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The Use of Model Tests in Bridge Analysis

L'emploi d'essais sur modèles dans l'étude des ponts

Modellversuche im Brückenbau

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1. Introduction

The lack of a rigorous mathematical treatment of certain types of bridge structures very often compels designers to use model tests to understand their behaviour. Such is the case, for instance, of bridge decks formed by a rectangular, tee-beam or hollow slab, non-rectangular in plan, or with marked curvature in horizontal and vertical planes (fig. 1) and of all bridge solutions with an important three-dimensional behaviour.

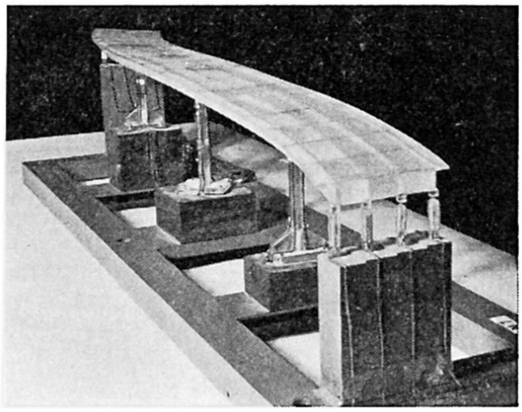

Fig. 1.

These difficulties are related in the papers of R. E. ROWE and BEST [1] and VOJTECH MICHÁLEK and VLADIMIR BKEZTNA [2] presented at the Congress under theme Ib.

In the present contribution the author summarizes his experience in model tests of bridges developed at the "Laboratório Nacional de Engenharia Civil" (Lisbon) illustrating it with some studies he had the opportunity to perform.

Some aspects connected with the above mentioned papers are discussed.

2. Construction of the Model

2.1. Scales

In order to minimize the construction of the model, structural studies for determination of the internal forces (i. e. M, N, T) in some cross sections of bridges are usually carried out on models as small as the dimensions of the measuring instruments available allow.

The scales of overall models range from $^1/_{50}$ to $^1/_{500}$, being as a rule approximately $^1/_{100}$ for bridges with a total apan of about 100 m. Models are sometimes distorted with regard to the similitude of their cross section: The members of the model are constructed with the same proportions as those of the prototype with regard to the moment of inertia but the shape of the cross sections is simplified, the similitude of normal and shear forces being therefore changed.

Structural studies of details in which the field of stresses in certain zones has to be analysed are usually carried out with larger models (scales $^1/_2$ to $^1/_{30}$). In these models only the member or group of members to be studied are reproduced as is emphasized by G. K. JEWGRAFOW and B. W. BOBRIKOW in their paper [3] presented at the Congress.

For these models boundary conditions are maintained as accurately as possible.

2.2. Materials

After attempts to use different materials, notably celluloid as employed by Prof. EDGAR CARDOSO in his elastic model studies [4], we have finally settled on acrylic resins for overall model studies. Other plastics, such as polyester resins and polyethylenes, were abandoned either because of difficulties with their mechanical characteristics or with the stability of measuring devices [6].

The acrylic plastics or methyl methacrylate resins are on sale under different trade-names such as "Perspex" (I.C.I.), "Plexiglas" (Röhm and Haas), "Lucite" (Dupont), etc. as sheets and profiles, 0.5 to 50 mm in thickness.

The average mechanical characteristics of acrylic plastics are as follows:

Modulus of elasticity	$30—40 \times 10^3$ kg/cm^2
Poisson's ratio	0.38
Ultimate tensile strength	300—500 kg/cm^2
Coefficient of thermal expansion	$7—10 \times 10^{-5}/°C$

The stress-strain diagram is nearly a straight-line (fig. 2) and there are a time dependent moduli of elasticity. The loading-readings are carried out in a constant period of time ($\sim$5 seconds) for all measurements.

The pieces cut from acrylic resin sheets or profiles are glued together with a chloroform solution of the material itself. A satisfatory gluing requires perfectly smooth flat surfaces which can be obtained by machining with a milling-cutter or a shaper.

In models constructed to smaller scales for detail studies of concrete bridges micro-concrete is often used to reproduce the properties of prototype material as is also emphasized in paper [1].

2.3. *Loading System*

The structural problems posed by the action of permanent loads and live loads can be solved, as a rule, knowing the influence surfaces of the internal forces in some cross sections due to vertical loads on the deck. These influence surfaces are obtained in our models by applying concentrated loads to various points of a grid system drawn on the surface of the deck. The loads are applied by means of a hook fitted with a counterweight (fig. 3).

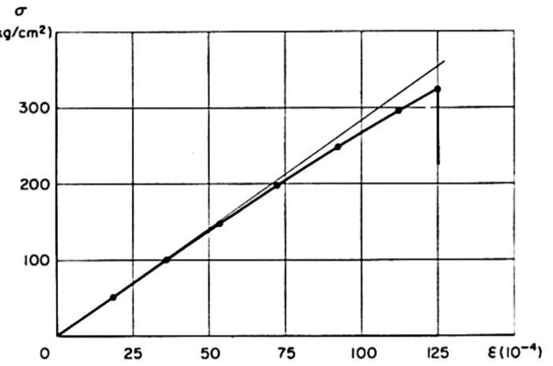

Fig. 2.

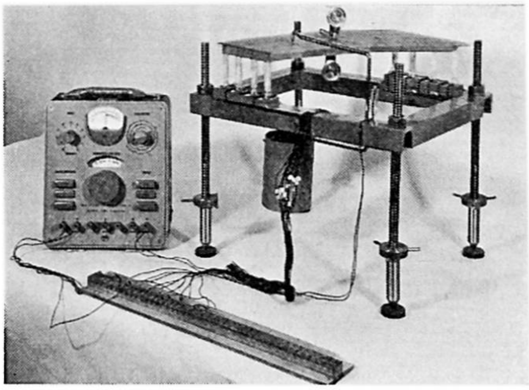

Fig. 3.

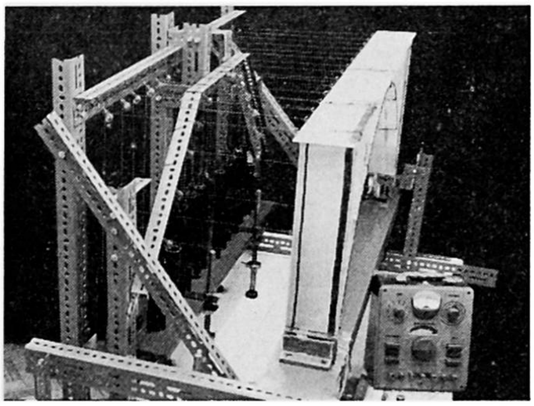

Fig. 4.

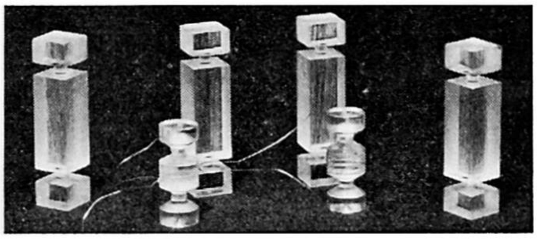

Fig. 5.

In order to minimize creep effects, strains and deflections are measured point by point 5 seconds after application and removal of the loads.

Other actions, such as wind loads, are studied by replacing them by the equivalent static forces (fig. 4).

3. Tests

3.1. *Measuring Instruments*

In our small-scale models we use the smallest and least stiff strain meters and dial gauges available. Strain-meter bases range from 5 mm to 20 mm, according to the dimensions of the model and the stress gradient around the observed point.

Paper-based electrical resistance strain gauges and rosettes glued on the models with "DUCO" cement are still the most widely used, in spite of attempts, due to their cost and inevitable loss, to replace them by small reclaimable strain meters.

The reactions of fixed or movable supports are measured in the models by replacing the supports by previously calibrated cells of acryllic material with a pendular behaviour (fig. 5).

Deflections in reference to one outside fixed system are measured with dial gauges.

3.2. Results

The internal forces in the cross sections observed are calculated from the experimental values by means of the similitude theory [5].

As a rule, the known quantities are the strains $\epsilon_1, \epsilon_2, \epsilon_3$ at the points observed on the surfaces on the model and the displacements u, v, w of some points of the model with respect to an external fixed system. The internal forces — M, N, T — and the displacements are required at the homologous points of the prototype.

The accuracy of the results obtained is always checked on basis of the deviations between the equilibrium of the applied forces and of the internal forces in the sections observed. Desviations up to 5% are deemed tolerable.

4. Examples

4.1. Increase of internal forces in the member of a ribbed deck due to the asymmetry of the live loads

M_m, N_m and T_m being the average values of the internal forces in a cross section of a deck rib (assuming that the action of the live load is uniformly distributed in all the members) and M_{max}, N_{max} and T_{max} being the maximum values of these same magnitudes in the same cross section due to asymmetric loads in the cross section under consideration, the designer usually requires the values of the coefficients:

$$\eta_M = \frac{M_{max}}{M_m}; \qquad \eta_N = \frac{N_{max}}{N_m}; \qquad \eta_T = \frac{T_{max}}{T_m} \tag{1}$$

for each rib and cross section.

Although for some typical decks analytic methods are available for determining η_M, model tests have to be resorted to in current cases for obtaining more accurate values.

In fig. 6 is shown the plan and the middle cross section S_0 of the three-cells box girder, curved in plan, presented in fig. 3.

The influence line along S_0 of the moments M_A in web A for vertical loads on the deck is indicated by the full line in fig. 7, and the values obtained by an approximate analytical computation by means of a mesh analogy are shown by the dotted line.

It was found that for our standard truck with wheel axles 2.0 m apart, the experimental value η_M is 1.5 and the expected analytical value 2.5.

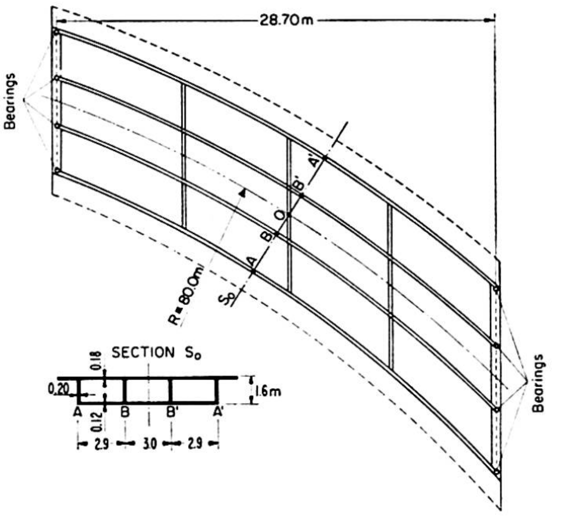

Fig. 6.

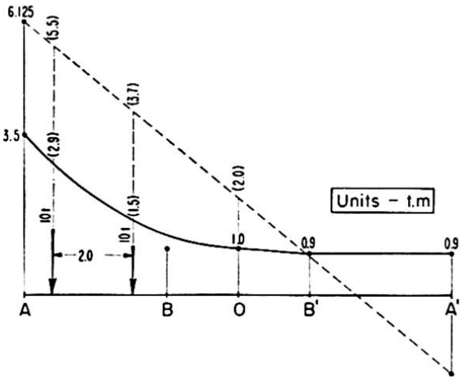

Fig. 7.

4.2. Influence Surfaces in Slab-Decks

This is a study, more general than 4.1, which can be included in it as a particular step of preceding analysis.

ϵ_x and ϵ_y being the strains due to a normal concentrated load measured along two orthogonal directions in one face of the slab-deck model, the following moments act along the same directions in the prototype*):

$$M_x = \chi\lambda\frac{E_m}{1-\nu^2}(\epsilon_x+\nu\,\epsilon_y)\frac{e^2}{6},$$
$$M_y = \chi\lambda\frac{E_m}{1-\nu^2}(\epsilon_y+\nu\,\epsilon_x)\frac{e^2}{6}. \qquad (2)$$

$1/\lambda$ being the scale of the model, $\chi = F_p/F_m$ the ratio of the forces acting on the prototype to those acting on the model, E_m and ν the modulus of elasticity and Poisson's ratio of the material of the model and e the thickness of the slab in the model. F_p are usually assumed equal to the unit force. If we had instead a ribbed or hollow slab the experimental problem would not be difficult as elongation ϵ_1 would be measured along the beam and ϵ_2 along a direction normal to it.

The moments in the beam in the prototype are now given by

$$M_1 = \chi\lambda\frac{E_m}{1-\nu^2}(\epsilon_1+\nu\,\epsilon_2)\,W_1. \qquad (3)$$

*) Internal normal forces in the slab are not considered.

W_1 being the modulus of the section of the beam in the model with respect to the face in which ϵ_1 was measured.

Fig. 8 shows the influence surface of the moments in cross section between a a' of rib 3' of a skew ribbed slab.

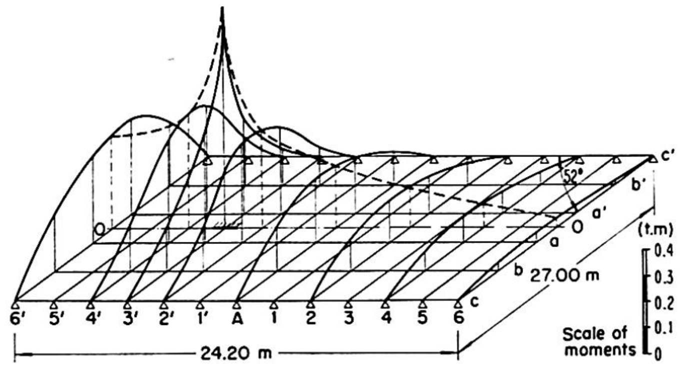

Fig. 8. Bending moments influence surface in beam 3' section 0—0'.

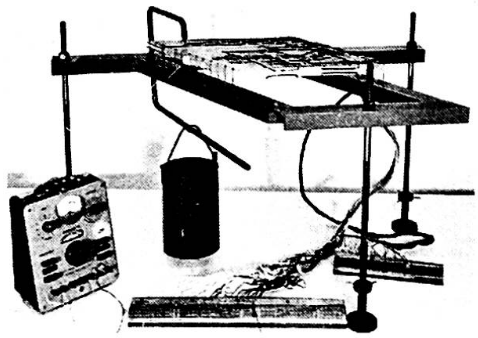

Fig. 9.

The model, made of "Plexiglass" to scale 1:75, was loaded with a concentrated force of 7.5 kg (fig. 9) and consequently $\chi\lambda = 10{,}000$.

The moments in the longitudinal and cross beams that meet at an angle of 52° were computed by (3).

4.3. *Three Dimensional Behaviour*

As a rule the analytical study of a bridge with an important three-dimensional behaviour is very difficult and inaccurate, whereas a model study is comparatively easier and more reliable. An instance of this is presented in the paper [2] about the model study of an important box-girder bridge.

These studies are also of particular interest in decks carried by very deformable substructures such as slender piers, deformable arches, ties, and so on.

As a rule the aim of a model study of this type is to obtain the influence surfaces of the internal forces M, N and T in a given cross section of a member of the bridge, under a vertical load acting at different points of the deck.

Assuming the common case of uniaxial stress let W_{I} and W_{II} be the moduli of the section with respect to the principal axes, A the section area and ϵ_{I_1}, ϵ_{I_2}, ϵ_{II_1}, ϵ_{II_2} the strains at surfaces along the planes containing the axes of the member and the principal axes I and II of the section, we have.

$$\begin{aligned} N &= \chi A\, E_m \frac{\epsilon_{\mathrm{I}_1} + \epsilon_{\mathrm{I}_2} + \epsilon_{\mathrm{II}_1} + \epsilon_{\mathrm{II}_2}}{4}, \\ M_x &= \chi\lambda\, W_{\mathrm{I}}\, E_m \frac{\epsilon_{\mathrm{I}_1} - \epsilon_{\mathrm{I}_2}}{2}, \\ M_y &= \chi\lambda\, W_{\mathrm{II}}\, E_m \frac{\epsilon_{\mathrm{II}_1} - \epsilon_{\mathrm{II}_2}}{2}. \end{aligned} \qquad (4)$$

Shear forces in a particular cross section of a member can be determined from the strain measurements in models with dimensions enabling the installation and reading of strain rectangular rosettes applied at an angle of 45° with the axis of the member.

Let ϵ_{a_1}, ϵ_{a_2} and ϵ_{b_1}, ϵ_{b_2} be the strains measured along two directions at 45° to the axis of the member in opposite directions in respect to a longitudinal plane containing one of the principal axis of the section. We can write for a rectangular profile of the model:

$$T_m = \frac{G_m A}{3} (\epsilon_{a_1} + \epsilon_{a_2} + \epsilon_{b_1} + \epsilon_{b_2}), \tag{5}$$

in which G_m represents the modulus of elasticity in shear of the material of the model.

In a prismatic piece subjected to linear bending the measurement of bending strains ϵ_1 and ϵ_2 at two cross sections, of the same face at a distance d, enable to calculate the constant shear force:

$$T_m = \frac{E}{d} (\epsilon_1 - \epsilon_2) W. \tag{6}$$

In fig. 10 and 11 is presented, as an example of a study of this type, the influence surface of the bending moments M_x at the base of one pier (in the direction of its maximum moment of inertia) of a skew bridge under the action of a concentrated vertical load applied in the deck. It is noteworthy that the points where bending moments change signs are difficult to determine by analytic means.

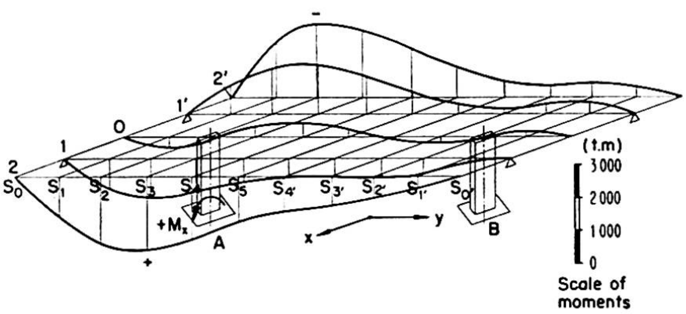

Fig. 10. Moments M_x in the base of pier A.

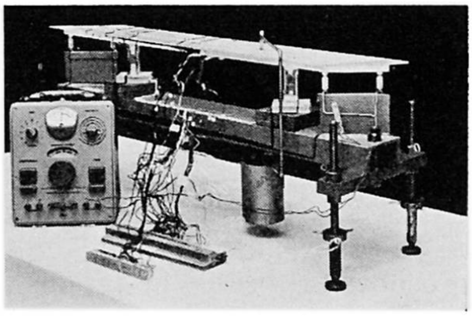

Fig. 11.

Another exemple of a three-dimensional study is presented in figure 12 in which are summarized some experimental results of the three dimensional behaviour of a deck of an arch bridge 211 m in span.

In figures 12a and 12b are represented the influence lines of the bending moments in two cross section of the longitudinal deck beams for different positions of a vertical load moving along the three vertical plans of the arch ribs.

Considerably differences was found between the experimental values and those that could be obtained from the current methods of analysis.

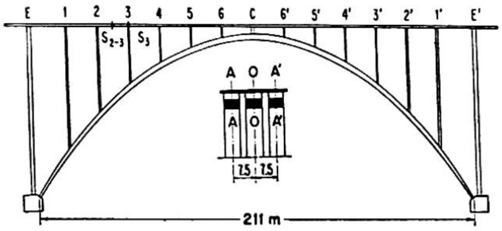

Fig. 12.

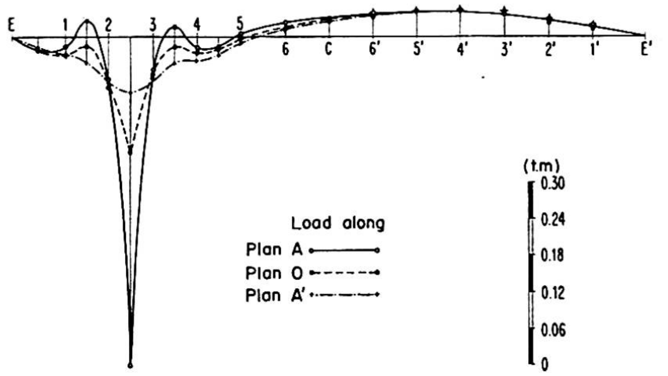

Fig. 12a. Moments in section S_{2-3} of deck beam A.

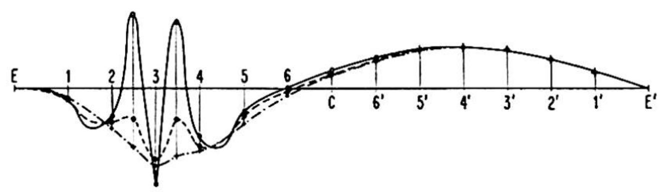

Fig. 12b. Moments in section S_3 of deck beam A.

5. Conclusions

Although not new, but now merely more exploited, model tests open new prospects in bridge design as the examples and the studies presented at Congress clearly show.

A. In bridge structures for which mathematical treatment is either insufficiently developed or deemed less accurate, model tests are an important basis for a research study program and a source of important design data.

B. In bridge structures for which mathematical methods of analysis exist, model tests sometimes suggest anomalies in design assumptions enabling the adoption of others, closer to their real behaviour.

C. Model tests also enable the development of new structural shapes, suggested by designer's experience and intuiton and seldom applied due to lack of an easy checking basis.

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Summary

The author sums up the model testing methods in use at the LNEC (Lisbon) in the study of bridge structures, presenting the results of major engineering interest of some completed studies.

Résumé

L'auteur résume les techniques employées au LNEC (Lisbonne) pour les essais sur modèles d'ossatures de ponts; il présente les résultats techniquement les plus intéressants de quelques-uns des travaux réalisés.

Zusammenfassung

In der vorliegenden Arbeit faßt der Autor die im LNEC (Lissabon) verwendeten Untersuchungsmethoden für Brückenmodelle zusammen. Er stellt einige Versuchsergebnisse von hoher technischer Bedeutung dar.

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