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Sectional versus full model wind tunnel testing of bridge road decks*

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Abstract. This paper reviews fundamental aspects of modelling procedures and bridge road deck behaviour with a view to appraising the advantages and disadvantages of the sectional, taut-strip and full model approaches. It is concluded that in the present state of the art, there is a time and place for each technique; which investigative procedure or combination of procedures is used will depend on a variety of considerations—the size of the bridge, the road deck configuration and the lead time available.

Keywords. Wind tunnel testing; bridge road decks; industrial aerodynamics.

1. Introduction

Through technological and engineering advances bridge road decks have been made lighter and structural damping has been reduced; consequently the modern intermediate and long span bridge has become more responsive to wind action. Today the avoidance of high stress levels and large amplitude motion as a result of dynamic behaviour in wind is, more than ever, a major consideration for the design engineer.

In a presentation to the First Research Progress Review in San Francisco in 1973 the present author discussed some of the aerodynamic considerations in bridge design and reviewed the state-of-the-art of wind tunnel investigation (Wardlaw 1973, 1975). It was pointed out, at that time, that we had '....not reached a point where the behaviour (of bridge road decks) as a result of wind action can be satisfactorily predicted by analytical means.' Attention was drawn to certain gaps in our knowledge, particularly, the effects of turbulence and terrain. Also stressed was the need for more extensive investigations of the motion of completed structures, in order to obtain more information on structural damping levels and, more importantly, to provide a basis for the comparison of model and full scale measurements.

While these problems have not been entirely resolved it is gratifying to be able to comment that significant progress has been achieved in all areas as a result of both field and laboratory investigations in several countries including Australia, Canada, Japan and the United States. Therefore, it is timely to attempt once more to bring into focus for the practising engineer some of the implications these advances have on our techniques and approaches to wind tunnel investigations. Certainly, the question to which this paper is addressed, sectional versus full model testing, deserves re-examination; however, it should be made clear at the outset that unanswered questions remain and the final chapters cannot yet be written.

The principal contemporary issue in need of discussion is that of the effects of the gustiness or turbulence in the earth's surface wind on the bridge dynamic behaviour. Quite apart from the effects of turbulence on aerodynamic stability the adequacy of the traditional gust factor approach for estimating peak wind loads in turbulent wind must be challenged. Several questions arise:

(i) Does testing in smooth flow give excessively conservative estimates of aerodynamic stability in the natural wind?
(ii) Can dynamic behaviour in the natural wind be predicted from results obtained with sectional models in smooth flow using analytical procedures as proposed by Scanlan (1975) and Scanlan & Gade (1977)?
(iii) Can the earth's surface wind be adequately modelled in the wind tunnel?
(iv) Can the modelling of the bridge itself at reduced scale be carried out with enough precision?
(v) Finally, do the advantages of the sectional model approach—low cost, large scale, configuration flexibility, and short lead time for model preparation—have to be sacrificed for the advantages of the full model—simulation of the natural wind, inclusion of three-dimensional aeroelastic effects, and inherent modelling of the bridge modal dynamics?

These and other questions relating to wind tunnel investigations of bridge behaviour will be examined in this paper. A compromise approach between full model and sectional model techniques, the taut-strip approach advocated by Davenport (Davenport *et al* 1971; Davenport 1972) will also be discussed. The emphasis throughout the paper will be on dynamic behaviour as opposed to static or mean wind load effects.

The early history of bridge failure in wind and the development of investigative techniques was briefly reviewed in Wardlaw (1973). Some of the basic aspects of the relevant aerodynamic fundamentals and testing methods were reviewed in the same paper and in more depth in a review paper prepared by Scanlan (1975) for the Federal Highway Administration; this latter paper also outlined analytical considerations in predicting bridge dynamic behaviour. The literature in the field is quite extensive and, rather than attempt a complete review, the reader is referred to the papers cited in Wardlaw (1973) and Scanlan (1975). It will be worthwhile, however, to re-examine certain aspects of the problem that bear closely on the question of wind tunnel testing technique.

2. Wind tunnel testing techniques

2.1 *The full model*

The full model is a reduced scale geometric facsimile of the entire prototype bridge that includes all structural elements, the towers, the suspension cables, the road deck and the road deck hangers. For dynamic studies, it is necessary, as well, to model the mass, the mass distribution and the elastic characteristics of the prototype according to well-established scaling principles. The scale ratio for a long span bridge may be very small; for example, the model of a 3000 ft (915 m) long bridge would have to be constructed at a scale ratio of about 1 : 400 if it were to be tested in an 8 ft (2·44 m) wide wind tunnel test section. Clearly large reductions in size will introduce difficulties in model design. Components become very small and it may become awkward to construct or assemble the model in a replica fashion. Figures 1 and 2 (plates 1 and 2) show a 1 : 110 scale full model in the National Aeronautical Establishment 30 ft × 30 ft (9·14 × 9·14 m) wind tunnel of a proposed widened version of the Lions' Gate Bridge that crosses the Burrard Inlet at Vancouver, British Columbia. In the background in figure 1 (plate 1) can be seen aerodynamic 'spires' at the entrance to the test section that are designed to generate the shear and turbulence properties of the earth's surface wind. Depending on the roughness of the terrain at the bridge site the wind layer will be between about 1000 (305 m) and 2000 feet (610 m) deep and consequently at a scale of 1 : 110, the wind layer will be between 9·1 ft (2·77 m) and 18.2 ft (5·54 m) deep in the wind tunnel.

2.2 *The sectional model*

The expression 'sectional model' derives from the aeronautical engineer's practice of measuring the two-dimensional or sectional properties of aerofoils in wind tunnels by using constant section models that span the test section.

Rather than model the complete bridge, the aerodynamics of the bridge road deck can be studied by constructing a model that represents a short, mid-span section of the deck. The model spans the test section and is supported rigidly at the walls if force measurements are to be made or is mounted on pairs of springs for dynamic measurements (figure 3) in which case the mass, the mass distribution and the elastic properties must be modelled according to scaling criteria as is done with the full model. The bending mode natural frequency is controlled by the spring stiffness and the ratio of the bending to torsional mode frequencies is controlled by the spacing between the pairs of springs. If necessary the horizontal stiffness can be modelled by the addition of a spring constraint in the lateral direction. A 1 : 30 scale sectional model of the Long's Creek Bridge, a cable-stayed bridge on the Trans-Canada Highway in New Brunswick, that was tested in the National Aeronautical Establishment 15 ft (4·57 m) diameter vertical wind tunnel is shown in figure 4 (plate 3). The junction between the ends of the model and the wall introduces three-dimensionality into the flow and in order to minimize this 'end effect' it is desirable to have the model as slender as is practicable and a span-to-chord ratio of 1 : 4 would be

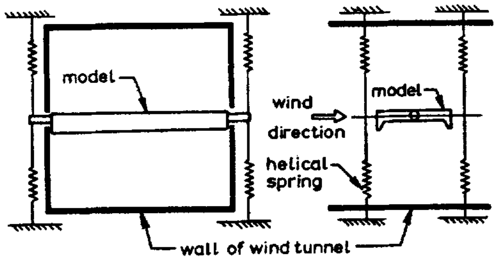

Figure 3. Section model suspension system

acceptable. The slenderness of the model is limited by it being strong enough to resist significant deformation when in motion and by the desirability of large scale. For testing in an 8 ft (2·44 m) wide test section a model chord of 2 ft (0·61 m) would be suitable and for a 100 ft (30·5 m) wide prototype this would give a scale ratio of 1 : 50.

The simpler concept of the sectional model and its larger scale result in a much less expensive model than the full model and one that can be built more quickly and can be quickly modified for examining corrective configuration changes. Although the air flow can be made turbulent by, for example, the use of coarse upstream turbulence grids, it is not fundamentally possible to simulate all of the natural wind properties, particularly the physical size of the gusts, the so-called turbulence scale. Research, such as is underway at the Colorado State University (Cermak *et al* 1979), aimed at the development of large longitudinal scale two-dimensional 'turbulence' should lead to a useful research and development tool for sectional model studies.

Although the road deck response to natural wind turbulence cannot be obtained directly, the prospect remains of predicting the response by analytical procedures such as those being developed (Scanlan 1975; Scalan & Gade 1977) which make use of sectional aerodynamic measurements made in smooth flow. Success with this approach would result in an ideal method for predicting bridge behaviour in natural wind. Formidable hurdles must be overcome before success is realized. For example, one question that must be resolved is the applicability to bridge road decks of the aircraft aerodynamicists classical strip theory, in which an aerofoil is divided into thin chordwise strips that are assumed to behave independently so that the overall aerofoil performance can be calculated by spanwise integration. Some alternative or modification to this technique may have to be devised.

It is quite common for slender elastic structures, as a consequence of their cross-sectional geometry, to be aerodynamically unstable in that energy is extracted from the airstream and oscillatory motion of the structure results. As will be discussed later, there are different aeroelastic mechanisms that may account for the instability. In some cases the phenomenon is amplitude-limited and although excessive stress levels may not result, the bridge road deck will still be considered unacceptable from a user point of view (Wardlaw & Buckland 1972). Other mechanisms can result in dramatic motion that reaches catastrophic levels in a small number of motion cycles.

It has become a conventional practice to use the spring-mounted sectional model in smooth flow to establish the susceptibility of road decks to aerodynamic instability. For amplitude-limited excitations, it must be established that amplitudes will not exceed a prescribed criterion of acceptability. As discussed in Wardlaw & Buckland 1972, the acceptable level of amplitude will depend on the probability of occurrence at the bridge site of the wind speeds at which the motion occurs and upon the natural frequency of the deck mode excited. For the catastrophic category of imstabilities it must be established that the motion will only occur at wind speeds above those that can be expected at the site. Experience todate, both in the field and in wind tunnel practice has corroborated the hypothesis that the sectional model approach will be conservative in predicting the occurrence of instabilities on prototype bridges. There have been no observations of unacceptable aerodynamic instability of prototype bridges in those cases where the road decks have been wind tunnel-tested in smoth flow in advance of construction. There are several examples, The Golden Gate Bridge (Vincent 1958), the original Tacoma Narrows Bridge (Farquharson *et al* 1950-54) and the Long's Creek Bridge (Wardlaw 1971) that were not tested in advance of construction and turned out to be aerodynamically uns table. In these cases, subsequent wind tunnel studies in smooth flow confirmed the existence of the instabilities and demonstrated that the problems could have been circumvented if the wind tunnel testing had been done in advance.

2.3 *The taut-strip model*

For this technique, that has been developed by Davenport and his co-workers (Davenport *et al* 1971; Davenport 1972), the road deck model is attached to two parallel taut wires suspended across the wind tunnel test section (figure 5). The vertical and horizontal bending mode natural frequencies are controlled by the wire tension while the ratio of the bending mode to torsional mode natural frequencies is controlled by the separation between the wires. Davenport *et al* (1971) suggest that the wires be at the level of the bridge road deck shear centre. The dynamic motion of the model will be primarily in the fundamental half-wave modes. As with the other modelling concepts the scaling of the mass and the mass distribution has to be correct.

The advantages sought by this approach over the sectional model are that the model behaviour can be observed in an appropriately simulated wind and the three-dimensionality of the model deformations are inherently included. At the same time the model is simpler in concept than the full model and to some extent retains other advantages of the sectional model.

With the taut-strip concept, the model scale is constrained not so much by the size of the prototype bridge but by how deep a wind layer, and hence how large a turbulence scale can be accommodated in the wind tunnel to be used. It is practical to think in terms of wind layer depths that are about one-half the height of the wind tunnel test section. Therefore, in an 8 ft (2·44 m) high test section, a 4 ft (1·22 m) deep wind layer could be developed representing a 1000 ft (305 m) deep full scale

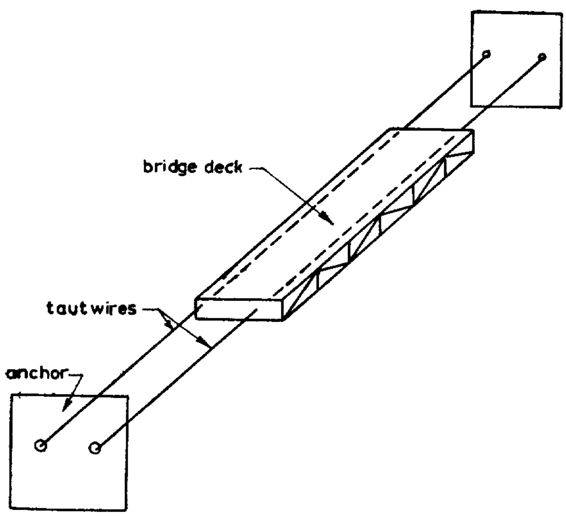

Figure 5. Taut-strip model suspension

layer at a scale ratio of 1 : 250. If the model were to be installed in an 8 ft (2·44 m) wide test section the half-wave could represent as much as 2000 ft (610 m) of bridge road deck at prototype scale. While the taut-strip model may offer some advantage in scale over the full model it will still be much smaller than the sectional model.

3. Model scaling considerations

3.1 *Scaling parameters*

Model scale observations can only be extrapolated with confidence to prototype scale if sound scaling principles have been applied in the design of the model and the experiment. This will ensure that the relative magnitudes of the various forces involved in the bridge dynamics—the gravitational, inertial, aerodynamic, elastic and structural damping forces—will be the same for the model and the prototype and that the motion amplitudes will be in the same proportion as the geometric scale ratio. As will be shown, the scaling of different physical variables will not always be compatible and judicious relaxations of one or more of the dimensionless scaling parameters will be required after careful examination of their relative importance in the behaviour of the bridge.

It has become conventional to express the various forces as ratios of the aerodynamic forces, which give rise to the following dimensionless scaling parameters.

(i) U^2 / bg, Froude number,

(ii) $E / \rho U^2$,

(iii) $m / \rho b^2$, $I / \rho b^4$, etc.,

(iv) $\zeta = c / c_c$,

(v) $\rho U b / \mu$, Reynolds number,

where b is the bridge width, c is the structural damping, c_c is the critical structural damping, E the modulus of elasticity, g the acceleration due to gravity, I the mass moment of inertia of structure/unit length, m is the mass of structure/unit length, U the wind velocity, ζ the critical damping ratio, μ the viscosity of air and ρ the density of air.

3.2 *Dynamic scaling*

It is normal to respect parameter (i), the Froude number, in modelling long span bridges since there are significant gravitational forces affecting the bridge static and dynamic behaviour. The requirement for equality of model and prototype Froude numbers sets the velocity scaling of the experiment. That is

$$U_m^2 / b_m g = U_p^2 / b_p g \text{ and consequently } U_m / U_p = (b_m / b_p)^{\frac{1}{2}},$$

where subscripts m and p refer to model and prototype respectively. It follows that the time scaling will be $\tau_m / \tau_p = (b_m / b_p)^{\frac{1}{2}}$. For a scale ratio $b_m / b_p = 1/100$, a full scale wind speed of 100 miles/hr (161 km/hr) would be represented by 10 miles/hr (16·1 km/hr) at model scale speed in the wind tunnel.

From parameters (i) and (ii) together we get:

$$E_m / E_p = (U_m / U_p)^2 = b_m / b_p.$$

Therefore if the model is to be made as an exact replica, it would be necessary to use materials having lower values of E than the prototype material in proportion to the geometric scale ratio. Alternatively the scale stiffness can be made correct by modifying the material thickness t or in the case of cables the cross-sectional area A so that

$$E_m t_m / E_p t_p = b_m / b_p, \text{ or for cables } E_m A_m / E_p A_p = b_m / b_p.$$

In modelling cables, this approach can be used to get the stiffness correct; however the mass scaling requirement of parameter (iii) is then violated, and, as well the cable diameter will no longer be at the correct geometric scale size. The deficiency in mass can be corrected by adding distributed weights to the cables, while the correct aerodynamics can be restored by suitably choosing the geometry of the weights. Similarly, it is possible, for box section road decks to design the model so that its dynamic properties are intrinsically correct. However, for open truss designs the elastically-scaled values of component thickness are usually impractically small and some other way of constructing the model has to be devised. This can be done by designing a structural spine for the road deck on which is mounted non-structural modules that give the correct shape aerodynamically. The modules must be carefully made to keep the weight equal to or below that dictated by the mass parameter. Weights can then be added to adjust the mass and moment of inertia. When this approach is used, the elastic and dynamic properties are not intrinsically correct and the spine must be designed so that its elastic properties correctly scale those of the prototype. It may be difficult to design a spine that is aerodynamically unobtrusive. For example in the model of the original Lions' Gate Bridge confiugration, it was difficult to design a spine to duplicate the prototype that did not, at the same time, modify the aerodynamic characteristics of the section (Irwin & Schuyler 1977). The credibility of the final design was established by comparative sectional model tests of a replica model and a model that included the spine.

The sectional and taut-strip modelling concepts pre-suppose that the elasto-dynamic behaviour of the prototype is known or can be adequately predicted. An advantage of the full model is that the need for this assumption is obviated because the correct behaviour is modelled implicitly.

Parameter (iii) must be respected in order that the inertial forces of the bridge mass are in the correct proportion to the other forces. It follows that

$$m_m / m_p = (b_m / b_p)^2 \text{ and } I_m / I_p = (b_m / b_p)^4.$$

The damping parameter (iv) must be modelled in order that the dissipative forces due to structural damping are properly accounted for. Adjustment of this parameter can be precisely controlled with sectional models but not with taut-strip or full models.

3.3 *Aerodynamic scaling*

Parameter (v), the Reynolds Number, is a measure of the relative magnitude of the aerodynamic viscous forces and the aerodynamic inertial forces. Reynolds number scaling is a fundamental requirement for aerodynamic similarity; however there are many problems where the viscous forces are small and relatively unimportant compared to the inertial forces, in which case the requirement for scaling the Reynolds number is negated. Relaxation of this requirement must be undertaken with care.

Respecting the modelling of the Reynolds number requires that

$$U_m \,/\, U_p = b_p \,/\, b_m.$$

Clearly, this is incompatible with Froude number scaling and, furthermore, would lead to model scale wind speeds that are impractical for a variety of reasons. The limitations of assuming that the bridge behaviour is independent of the Reynolds number must be carefully examined.

An important illustration of the importance of the Reynolds number to aerodynamic stability is the flow around a circular cylinder. Above a value of the Reynolds number—based on the cylinder diameter—in the range 3×10^4 to 3×10^5 there is a dramatic change in the flow. The most apparent change is the reduction of the wake width immediately behind the cylinder. There is a corresponding reduction of the drag coefficient C_D and an increase in the frequency of formation of vortices n in the wake as shown in figure 6. The wake vortex formations are shown in figure 7 (plate 3). The value of the Reynolds Number at which the changes occur is dependent on the surface roughness of the cylinder and the turbulence level in the airstream. It is readily apparent that in modelling circular or other curved cross-sections that these effects have to be allowed for. In the case of cables the prototype Reynolds number will often be above the critical values at which changes occur, whereas the model value will be below. The resulting differences in C_D can be compensated for in the model by increasing the projected area of the cables by appropriately selecting the shape of the added weights referred to earlier.

The change in wake width is a consequence of a rearward shift on the cylinder surface of the so-called 'separation points' where the smooth flow on the forward

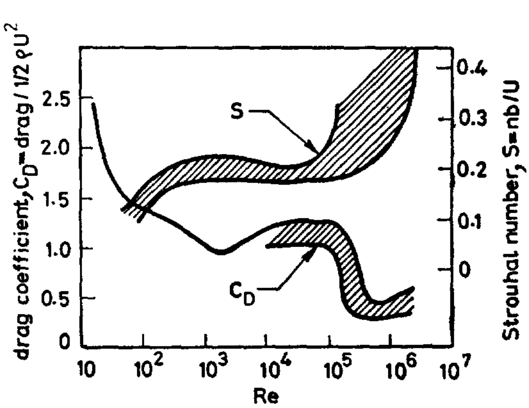

Figure 6. Drag coefficient and Strouhal number of a circular cylinder—adapted from Fung (1960)

part of the cylinder detaches from the surface of the cylinder. In the case of rectangular cylinders the separation point is fixed at the sharp upstream corner of the cylinder and as a consequence the Reynolds number dependency disappears—this is not so for rectangles with rounded corners. As a result it is normal to assume that sharp-cornered shapes are insensitive to Reynolds number effects and in general this premise is acceptable. However at very small scale it becomes difficult to reproduce precisely the prototype geometric shape, particularly the small corner radii of structural components.

There are other Reynolds number effects. The flow over a square cylinder with a side facing the wind will form a broad wake after separation from the upstream corner; however, for a rectangle where the streamwise dimension is much larger than the lateral dimension the separated flow will reattach to the streamwise surface and consequently the wake will be much narrower (figure 8). As with the cylinder this results in a lower value of C_D and a higher value of the dimensionless vortex frequency, the Strouhal number, S. The length: width ratio at which this change occurs depends on the Reynolds number, the corner radius and the airstream turbulence level. This should not normally be a problem with road decks because of their slenderness; although caution is warranted where curved fairings or large vertical wind angles are involved. The flow around components may also be affected.

It is difficult to answer the question, how large should the model scale be to avoid Reynolds number problems. There is some favourable evidence from model-prototype comparisons and from wind tunnel investigations over a range of scales that substantiates the premise that we can neglect Reynolds number scaling. An example is the Long's Creek Bridge (figure 9, plate 4) (Wardlaw 1971) a cable-stayed orthotropic girder bridge. Wind tunnel sectional model measurements at 1 : 30 scale are shown extrapolated to prototype scale in figure 10. The peak amplitude of 4·2 in. (10·7 cm) occurring near 28 miles/hr (45·06 km/hr) agrees with several observations at the bridge site and the narrow velocity range over which the excitation has been observed corresponds closely for the model and the prototype. Winds normal to the bridge at velocities above the critical range, that is above 35 miles/hr (56·3 km/hr) were measured at the site and no bridge motion was observed. Amplitudes as high as 8 in. (20·3 cm) were also reported and it is believed that these larger responses were due to snow blockage of the handrails—in the wind tunnel a peak amplitude of 7 in. (17·8 cm) was recorded with the handrail blocked. No torsional motion was observed in either the model or the prototype. The structural damping

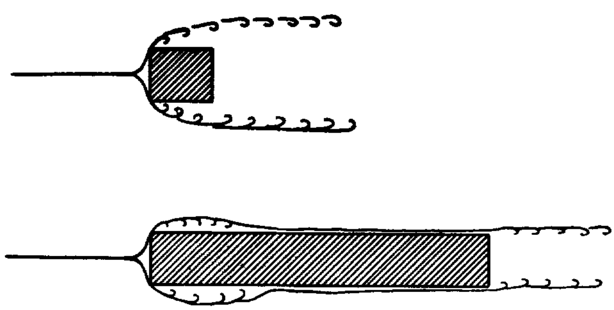

Figure 8. Flow over square and rectangular cylinders

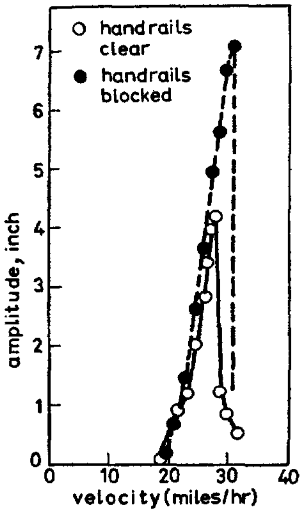

Figure 10. Sectional model response of the unmodified Long's Creek Bridge extrapolated to full scale

in the model was in the range $\zeta = 0{\cdot}008$ to $0{\cdot}016$. A record of the decay of an impact-induced flexural vibration of the bridge indicated a damping value of $\zeta = 0{\cdot}010$. Encouraging comparisons have been made for sectional and full models of the Golden Gate Bridge (Vincent 1958) and the original Tacoma Narrows Bridge (Farquharson *et al* 1950–54). Also, further confidence is derived from the absence of unsatisfactory aerodynamic behaviour in prototype bridges whose aerodynamic stability has been demonstrated in wind tunnels in advance of construction.

Dynamic sectional model testing of the Lions' Gate Bridge has been done with two different model scales, 1 : 110 and 1 : 24 (Irwin & Wardlaw 1977; Irwin & Schuyler 1976). The velocity scaling for the 1 : 110 scale model was selected to satisfy Froude number similarity, whereas the velocity scale for the 1:24 scale was set arbitrarily at about 1 : 4. (Velocity scaling of sectional models will be discussed later). The Reynolds numbers, based on bridge chord, and corresponding to a prototype wind speed of 75 miles/hr (121 km/hr) were $3{\cdot}5\times10^4$ and $6{\cdot}5\times10^5$ for the 1 : 110 and 1 : 24 scales respectively. At the same speed the prototype Reynolds number would be $3{\cdot}8\times10^7$. There were small differences such as a decreased sensitivity to angle of attack at the higher Reynolds number, but the overall behaviour was similar in both cases. Davenport *et al* (1971) have compared sectional models at 1 : 40 and 1 : 320 scale and found '.. .reasonably good agreement....' in the behaviour. He has, however, found differences between the behaviour of the full model in smooth flow and the sectional model which he attributes to the modelling concepts rather than the scale. This difference has not been observed by Irwin and co-workers with the Lions' Gate Bridge models (Irwin & Schuyler 1976, 1977; Irwin & Wardlaw 1977), nor by Farquharson *et al* (1950-54) with the Tacoma Narrows Bridge or by Frazer & Scruton (1952) with the Severn Bridge. Sectional model force measurements for the Severn Bridge by Walshe & Rayner (1962) showed some Reynolds number dependency below $\mathrm{Re}=2\times10^6$ which practically disappeared at higher values.

With the sectional and taut-strip models gravitational forces do not affect the model dynamics and velocity scaling can be selected arbitrarily rather than by respecting the Froude number. In this case, it is conventional by combining scaling parameters (ii) and (iii) to replace (ii) with a new parameter U/nb where n is the

$$U_m \;/\; U_p = (n_m \;/\; n_p)\,(b_m \;/\; b_p),$$

natural frequency of the bridge mode being modelled. The velocity scaling is now and we are free to select n_m. From a Reynolds number point of view, it is desirable to select n_m as large as possible within the limit of speed available in the wind tunnel. Gravitational effects such as the blowback of the cable plane and rotation of the road deck are not intrinsically included with these modelling concepts. Allowance can be made for aerodynamic effects of road deck rotation by setting the model chord plane at an angle to the wind.

For a 1 : 50 scale sectional model and a velocity scaling $U_m : U_p = 1 : 2$ the Reynolds number ratio would be $\mathrm{Re}_m : \mathrm{Re}_p = 1 : 100$. By comparison, a full model of a 3000 ft (914·4 m) span bridge in an 8 ft (2·44 m) wind tunnel would have a scale ratio of 1 : 400, and with Froude number similarity the Reynolds number ratio would be about $\mathrm{Re}_m : \mathrm{Re}_p = 1 : 8000$. The model scale Reynolds number would be about 8×10^3 for a 100 ft (30·48 m) wide road deck at 70 miles/hr (112·7 km/hr). At this scale the road deck width would be about 3 in. (7·62 cm) and components such as cables would be of the order 1/32 in. (0·794 mm) in width. Clearly at these scales model geometric precision becomes difficult and the integrity of the assumption of aerodynamic similarity would have to be seriously questioned.

4. Effects of turbulence

4.1 *The earth's surface wind layer*

The planetary winds are retarded near the earth's surface by the resistance to flow introduced by roughness elements on the ground and by fluid friction associated with the air viscosity. As a result of this shearing action, the velocity varies from zero at the surface—the fluid dynamicist's no-slip condition—to the 'gradient wind' at about 900–2000 ft (274–610 m) above the surface (figure 11). At greater altitudes it is assumed that there are no further mechanical effects of the earth's surface. The rate of shear depends on the roughness of the ground and is often described by a power law such that,

$$U(z) \;/\; U(z_0) = (z \;/\; z_0)^{\alpha},$$

where the exponent α is in the range 0·15 to 0·5, having the higher values for rougher terrain, z is height above ground and z_0 an arbitrary reference height.

The shearing action also causes mechanical agitation of the flow, or turbulence. To an observer fixed on the ground the turbulence manifests itself as gustiness with continuous and sometimes abrupt changes of direction and of magnitude. A measure of the magnitude of the fluctuating component of the wind is its root-mean-square value which is known as the turbulence intensity. At the height of the gradient wind the turbulence intensity is nearly zero but increases toward the surface

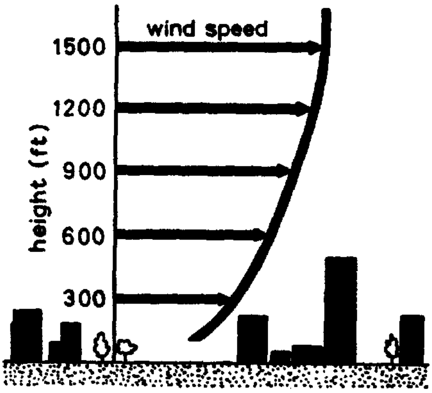

Figure 11. The variation of mean wind velocity with height—After Templin (1970)

and the longitudinal or streamwise component can be as high as 30 to 40% of the local mean wind speed near ground level (figure 12). Peak excursions can be several times the RMS value.

The wind turbulence is characterized by a nearly random distribution of the physical size of the disturbances. In the longitudinal direction the size can vary from near zero to several thousand feet (meter) in length. The dimensions of the disturbances in the lateral direction are somewhat less. The random fluctuations in wind velocity, seen by a fixed observer, represent wind energy distributed over a wide range of frequencies. The distribution of frequency f can be characterized by the power spectral density function ϕ. Figure 13 shows the von Karman formula for the power spectrum of the longitudinal component. The position of this curve along the frequency axis can be fixed by adjusting the value of a length constant in the formula that is known as the integral scale and is a measure of the mean size of the disturbances. This curve is in good agreement with observed spectra for an integral scale of 400 ft (122 m).

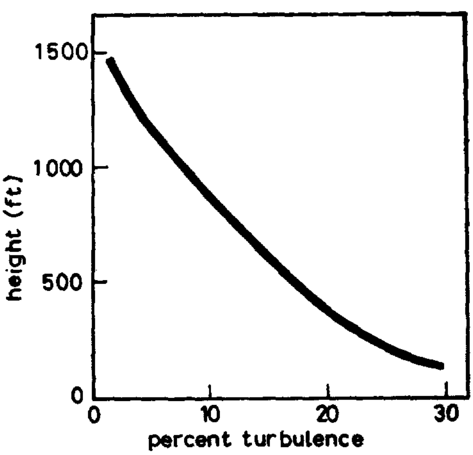

Figure 12. The variation of the longitudinal turbulence intensity with height—After Templin (1970)

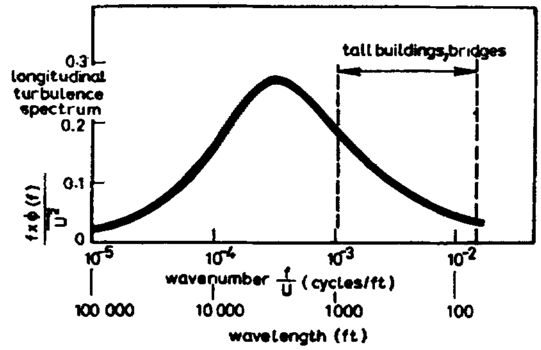

Figure 13. The longitudinal turbulence spectrum—After Templin (1970)

4.2 *Modelling the wind layer*

There are several different methods for simulating the properties of the wind layer in the wind tunnel. A well-established approach that is used in special purpose, long working section wind tunnels is to develop the layer 'naturally' by having the wind blow over a long fetch of surface roughness elements. A second method that is suitable for shorter working section aeronautical wind tunnels is to instal spires at the entrance to the test section (Standen 1972) as shown in the background of figure 1 (plate 1). With both of these techniques it is practical to develop wind layer depths approaching one-half the height of the test section.

4.3 *Testing in turbulent wind*

The effects of the turbulence on bridge behaviour depend on the scale of the turbulence relative to the size of the bridge, its intensity and its frequency spectrum. For example, if the lateral scale were large enough that the velocity at any one instant in time was constant along most of the span, one would expect the turbulence to play a different role than if the scale was much smaller and the velocity varied considerably along the span. Similarly, if the natural frequencies of the bridge were in the higher energy part of the spectrum, one would expect a greater response to the turbulence than if they were in a low energy part.

It is important to simulate all the properties of the turbulence that have been discussed but because of the large scale components this cannot be done with the sectional model. Therefore to fully study the effects of turbulence it must be done with the full model or taut-strip model.

4.4 *Buffeting response*

Since there is significant turbulence energy near bridge natural frequencies (figure 13), the dynamic buffeting response becomes very important at high wind speeds for light weight, low damping, modern suspended bridges and the gust factor approach to estimating loads may not be satisfactory. An alternative, as demonstrated by Irwin (1977) is to estimate the stress levels due to the dynamic response from the motion measured using full models in simulated wind. As more experience with full models is being obtained, the goal of being able to adequately predict the response from the sectional model data, as has been proposed by Scanlan (1975) and Holmes

(1975), or from taut-strip models as has been proposed by Davenport (1972), should be pursued more vigorously.

4.5 *Road deck flutter*

The term flutter is used to describe an oscillatory instability of the road deck that occurs when a critical wind speed is reached. It is characterized by rapid build-up of amplitude and catastrophic levels may be reached in a few cycles of motion. At higher wind speeds the build-up rates would normally be increased. Typically torsion is the dominant vibration mode but the instability is normally considered to be a consequence of aerodynamic coupling between vertical bending and torsion; although single-degree-of-freedom torsional flutter may occur. Short of having an aerodynamically stable shape it is, of course, essential that critical flutter speeds be well above wind speeds expected at the site.

Flutter stability can be readily assessed using sectional models and it is common practice to assume that such observations provide a conservative approach to design against flutter, on the basis that the stability in turbulent flow will be greater than in the uniform flow of the section model test.

There is now some evidence to support the view that the section model method can be overly conservative. Davenport's investigation of the Halifax Harbour Bridge (Davenport *et al* 1971) included the first full model test in a simulated natural wind. Like the Lions' Gate Bridge it is an open truss bridge, and for both bridges it has been found that the flutter instability observed with the sectional model was not present for the full model in the turbulent flow, even for velocities well above the sectional model critical speeds. Observations of the response of the Lions' Gate Bridge are shown in figure 14 (Scanlan & Wardlaw 1978).

For the plate girder and box section road deck structures, the evidence that the sectional model is conservative is less compelling than for the open truss design. Davenport *et al* (1971) observed with his taut-strip model of the original Tacoma Narrows Bridge H-section road deck that turbulence inhibited '... .non-catastrophic (possibly vortex-induced) motion at subcritical windspeeds but only marginally

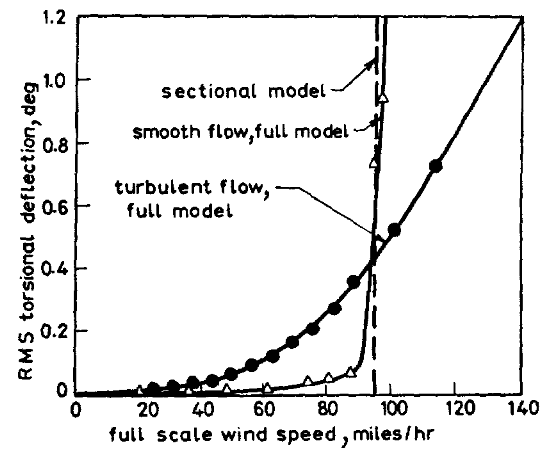

Figure 14. The Lions' Gate Bridge torsional response at the 1/10th span position in smooth and turbulent flow

postponed the onset of catastrophic torsional motion.' The effects became greater as the turbulence intensity was increased to represent rougher terrain. The box section road deck of the West Gate Bridge was tested by Melbourne in simulated natural wind (Melbourne 1973); however, the section was aerodynamically stable in smooth flow and therefore does not provide a good assessment of the effects of turbulence. The author is not aware of an example of an aerodynamically unstable box section that has been tested in turbulent flow.

4.6 *Vortex shedding response*

The wake structure behind slender, bluff structures consists of an orderly sequence of vortices as illustrated by flow visualization of the flow behind a circular cylinder in figure 7 (plate 3). The vortices form alternately on either side of the wake in a regular periodic manner. The frequency of vortex formation (on one side of the wake) can be expressed dimensionlessly as

$$S = nb \,/\, U.$$

The value of the Strouhal number S depends on the section geometry and in varying degrees on the Reynolds number. The influence of the Reynolds number on the Strouhal number of a circular cylinder, already mentioned in § 3.3, is shown in figure 6. The Strouhal number for sharp-cornered shapes such as rectangular cylinders is insensitive to changes in Reynolds number.

As the wind speed is increased over a slender, elastic structure, the frequency of vortex formation increases and when this frequency matches a structural natural frequency, quite large crosswind vibration amplitudes can develop. The vertical bending oscillations of the Long's Creek Bridge, shown in figure 9 (plate 4) (Wardlaw 1971) are caused by the periodic wake vortices. The finite, non-destructive amplitudes and the narrow velocity range over which the motion occurs are characteristic of vortex shedding response. Torsional modes are equally susceptible to this form of excitation. While in the short-term amplitudes are not damaging, they can be large enough to make the bridge unacceptable to the user and may result in long term damage. The critical wind speed range often will be at quite common wind speeds.

Sectional models are well-suited to studying vortex shedding response—the ease with which configuration changes can be made, being a particularly attractive feature for developmental or remedial investigations. Experience with the Long's Creek Bridge demonstrates that the section model result can reliably predict full scale vortex shedding behaviour under certain circumstances. Whether or not it is unduly conservative for more streamlined box sections, for truss bridges or for higher turbulence levels has yet to be established.

5. Conclusions

In the foregoing discussion fundamental aspects of modelling procedures and bridge road deck behaviour have been reviewed with a view to appraising the advantages and disadvantages of the sectional, taut-strip and full model approaches. Is it now possible to draw up the balance sheet in favour of one or the other of these approaches? The answer would appear to be 'no'. With the present state-of-the-art there is a time and a place for each technique. Which investigative procedure or combination of procedures is used will depend on a variety of considerations—the size of the bridge, the road deck configuration, the lead time available.

It is worthwhile in conclusion to summarize some points that came out in the earlier discussion.

(i) Well-established dimensionless scaling parameters must be respected in wind tunnel modelling of the bridge dynamics. Apart from the aerodynamic similarity parameter, the Reynolds number, it is possible to satisfy these requirements as long as a large enough wind tunnel is available.

(ii) There is little evidence from wind tunnel tests done over a range of Reynolds number to suggest that aerodynamic similarity is a problem at the small scale of full models; but model-to-full scale comparisons are not available and caution must still be the watchword.

(iii) Satisfactory techniques are available for simulating the earth's surface wind that can be used with full and taut-strip models. For sectional testing it is not possible to reproduce turbulence having the large scale that exists in the natural wind.

(iv) Sectional testing is demonstrably reliable in design to avoid vortex shedding excitation and flutter. The question remains as to whether or not it is excessively conservative. Evidence suggests that it is for truss stiffened road decks in view of the suppressive effect of turbulence on flutter. For closed box deck sections and plate girder systems this is likely not the case as the sectional model appears to predict full scale vortex shedding excitation, and there is evidence from wind tunnel studies that turbulence has only a minor effect on critical flutter speeds.

(v) Bridge buffeting is an important design consideration for long, slender, lightweight spans. Stress levels can be computed analytically from motion response observed in full model studies in simulated natural wind. Another attractive approach is the prediction of prototype behaviour based on sectional model data. Development of these procedures should continue to be pursued at the research level, including analytical studies, and laboratory and full scale experimental investigations.

As stated at the outset the advantages of the sectional model are (i) low cost, (ii) large scale, (iii) short lead time and (iv) provides data for prediction procedures now under development.

The advantages of the full model technique are (i) the test can be done in a complete simulation of the earth's surface wind so that the turbulence response is obtained directly and the effects of turbulence on flutter and vortex shedding are intrinsic and (ii) all three-dimensional aeroelastic effects are modelled implicitly.

The taut-strip model can also be tested in simulated natural wind, but is simpler and less costly than the full model. Within the limits of this simplified model, some of the three-dimensional aeroelastic effects are included. To a certain extent it shares the advantages of the sectional model of low cost and short lead time. Analytical procedures for predicting prototype behaviour from taut-strip measurements have been described in the literature.

For a large bridge, extensive aerodynamic investigations are justified and can include in their scope a full model wind tunnel programme. It can be advantageous to precede the full model programme with sectional investigations so that stable aerodynamic deck shapes, free from vortex shedding excitation are developed using this cheaper, quicker approach. This will also permit the assessment of Reynolds number effects for the small scale full model. With smaller bridges it may be difficult to justify the full model experiment, in which case, the sectional model, or the sectional model plus taut-strip model can be used.

Finally, all things considered, in making the choice of testing procedure it should be remembered that the cost of the aerodynamic investigation will be a fraction of one percent of that of the full scale structure. Bearing in mind the important implication of the aerodynamic behaviour on the final design, undue restriction of the investigation on cost grounds should be avoided.

It is apparent that our knowledge of the phenomena and of investigative procedures has improved, but that there are still gaps to fill, particularly concerning turbulence and three-dimensional effects, and with analytical prediction procedures. Emphasis is needed on model to full scale comparison to further validate all prediction procedures.

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References

Cermak J E, Bienkiewicz, Peterka J A & Scanlan R H 1979 Active turbulence generaror for study of bridge aerodynamics, *Proc. ASCE Third Engineering Mechanics Division Speciality Conference*, Univ. of Texas, Austin, Texas, Sept. 17-19, p. 183.

Davenport A G 1972 The use of taut-strip models in the prediction of the response of long span bridges to turbulent wind, *Proc. IUTAM/IAHR Symp. on flow-induced structural vibrations*, Karlsruhe, Germany, August 14-16

Davenport A G, Isyumov N & Miyata T 1971 The experimental determination of the response of suspension bridges to turbulent wind, *Proc. Third Int. Conf. on wind effects on buildings and structures*, Tokyo, September, p. 1207

Farquharson F B, Smith F C & Vincent G S 1950-54 Aerodynamic stability of suspension bridges with special reference to the Tacoma bridge, Univ. of Washington, Engg. Exp. Station Bull. No. 116, Parts I to V

Frazer R A & Scruton C 1952 A summarized account of the Severn bridge aerodynamic investigation, NPL Aero Rep. 222, National Physical Laboratory, England

Fung Y C 1960 Fluctuating lift and drag acting on a cylinder in a flow at supercritical Reynolds numbers, Inst. Aeronaut. Sci., Paper No. 60-6

Holmes J D 1975 Prediction of the response of a cable-stayed bridge to turbulence, *Proc. Fourth Int. Conf. Wind Effects on Buildings and Structures*, Cambridge University Press, Heathrow.

Irwin H P A H 1977 Wind tunnel and analytical investigations of the response of Lions' Gate Bridge to a turbulent wind, National Research Council of Canada, NAE Rep. No. LTR-LA-210, June

Irwin H P A H & Schuyler G D 1976 Wind effects on a full aeroelastic bridge model, ASCE Preprint, 3268

Irwin H P A H & Schuyler G D 1977 Experiments on a full aeroelastic model of Lions' Gate Bridge in smooth and turbulent flow, National Research Council of Canada, NAE Rep. LTR-206

Irwin H P A H & Wardlaw R L 1977 Sectional model experiments on Lion's Gate Bridge, Vancouver National Research Council of Canada, NAE Rep. LTR-LA-205

Melbourne W H 1973 West Gate Bridge wind tunnel tests, Report to the Lower Yarra Crossing Authority by Monash University, Dept. of Mech. Engg., Melbourne, Australia

Scanlan R H 1975 Recent methods in the application of test results to the wind design of long suspended span bridges, Federal Highway Administration, Report No. FWHA-RD-75-115

Scanlan R H & Gade R H 1977 *J. Struct. Div., ASCE,* **103, ST9** 1867

Scanlan R H & Wardlaw R L 1978 Aerodynamic stability of bridge decks and structural members, from cable-stayed bridges, Structural Engineering Series No. 4, US Dept. of Transportation, Federal Highway Administration

Standen N M 1972 A spire array for generating thick turbulent shear layers for natural wind simulation in wind tunnels, National Research Council of Canada, NAE Rep. LTR-LA-94

Templin R J 1970 *Can. Aeronaut. Space J.* **16** 317

Vincent G S 1958 *J. Struct. Div. ASCE,* **84 ST6**

Walshe D E J & Rayner D V 1962 A further aerodynamic investigation for the proposed River Severn Bridge, NPL Aero. Rep. 1010, National Physical Laboratory, England

Wardlaw R L 1971 Some approaches for improving the aerodynamic stability of bridge road decks, *Proc. Third Int. Conf. on wind effects on buildings and structures,* Tokyo

Wardlaw R L 1973 A review of the aerodynamics of bridge road decks and the role of wind tunnel investigations, US Dept. of Transportation, Federal Highways Administration, First F C P Research Progress Review, San Francisco, USA, NTIS Accession No. PB-224 876/3 AS

Wardlaw R L 1975 *Public Roads,* **39** 122

Wardlaw R L & Buckland P G 1972 *The Engg. J. (JEIC)*

Plate 1

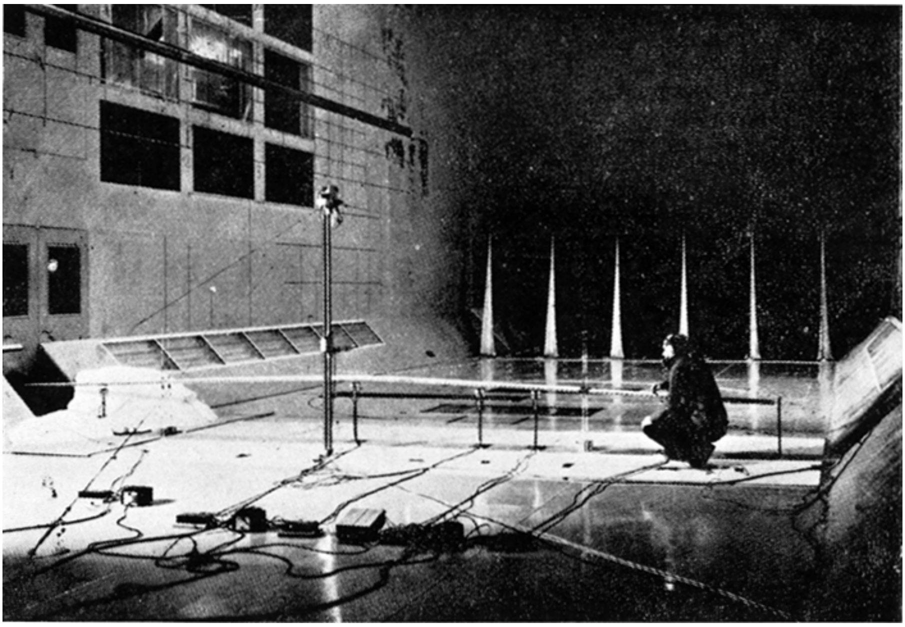

Figure 1. The 1 : 110 scale full model of the Lions' Gate Bridge in the National Aeronautical Establishment 30 × 30 ft. (9·14×9·14 m) wind tunnel

Plate 2

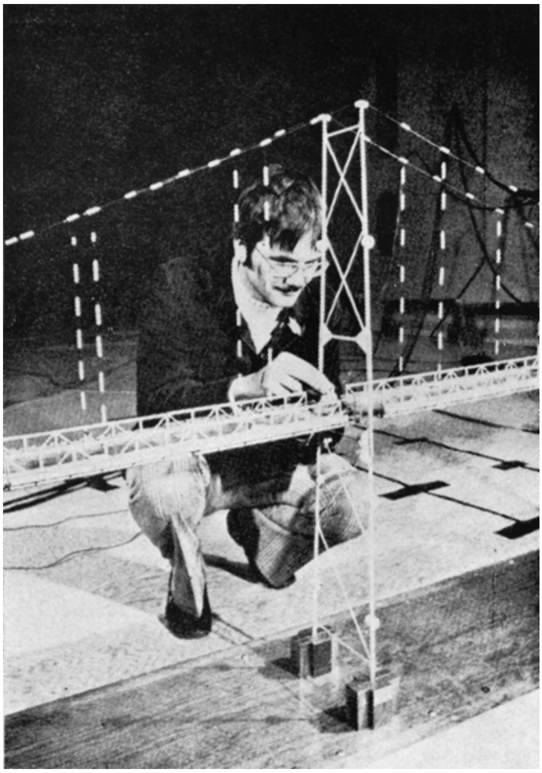

Figure 2. The 1 : 110 scale full model of the Lions' Gate Bridge

Plate 3

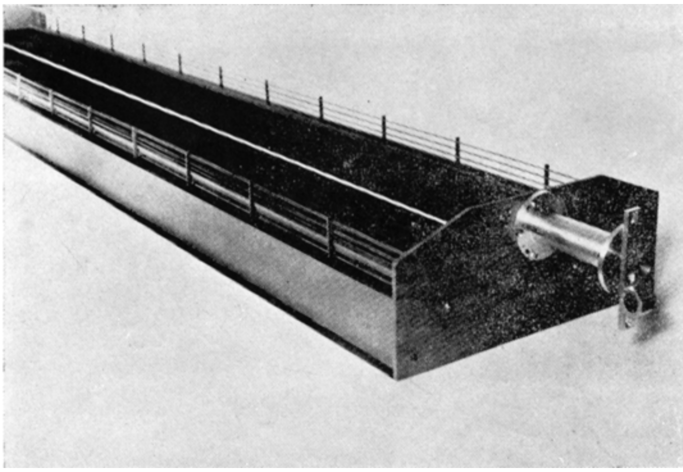

Figure 4. 1 : 30 scale sectional model of the Long's Creek Bridge-original road deck configuration

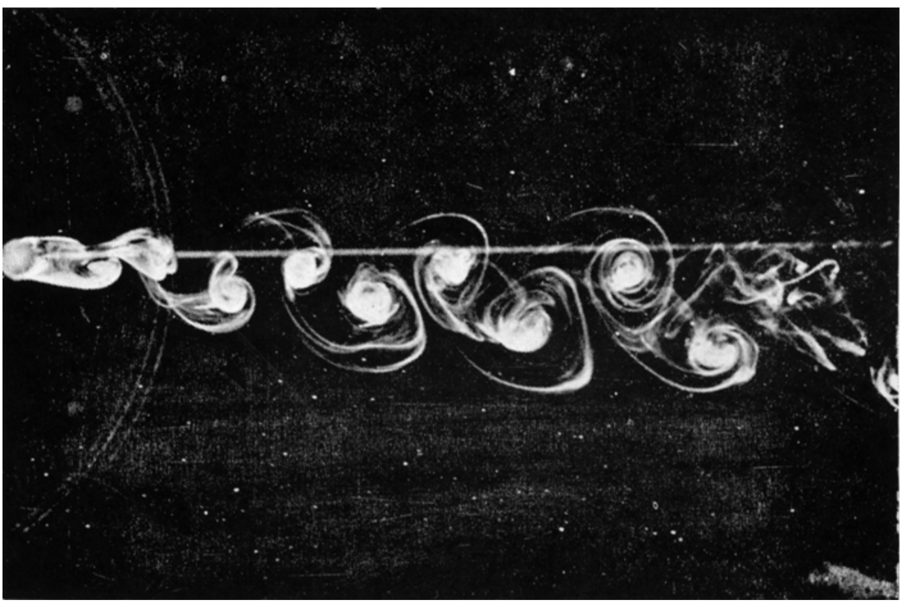

Figure 7. The vortex wake behind a circular cylinder

Plate 4

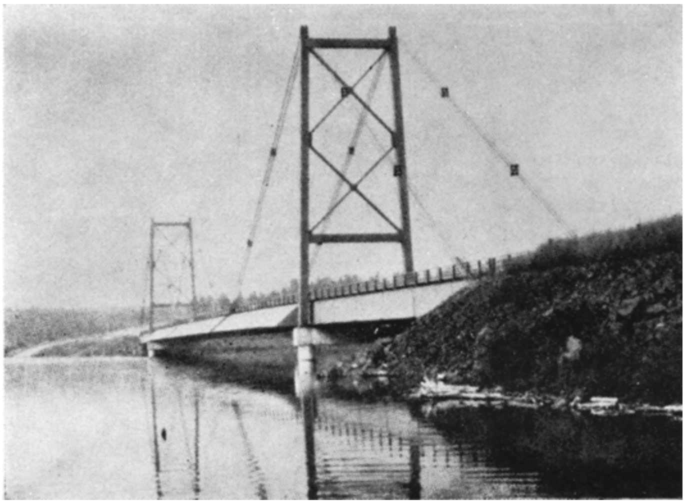

Figure 9. The modified Long's Creek Bridge