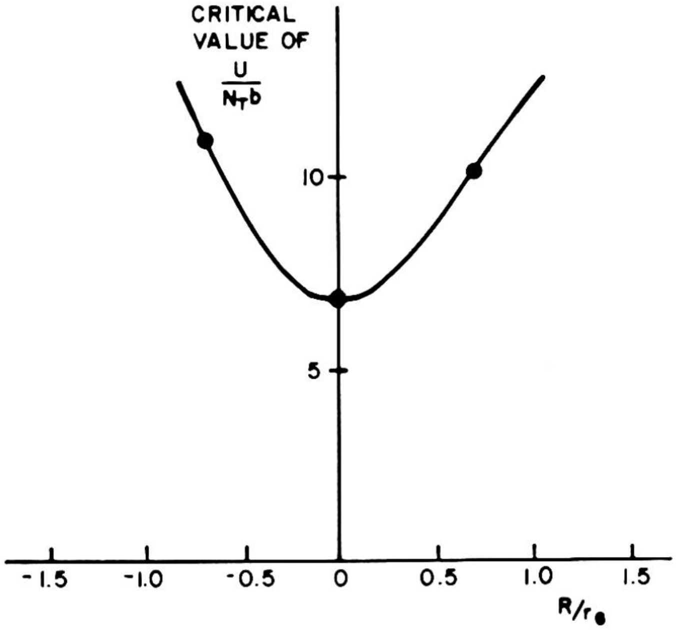

FIGURE 8 - CENTRE OF ROTATION EFFECT ON ON ORIGINAL LIONS GATE BRIDGE

7. EFFECT OF CENTRE OF ROTATION FOR TORSION

For bridges where the shear centre of the deck cross-section is substantially above or below the centre of mass the modes of vibration involving twist and horizontal motion normal to the span can no longer be classified as pure torsional or horizontal modes. Each mode involves simultaneous torsional and horizontal motions and this affects the aerodynamic stability. This type of motion can, however, be thought of as pure torsional motion, if the centre of rotation is taken to be an appropriate distance, r, above (or below) the deck centre of mass. Since r usually varies along the span, to simulate the centre of rotation effect on a sectional model it is necessary to select a representative single value for r which is denoted by R. Reference [11] gives an expression for calculating R. Figure 9 shows the effect of centre of rotation on the torsional instability of the original Lions' Gate Bridge [7, 12] in smooth wind. Since R/r_G was 1.05 for the first symmetric mode the critical wind speed can be seen in Figure 9 to be increased by 40% compared with $R/r_G = 0$. This illustrates how important the centre of rotation can be for some decks.

8. USE OF PART-SPAN FAIRINGS

Wind tunnel tests to develop fairings, an extensive topic in itself, have usually been done on sectional models (e.g. References 1, 3, 5, 7, 8, 9) which cannot be used to accurately assess the use of fairings on only part of the bridge length. However, in the full aeroelastic tests on Lions Gate Bridge [6] the use of part-span fairings was investigated. Figure 9 illustrates how fairings on only about one-eighth of total bridge length were very effective in eliminating torsional instability on one version of this bridge. The fairings were located on the centre section of the main span. Theoretical estimates [1] indicate that when fairings are used they need only be put along portions of the span where the amplitude is highest.

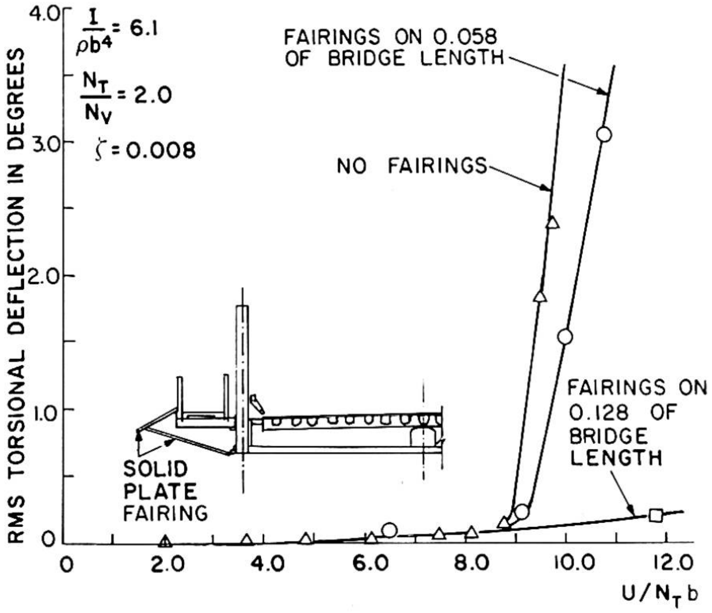

FIGURE 9 - EFFECT OF PART-SPAN FAIRINGS, LIONS GATE BRIDGE

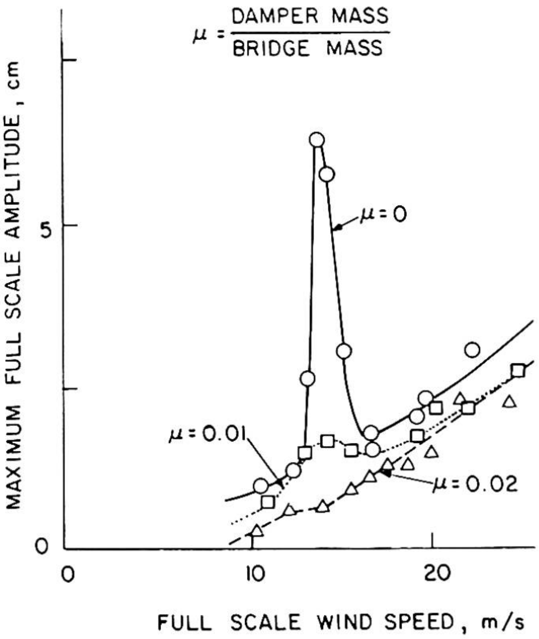

FIGURE 10 - EFFECT OF TUNED MASS DAMPER, PALMERSTON BRIDGE

9. EFFECTIVENESS OF TUNED MASS DAMPERS

A tuned mass damper consists of a damped mass spring system with a natural frequency nearly equal to that of mode of vibration it is desired to damp. The ratio of damper mass to bridge mass is denoted here by μ . Figure 10 shows the great effectiveness of a tuned mass damper in quelling vortex excitation on the Palmerston Bridge model [8] in turbulent wind.

10. CONCLUSION

The foregoing observations illustrate some of the many factors that affect a bridge's aerodynamic stability. It is important to consider the likely effects of as many of these factors as possible since any one of them may emerge as dominant for a particular bridge.

Acknowledgements

There would not be space to acknowledge individually all the numerous contributions from others in the various wind tunnel investigations. These came from the bridge authorities, the structural engineers, co-authors and other colleagues. However, the author particularly benefited from discussions with R. L. Wardlaw while at the National Research Council. Also, many valuable inputs came from P.G. Buckland and P. R. Taylor of Buckland and Taylor Ltd. during the investigations for the Lions Gate, Similkameen and Annacis Island bridges.

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