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PROGRAMME AND METHODS OF TEACHING OF EXPERIMENTAL MECHANICS

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PROGRAMME AND METHODS OF TEACHING OF EXPERIMENTAL MECHANICS

by

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At the 4th International Conference on Experimental Stress Analysis in Cambridge in 1970, an informal meeting was held on the teaching of experimental stress analysis, during which the following fundamental aspects were discussed:

Purpose of teaching experimental stress analysis (e.s.a.).
How general can the teaching of e.s.a. be?
Textbooks or lecture notes.
The role of laboratory work.

This meeting is reported in detail in [1], which also enlarges upon the principles applied and the subject matter of three courses in e.s.a. As a result of the meeting, a collection of abstracts of lecture notes have been published for the use of instructors in courses in this field [2].

As a supplement to the matters discussed at the above meeting, I give in the following a detailed description of a course in e.s.a., together with a corresponding description of a course on measuring systems.

PLACING OF COURSES

The courses described are given during the 3rd and 4th years of a 5-year curriculum in civil engineering at the Technical University of Denmark. About 130 civil engineers graduate each year. About 20 of these have had course 1 (e.s.a.) as a compulsory subject in their 3rd year, while about 10 have taken it as an optional subject in their 4th year. Course 2 (measuring systems) is an optional subject and is taken by about eight students a year in their 4th year.

With the introduction of a new curriculum in the summer of 1972, both courses will become optional. This opens the way for students to make up their own curricula, allowing them to cross the present barriers between civil engineering, mechanical engineering, electrical engineering and chemical engineering.

The Structural Research Laboratory is responsible for the instruction in course 1. Its other spheres of responsibility are:

mathematical theory of elasticity, applied elasticity, theory of plasticity, numerical methods, theory of structures and dynamics of structures, structural design and loading theory.

The instruction in course 2 is shared by the Structural Research Laboratory, the Institute of Hydrodynamics and Hydraulic Engineering and the Thermal Insulation Laboratory, all of which are laboratories in the Civil Engineering Department.

PURPOSE OF COURSES

Course 1 is held because a number of the students will, as engineers, encounter design problems, the solution of which entails tests or the evaluation of test results, since

Tests can be used to check methods of calculation.
Tests can provide information about geometrically complicated structures, where calculations may be inaccurate or impossible.
Tests may be necessary when material properties are not well known (concrete, granular materials).
Tests may be necessary in the case of structures for which the loads are not clearly defined (wave and wind forces, impact loads).
Tests may be necessary in the case of structures in which the residual stresses are unknown (welding and shrinkage stresses).

Efforts are therefore made to plan the instruction to give the students sufficient background knowledge to:

decide whether tests are likely to provide a reasonable solution to a problem,
carry out simple tests,
plan more complicated tests,
evaluate articles in which important conclusions are drawn on the basis of described tests.

To achieve this, the instruction includes model problems and the principles and limitations of the most important methods of measuring stress and strain in models and structures.

Emphasis is laid on the elaboration of experimental and theoretical methods as complementary means of solving a problem.

The students have no special motivation for devoting themselves to e.s.a., i.e. they are not faced with testing problems to which they seek a solution by means of the course. The instruction is therefore made as general as possible, so that the knowledge acquired can later be brought to bear in a more specialized context. The principles, assumptions and limitations of the subject are studied, and it has been found preferable to concentrate on a thorough study of a few measuring principles rather than to give a more descriptive exposition on many.

In continuation of this, it is reasoned that the students do not know what experimental work really involves until they themselves have planned and carried out a test, i.e. until they have utilized the general knowledge acquired from the lectures on a special problem formulated as a practical measuring assignment. The students therefore have to solve such an experimental problem, and must themselves find and solve the constituent and frequently practical problems that are characteristic of tests and decisive of the practicability of a given experimental method. For pedagogic reasons, the test is used for a comparison with a calculation of the same problem, also carried out by the students.

Course 2, on electrical measuring systems, is for students who wish to work with a partially experimental problem in their final year project or post-graduate research, and who may later desire employment in a research laboratory in the field of civil engineering.

The instruction seeks to enable the students to use complicated measuring systems as a 'tool of their trade.' They must thus be able to decide whether the tool is functioning properly, i.e. be able to determine the degree of accuracy of the results of measurements and, if possible, to improve this accuracy and, further, to determine in which part of the system a possible error has arisen. The problem of whether the measuring technique applied will affect the measuring results is considered to be of great importance and is one of the main reasons for having instructors with experience in applications. Apart from an introductory revisional course consisting of four lectures, no instruction is given in electronics.

The experimental part of this course consists of four all-day experiments. The measuring systems used for these tests are the same as are used by the laboratories in actual research. Each of the laboratories parcicipating in the instruction has arranged one of these experiments. In this way, the students gain insight into the spheres of operations of the various laboratories that can later be used in their choice of specialization. In addition, the students come to realize that the general principles involved are fairly independent of the measuring applications.

CURRICULUM FOR COURSE 1

Lectures

The students are assumed to have been through courses in mathematical theory of elasticity, applied elasticity, theory of structures, structural design and elementary theory of measurement.

A total of 26 lectures are given, each of a duration of 45 min., the subject distribution being as follows:

Subject	No. of lectures	Lecturenotes
Introduction	1	
Model laws	3	[3]
Model materials	1	[3]
Stress measurement with pressure cells	2	[3]
Strain gauges	3	[4]
Photo-elasticity	4	[5]
The Moiré method	4	[6]
Exercises and problems from previous examination papers	8	

Great importance is laid on the introductory lecture, since this illuminates the background and reason for the course by means of examples of the application of tests. The tests referred to here have all been carried out at the Structural Research Laboratory.

The lectures on model laws cover, inter alia, the case in which the construction material and the model material are identical but may otherwise have arbitrary, unknown, constitutive relations. Emphasis is laid on the definition of assumptions for the establishment of model laws and on the indication of a possible discrepancy in the requirements laid down or difficulties of a practical nature in the fulfilment of the requirements.

The model conditions in the special case in which the materials are linear elastic, isotropic and homogeneous, are established on the basis of the system of equations from the mathematical theory of elasticity. The importance of the requirement to Poisson's ratio is illustrated by means of examples. The requirements for modelling the conditions in a structure of linear elastic, isotropic and homogeneous material in a model of time-dependent material are discussed.

In the lectures on model materials, micro-concrete and plastic materials are discussed. Efforts are made to produce the former material with the same properties as the concrete in the prototype, and the fundamental problems involved in this are pointed out. In the case of the plastics, a qualitative description is given of their time-dependence and freezing characteristics based on an assumption regarding primary and secondary bonds.

The possibility of producing model materials with the desired physical constants is discussed, and Budiansky's expression [8] for the physical constants for a mixture of components of linear elastic, isotropic, homogeneous materials is derived. The measured and calculated values are compared [9].

Measurement of the stress fields in materials like earth, sand and concrete is important in civil engineering. The design of pressure cells for this purpose is dealt with, the pressure cell being geometrically approximated to an ellipsoid of rotation, and pressure cell and matrix material being assumed to be linear elastic, isotropic and homogeneous. Eshelby's solution [10] to this problem is given, with certain omissions, and two special cases are considered. The solutions to these are evaluated on the basis of the following requirements, which it is necessary to try to fulfil if we are to envisage an extension of the field of applications of the pressure cell to include registration of the pressure in a medium of arbitrary material.

There must be a unique relationship between the signal measured and the stress component to be measured in the matrix.

The signal measured must be independent of the physical constants of the matrix material.

The signal measured must not register a homogeneous, stress-free state of strain in matrix or pressure cell.

The pressure cell must not interfere with the stress field in the matrix.

An evaluation of these requirements leads to criteria for the design of pressure cells [11].

The three lectures on strain gauges deal with the temperature and strain properties of resistance materials, the transmission of strain from structure to resistance wire and measuring circuits.

Equilibrium diagrams for solid solutions of two metals (Cu-Ni) and for binary eutectic alloys (Cr-Ni and Pt-W) are studied, and the compositions at which reversible temperature-dependence can be expected are specified.

The relationship between the relative change in resistance and the state of strain in the resistance element is formulated in tensor form and is then specialized to cubic crystals (Si, Ge) and isotropic materials (metals).

This relationship shows that the change in resistance is not a unique function of the normal strain in the longitudinal direction of the resistance element, but depends to a considerable degree on the normal strains perpendicular to this. However, it is shown that the low ratio between the moduli of elasticity for the carrier material and the resistance element, together with the small dimensions of the resistance element in the transverse direction, usually results in an almost unique relationship between the change in resistance and the normal strain of the structure in the longitudinal direction of the resistance element. Attention is drawn to the fact that moisturedependent changes in the volume of the carrier may have a serious effect on the state of strain in the resistance element [12]. The fundamental difficulties involved in preventing the penetration of moisture to the glued joints between carrier and high-energy materials such as, for example, metals, are discussed [13].

The third lecture on measuring circuits gives the expressions for the Wheatstone bridge in complex form, and its use for the subtraction of noise signals and for the execution of mathematical operations for, e.g., the solution of a linear expression.

Appendix B gives the text of a problem from the written examination that concludes the course. Lecture notes may be used during the examination. 2 hours are allowed for solution. The mean value of the marks given lies somewhat under average, and the standard deviation is large. The problem is taken from an application mentioned in [14].

In the lectures on photo-elasticity, only the linear relationship between the birefringence and the state of stress and strain is discussed. Neumann's own reasoning is used for deriving the relationship between wave velocity and state of strain. The corresponding expressions derived on the basis of Maxwell's electromagnetic field theory are discussed.

Methods of interpreting the optical signal from a plane model placed in a polariscope are then dealt with. The possibilities of interpreting the optical signal received when the light beam passes an inhomogeneous state of stress are discussed. Finally, the students are taken through the freezing technique.

The lectures on the Moiré technique deal with the application of two superposed line grids. First the moiré pattern from two undeformed line grids and its application for measuring displacements are discussed. After that, the parametric description of the moiré pattern when the specimen grating is deformed is given, followed by the evaluation of such a pattern. Finally, the expressions derived are used on the following special cases: direct moiré, shadow moiré and reflexion moiré.

Experimental work

The lectures are followed by two weeks of all-day practical work. The students work in 2-man teams and submit one report per team, which forms the basis for marking.

Appendix D gives the text of such an assignment. (It is important that the teams have different types of problems). For pedagogic reasons, a comparison is required between the calculation and the test, with both parts carried out by the students. In addition, an evaluation of possible discrepancies between the two methods must be provided. The theoretical part of the assignment is not intended to present the students with new subject matter, so it is limited to plane frame structures.

In the assignment in appendix D, the students encounter the following problems:

Planning of work,
Design of model arrangement,
Partial production of model,
Assembly of model,
Estimation of the order of magnitude of the expected signals,
Establishment of requirements to measuring accuracy,
Specification of locations of measuring points,
Mounting of thermo-couples and strain gauges,
Stabilization of strain gauges,
Use of measuring equipment,

Application of model laws,
Evaluation of accuracy.

It is considered very important that the students should all the time feel that the initiative and the responsibility are theirs. They may seek advice from anyone they wish, but are themselves responsible for the use to which they put such advice. The supervisors follow the students' work very closely, but only intervene if this is necessary to get the assignment finished on time. The students are therefore not prevented from making an unsuccessful test as long as there is time for them to carry out another test.

The test arrangement constructed by the students on the above assignment is shown in fig. 1.

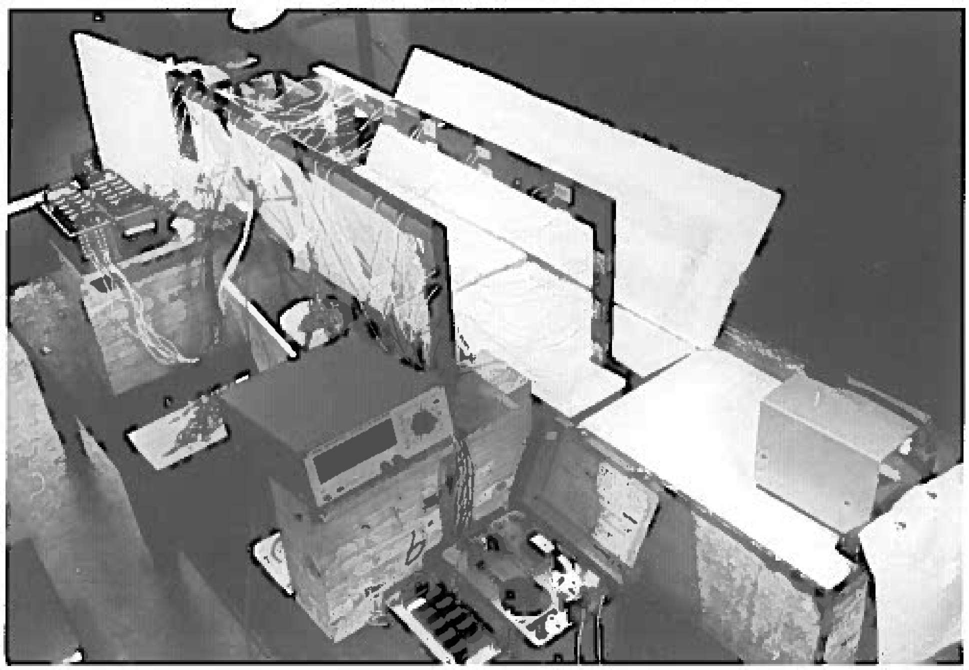

Fig. 1. Example of experimental assignment in course 1. Thermo-elastic stresses in a frame.

The students' reports are checked immediately after submission, and the students are then given the opportunity of looking them through and possibly raising objections to corrections and comments before the reports are passed on for marking.

The mean value of the marks for the experimental work has up to now been slightly above average, with little standard deviation. About 15 hours of assistance per student are spent on workshop work, supervision and correction. This does not include the time spent on planning the assignments (in which the Laboratory's Ph.D. students play a very important part) because the assignments can be used for several years.

CURRICULUM FOR COURSE 2

Lectures

The students are assumed to have been through courses on basic electricity and elementary theory of measurement, and to have some acquaintance with the types of problems that can be solved by means of the measuring systems.

The course includes a total of 20 lectures, each of 45 min., and 8 half-hour sessions are spent on going through problems. The subject distribution is as follows:

Subject	No. of lectures	Lecturenotes
Revisional course: Electronic components and circuits	4	[15]
Laboratory exercise	2	
Transducers	2	[16]
Signal conditioning	2	[17]
Electrical noise and distortion	2	[18]
Analog recording	2	[19]
Use of operational amplifiers	2	[19]
Digital methods of measurement	2	[20]
Digital methods of computation	2	[20]

Only the transducer principles commonly applied in laboratories in the civil engineering field are discussed, i.e. the active transducers: thermo-couples and piezoelectric crystals, and the passive impedance transducers. Examples are used to illustrate the problem of ascertaining whether the measuring technique affects the measured signal and the problem of uniqueness. The study of transducer principles is based mainly on Rohrbach [21] and Neubert [22]. The order of magnitude of the signals and major sources of error are specified.

Signal conditioning of the above types of transducers is discussed. General expressions for a Wheatstone bridge are specified. These are applied to resistance, inductive and capacitive transducers in the bridge arms. For example, the influence of conductor capacities on the reading for a Wheatstone bridge with strain gauges is considered.

The lectures on distortion and noise include an account of sources of interference and general principles for combating noise.

In the lectures on analog recording, the problems of non-linearity and the sensitivity of different types of instruments are discussed, together with frequency and transient behaviour. The lectures on the use of operational amplifiers include linearization, addition, integration and other operations. The lectures on digital methods of measurement include number systems, binary elements, multivibrators, counters and voltage-frequency converters, while those on digital methods of computation deal with digital computers, binary operations, digital recorders and input-output devices.

Experimental work

The students work in 2-man teams. Each team has to carry out four exercises, each lasting a day, after which the results have to be processed and evaluated, and a report prepared, which forms the basis for the marking.

The exercises consist of arranging instruments for the solution of a special measuring problem, i.e. the assignment includes checking the measuring system and correcting possible faults.

Appendix E gives the problem text for the exercise carried out at the Thermal Insulation Laboratory. Fig. 2 shows the corresponding test arrangement. Fig. 3 shows another arrangement, which is used for measuring the turbulence in a water flume. This exercise is carried out at the Institute of Hydrodynamics and Hydraulic Engineering.

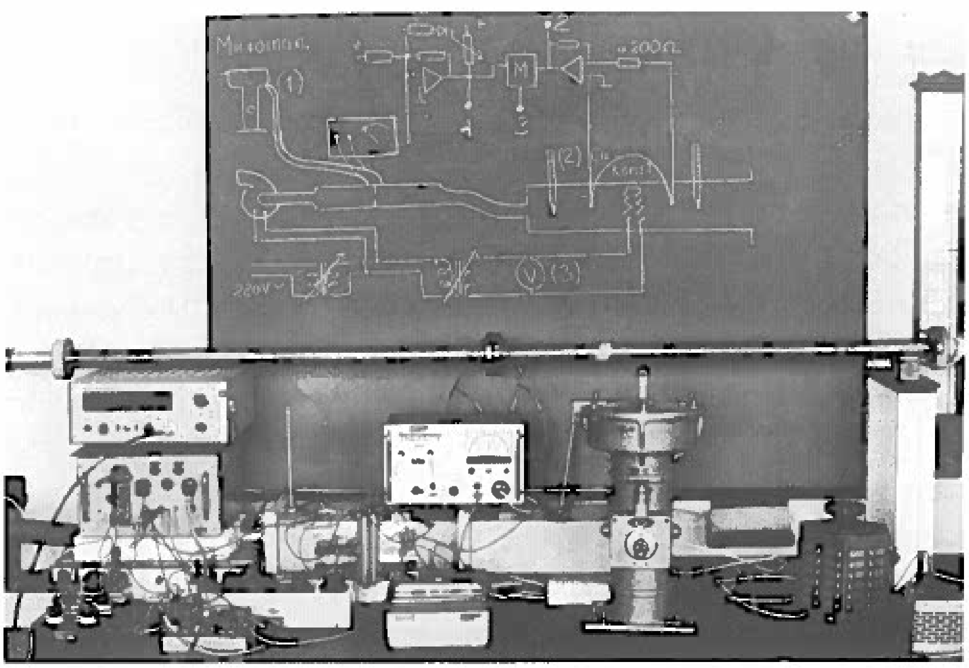

Fig. 2. Exercise in course 2. Linearization and multiplication of signals. Thermal Insulation Laboratory.

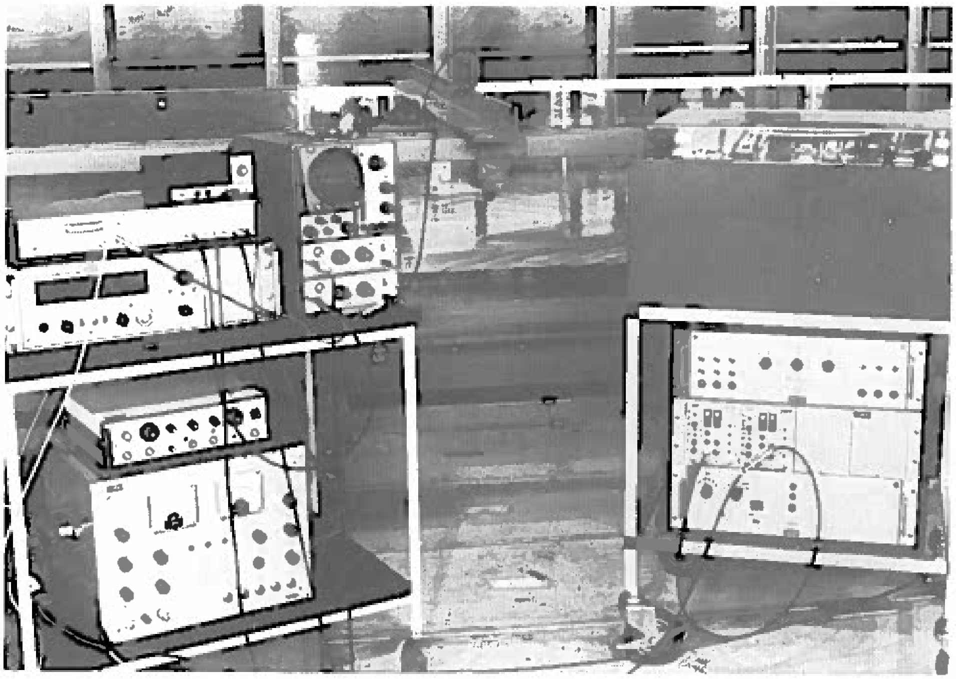

Fig. 3. Exercise in course 2. Measurement of turbulence in a water flume. Institute of Hydrodynamics and Hydraulic Engineering.

The mean value of the marks given in these experimental assignments lies slightly above average, with little standard deviation. About 8 hours per student are spent on the work of supervision and correction.

CONCLUSION

The aim of course 1 is to give the students the necessary background knowledge to

1. decide whether tests are a reasonable solution to a problem,
2. carry out simple tests,
3. plan more complicated tests,
4. evaluate articles describing tests.

The results achieved by the students on the experimental assignment show that point 2 is in order and that they have obtained sufficient experience in testing technique to give them reasonable qualifications also as regards points 1 and 3. Special courses have been held for the students with the aim of training them in evaluating articles on experimental subjects. Here it has been possible to compare students who have both attended the lectures and carried out the experimental assignment in course 1 with students who have only attended the lectures. The former group dealt more independently with the articles than the latter and seemed better equipped to evaluate such articles (point 4).

Course 2 has only been held twice, so there is as yet insufficient basis for a general evaluation. The principle followed in the courses, of giving a general exposition in the lectures and specializing in the applications at the individual laboratories in the experimental part, seems to result in a satisfactory cooperation between several laboratories.

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ABSTRACT

The article describes two courses for students of civil engineering at the Technical University of Denmark. One of the courses deals with experimental stress analysis, and the other, with measuring systems.

The general principles on which the courses are based are first to give a clear formulation of the aim of the instruction and then to split the instruction up into lectures, in which the topics are dealt with in as general a form as possible, and tests, in which the subject matter of the lectures is used for the solution of problems. The formulation of the experimental assignments is considered to be of decisive importance to the degree of benefit derived by the students from the course.

KURZFASSUNG

Der Artikel beschreibt zwei Kurse für Bauingenieurstudenten an der Technischen Universität Dänemarks. Der eine Kursus behandelt experimentelle Spannungsanalyse, der andere Messysteme.

Die allgemeinen Richtlinien beim Aufbau der zwei Kurse waren erstens: Eine klare Formulierung für den Zweck des Unterrichts, zweitens: Eine Aufteilung des Unterrichts in Vorlesungen, in welchen die Themen so allgemein wie möglich behandelt werden, und Versuche, in welchen der Unterrichtsstoff zur Lösung der Probleme angewandt wird. Die Formulierung der experimentellen Aufgaben wird dafür angesehen, von entscheidender Bedeutung für den Gewinn der Studenten zu sein.

APPENDIX A.

The plate section shown in fig. 4 has the thickness h and is made of a linear elastic material with the modulus of elasticity E and Poisson's ratio ν.

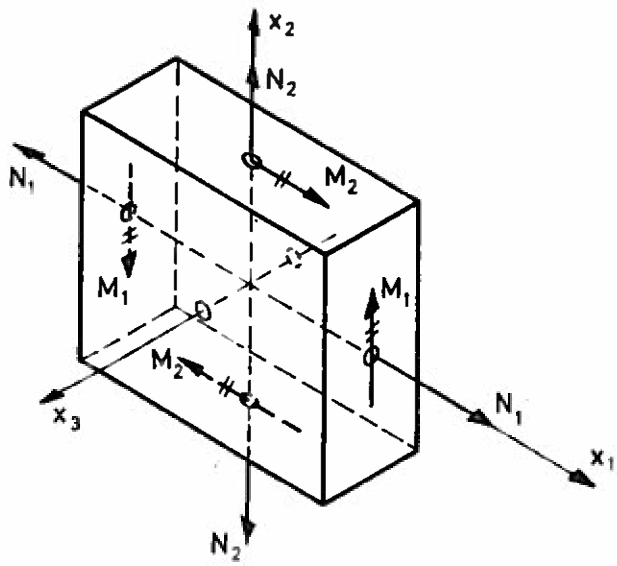

Fig. 4.

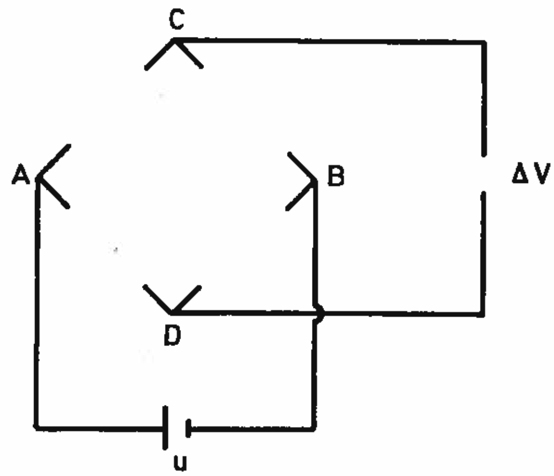

Fig. 5.

A cartesian coordinate system is inserted so that the x_1 and x_2 axes lie in the central plane of the plate. A linear stress distribution is assumed in the x_3 direction of the plate. The variation in stress in the x_1 and x_2 directions is assumed to be negligible.

M_1, which is the bending moment per unit length of the plate (see fig. 4) is to be determined by measuring the signal from a Wheatstone bridge (see fig. 5), in which 4 strain gauges placed on the surfaces parallel with the x_1-x_2 plane and fixed resistances are combined. The bridge voltage is u. The signal voltage ΔV is assumed to be zero when the plate is not under load. The resistance of the strain gauges is R, and the gauge factor is k.

The signal measured must be independent of the bending moment per unit length M_2 and of N_1 and N_2, which are the normal forces per unit length in the x_1 and x_2 directions, respectively.

1. State how the four strain gauges should be placed on the plate.
2. Specify how the gauges and the fixed resistances should be combined in the Wheatstone bridge. Find the size of the fixed resistances.
3. Find M_1, expressed by the signal $\frac{\Delta V}{u}$ from the Wheatstone bridge.
4. Prove that the signal measured is independent of M_2, N_1 and N_2.

APPENDIX B.

Fig. 6 shows a plane concrete structure with the same temperature throughout. If the structure is subjected to an influx of sunlight the temperature distribution will become inhomogeneous, whereby stresses will arise in the structure. The foundations and the soil can be regarded as a heat reservoir of infinite size, the temperature of which remains constant.

Fig. 7 shows a model of the concrete structure made in steel in the scale of about 1:20. (Concrete is assumed to be linear elastic, isotropic and homogeneous). It is assumed that tests have shown that the stable temperature condition in the model exposed to heating lamps as shown in fig. 7 gives twice the increase in temperature of the structure exposed to the sun.

1. Make the model (workshop assistance provided).
2. Calculate, by means of measurements with thermo-couples, the bending moments and normal forces in the model during thermal equilibrium.
3. Calculate the corresponding bending moments and normal forces on the basis of strain measurements with strain gauges on the model.
4. Calculate the moments and normal forces in the concrete structure.
5. The report must include an evaluation of the results obtained.

The following measuring equipment may be used for solution of the problem:

Cu-Ni thermo-couple wire,
BT-1 strain gauges,
Strain indicator,
Switching unit,
Digital voltmeter.

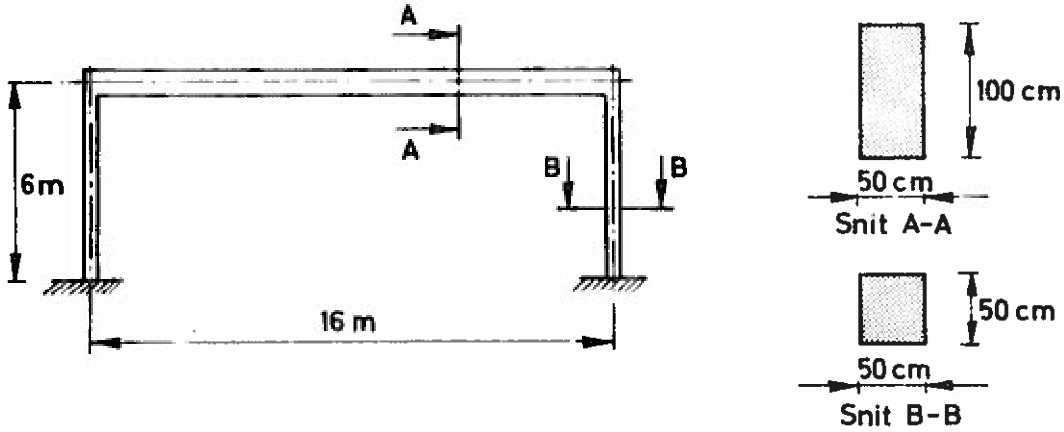
A
A
B
B
6m
16 m
100 cm
50 cm
Snit A-A
50 cm
50 cm
Snit B-B

Fig. 6.

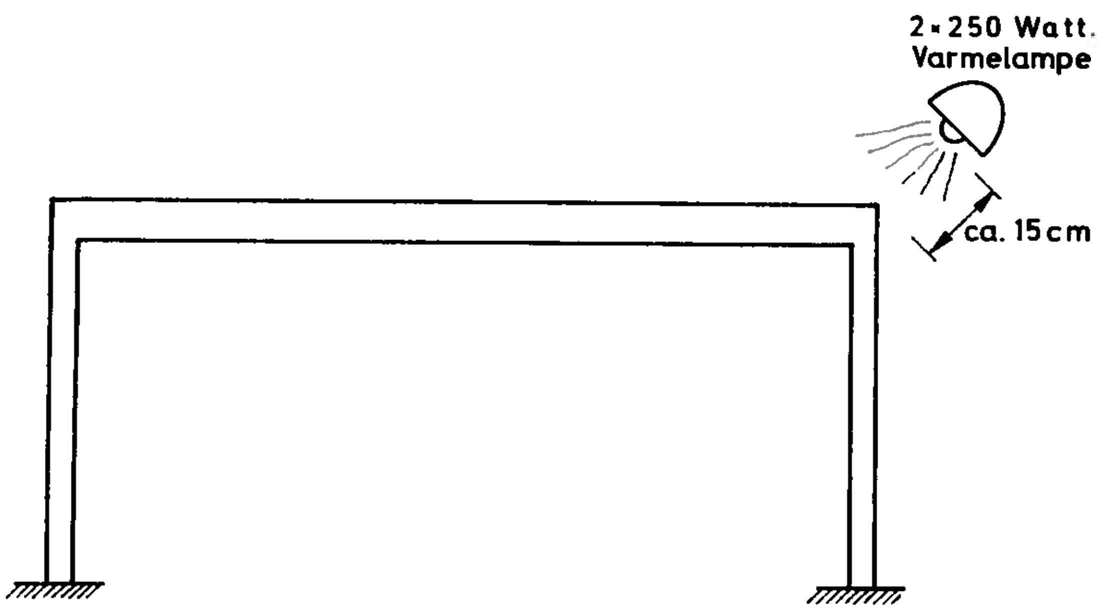
2×250 Watt.
Varmelampe
ca. 15 cm

Fig. 7.

APPENDIX C.

Object: An air duct, in which the rate of air flow is measured by means of an electronic micromanometer over an orifice, and the difference in temperature of the air in front of and behind a heating coil is measured by means of thermo-couples.

The quantity of air and the difference in temperature give the induced power.

1. Make a linearizing circuit to be used on the micromanometer output to obtain a signal proportional to the quantity of air in a prescribed interval.

2. Using a multiplier, multiply this signal by the temperature difference measured to get the induced power. This can then be compared with the power actually supplied to the heating element.

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