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Recherches expérimentales sur la stabilité aérodynamique des ponts suspendus

Experimentelle Untersuchung über die aerodynamische Stabilität der Hängebrücken

An experimental investigation of the aerodynamic stability of suspension bridges

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Introductory

The collapse of the Tacoma Narrows Bridge in 1940 provided a dramatic illustration of aerodynamic oscillations on suspension bridges, and stressed the importance of research on the subject. Since 1940 the problem has been studied particularly extensively in the U. S. A., by F. B. Farquharson, D. B. Steinman, Theodore von Kármán, Louis G. Dunn, Hans Reissner and F. Bleich and others (1). In many cases these investigations have

(1) F. B. FARQUHARSON, *General Discussion of the Torsional Stability of Suspension Bridges under wind action* (*Report No. 17 of the Structural Research Laboratory*, Unisersity of Washington).

F. B. FARQUHARSON, *Prototype prediction based on section model tests of configuration LXXVI tested at N = 40 c. p. m. with various degrees of damping* (*Report No. 18 of the Structural Research Laboratory*, University of Washington).

F. B. FARQUHARSON, *Prototype prediction based on full model tests at configuration LXXVI tested at two values of truss stiffness* (*Report No. 19 of the Structural Research Laboratory*, University of Washington).

F. B. FARQUHARSON, *Lessons in Bridge Design Taught by Aerodynamic Studies* (*Civil Engineering*, August, 1946).

D. B. STEINMAN, *Rigidity and Aerodynamic Stability of Suspension Bridges* (*Proceedings of the American Society of Civil Engineers*, November 1943).

D. B. STEINMAN, *Design of Bridges against Wind* (*Civil Engineering*, October, November and December issues 1945).

D. B. STEINMAN, *Wind tunnel tests yield aerodynamically stable bridge sections* (*Civil Engineering*, December 1947).

Hens REISSNER, *Oscillations of Suspension Bridges* (*Journal of Applied Mechanics*, March 1943).

Theodore von KÁRMÁN, with the co-operation of Louis G. DUNN, *Aerodynamic Investigations for the Design of the Tacoma Narrows Bridge* (*Report submitted to the Board of Consulting Engineers*, May 1942).

been mainly concerned with the stability of specific bridges, and these are well exemplified by the model experiments made in connection with the failure of the Tacoma Narrows Bridge by F. B. Farquharson at the University of Washington and by Louis G. Dunn at the California Institute of Technology. Although much valuable knowledge has been gained, there is as yet no reliable purely theoretical basis for the prediction of the stability characteristics of a preferred design. This, in fact, is not surprising since with many conventional types of suspended structure the airflow can be extremely complex. As will be shown later in this paper, the form of small structural details such as handrails and roadway stringers have a marked effect on the stability. It appears therefore that, with the present state of knowledge, the most reliable assessment of the aerodynamic stability of a proposed bridge is to be obtained by tests on oscillatory models in wind tunnels.

The investigation described in this paper is specifically intended to provide guidance in the design of the proposed Severn Suspension Bridge, and is being carried out in close collaboration with the Consulting Engineers associated with that project. However, although this particular application has been in view, the tests have so far included comparisons between a fairly wide range of structural forms, and have led to certain conclusions which should hold good for truss-stiffened types generally. On the other hand, as the investigation has a specific limited objective, time has not been available for a systematic fundamental study.

The following two complementary experimental techniques are being used :—

1) *Tests of Sectional Models.* These involve tests of oscillatory behaviour in a single degree of freedom. For this purpose a rigid model of a representative length of the suspended structure is mounted in a wind tunnel in such a way that it is free to oscillate against a spring constraint, either in a vertical translatory motion or in a rotational motion about a spanwise axis. These motions may be taken to correspond respectively to those in vertical flexure and in torsion occurring on the prototype structure.

2) *Tests of Full Models.* Tests of sectional models, in the simple form adopted for the present investigation, give no information on the possible influence of oscillation form or on the effects of couplings between the natural modes of oscillation : nor can they be carried out satisfactorily in a quartering wind without the use of a large wind tunnel and special apparatus. Since sufficient evidence on the importance of these factors is not yet available it is necessary to verify the stability of a proposed design by tests on a full model constructed to be dynamically similar to the prototype. For this purpose a large wind tunnel has been constructed by the Ministry of Transport in which models of up to 60 feet in length can be tested at various vertical and horizontal inclinations of the wind. Tests are expected to start in June, 1948.

Louis G. DUNN, *Aerodynamic Investigation of the Bending Oscillations of the Original Tacoma Narrows Bridge (Report submitted to the Board of Consulting Engineers*, April 1943).

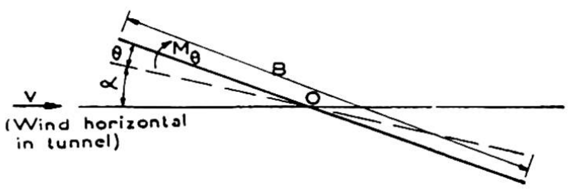
Louis G. DUNN, *Experimental Investigations on the Aerodynamic Characteritics of the suspended Structure of the Tacoma Norrows Bridge* (Appendix VIII of the failure of the Tacoma Narrows Bridge. *Bulletin 78 of the School of Engineering, Texas Engineering Experiment Station*, 1944).

F. BLEICH, *Dynamic Instability of Truss Stiffened Suspension Bridges under Wind Action (Report to the Advisory Board on the Investigation of Suspension Bridges*, February, 1947).

The paragraphs which follow refer throughout to experiments with sectional bridge models. In these the aim is to find acceptable forms of suspended structure which show no tendency to oscillate in either vertical or pitching motions up to wind speeds corresponding to 100 miles per hour at vertical inclinations ranging from — 15 to + 15 degrees. Owing to limitations regarding time and availability of wind tunnels, a simple technique of testing had to be adopted. Oscillations are classed equally as unstable whether they appear as steadily maintained non-catastrophic oscillations of limited finite amplitude or whether they show signs of growing to a dangerous amplitude such as might lead to failure. The model is mounted in a 4 ft square wind tunnel and the wind speed in the tunnel is increased until an oscillation started by a small disturbance is just maintained. The value of the reduced velocity V_r is then calculated from the measured values of wind velocity and frequency of oscillation. By this simple procedure a large number of model variations can be rapidly tested and the results used to indicate general design features which tend to produce stability.

Theoretical basis of selectional tests

The following theory relates to the pitching oscillations. With the necessary changes in notation and in expressions for the aerodynamic force it is equally applicable to tests of the vertical oscillations.



a) *Notation*

I_θ = moment of inertia about centre of rotation O per unit spanwise length.
K_θ = structural damping coefficient per unit spanwise length.
e_θ = elastic stiffness per unit spanwise length (2).
α = angle of attack, or mean incidence about which pitching oscillations occur.
θ = angular deviation from mean incidence at any instant of oscillation.
θ_0 = amplitude of simple harmonic oscillations.
B = distance between stiffening trusses.
V = airspeed.
ρ = air densiy (3).
N_θ = natural frequency (cycles/sec) corresponding to inertia I_θ and stiffness e_θ.
V_r = V/NB = « reduced velocity » corresponding to simple harmonic oscillations.
M_θ = increment of aerodynamic pitching moment per unit spanwise length at any instant of oscillation.
$\delta_\theta = \dfrac{K_\theta}{2I_\theta N_\theta}$ = natural logarithm of the ratio of successive amplitudes of oscillation in still air.

(2) I_θ, K_θ and e_θ assumed to be measured in consistent units, and to be applied uniformly along the unit spanwise length.
(3) Standard value of p in ft lb sec unitis is 0.0765.

b) *Basic formulae*

It is assumed that aerodynamic scale effect is absent (i.e. aerodynamic moments are independent of Reynold's number). In this case, if a simple harmonic oscillation is expressed in the usual complex notation by

$$\theta = \theta_0\, e^{2\pi N t i} \left(\text{where } i = \sqrt{-1}\right),$$

the aerodynamic moment M_θ takes the form.

$$M_\theta = \rho B^2 V^2 \theta_0 \left[f(V_r) + i g(V_r)\right] e^{2\pi N t i} \tag{1}$$

where $f(V_r)$ and $g(V_r)$ depend on the reduced velocity V_r only.

The conditions for free simple harmonic oscillations are

$$\rho B^2 V^2 g(V_r) = 2\pi N K_\theta \tag{2}$$

and

$$\rho B^2 V^2 f(V_r) = -4\pi^2 N^2 I_\theta + e_\theta . \tag{3}$$

Equations (2) and (3) may be re-written

$$V_r^2\, g(V_r) = \frac{2\pi K_\theta}{\rho B^4 N} \tag{4}$$

$$V_r^2 f(V_r) = \frac{e_\theta}{\rho B^4 N^2} - \frac{4\pi^2 I_\theta}{\rho B^4} = \frac{4\pi^2 I_\theta}{\rho B^4}\left(\frac{N_\theta^2}{N^2} - 1\right). \tag{5}$$

The possible critical values of V_r for simple harmonic oscillations (i.e. the roots of equations (4) and (5)) will have the same values for prototype and model provided both systems have equal values of

$$\frac{I_\theta}{\rho B^4}, \qquad \frac{K_\theta}{\rho B^4 N}, \qquad \frac{e_\theta}{\rho B^4 N^2}.$$

The practical interpretation of these formulae is greatly facilitated if (as is usually true) the changes of frequency due to the wind are small.

In this case the influence of the term $f(V_r)$ in (5) is negligible, and as an approximation $N = N_\theta$. If this value for N is substituted in (4) the equation becomes

$$V_r^2 g(V_r) = \frac{2\pi K_\theta}{\rho B^4 N_\theta} = \frac{4\pi I_\theta \delta_\theta}{\rho B^4}. \tag{6}$$

The critical values of V_r then depend only on the geometric shape of the structure and the ratio [4] $\dfrac{I_\theta \delta_\theta}{\rho B^4}$.

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[4] This condition is equally valid if the structural damping is represented by a phase lead on the elastic restoring force. The expression for free simple harmonic oscillations is then written

$$I\theta + \sigma e^{i\varepsilon}\theta = \rho B^2 V^2 \theta_0 \left[f(V_r)\right] + i g(V_r)\right] e^{2\pi N T i} \tag{i}$$

where $e_\theta = \sigma \cos \varepsilon$

If $N = N_\theta$

$$V_r^2 g(V_r) = \frac{\sigma \sin\varepsilon}{\rho B^4 N_\theta^2}. \tag{ii}$$

Substituting

$$\delta_\theta = \frac{\sigma \sin \varepsilon}{4\pi I N_\theta^2} \quad \text{in (ii)}$$

$$V_r^2 g(V_r) = \frac{4\pi I_\theta \delta_\theta}{\rho B^4} \tag{6}$$

If accented and unaccented symbols refer to the model and prototype respectively, $\rho' = \rho$ for tests in an atmospheric wind tunnel, and the only conditions necessary for equality of the values of V_r for model and prototype are geometric similarity and

$$\frac{\delta_\theta'}{\delta_\theta} = \left(\frac{I_\theta}{I_\theta'}\right)\left(\frac{B'}{B}\right)^4 . \tag{7}$$

The corresponding expressions for vertical motions is

$$\frac{\delta_z'}{\delta_z} = \left(\frac{I_z}{I_z'}\right)\left(\frac{B'}{B}\right)^4 . \tag{8}$$

where I_z = mass per unit spanwise length.

Model and test conditions

The tests were made on 1/100-scale models of representative types of representative types of suspended structures. Diagrams of the sections of the four truss-stiffened types so far tested are given in fig. 1. All were fitted with stiffening trusses of the single Warren type (see fig. 2) with a full-scale truss panel length of 60 feet and a depth of either 25 or 27.5 feet. A few tests were made with the girder-stiffened sections shown in fig. 3.

A spanwise length of the section to be tested was mounted in a 4 ft square wind tunnel so that it could either oscillate vertically or in pitch about a selected spanwise axis. No attempt was made to reproduce on the models the values of the inertial and elastic coefficients required for full dynamic similarity, as indicated by equations (4) and (5). With all the sections tested it was found that the condition $N = N_0$ was approximately satisfied, so that equation (6) could be used. The values of V_r obtained on the model were directly applicable to a prototype with the following logarithmic decrements due to structural damping :—

$$\delta_\theta = 0.03 \text{ to } 0.04$$
$$\delta_z = 0.07 .$$

The maximum values of V_r obtainable in the tests were approximately 17 and 13 for pitching and vertical oscillations respectively and in both cases corresponded to wind speeds over the prototype of more than 100 miles per hour. The inclination of the wind was in all cases normal to the span but was varied from the horizontal over an angular range from — 15 to 15 degrees.

Discussion of results

Notes :

All dimensions quoted have been converted to refer to full-scale;

Unless otherwise specified the results refer generally to all types of section shown in fig. 1;

Except for those described under (*d*) the tests on pitching instability were made with the central rotational axis shown in fig. 6.

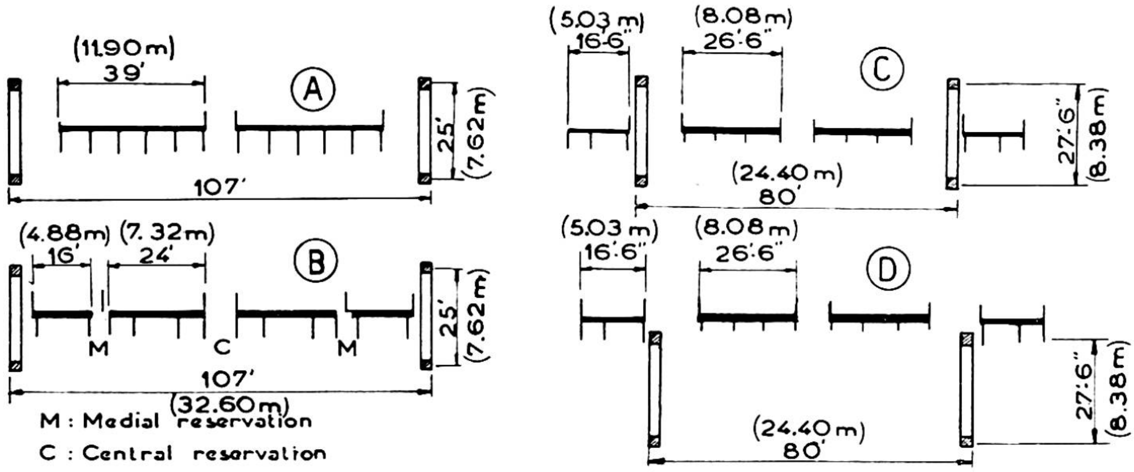


Fig. 1. Diagrams of bridge sections tested.

PITCHING OSCILLATIONS

The effect of various modifications and additions to the model are listed below.

a) *Modifications to Stiffening Trusses*

Width of chords : An increase in the width/depth ratio of the stiffening truss chords improved the stability;

Additional Members : The insertion of extra diagonal members (see fig. 2) improved the stability by moving the instability region to higher angles of incidence;

Depth : Increase of the depth of the truss, the same panel length and general structural form being retained, had no significant effect.

b) *Modifications to Decks*

Width and covering of reservations : The division of the total roadway width into a number of parallel tracks, each separated by an unblocked reservation, (5) was very benificial. Indeed, an unblocked reservation was found to be an essential feature for the attainment of a high degree of stability. Section B had in general better stability characteristics than those of section A. Improvements were also obtained with increase in the width of the unblocked reservations;

Position and type of roadway stringers and of handrailing : The stability of all sections tested was very sensitive to the form of fittings carried

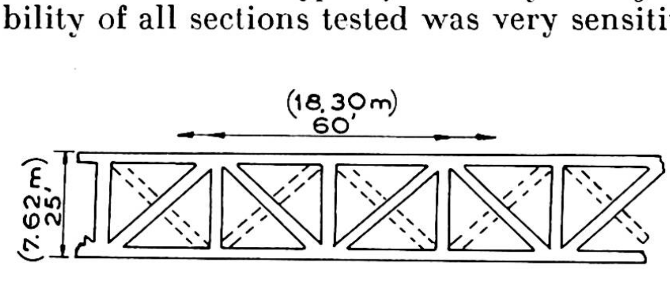


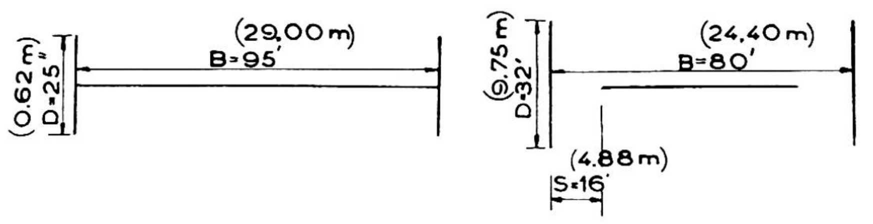
Fig. 2. General arrangement of stiffening truss.

——— Normal truss.

– – – – Additional members.

(5) An unblocked reservation is defined here as a reservation which is completely uncovered or is covered by a grating which permits easy flow of air through it (see fig. 1).

Fig. 3. Line diagrams of girder stiffened sections used in vertical oscillations tests.



Section E $\frac{D}{B} = 0.26$

Section F $\frac{D}{B} = 0.4$ $\frac{S}{B} = 0.2$

by the decks, such as stringers and handrails. Sections with plain decks, without stringers or handrails were unstable at both negative and positive angles of incidence but were stable at zero incidence. The sections were also unstable if either the handrails or the outermost stringers were of solid plate construction. Substantial improvements were effected by fitting designs of handrails and stringers which acted as aerodynamic spoilers by shedding eddies of mixed frequencies along the span. Such spoilers on the deck upper surfaces tended to suppress instability at positive angles of incidence while those on the lower surfaces improved stability at negative angles. By suitable choices of handrail and stringer design, and with unblocked reservations, it was found possible to obtain a high degree of stability for all the sections of fig. 1. Truss type deck stringers, if sufficiently deep (6), proved to be fairly effective aerodynamic spoilers and helped considerably to promote stability. By comparison with truss stringers, plate stringers were ineffective and models with all decks fitted with plate stringers were unstable. However, the stability characteristics of section C with truss stringers under the sidetracks and shallow plate stringers under the carriageways were not much less favourable than when all the decks were fitted with truss stringers. The use of paling handrails (fig. 4*a*) was beneficial but their effectiveness as spoilers was much augmented by the addition of solid castellations to provide larger-scale break up of the airflow. Two forms of castellated handrail are shown in fig. 4; the most effective of which was the single spaced castellated handrailing (fig. 4*b*). By the omission of alternate castellations a handrail of much better appear-

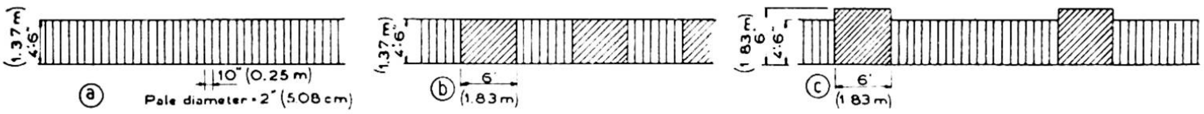


Fig. 4. Types of handrailing :
a. Paling handrailing; **b.** Single-spaced castellated handrailing; **c.** Modified castellated handrailing.

ance (fig. 4*c*) was produced. Although this type was not so efficient as a stabilising agent as that of fig. 4*b*, the advantages gained by the use of castellations were still considerable. Further arrangements of castellated handrailing, involving less frontal area and wider spacing of the castellations, were tested with a view to producing a form of handrail which would be satisfactory from both architectural and aerodynamic considerations. Most of these arrangements showed only small improvements

(6) Truss stringers of depths 6 feet, 5 feet and 3 feet were used in the tests. Those of depth 6 feet and 5 feet were the most satisfactory.

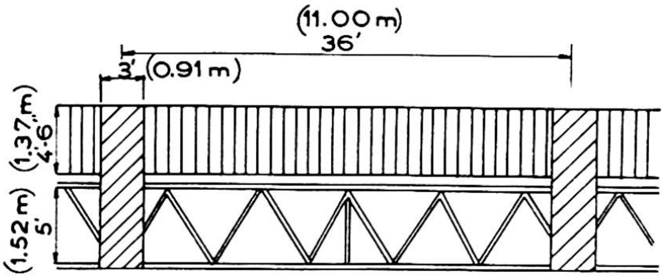


Fig. 5. Castellations extending over stringers and handrails.

on the plain paling handrailing. The castellations were not found to lose their effectiveness when the sets for the various handrails were staggered spanwise relative to each other by various amounts. A further type of castellation, used on sections C and D, was fitted to the outside edge of the sidetrak and extended over the handrails and stringers (see fig. 5). These were effective as stabilisers when placed immediately opposite the vertical posts of the stiffening truss, but were ineffective if displaced spanwise by half the distance between the posts. This result indicates that the stability of a section fitted with these castellations might prove to be sensitive to horizontal wind direction;

Traffic : In view of the marked influence on stability exerted by fittings to the deck surfaces it was desirable to determine the aerodynamic effect of traffic. Several arrangements of models of various types of vehicular traffic were placed on the decks of section B in random order and in different degrees of congestion. None of these had any adverse effect;

Vertical position of the decks : With the central axis of rotation there was little significant difference between the stability characteristics of sections C and D; those of section D were perhaps slightly inferior to those of section C. Some improvement was effected by raising the decks of section D to give a clearance of 2 feet between the bottom edges of the plate stringers used under the carriageways and the plane through the top surfaces of the upper chords of the stiffening trusses.

c) *Type and Position of Lateral Wind Bracing*

Tests on the type and position of the lateral wind bracing were made on model C only. The results indicate that, while the influence of the type of wind bracing located at the level of the stiffening truss bottom chords was not great, lattice type bracing yielded slightly better stability characteristics than the plate girder types. An improvement was obtained by raising the lattice type wind bracing to a position just underneath the roadway stringers. This result is consistent with a spoiling effect in proximity to the decks due to the bracing.

d) *Influence of Axis of Rotation*

The effects of the various modifications to the bridge sections mentioned in the preceding paragraphs were studied by experiments with a spanwise axis of rotation located at an approximately central position with respect to the four stiffening truss chords. A series of experiments was carried out on section B (modified to have stiffening trusses 120 ft apart) in which the pitching axis was moved to the several positions shown in fig. 6*a*. Axes located vertically up, or down, or horizontally upstream from

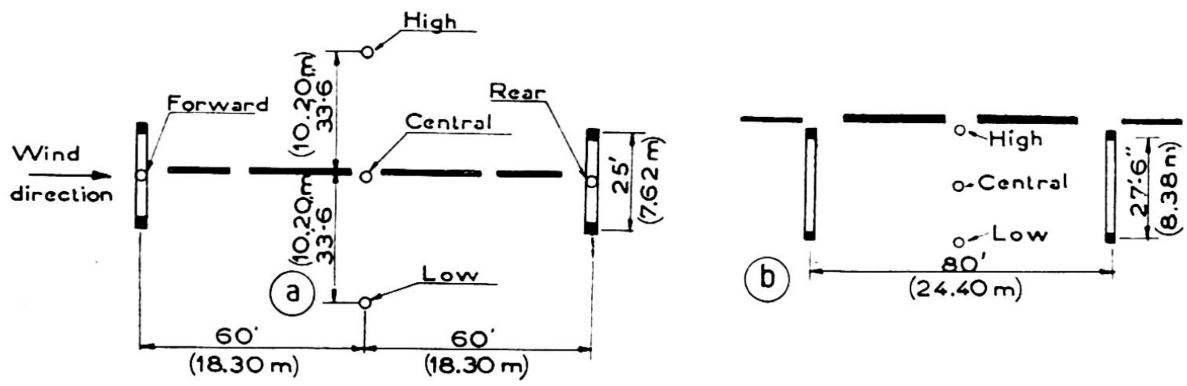


Fig. 6. Location of pitching axes.

the central position proved to be beneficial. A downstream movement of the axis had an adverse effect on stability (7).

Of the three axis positions tested with section D the upper position shown in fig. 6*b* was the least favourable for stability.

Thus for axes lying midway between the stiffening trusses the stability of both sections B and D was least when the axis was located near deck level.

e) *Types of Section*

By incorporating a number of the stabilising features mentioned in the preceding paragraphs high stability in pitch about the central axis was obtained for all sections shown in fig. 1. Sections C and D required the least number of these features and in that respect may be classed as the most stable sections. On a similar basis section B was more stable than section A.

Vertical oscillations

No vertical oscillations could be excited for any condition of the truss stiffened sections shown in fig. 1. These conditions included that of a solid deck extending over the whole area between the stiffening trusses and fitted with plate handrails of height 4.5 feet and plate girder stringers of depth 6 feet.

Both the plate girder stiffened sections shown in fig. 3 showed instability at low incidences. The instability of section E is not inconsistent with Steinman's criterion for stability $D/B < 0.25$.

General conclusions

There is as yet insufficient knowledge of the problem to enable the aerodynamic stability of a proposed design of suspension bridge to be predicted without recourse to oscillatory tests on models. Both model and

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(7) In view of the symmetry of the distribution of mass and elastic stiffness of suspension bridges, any lateral displacement of the effective axis of rotation must arise from aerodynamic couplings between the pure flexural and torsional motions about the axis of symmetry. It is hoped that evidence on this matter will be forthcoming from a study of the modes of oscillation of the full model.

full-scale experience show that the stability of plate girder stiffened bridges compares unfavourably with that of truss-stiffened bridges. The present investigation indicates that if the results of the sectional tests are confirmed by full-model tests, truss stiffened bridges of the types tested are stable in vertical motion and the tendency to instability in torsional oscillations can be corrected by incorporating a number of stabilising features in the design. These include :—

Stiffening truss chords of high width/depth ratio;
Traffic lanes separated from each other by open slots or gratings;
Truss type deck stringers in preference to the plate girder type;
Castellated handrails, or other types of handrailing designed to break up the spanwise continuity of the airflow pattern;
Lattice type wind bracing fitted near deck level;
Sidetracks (e.g. footpaths, cycle tracks) mounted outboard of the stiffening truss.

Acknowledgements

The work described above was carried out in the Aerodynamic Division of the National Physical Laboratory for the Ministry of Transport, by whose permission this paper is published. Valuable help is being received from representatives of the Consulting Engineers, Mssrs. Mott, Hay and Anderson and Messrs. Freeman, Fox and Partners.

To Dr. R. A. Frazer, F. R. S., who is in charge of the aerodynamic investigation, and to other colleagues associated with the work, the author is heavily indebted for valuable advice and close collaboration.

Résumé

Le présent mémoire donne un court aperçu sur les recherches sur la stabilité aérodynamique des ponts suspendus, réalisées dans la division aérodynamique du National Physical Laboratory. Les essais exécutés jusqu'à présent l'ont été sur des éléments de modèles; des travaux sont en cours pour réaliser des essais sur des modèles entiers d'une longueur maximum de 60 pieds dans un tunnel aérodynamique *ad hoc*. Ce mémoire donne les résultats obtenus sur des éléments de modèles et qui ont permis d'établir des détails de construction donnant une stabilité plus favorable.

Zusammenfassung

Die vorliegende Arbeit gibt einen kurzen Ueberblick über eine Untersuchung bezüglich der aerodynamischen Stabilität der Hängebrücken, die in der Aerodynamischen Abteilung des National Physical Laboratory durchgeführt wurde. Bis jetzt wurden die experimentellen Untersuchungen auf Versuche an Teilmodellen beschränkt, doch sind die Vorbereitungen für Versuche an vollständigen Modellen bis zu einer Länge von 60 Fuss in einem speziell für diesen Zweck gebauten Windkanal demnächst beendet. Es werden die bis jetzt erhaltenen Ergebnisse an Teilmodellen angegeben und die zur Erlangung grösserer Stabilität günstigen Konstruktionsdetails beschrieben.

Summary

The paper presents a brief review of an investigation on the aerodynamic stability of suspension bridges which is being carried out in the Aerodynamics Division of the National Physical Laboratory. Experiments have so far been confined to tests of sectional models but preparations are nearly complete for testing full models of lengths up to 60 feet in a large wind tunnel specially constructed for the purpose. The results so far obtained in sectional model tests are discussed, and design features favourable to the promotion of stability are indicated.

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Quelques détails sur le montage des ponts en arc métalliques

Einige Angaben über die Montage stählerner Bogenbrücken

Some details about the erection of steel arch bridges

PROF. IR. A. ROGGEVEEN
Wassenaar (Hollande)

A stiffened flexible arch bridge with the arch above the stiffening girder can be erected in very much the same way as an ordinary beam bridge, i. e. on a large number of jacks, either hydraulic or screw jacks, resting on a centering under the entire length of the bridge. On these supports the stiffening girder and the system of floorbeams are laid out and by jacking the designed camber is obtained.

On top of the stiffening girders the hangers are erected and on these the arches. By means of the jacks care is taken that throughout these operations the right camber, computed for the unstressed condition, is maintained.

Thereupon the holes for the fieldrivets may be reamed in the arches and in the stiffening girders after which the rivets can be driven and when this has been done the bridge is gradually jacked down until it carries its own weight.

For this type of erection a large number of supports has to be placed in the river or whatever the bridge has to cross. In the case of a navigable stream, this may entail closing the fairway to traffic or building over at least part of it an erection-bridge, on the top of which the permanent bridge can be built.

In such an instance a stiffened flexible arch bridge may have advantages, as this type of bridge can be made to work as its own erection bridge, thus avoiding the need for a separate one. By doing so there is an added advantage, as by concentrating the erection supports at a few points the total cost of supports is usually considerably less, due to the fact that it is far easier to obtain sufficient stiffness for one large support than for a number of supports which, together, are supposed to carry the same load as the large one.