A résumé of the aerodynamic investigations for the Forth Road and the Severn Bridges

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The Paper brings out the importance of aerodynamic investigations for erection conditions on structures such as long-span suspension bridges, since these conditions differ in many important respects from the completed condition which has probably been studied already for the designer. Superficially the incomplete and the complete structures may appear similar but their aerodynamic behaviour can be very different. If this is not recognized and studied, erection procedures can easily be adopted which place the incomplete structure in a dangerous condition.

59. Certain aspects of the erection procedures for the Severn Bridge deck, which were modified as a result of the wind tunnel tests at the National Physical Laboratory (NPL) mentioned in the Paper, could well be explained at greater length.

60. It is not very clear from Figs 9 and 10 that the balance beams lay transverse to the longitudinal axis of the bridge and that their function was to ensure equal loading of each of the four sets of tackle hanging from the single lifting carriage on the main cables.

61. The lifting lug described in § 41 was the permanent lug to which the two inclined hangers were to be attached when the deck unit was in place. Thus the two hanger connexion holes in the lug had to be kept clear, and it was not possible in most cases to place the extra lifting hole correctly on the line of the centre of gravity of the unit. Counterweights were to be used to compensate for this, and slack stay wires installed to prevent undesirable oscillations.

62. Tests in the NPL wind tunnel, however, revealed the possibility of pitching motion, as shown in Fig. 11(a), with winds in excess of 25 miles/h within ±30° (approximately) of the longitudinal axis of the bridge. With both stay wires tight, the type of pitching motion shown in Fig. 11(b) could occur, but it was shown that with one wire tight and one just slack there would be a marked improvement in stability. It was also shown that violent pitching would occur at quite low wind velocities if the slack wire was omitted altogether. The stay wires were therefore made by the rope manufacturer to the correct calculated lengths, and the required degree of tightness and slackness was achieved by omitting the counterweights from the deck units. In the few cases where the units were almost in balance they were deliberately unbalanced by installing the counterweights.

63. The crossed restraining wires, shown in Fig. 12(a), were also adopted as a result of the wind tunnel tests, to prevent yawing. As these wires were attached to the same end of the unit as the tight stay wires it was important to avoid over-tightening of the restraining wires and unloading the stay wires.

64. The value of the NPL tests in the development of a safe lifting configuration will be appreciated when it is realized that there were 88 deck units to be lifted over a period of a year, which could include a wide range of wind conditions.

65. In § 35 the Author states that it was the original intention not to join the units together until the span was complete. It was, of course, always intended to connect units to the adjacent ones at the crown of the road, which was the only point of contact

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until the deck took up its final shape at a late stage of erection. The NPL tests, however, showed that it was necessary to redesign this simple connexion into one which would develop the full torsional rigidity of the box section across the open joints.

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It seems worthwhile to emphasize the way in which the aerodynamic properties of the box design for the Severn Bridge differed from previous types, and to consider the implications for future designs.

67. Previous tests of coupled-motion oscillation of bridge sections with a continuous deck (i.e. without the longitudinal gaps that have become the conventional solution for truss-stiffened bridges) have shown critical speeds much below the critical speed for flutter of an ideal flat plate. This reduction may be of the order of 50%, and has been attributed by Farquarson and Bleich[19] to superposition of vortex shedding on the flat-plate behaviour.

68. The exploratory tests referred to in § 32 involved close collaboration with the NPL and the bridge designers, and the box design was made possible by the development of a sectional shape which combined very high torsional stiffness with virtually the full flat-plate critical speed (§ 38). The high 'aerodynamic efficiency' seems to be related to the degree of 'streamlining' of the cross section.

69. The effect of design modifications on the calculated flat-plate flutter speed can be determined from charts giving the reduced velocity V_r based on the torsional frequency of the bridge, in terms of the mass and mass moment of inertia of the section. These charts are easy to use for practical cases of long-span bridges where the torsional-to-vertical frequency ratio is high, or alternatively the empirical formula given by Selberg[20] may be used. The conclusion is that by far the best way of increasing the flat-plate flutter speed is to increase the torsional stiffness of the box. For bridges of longer span or environments with exceptionally high winds the designer will therefore seek to increase the depth of the box and generally to make it less streamlined. It would be valuable to designers if the Author could give any further results indicating the degree to which this may be possible without serious loss of aerodynamic efficiency.

70. Although the streamlined box section may achieve the full calculated speed for flutter, limited excitation in single-degree-of-freedom motions may still occur within the design range of wind speed. For this reason, structural damping is still important, and I therefore do not entirely agree with § 15 of the Paper. The structural dampings measured by Selberg refer to bridges of entirely different construction from that of the all-welded box, and it seems likely that the natural damping of such a structure would be small. Values of logarithmic decrement of 0·02 or less have been recorded for all-welded structures.[21, 22] This deficiency is made up, in the case of the Severn Bridge, by hysteretic energy dissipation in the wire ropes by which the deck is suspended from the cables. The increase in overall logarithmic decrement was calculated by the accepted energy equation, using rope hysteresis data derived from a series of special tests. The arrangement of the suspender ropes by which the optimum effect is obtained is an important feature of the design.

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I should like to thank Mr Morley and Dr Wyatt for their contributions.

72. It may not be clear from Mr Morley's remarks that the diagonal restraining wires were suggested for the lifting system of the deck units as a means of preventing both the pitching and yawing oscillations.

73. In reply to Dr Wyatt, it is not possible without further investigation to deduce the minimum value of the width/depth ratio for a suspended structure of the Severn Bridge type for which the classical flutter theory would apply. The flutter theory

calculations for the Severn Bridge used flat-plate derivatives derived from potential flow theory, and the validity of this would depend, therefore, on the extent of flow separation. Thus, flat-plate derivatives may become invalid not only because of the depth of the section, but also because of flow separations induced by other departures such as handrails, etc.

74. The material in § 15 was part of a general discussion on model testing. In the absence of measurements of structural damping of long-span suspension bridges, Selberg's measurements are useful as a rough guide. Calculation of the contribution to the damping made by the diagonal suspender ropes used for the Severn Bridge was possible once the hysteresis characteristics of the wire ropes had been experimentally determined, but the contribution from the welded box structure and any contribution from the cable remains uncertain.

References

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Corrigenda

Fig. 14. In the column headed '$M\delta_s/\rho D^2$' for values 1·1, 1·8 and 3·2 read 11, 18 and 32 respectively.

Ref. 2. Delete 'ROCARD, Y'.