TECHNICAL REPORT NO. 6-811

STRAIN METERS AND STRESS METERS FOR EMBEDMENT IN MODELS OF MASS CONCRETE STRUCTURES

Report 1

SUMMARY OF INFORMATION AVAILABLE AS OF MARCH 1967

by

H. G. Geymayer

January 1968

Sponsored by

Office, Chief of Engineers
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FOREWORD

This investigation forms part of the Corps of Engineers Civil Works Investigations-Engineering Studies Item ES 036.1, and was authorized by first indorsement from the Office, Chief of Engineers, dated 13 June 1966, to U. S. Army Engineer Waterways Experiment Station (WES) letter dated 18 April 1966, subject, "Project Plan for Investigation of Small Gages for Embedment in Models of Mass Concrete Structures."

The work was performed at the WES Concrete Division during the period from July 1966 to February 1967 under the direction of Messrs. Bryant Mather and James M. Polatty and Dr. Helmut G. Geymayer. This report was prepared by Dr. Geymayer.

Director of the Waterways Experiment Station during the investigation and the preparation and publication of this report was COL John R. Oswalt, Jr., CE. Mr. J. B. Tiffany was Technical Director.

CONTENTS

CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
inches	2.54	centimeters
pounds per square inch	0.070307	kilograms per square centimeter
square inches	6.4516	square centimeters
microinches	0.0254	microns
micrcinches per inch	0.001	microns per millimeter
Fahrenheit degrees	5/9	Celsius or Kelvin degrees*

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.16$.

SUMMARY

This report summarizes the results of an extensive literature review and a worldwide survey to develop information on small, embedded stress meters and strain meters suitable for model work and long-term investigations. Following a discussion of general problems of internal strain and stress measurement in concrete, including a brief review of the advantages and disadvantages of various systems of measurement, numerous particular meters are described in detail, and their applicability to model work is tentatively assessed. Although this report is primarily concerned with internal strain meters, some of the most important stress meters will also be discussed briefly.

The information collected reveals a lack of small, embedded meters suitable for long-term model studies, and indicates that in the past primarily two measuring principles were used for long-term measurements in concrete; these were the unbonded wire and the acoustic meter. Neither system, however, lends itself well to construction of very small meters (less than about 2-in. maximum dimension).

Many methods of utilizing bonded-wire strain gages for internal measurements in concrete have been proposed. Several of these methods appear quite satisfactory in applications where drifting is not a problem, yet the long-term stability of embedded bonded-wire gages remains unproved.

A number of other systems of measurement (inductance-capacitance, semiconductor, hydraulic, and pneumatic meters) that appear rather promising for internal stress and strain measurement in concrete have hardly been investigated to date.

Based on the results of this preliminary study, it is concluded that further efforts to select or develop suitable instrumentation for internal long-term stress and strain measurements in concrete models should concentrate on the evaluation and improvement of bonded-wire meters, on the development of new inductance and semiconductor meters, and on the use of existing small acoustic meters.

STRAIN METERS AND STRESS METERS FOR EMBEDMENT IN MODELS OF MASS CONCRETE STRUCTURES

SUMMARY OF INFORMATION AVAILABLE AS OF MARCH 1967

PART I: INTRODUCTION AND BACKGROUND

Introduction

1. To obtain information on the actual state of stress and deformation within a concrete structure or a concrete or mortar model, it is of primary importance to make measurements in the interior of the structure or the model. These measurements appear particularly important in the case of mass concrete structures (or models thereof) of large volume where load-induced three-dimensional stresses usually have superimposed on them considerable shrinkage and temperature stresses, resulting in a complex state of stress (and strain) of largely unknown magnitude and distribution. The facts that actual stress-strain curves of concrete are not linear, and that concrete creeps and shrinks and is notoriously weak in tension, combined with the stringent safety requirements for these generally very large, expensive, and important structures, strongly suggest the need for experimental control of the results of present simplified linear elastic analysis procedures, not to mention structures for which a realistic analysis has not even been attempted.

2. If one can place in a structure, or even better, in a scale model of the structure, measuring devices small enough not to significantly disturb the stress field, yet large enough to give a meaningful average reading within the heterogeneous material and of sufficient sensitivity to yield quantitative information about strains (or stresses) at particular locations, knowledge of the behavior of such a structure would be considerably enhanced. Such knowledge might eventually lead to improved design and construction methods or analysis procedures.

3. Thus, the main problem is to find or construct devices which will permit the measurement of internal strains or stresses at multiple locations and in various directions within the structure (or model), and

preferably over long time periods in order to make possible evaluation of the effects of the very important time-dependent mechanisms. Yet such a device should be constructed so that proper embedment in the concrete is fairly easily accomplished, and so that adverse environmental conditions will not impair its function for at least several months or, preferably, years. The ideal meter would perfectly match the viscoelastic and thermal properties of concrete, be completely waterproof, be insensitive to (or easily corrected for) temperature changes, have zero cross-sensitivity and drift, have a resolution of a few units of microstrain and a total range of several thousand units of microstrain, be reliable, be noncorroding in the environment in which it is used, be easy to place and read, be inexpensive, and come in various sizes.

4. The present report attempts to give a fairly comprehensive survey of currently used embedded strain meters, with particular emphasis on small meters suitable for model work. In addition, the report lists some of the (direct) stress meters, most of which are based on the same measuring principles as strain meters and are produced to complement the strain meters. The report is the result of an extensive literature review, and of a worldwide survey involving some 100 research laboratories, universities, and meter manufacturers.

Basic Considerations in Design of Internal Meters

5. When a meter is embedded in a material it is obvious that it will have to occupy space normally occupied by the material and will, therefore, disturb the continuity of the material unless the meter and the displaced material have identical elastic or viscoelastic properties, coefficients of thermal expansion, and volume stability, and the meter is perfectly bonded to the surrounding material. For a material such as concrete, whose complicated viscoelastic properties change with time, complete matching of meter and displaced material is practically impossible. Hence, the designer's objective is to construct a meter so that the error introduced in the measurements by the imperfect matching of physical properties is as small as possible. In the case of internal strain measurement, therefore,

the deformation of the meter and the deformation which the displaced concrete would have normally undergone should be as nearly equal as possible, or should bear a constant ratio to each other. Similarly, in the case of internal stress measurement the load acting on the meter and the load which would have normally been acting on the concrete displaced by the meter should either be equal or maintain a constant ratio to each other.

6. Fig. 1 shows a meter embedded in a concrete or mortar body (elastic modulus E_c) which is subjected to a uniform uniaxial stress σ. To simplify matters further it is assumed that the meter is a solid cylinder of radius R and length L, with an equivalent modulus of elasticity E_m. The pressure exerted on the meter by the concrete is designated p (psi)* and is normally different from σ, unless of course the physical properties of the concrete and the meter happen to be the same. Under the applied load p, the meter will deform elastically and the deformation can be measured by various electric, acoustic, pneumatic, or hydraulic methods; these methods will be discussed in detail later. The signal output of the meter can then be expressed in terms of (actually measured) meter deformations or strains, or in terms of the stress (applied to the meter) necessary to produce the measured meter deformation.

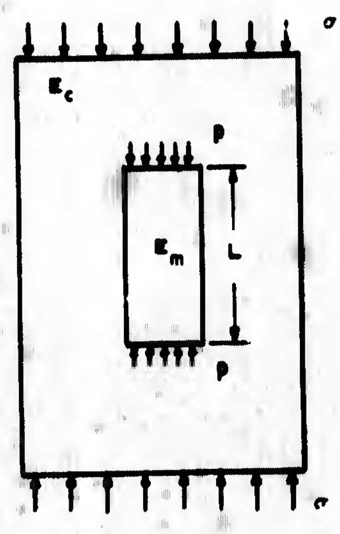

Fig. 1. Meter embedded in elastic medium

7. If, as usual, the validity of linear elasticity is assumed for this problem, the relation between σ, E_c, and the concrete strain ϵ_c or between p, E_m, and the meter strain ϵ_m is given by Hooke's Law:

$$\sigma = E_c \cdot \epsilon_c \qquad\qquad p = E_m \cdot \epsilon_m \tag{1}$$

It was mentioned previously that the indicated stress p will generally be different from the actual stress σ and the indicated strain ϵ_m different from the actual strain ϵ_c. The relation between p and σ and

* A table of factors for converting British units of measurement to metric units is presented on page ix.

between ϵ_m and ϵ_c can then be expressed by the following equations (after Loh[1])

$$p = \sigma(1 + C_s) \tag{2}$$

$$\epsilon_m = \epsilon_c(1 + C_e) \tag{3}$$

where C_s = the stress concentration factor
C_e = the strain increment factor

C_s and C_e are the errors introduced in the internal measurements by the imperfect matching of the physical properties of the concrete and meter. If perfect matching were achieved, both C_s and C_e would become zero and the meter would be equally well suited for stress and strain measurements. In practice, however, perfect matching is not feasible and the numerical values for C_s and C_e will largely depend on the shape and construction of the meter, and may well be very different. In fact, they usually are very different, which makes one type of meter suitable for strain measurement and another for stress measurement.

8. Some of the most important mismatches of properties between the meter and the surrounding material, e.g. differences in the elastic modulus, Poisson's ratio, and thermal expansion, and their effects will be discussed individually in the following paragraphs.

Error Introduced by Imperfect Matching of Moduli of Elasticity

9. Since evaluation of the stress concentration factor or the strain increment factor requires the determination of the stress field in the surrounding concrete as well as in the embedded meter, only a few simple cases have been solved and all known solutions are linear elastic solutions.[2-5]

10. The most important and frequent case, that of an embedded cylindrical meter with loads applied along its axis, is discussed by Loh;[1] and stress concentration and strain increment factors are derived for this case by a modified approximate method originally used by Hast.[3] For a solid,

cylindrical, elastic meter, with rigid (nondeforming) end plates, embedded in an infinitely large, homogeneous, linear elastic concrete body, the following equations are obtained. For $L > \pi(1 - \mu_c^2)R$

$$C_e = \frac{\left(1 - \frac{E_m}{E_c}\right)\frac{\pi R}{L}\frac{1 - \mu_c^2}{2 - \frac{R}{L}(1 - \mu_c^2)}}{1 + \frac{\pi R}{L}\frac{E_m}{E_c}\frac{1 - \mu_c^2}{2 - \frac{\pi R}{L}(1 - \mu_c^2)}} \tag{4}*$$

$$C_s = \frac{\frac{E_m}{E_c} - 1}{1 - \frac{\pi R}{L}\frac{E_m}{E_c}\frac{1 - \mu_c^2}{2 - \frac{R}{L}(1 - \mu_c^2)}} \tag{5}*$$

and for $L < \pi(1 - \mu_c^2)R$

$$C_e = \frac{\left(1 - \frac{E_m}{E_c}\right)\frac{\pi R}{L}(1 - \mu_c^2)}{1 + \frac{\pi R}{L}\frac{E_m}{E_c}(1 - \mu_c^2)} \tag{6}*$$

$$C_s = \frac{\frac{E_m}{E_c} - 1}{1 + \frac{\pi R}{L}\frac{E_m}{E_c}(1 - \mu_c^2)} \tag{7}*$$

$1 + C_e$ and $1 + C_s$ values as a function of E_m/E_c are plotted for various L/R values in figs. 2 and 3 assuming a Poisson's ratio for concrete (μ_c) of 0.2.

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* For derivation, see Appendix I of reference 1.

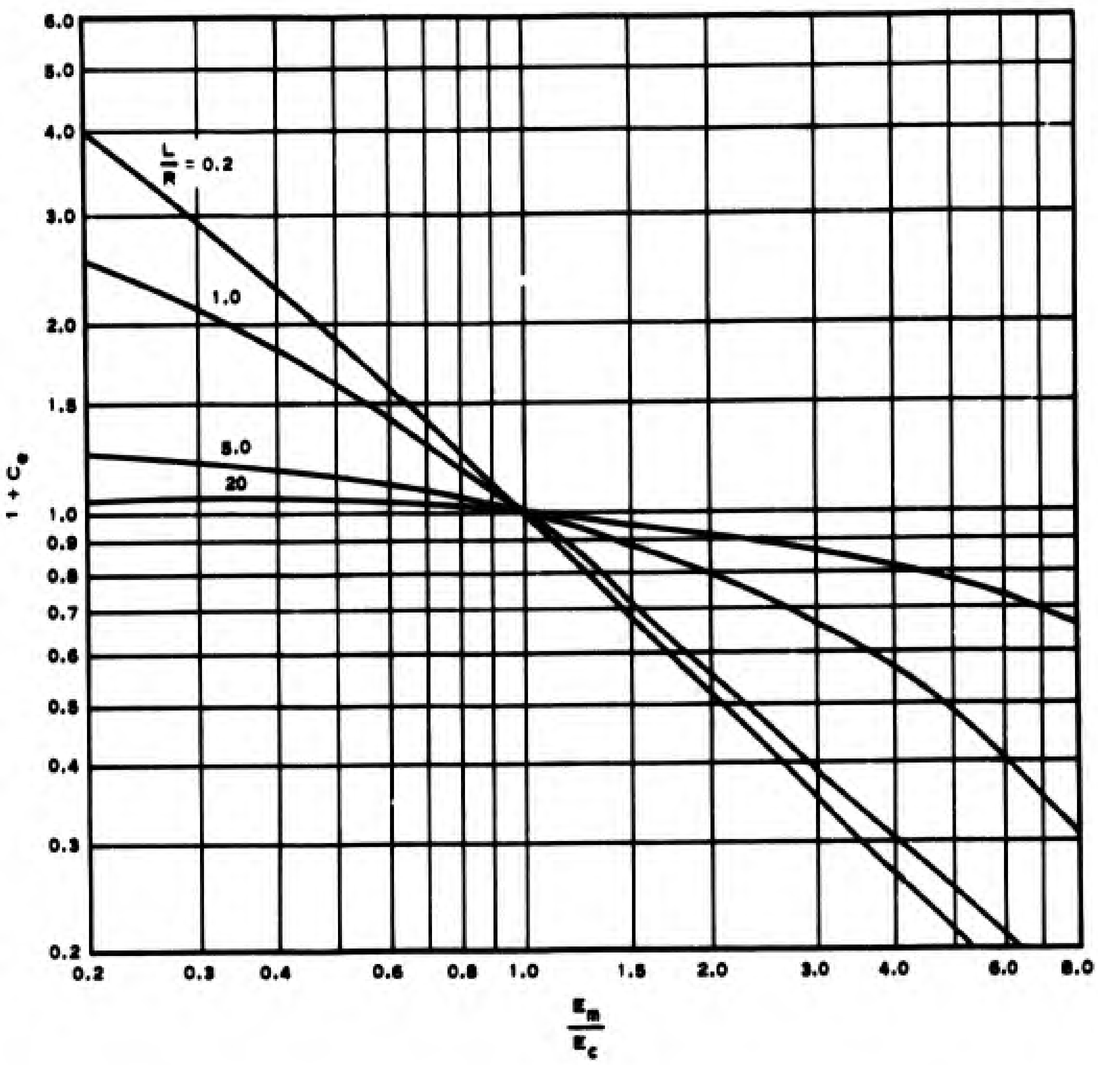

Fig. 2. Strain increment factor (after Loh[1])

Discussion of equations 4 and 6 for C_e

11. It is obvious from equations 4 and 6 that C_e is not only a function of E_m/E_c, but also of R/L and μ_c. The numerical value of C_e is positive when E_m/E_c is less than unity, and is negative when E_m/E_c is greater than unity. For a given value of E_m/E_c, C_e decreases as L/R increases. Hence, for an embedded strain meter it is desirable to keep L/R as large as practical. Due to the nonlinearity and time dependency of the stress-strain curve of concrete, the meter should also be so constructed that C_e is only moderately affected by significant changes in

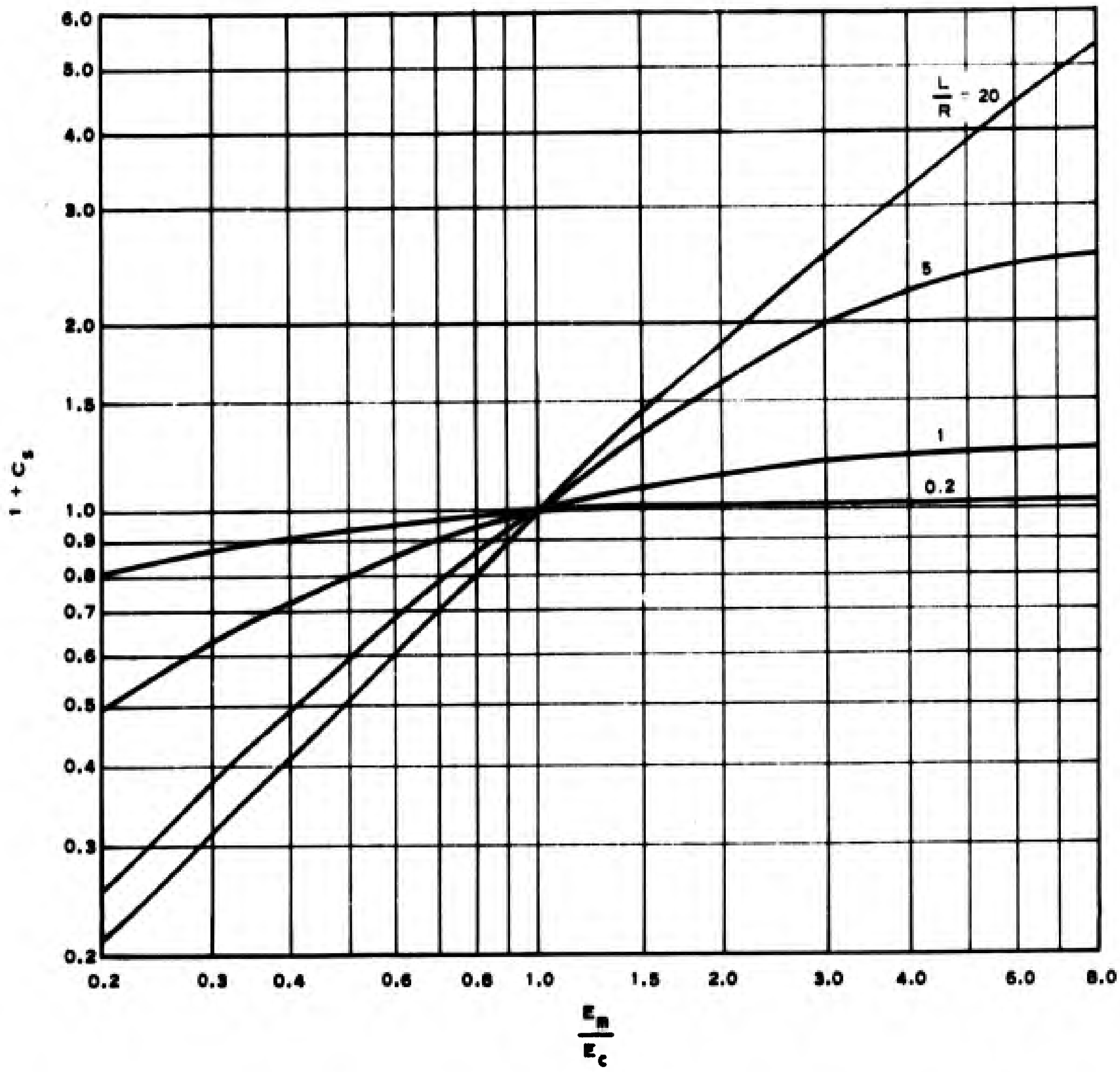

Fig. 3. Stress concentration factor (after Loh[1])

E_m/E_c . This can best be accomplished if the initial value of E_m/E_c is as small as possible (see fig. 2). However, even for an extremely "soft" meter ($E_m/E_c \sim 0$) the indicated (elastic) strain is not equal to the actual strain in the concrete. Loh[1] gives an example: For a rectangular meter of the type developed by Valore[6] ($E_m \cong 0$) with an equivalent L/R value of 39.4(!) the indicated (elastic) strain is still 4 percent higher than the actual (elastic) strain in the concrete. For a soft cylindrical meter ($E_m \cong 0$) with an L/R ratio of 10 (representative of the slimmest cylindrical gages currently used), the difference between actual and indicated deformation is about 15 percent (see fig. 2). This result and the fact that the base length of strain meters is often not well defined lead Rocha[7] to the conclusion that an empirical calibration is always necessary for every kind of strain meter.

Discussion of equations 5 and 7 for C_s

12. Comparing figs. 3 and 2, it can be seen that the characteristics of C_s are just the opposite of those of C_e. The numerical value of C_s is positive when E_m/E_c is greater than unity, or negative when E_m/E_c is smaller than unity, and for a given value of E_m/E_c it increases as L/R increases. Hence, the L/R ratio should be low and, in order to keep the variation of C_s small, the initial value of E_m/E_c should be large, preferably greater than 2. Of course, if E_m/E_c is greater than 2, the indicated stress always exceeds the actual stress; however, the ratio of indicated stress to actual stress is almost a constant and insensitive to the inevitable changes in E_c, provided that the meter is flat ($L/R \sim 0.2$). Summarizing the above discussion, we may therefore conclude that a strain meter should preferably be long, slender ($L/R \gtrsim 5$), and soft ($E_m/E_c \sim 0$), and a stress meter should be wide, flat ($L/R \lesssim 0.2$), and rather stiff ($E_m/E_c > 2$).

Errors Introduced by Imperfect Matching of Poisson's Ratios

13. If the Poisson's ratios of the meter and the concrete are different, the lateral expansions of the meter and the concrete will also be different, and additional lateral stresses will develop between the meter and the surrounding concrete, which will in turn influence the state of stress and deformation within and around the meter and, consequently, the meter reading. Loh[1] derives the following equations for this problem:

$$\frac{p_e}{\sigma} = \frac{\mu_m - \mu_c}{2 - \mu_m - \mu_c} \qquad (8)$$

$$\frac{\Delta\sigma}{\sigma} = \frac{2(\mu_m - \mu_c)^2}{2 - \mu_m - \mu_c} \frac{1}{1 + \frac{\pi R}{L}(1 - \mu_c^2)} \tag{9}$$

where p_e = induced lateral pressure

μ_m = Poisson's ratio of the meter

$\Delta\sigma$ = increment of stress applied to the meter

σ , μ_c , R , L as defined before

From equations 8 and 9 it can be seen that p_e is proportional to $(\mu_m - \mu_c)$, while $\Delta\sigma$ is proportional to $(\mu_m - \mu_c)^2$. Since $(\mu_m - \mu_c)$ is always a small quantity, the error introduced in internal measurements by imperfect matching of Poisson's ratio is generally very small and may thus be neglected.

Errors Introduced by Differences in Coefficients of Thermal Expansion

14. Usually the coefficients of thermal expansion of the meter and the surrounding material will be different; this difference results in thermal stresses in the meter as well as in the surrounding material and, consequently, in an erroneous meter reading. An elastic analysis of thermal stresses leads to the following equation.[1] For $L > \pi(1 - \mu_c^2)R$

$$\sigma_T = \frac{(\alpha_m - \alpha_c)\Delta T\, E_c}{1 + \frac{\pi R}{L} \frac{(1 - \mu_c^2)}{2 - \frac{\pi R}{L}(1 - \mu_c^2)}} \tag{10}$$

and for $L < \pi(1 - \mu_c^2)R$

$$\sigma_T = \frac{(\alpha_m - \alpha_c)(\Delta T)E_c}{1 + \frac{\pi R}{L}(1 - \mu_c^2)} \qquad \epsilon_T = \frac{\sigma_T}{E_m} \tag{11}$$

where σ_T = thermal stress acting on the meter

α_m = coefficient of thermal expansion of the meter

α_c = coefficient of thermal expansion of the concrete

ΔT = temperature change in the meter and the concrete

ϵ_T = meter strain caused by σ_T

From equations 10 and 11 it is clear that the thermal stress is a linear function of the difference between the coefficients of thermal expansion of the concrete ($\alpha \sim 10 \times 10^{-6}$/deg C) and the meter; for this reason steel ($\alpha \sim 12 \times 10^{-6}$/deg C) makes a more suitable meter material than do aluminum or copper alloys ($\alpha \sim 18 \times 10^{-6}$/deg C), or, particularly, most plastics (e.g. polyester resins ($\alpha \sim 20$ to 50×10^{-6}/deg C), and epoxy resins ($\alpha = 20$ to 100×10^{-6}/deg C)).

Special Problems and Requirements for Meters Embedded in Concrete and Mortar

Inhomogeneity of concrete and mortar

15. The equations and discussion given above were essentially based upon the assumption that concrete is a perfectly linear elastic and homogeneous material--which, of course, is far from true. Accordingly, some design principles used to minimize the effects of nonlinearity and plastic flow on the internal measurements were discussed previously; however, a few comments remain to be made on the effect of nonhomogeneity.

16. Concrete or hydraulic cement mortar is a heterogeneous substance consisting of aggregates of various sizes and often various types, hardened cement paste, voids, and water in different states of chemical and physical bonding. Within this conglomeration, local strains and stresses can and will vary extremely. It is generally agreed that for a valid average strain reading in such a material, the meter length should be at least two to three times the maximum aggregate dimension.[1,8,9] However, many investigators[7,8,10,11] (including the author) feel that this figure should be approximately five times the maximum aggregate dimension, and that the expected strain gradient should determine the maximum length of the meter. Fig. 4 shows the relation between maximum aggregate size and meter length as given by Cooke and Seddon.[8] Similarly, for a valid average stress measurement, the cross-sectional area of the meter should be several times the

projected area of the largest aggregate. Loh[1] mentions a meter diameter factor of at least three to four times the maximum aggregate dimension, but, again, the author advocates a higher value. Since the load distribution on the meter is not uniform, the meter should also be insensitive to moderate bending and should, of course, be unaffected by lateral pressures (i.e. it should have "zero cross-sensitivity").

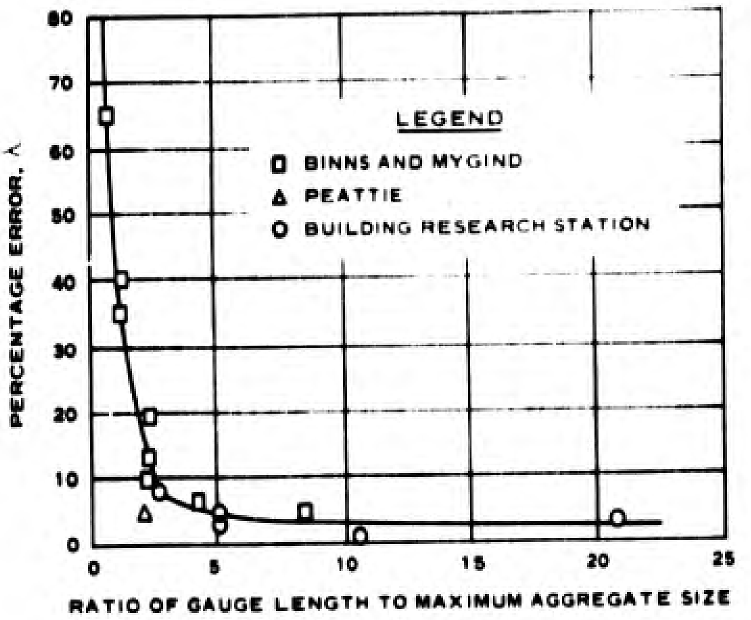

Fig. 4. Strain-gauge errors for various ratios of gauge length; nominal maximum aggregate size (after Cooke and Seddon[8])

Shrinkage and swelling

17. While concrete or mortar undergoes considerable volume change with a changing moisture content, the meter usually does not, and will thus cause disturbance. However, if previous considerations for the design of strain and stress meters are applied, the resulting error in the readings should be small. But the range of the embedded meters must be large enough to allow measurement of strains or stresses due to shrinkage or swelling as well as those due to loads, and measures must be taken to facilitate the separation of the two types of strains or stresses (e.g. by use of embedded, unloaded shrinkage meters).

Temperature

18. Meters embedded in mass concrete structures should remain operable during and after exposure to a wide temperature range, approximately -20 to +150 F (-29 to +65 C). Conditions for model tests are usually less severe, but such modern massive concrete structures as prestressed-concrete reactor vessels may involve temperatures in excess of 150 F, which would also be reflected in models of these structures.

Moisture and corrosion

19. Embedded meters and associated wiring will be in direct contact with water of very high pH values, at least during the placing and hardening of the concrete and often throughout their lives. The meters and wiring must therefore be unaffected by water, even water under fairly high pressures and sometimes containing various aggressive agents. In some cases, pore pressure may cause difficulty and make special measures necessary to avoid or compensate for its influence on measurements.

Long-term stability and reliability

20. One of the greatest problems with embedded meters is that of ensuring their long-term stability in order to obtain reliable and accurate observations over long periods of time, which is extremely important in evaluating the performance of mass concrete structures. The main threats to the reliability of meters are moisture effects resulting in a change of electrical properties, corrosion, and creep or volume changes within some parts of the meter itself (e.g. relaxation of wire in vibrating-wire meters or unbonded resistance-wire meters, creep or volume changes in encapsulating plastic materials or adhesives in bonded resistance meters, etc.). Details of this very important aspect of internal stress or strain measurement will be discussed in the description of individual meters or meter types.

Measuring range and resolution

21. For most purposes a total strain range of about +500 to about -1000 microstrains or a stress range of +600 to about -3000 psi will probably suffice. However, excessive creep, as recently observed in concrete under elevated temperatures,[12] high concrete strength, or the need to test models to failure may call for meters with an extended range up to about 3000×10^{-6} microstrains maximum strain and 6000 psi maximum stress, or even higher. The resolution and accuracy of meters should preferably stay within a range of only a few microstrains or pounds per square inch.

Placing and orientation

22. The position and orientation of the meter within the concrete body must be precisely known and therefore prevention of any shift or tilting of the meter during the placing and consolidation of the concrete

or mortar is important. In addition, meters and wire connections must be rugged enough to safely withstand the often rough placement and compaction procedures.

PART II: BRIEF SUMMARY OF MEASURING PRINCIPLES AND METER TYPES

23. Functionally, an internal meter can be considered to consist of two components:

a. A casing that protects the gaging system and carries the loads acting on the meter.

b. A sensitive gaging system which transforms the minute deformations of the casing (i.e. the small relative displacement of its end plates) into measurable signals.

The conditions under which signals from the meter are capable of remote indication render unsuitable ordinary mechanical gaging systems, in which a series of levers and gears are used for magnification (e.g. Huggenberger, Whittemore, or Berry gages, etc.). These conditions also eliminate practically all optical methods, including optical magnification of mechanical measurements (Martens mirror, comparators, Tuckerman gage, etc.), methods based on the principle of stress-induced double refraction (photoelasticity*) on optical interference (grid and Moirre methods), and X-ray diffraction methods (X-ray stress analysis).

24. Essentially, six different types of gaging systems remain that can be used in the construction of internal gages:

a. Systems based on changes in electrical resistance.

b. Systems based on changes in electrical inductance (including magnetostrictive systems).

c. Systems based on changes in electrical capacitance.

d. Piezoelectric systems.

e. Acoustic systems.

f. Pneumatic and hydraulic systems.

Systems based on a and e are by far the most widely used, notwithstanding the fact that some others (such as b) are potentially superior for certain applications. A very interesting and informative summary, comparing the basic advantages and limitations of these systems, was taken from Loh's report[1] and is reproduced in a modified and extended form in table 1.

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* Recently developed photoelastic borehole stress meters may have a limited field of application in concrete models.[13,14]

PART III: DESCRIPTION AND DISCUSSION OF PARTICULAR METERS

Electrical Resistance Meters

25. The resistance meter expresses a displacement of the concrete as a resistance change. The resistance change is usually measured by determining the change in potential produced in an electric circuit called the gaging circuit. There are several different methods by which a change in resistance can be coupled with deformation or displacement and these methods are used to designate the several types of electrical resistance meters.*

Varying potentiometer resistance meters

26. Based on the principle of the slide-wire potentiometer, this type of meter is ordinarily used for relatively large displacements and does not appear to be suitable as an internal meter.

Unbonded metallic resistance meters

27. Physicists have known of and used the change in electrical resistance of metals with a change in external forces on the metals for some time. However, the first engineering application in the field of concrete strain measurement appears to have been made by R. W. Carlson in the early thirties, when he first designed his famous strain meter.[15] The principle of the Carlson strain meter (as well as that of bonded metal gages to be discussed later) is based on the change in electrical resistance of a fine elastic wire (or foil) due to the change in longitudinal stress in the wire. The relation between the percentage change in resistance and the longitudinal strain ϵ is given by the following equation:

$$\frac{\frac{dR}{R}}{\frac{dL}{L}} = 1 + 2\mu + \frac{\frac{d\rho}{\rho}}{\frac{dL}{L}} = K_s \quad \text{(reference 1)} \qquad (12)$$

or

$$\epsilon = \frac{1}{K_s} \frac{dR}{R}$$

* A summary of the most important electrical resistance strain meters is given in table 2.

where R = total resistance of the wire

L = length of the wire

μ = Poisson's ratio of the wire

ρ = specific resistance of the wire

K_s = gage factor of the wire

The numerical value for K_s depends on the type of wire material used, and is usually within the range of approximately 2 to 3.5. Gage factors for particular wire materials are listed in reference 16.

28. To measure the small changes of resistance involved, a number of different circuits can be used, the best known of which is certainly the Wheatstone bridge. Details, advantages, and disadvantages of specific measuring circuits may also be found in references 8, 16, and 17.

29. As far as is known, only two meters that fall in the category of unbonded resistance meters are presently used or manufactured for the purpose of internal measurements in concrete, i.e. the Carlson meter and the Monfore Standardizing strain gage. Both are discussed in detail below.

30. Carlson strain meter.[18] Fig. 5 shows a cross section and fig. 6 a photograph of the Carlson strain meter. The meter is in the general form of a long cylinder with anchors on the end to engage the surrounding concrete. Within the flexible brass cover tube a steel framework supports porcelain spools around which two equal coils of very fine steel music wire, 0.0025 in. in diameter, are wound under 100,000-psi tension. When the ends of the strain meter are displaced relative to each other, one of the wires undergoes an increase and the other a decrease in resistance of practically the same amount. Thus, when the two wires are connected in

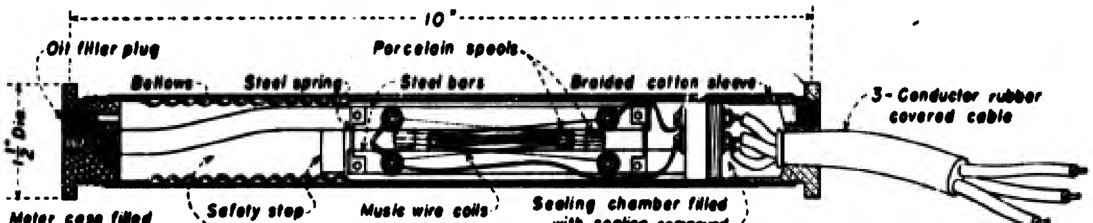

Fig. 5. The Carlson elastic wire strain meter (after reference 15)

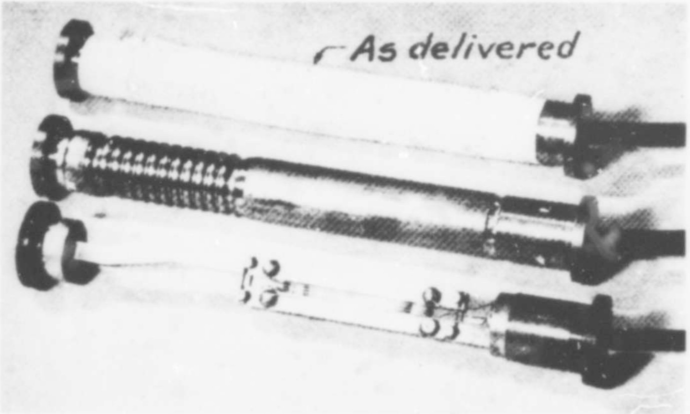

Fig. 6. Carlson strain meter (after reference 18)

series and applied at one arm of the Wheatstone bridge, the variation in their electric resistance depends on their temperature change alone and will facilitate temperature measurements. When the two wires are applied at two arms of the bridge, the ratio of the variations in their electric resistances depends on the deformation of the instrument alone. The accuracy commonly obtained in strain measurements is about 5 microstrains, and that of temperature measurements about 0.1 F, with a total strain range of around 500 microstrains expansion to 1000 microstrains contraction,[18] and a temperature range of approximately 0 to 150 F.

31. The Carlson strain meter has been widely used in the United States for almost 30 years[7, 18-20] and more recently in Europe[21,22]* (mainly in the observation of concrete dams) and has proven its exceptional reliability and accuracy in numerous long-term studies. Unfortunately, the smallest version presently available (gage length 4 in., body chamber 0.9 in.) is still too big for successful use in small-scale models. Further reduction of the size appears to be a problem. For certain applications (prestressed reactor vessels, etc.) a wider range of strain and

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* Also from communication with M. Rocha, Laboratorio Nacional de Engenharia Civil, Lisbon, October 1966.

temperature measurement might be desirable. Also, for model work, costs per gage will be a problem.

32. Carlson stress meter.[18] As stated earlier, although this report is primarily concerned with internal strain meters, some of the most important direct stress meters will also be discussed briefly. The Carlson stress meter, illustrated in fig. 7, is certainly one of these. It has the

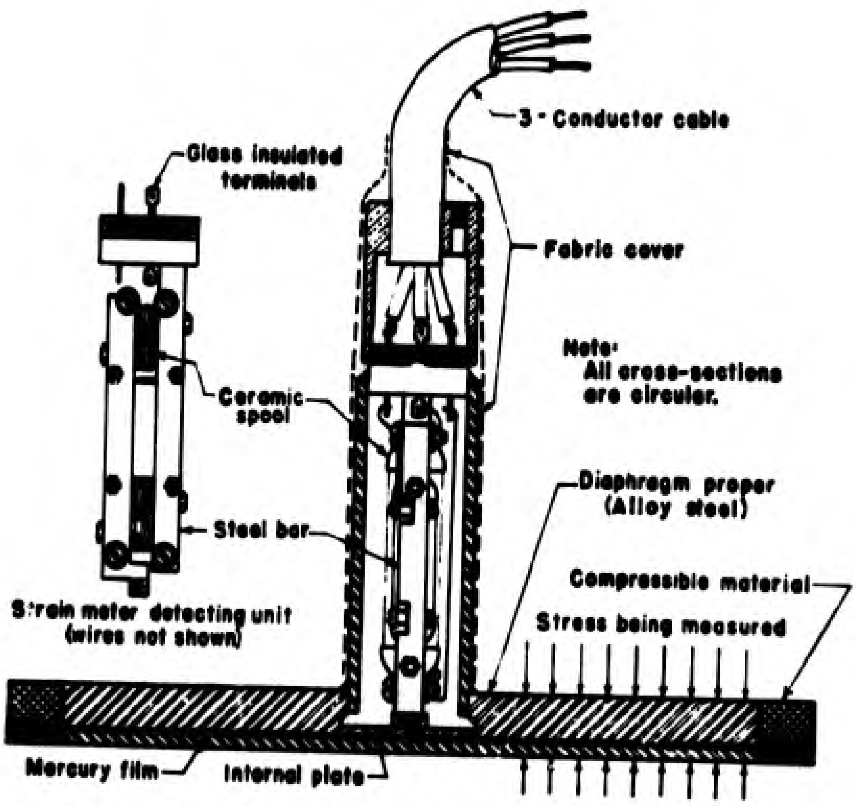

Fig. 7. The Carlson stress meter for concrete (after reference 18)

shape of a circular plate, 7.25 in. in diameter and 0.5 in. thick, which makes contact with the concrete (see fig. 7). A chamber protruding from one side of the plate contains a measuring unit, which is covered with a fabric sleeve and is thus free from contact with the concrete. The plate is actually a mercury-filled diaphragm, so designed that the pressure in the mercury is always substantially equal to the pressure in the surrounding concrete normal to the plate. The center portion of the plate is made slightly flexible by cutting away a portion of the thickness. The mercury is in contact with this more flexible center portion and deflects it elastically in direct proportion to the intensity of stress. The measuring unit is a small, elastic, wire strain meter as described earlier, again measuring the temperature along with the stress. This temperature reading is necessary to facilitate a small correction designed to compensate for the tendency of the stress meter plate to expand more than the surrounding concrete. The sensitivity and range of the instrument are interrelated and may be varied by changes in the thickness of the internal diaphragm. Normally, the meter is built for a range of 0- to 800-psi compression with a sensitivity of about 5 psi per 0.01 percent change in resistance ratio. Analyses and tests[18,23] show that the Carlson stress meter is only slightly affected by volume changes due to causes other than stress.[18,24] The reliability of its gaging system makes it a very powerful instrument for long-term studies in full-scale structures or large models. However, there are a few limitations. The meter is not suitable for tension measurements or for operation in elevated temperatures (above approximately 150 F). Its size and the difficulties involved in reducing this size practically exclude any application in small-scale models.

33. Monfore Standardizing strain gage. The operation of this gage is best described by means of fig. 8, which shows the gage mounted on the surface of a solid (but the same principle is, of course, used for the embedded version). The essential parts of the gage are a tube, a piston fitted into one end of the tube, and a small-diameter elastic wire stretched inside the tube from the piston to the other end of the tube. The wire is adjusted so that it is under slight tension when the piston is in the normal position (that is, when the piston's shoulders are in contact with the end of the tube). A spring (not shown in fig. 8) provides positive contact between the piston's shoulders and the end of the tube. The tube and piston assembly is attached to the

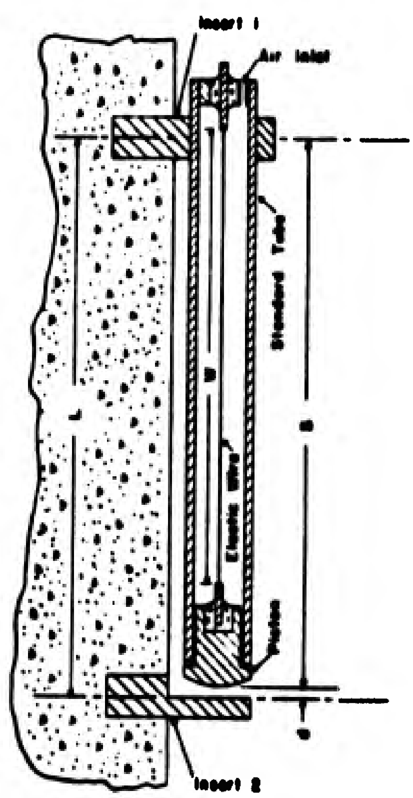

Fig. 8. Monfore Standardizing strain gage (after reference 25)

solid by means of insert 1. Insert 2, located at distance L from insert 1, serves as a stop for the outward movement of the piston which is caused by the application of air pressure within the tube (16 psi). The purpose of the gage is to measure strain by changes in length L . From fig. 8, L = S + d , in which S is the length of the standard, which was made of Invar in the case of the gage shown in fig. 8. For small temperature changes, S will be essentially constant; for large temperature changes (or if the standard is not made of Invar), a temperature correction may be applied. If S is assumed to be constant, changes in L can be measured by measuring equal changes in d , and an Advance elastic wire is used for this purpose. The change in the electrical resistance of the wire as the piston is moved outward from the standardizing position until it contacts insert 2 provides the data necessary for determining d . At the beginning of a test, d_o is determined, and at any later time d_i is measured in the same manner by measuring the resistance change from the standardizing position. Thus, a zero reading is taken for each measurement, and drift effects are thereby eliminated. The strain of the material under test is finally computed from d/L . The range of the embedded version is about 3000 microstrains with a resolution of a few millionths. The standard gages are about 4 in. long and 1/2 in. in diameter, but larger sizes pose no problem. Since the resistance wire is not permanently stressed, creep is of no concern and the gage should be operable in relatively high temperatures (up to at least 250 F). According to Mr. Monfore, it should also be feasible to construct rather small gages, about 2 in. long, which would be more suitable for model work. However, the necessity for air-pressure lines (16 psi) in addition to an electrical cable to each gage as well as the high cost are major disadvantages. Incidentally, the "standardizing gage" principle can also be utilized in the construction of a stress meter similar to the Carlson stress meter.

Bonded metallic resistance meters

34. In the late thirties, the idea of bonding the resistance wire directly to the material was conceived by Simmons, Clark, and Dutwyler at the California Institute of Technology; and at about the same time, Ruge at the Massachusetts Institute of Technology started to use the first

paperbacked-bonded wire gage. The continuous bonding restrained the resistance wire enough to make it usable for compressive strain measurements without prestressing, and also helped to dissipate the heat created in the wire during measurement.

35. Since these early days of bonded resistance wire strain gages of the SR-4 type, numerous different types of wire and foil strain gages have been developed for all kinds of special applications, and various attempts have been made to use bonded metallic resistance gages for internal measurements in concrete. However, two major obstacles stand in the way of success: the extreme sensitivity of the bonded wire gage to moisture, and creep or volume changes in the plastic bonding and/or encapsulating materials.

36. Plastic-encapsulated SR-4 gage. The most economical and direct method of protecting the bonded wire gage from moisture is obviously to encapsulate a regular bonded metallic resistance gage of adequate length in some waterproof plastic material. This method has been used by several researchers; however, their results and conclusions were rather different. Problems arose primarily from three sources:

a. Deficiency of the waterproofing. Most plastics are not the completely effective moisture barriers they are often believed to be. Over long periods of time, therefore, some moisture may penetrate the plastic shielding and cause serious zero drift. In addition, many (if not all) plastics absorb small amounts of water; this causes them to undergo volume changes which affect the embedded strain gage.

b. Mismatch of thermal expansion and self-heating effect. The coefficient of thermal expansion for plastic materials suitable for insulation is generally much higher than that of concrete or the resistance wire. This difference causes thermal stresses that may significantly affect the reading. In addition, since the thermal conductivity of plastics is low, serious self-heating effects will occur unless special precautions are taken.[26]

c. Creep and relaxation. As a rule, plastic materials exhibit considerable creep. Since the setting mechanism of resins usually leaves frozen-in thermal stresses, and since the modulus of the resistance wire or of the gage will not be the same as that of the material in which it is embedded (nor will the coefficients of thermal expansion), it is obvious that for long-term tests, creep is an important problem. Due to the thick plastic layers involved. creep is probably a much more critical factor than it is for conventional surface-mounted strain gages.[26]

37. Several investigators have built and evaluated epoxy- or other resin-encapsulated gages. Details of this work are discussed below.

38. Japanese polyester mold gage. To the author's knowledge, there is only one resin-encapsulated gage presently on the market that is specifically designed for embedment in concrete, i.e. the "polyester mold gage" manufactured by Tokyo Sokki Kenkyujo Company, Ltd. It consists of a regular polyester-backed wire gage 30 to 60 mm long (1.2 to 2.4 in.) sandwiched between two pieces of resin plate and attached with a 2-in.-long outgoing vinyl lead wire (fig. 9). To improve bond between the gage and the surrounding concrete the surface of the flat gage is sand-coated. Kubota and Sakane[27] recently reported very good agreement between "hardening" strain measurements obtained with the "embedded" polyester mold gage and surface strain measurements obtained by means of a microscopic comparator over a total test period of 30 days. However, preliminary tests performed at the PCA,* as well as at the Waterways Experiment Station (WES) in 1962 and again recently, indicate that the meter responds strongly to changing moisture conditions (probably because of water absorption or loss on the surface and a resulting shrinkage or swelling mechanism), and may drift up to 1000 microstrains during a period of two weeks if stored in a 100 percent relative

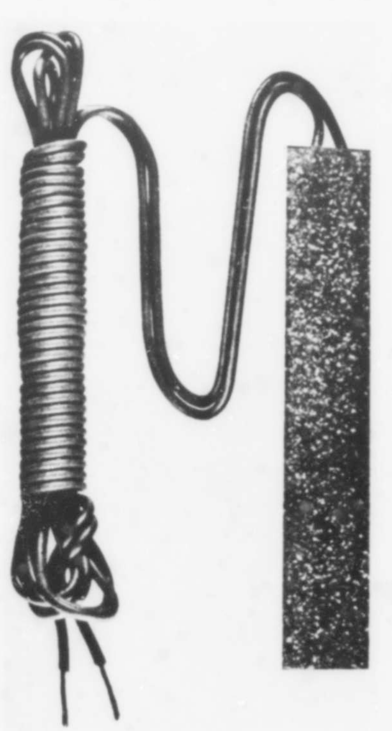

Fig. 9. Polyester mold gage

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* Information furnished in private communication by Mr. G. J. Verbeck, Portland Cement Association Research and Development Laboratories, Skokie, Ill., in November 1962.

humidity environment or immersed in water (see results of performance tests described in Appendix A). These values were obtained on freely suspended meters and not on meters embedded in concrete. Though it is of course realized that the "swelling" deformation of an embedded gage will largely be restricted by the surrounding concrete, thus significantly reducing the drifting effect, considerable doubt remains about the reliability of the gage in long-term applications, particularly in view of the previously mentioned potential problems of plastic-encapsulated meters. The gage appears to have good potential for short-term strain measurements, and, indeed, the correlation between readings of centrally embedded "polyester mold gages" and surface-mounted strain gages on standard 6- by 12-in. cylinders was found to be very good in several static compression tests at WES, and also in tests performed at Waseda University and the University of Tokyo.*

39. Other resin-encapsulated meters. Obviously, a plastic-encapsulated meter similar to the above-described "polyester mold gage" can easily be locally produced by the embedment of an ordinary wire or a foil strain gage of adequate length in a plastic body. Several laboratories have, in fact, made their own plastic-encapsulated meters. The Cement and Concrete Association, for instance, embedded a 1-in. foil gage in a sheet of Araldite with a surface coating of sand to improve bond characteristics; the meter was 1-1/4 by 5/8 by 1/10 in. overall, and had a modulus of elasticity of 0.48×10^6 psi. Readings obtained during setting, hardening, and curing of the concrete reportedly indicated satisfactory performance of the meter under saturated conditions.**

40. A very similar technique, and satisfactory result, had also previously been reported by Bossi and Moravia[28] of the Politecnico di Milano, Italy.

41. In the early fifties Thoma and Schneebeli[29] described a successful application of SR-4 gages embedded in a thermosetting alkyl-ester monomer (Kriston) for strain measurement in highway pavement slabs under

* Photocopied test results, together with a strain gage catalog, were supplied in November by Tokyo Sokki Kenkyujo Company, Ltd., 8-Ban 2-Go, 6 Chome Minami-Ohi, Shinagawa-ku, Tokyo.

** Information provided in private communication from Mr. J. B. Read, Cement and Concrete Association, in October 1966.

heavy traffic loads. After 18 months immersion in agitated water and 13 months embedment in a pavement slab subjected to heavy traffic, the 3-1/2- by 1/2- by 1/4-in. transparent meter (elastic modulus approximately 500,000 psi) still had a resistance to ground of more than 1000 megohms. Strain readings of meters embedded in 6- by 12- and 2- by 4-in. cylinders compared favorably with surface measurements in static tests, but, unfortunately, no mention was made of zero drift in long-term applications in the paper.

42. The Oak Ridge National Laboratory has recently embarked on a study of epoxy-encapsulated meters (SR-4 gages in a cylindrical body of Shell epoxy 815, or other epoxies, with profiled surface to engage the concrete) the results of which are not yet available. Similarly, WES has initiated various tests on different epoxy- and polyester-encapsulated meters and some preliminary results are described in Appendix A.

43. It appears that for reasons discussed above, the long-term stability of plastic-encapsulated meters is, to put it mildly, still questionable, and substantial research is needed to provide a reliable and accurate instrument using this very economical method. If a satisfactory embedment material and technique could be found, the versatility and economy of a plastic-encapsulated meter would be almost unchallenged and the meter would be particularly suitable for use in small models.

Metal resistance meters bonded to or enclosed in metal

44. Some of the problems associated with plastic-encapsulated resistance meters can be eliminated if the resistance gage is glued to a metal insert, securely waterproofed, and then embedded in the concrete. For a number of years, bonded wire (or foil) strain gages have successfully been employed to measure strains in reinforcing rods within reinforced concrete structures, frequently under severe conditions or for long-term tests.[8,9,17,30,31] SR-4 type gages, sometimes bonded to a metal carrier[8,30] attached to the concrete surface, are widely used for surface strain measurements on concrete.[48] The established waterproofing techniques can obviously also be employed for an embedded strain gage bonded to a carrier. Thus, the critical question with such a meter is not

necessarily stability (even though long-term stability will inevitably be of major concern with embedded bonded resistance meters) but rather whether the metal enclosure can be made soft enough to ensure the desired constant strain increment factor despite considerable changes in E_m/E_c (see Part I). Naturally, due attention must also be given to effects of mismatches in thermal expansion, to bond problems, and to embedment procedures.

45. The simplest approach to the use of metal inserts is to bond a regular resistance gage to a piece of shimstock, properly shaped and/or surface-treated to ensure good bond to the concrete, and then waterproof the meter in a conventional way. Compared to the performance of plastic-encapsulated meters, this method eliminates the adverse effects of swelling and shrinking in the coat (since the strain gage is cemented to a stiff carrier, softer waterproofing materials can be used and slight volume changes of the exposed surface of the waterproofing material will not affect the gage), and should reduce creep and temperature problems considerably. The only disadvantages in this approach appear to be the high elastic modulus of the solid metal and its tendency to buckle if not rigidly confined, and problems in positioning and protecting the flexible meter from mechanical damage or shifting during and after emplacement. However, a shimstock meter is very economical to construct, and, if it is well constructed and calibrated, its performance in long-term tests should be superior to that of a plastic-encapsulated meter.

46. Whiffin[32] describes a meter successfully used by the Road Research Laboratory in England. It consists of a 5- by 2- by 0.048-in. steel strip with four pieces of 1/2-in. angle iron welded to the ends to engage the concrete. The steel strip carries four 1-in. foil gages, 55 ohm resistance, waterproofed by Araldite. A brass cover is wrapped around the steel strip, but not soldered closed to provide moisture protection, partly to protect the gages from damage by the concrete and partly so that the load on the unit is applied solely between the ends. The cross section is adjusted by the cover so that the overall modulus of elasticity of the unit is equal to that of the concrete which it displaces. Checks on the individually calibrated meters revealed good agreement between the strain

readings of embedded meters and optical surface measurements in static uniaxial tests. Long-term stability problems were not mentioned in the paper.

47. SR-type gages are frequently totally enclosed in metal foil envelopes or metal tubes. This provides more reliable moisture protection than does merely cementing the gages to metal carriers, and leaves only the wire inlets exposed to moisture.

48. <u>Valore brass envelope or NBS meter.</u> The best known of these enclosed meters is certainly the Valore brass envelope strain meter.[6,33,34] It consists of an SR-4 strain gage (A-9 or temperature compensated) glued to and enclosed by a rolled brass shimstock (70 percent copper, 30 percent zinc) of 0.001- or 0.002-in. thickness, which is then soldered closed (see fig. 10 and fig. A1). Since low modulus materials dominate the idealized cross section of the meter (fig. 10), the equivalent elastic modulus of the meter is fairly low, and combined with an extremely high length-to-thickness ratio this ensures the desired small effect of variations in the concrete modulus. However, the coefficient of thermal expansion of brass (18×10^{-6}/deg C) is considerably higher than that of concrete, which makes the use of a brass foil envelope somewhat objectionable. At any rate, the coefficient is still much lower than that of many plastics, and if a good bond between the concrete and the brass envelope is achieved (and maintained) the meter should give satisfactory readings. The difficulty of achieving proper embedment and exact alignment of the very flexible and fragile meter restricts its use essentially to the laboratory, except when it is protected by a precast concrete body. Compression tests on standard 6- by 12-in. cylinders with internally embedded Valore meters have shown a satisfactory agreement between internal and surface measurements in static tests, and some successful long-term shrinkage measurements have also been reported.[6] Results in Appendix A prove that the meter drifts very little when immersed

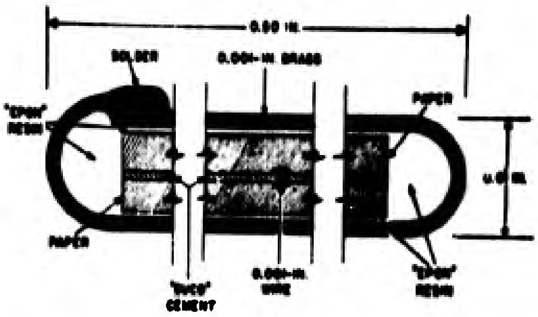


Fig. 10. Idealized cross section of Valore A-9 brass-envelope strain meter showing one of the two cross sections of strain-sensitive wire of the 6-in.-long "loop" (after reference 6)

in water (as opposed to all tested plastic-encapsulated meters); thus it would appear more suitable for long-term tests.

49. However, in a reply to our inquiry, Professor A. M. Neville and Dr. A. Ghali (University of Calgary, Calgary, Alberta, Canada) reported having experienced problems with the BLH Valore meter in repeated loading and long-term applications, possibly because of a gradual loss of bond between the meter and the surrounding concrete. The performance of the meter under repeated loading was improved when the meter was precoated with cement mortar, which also made it easier to place; however, the problem of zero drift remained. Since WES experience was similar, we may conclude that the Valore meter appears satisfactory for static tests or tests of relatively short duration (about two weeks or so), but does not seem to be entirely dependable in long-term measurements such as those for creep and shrinkage. This difficulty may possibly be resolved if waterproofing, bonding, and placing methods are further improved.

50. Other metal foil resistance meters. Several investigators have modified the Valore meter or tried a very similar approach. Worley and Meyer[10] brought the lead wires out through the open end of a Valore-type meter in a 3/16-in. copper tube which was soldered to the meter and extended the length of the lead wires. Although great care was taken in soldering, the meters were still not completely waterproof when subjected to 60-psi water pressure. Klein and Trescony[35] manufactured epoxy-sealed, aluminum-wrapped SR-4 type strain meters using household aluminum wrap, 0.002 mm thick, but data on long-term performance of these meters are not available.

51. Philips strain meter PR 9239 (fig. 11). Another strain meter based on the principle of a bonded-metal strain gage enclosed in a metal envelope is being manufactured by Philips,[36] and has reportedly been

Fig. 11. Philips strain meter PR 9239 (after reference 36)

used with satisfactory results by several European laboratories.*,** The standard version of the meter exhibits overall dimensions of 200 by 12 by 0.4 mm, and consists of a 120 Ω, temperature-compensated strain gage cemented to a metal support and protected by a tightly sealed, flattened silver tube. The meter has a total strain range of about 2000 microstrains, a gage factor of 2, and a maximum safe operating temperature of 140 F. It would appear that the meter size could easily be reduced to make it suitable for model work; however, stability and repeated-loading performance remain to be investigated further.

Bonded metal resistance gages
enclosed in rigid metal casings

52. Since the metal foil envelope meters are very flexible and easily damaged, and thus difficult to cast in concrete, several attempts have been made to enclose the bonded-wire element in a more rigid metal casing, thereby facilitating proper embedment and alignment and making the meter more suitable for field measurement.

53. Thin-walled copper cell. A 5/32-in. copper tube expanded in a lathe to an inside diameter of 1/4 in., resulting in approximately 0.015-in. wall thickness, was used by Worley and Meyer.[10] The expanded portion of the tube served as the meter cell proper, and the small-diameter portion served as a shield for the lead wires. A 6-in. strain gage coated with cement was then drawn into the tube along with two layers of felt. The copper tube was then flattened so that the meter was held tightly in contact with one side of the cell. The layers of felt afforded protection to the gage and also increased the thickness of the finished cell to about 0.070 in., thereby decreasing the equivalent modulus of elasticity. After the cement bonding the gage to the cell had thoroughly dried, the open end of the flattened tube was carefully soldered closed and the air space in the cell and the copper tubing was filled with petrosine wax.[37] Testing under 60-psi water pressure for 48 hr caused no decrease in resistance

* Information from communication from Professor A. Slattenschek, Technische Hochschule, Wien, Austria.

** Information from communication from Messrs. P. Dutron, Centre National de Recherches Scientifiques et Techniques pour L'Industrie Cimentiere, and A. Doyen, Ministère des Travaux Publics, Brussels, Belgium.

between the strain gage and cell. Satisfactory results were also obtained in field tests on concrete pavement slabs, the ground resistance of the meter remaining well above 1000 megohms for a period of 10 months. The authors[10] do not mention any problems due to zero drifting.*

54. Other meters. In 1951 Boiten[30] reported that good results have been obtained with the embedded tubular meter shown in fig. 12. Though no dimensions are given and further information is not at hand, it appears that the meter is rather large, expensive, and sensitive to bending and/or lateral pressures, and thus holds little promise for application in models.

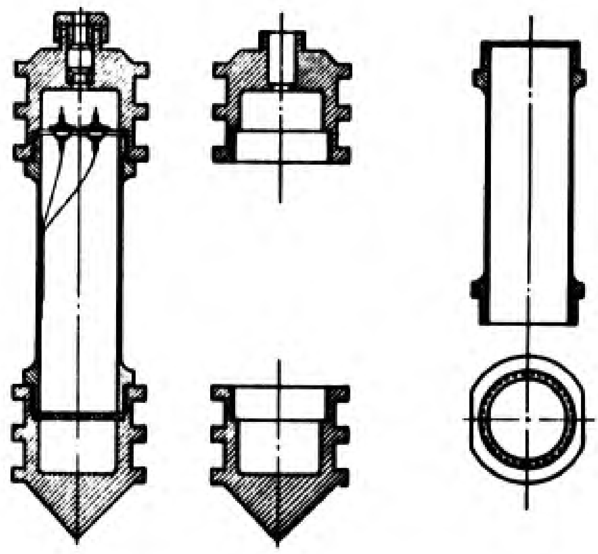


Fig. 12. Strain meter for measurements inside concrete structures (after Boiten[30])

55. Pilny strain meter. A more sophisticated, but still rather economical, bonded-wire strain meter for embedment in concrete was developed by Pilny[38] at the Technical University of Berlin (Germany), and has reportedly been used with success for a number of years. The meter consists of a tubular steel casing containing a pretensioned steel band (about 47,000-psi tension) with three strain gages attached on either side indicating the strains and temperature of the band. The central steel band and the tubular casing are connected by steel dowels, which also ensure safe bonding to the concrete (fig. 13). Due to the symmetrical arrangement of the strain meters, the cell is very insensitive to bending and its construction ensures rather good matching of the elastic and

* It was recently learned that Microdot, Inc., Pasadena, Calif., produces an integral lead weldable gage that appears very promising for embedment in mortar models. According to Microdot Bulletin SG-18, the gage consists of an etched resistance wire encased in a small stainless steel tube, which is densely packed with insulating MgO powder. The lead wires are also enclosed in a stainless steel tube which is brazed to the gage. The lack of any cement, good waterproofing, and availability in various sizes make this appear a promising gage.

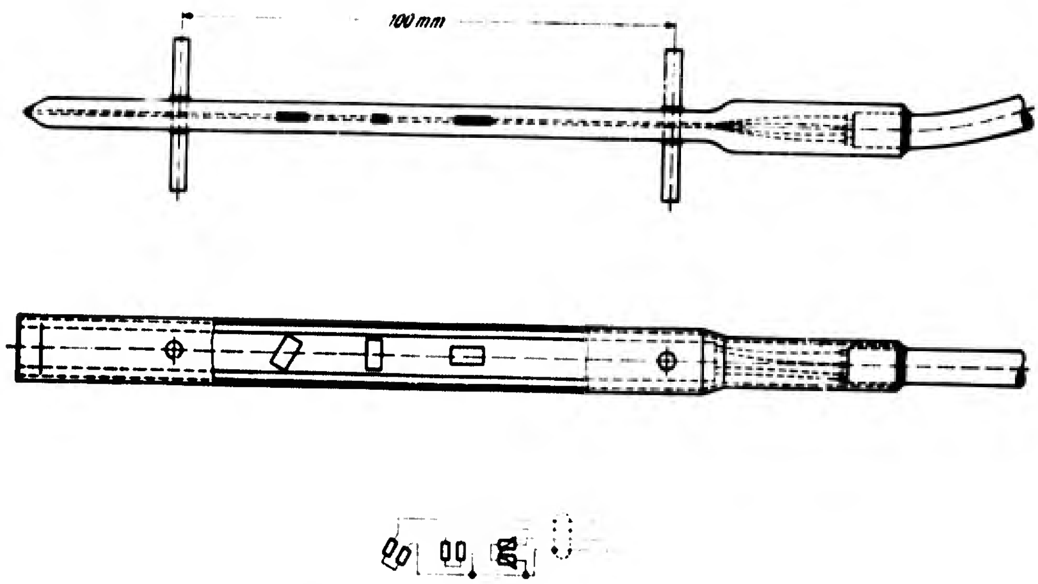


Fig. 13. Strain and temperature indicator for use in concrete (after Pilny[38])

thermal properties of concrete. The standard meter length is about 4 in.; however, smaller meters could certainly be built. The latest version of the meter has a total strain range of approximately 1000×10^{-6} (or microstrains) and an accuracy of about 10 microstrains. The accuracy for temperature measurements is about 0.5 C with a maximum safe operating temperature of 80 C.*,**

56. Professor Pilny* stated that the meter has been very successfully employed in extensive measurements within a model of a prestressed concrete reactor vessel and, in his opinion, has proved more reliable than vibrating wire strain meters, which had been used before. Some special development work would certainly be necessary to reduce the meter size considerably; however, there is no apparent reason why it could not be done.

Embedded stress meters utilizing bonded metal resistance gages

57. Bonded metal meters have successfully been used in the construction of several well-known earth pressure cells; similar design principles

* From communication from Professor F. Pilny, Technische Universität, Berlin, Germany, November 1966.

** Information furnished by Dr. Ing. G. Wazau, Postfach 103, 1 Berlin Tempelhof., W. Germany, October 1966.

can be and sometimes have been used for direct stress meters in concrete, the only difference usually being that a more rigid casing is needed for concrete. However, practically all stress meters for concrete that were developed from earth pressure cells and, in fact, the vast majority of embedded direct stress meters for concrete suffer from one distinct disadvantage: they are unable to measure tensile stresses.

58. Some of the more prominent internal concrete stress meters that have bonded metal resistance gages as the gaging system will be briefly discussed below.

59. WES pressure meter. Fig. 14 shows a schematic cross section through this disk-shaped meter; parenthesized numbers in this paragraph refer to numbered parts in Fig. 14. The principle of operation is rather

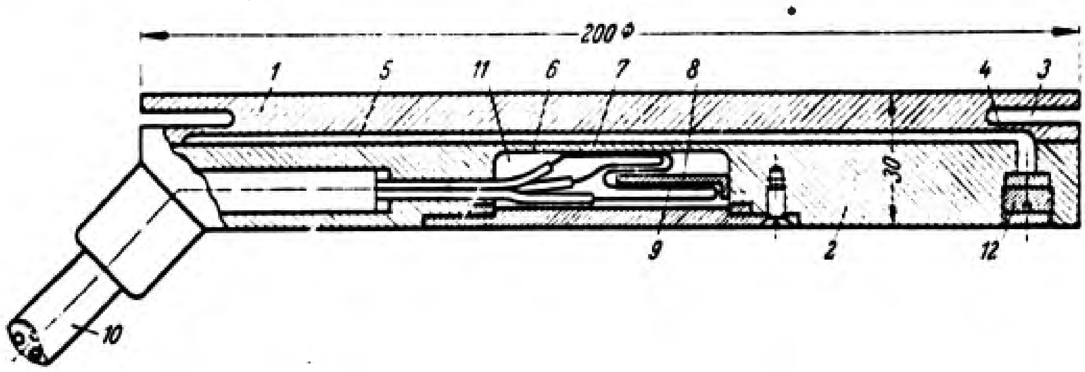


Fig. 14. WES pressure gage[12]

similar to that of the Carlson stress meter, except that the diaphragm in the WES meter is filled with oil rather than mercury (5) and a bonded strain gage (7) is used to measure the deformations of the central flexible portion (6). A dummy gage (9) mounted on a free cantilever (8) serves for temperature compensation. The very limited scale on which WES meters have been used for stress measurements in concrete does not allow a final assessment, but it appears that the meter can successfully be used for this purpose. However, the size negates any use for model work.

60. Loh (or MIT) stress meter. One of the few embedded direct stress meters for concrete that allows the measurement of tensile stresses (besides compressive stresses) was developed by Loh[1] at MIT. The cylindrical meter is made of high-strength steel and consists of a center piece

with an attached bonded wire gaging system, a rigid threaded-on end piece, and an outer shell (fig. 15). It is obvious that a good bond between the outer shell and the surrounding concrete is necessary to facilitate a tension measurement. The meter is designed for a range of +1000-psi tension

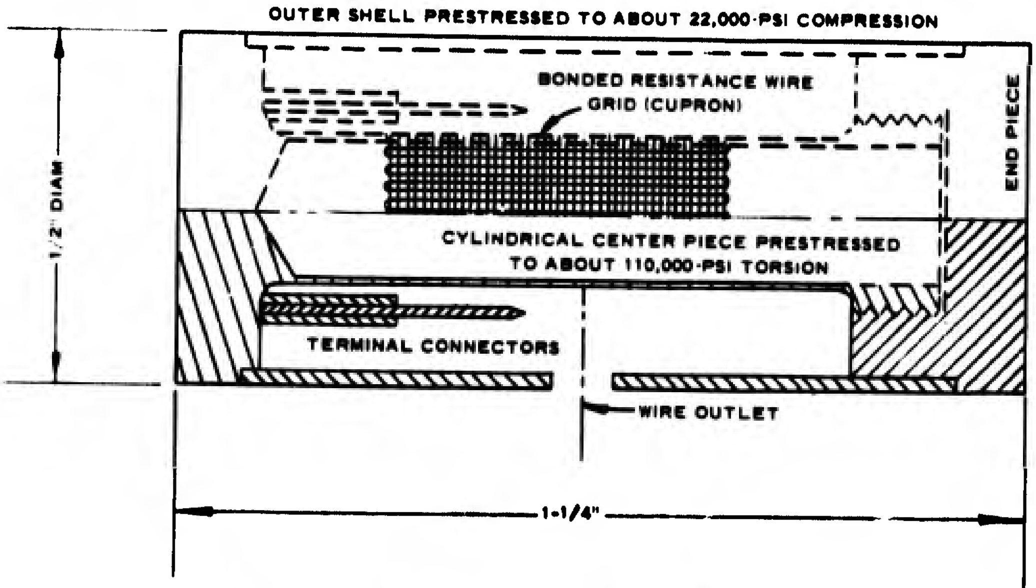


Fig. 15. The Loh or MIT stress meter[1]

to 9000-psi compression, with an accuracy of ±50 psi. Its linear dimensions are at least twice the linear dimensions of the largest aggregate. Rather extensive performance tests of the meter gave satisfactory results but also revealed one problem. The meter is sensitive to lateral pressures, which makes it desirable to insulate the lateral faces with some soft material, which, of course, would interfere with the measurement of tension. Loh's conclusion was, therefore, that it would be better to use separate meters to measure tension and compression. The rather expensive instrument has not been widely used in practice and, therefore, information on its reliability is lacking, but the very small size would make it rather promising for use in models if it were not for its high cost.

<u>Nonmetallic resistance meters</u>

61. There are a number of different types of nonmetallic piezoresistive meters, among them the carbon meter and recently developed pressure-sensitive paints.[39] The carbon meter is based on the change of resistance of a series of carbon plates with the variation of the pressure

exerted on the plates. The pressure-sensitive paints may conceivably open an entirely new and very economical approach to the construction of internal stress meters if current problems concerning sensitivity, hysteresis, and reproducibility of results can be resolved.

62. At the present, however, the only group of nonmetallic resistance meters that holds promise for application in internal strain or stress meters appears to be the new, but rapidly expanding family of semiconductor strain gages.

<u>Semiconductor strain gages</u>

63. The semiconductor gage originated in 1956 with the observation by C. S. Smith of a piezoresistive effect in doped germanium and silicon which was of far greater magnitude than that of metals and alloys. However, the development and production of semiconductor meters have taken place effectively only over the last few years so that as yet there has been little time for full acceptance of this unquestionably valuable device.

64. As compared with conventional metal gages, the semiconductor gage has the following important advantages.

- a. A very high strain sensitivity or gage factor, which may be as high as 250 (compared with about 2-3.5 for conventional metal resistance gages).
- b. Excellent stability and fatigue life, as well as practically no creep or hysteresis if properly constructed.
- c. Feasibility of extremely small sensory elements.

There are, of course, also a few disadvantages:

- a. The linearity of the meter is poor, but may be improved at the expense of sensitivity.[40]
- b. The temperature compensation falls somewhat short of the performance of conventional strain gages and is definitely inferior to that of newer "selected melt" gages.[40]

65. Regarding the application of semiconductor gages to the problem of internal strain and stress measurement in concrete, particularly in microconcrete or mortar models, a number of potential advantages and problems may be expected (to the author's knowledge, no such application has as yet actually been tried).

- a. Due to the higher strain sensibility of the gage, smaller strains can be measured and minute leakages in the insulation could probably be tolerated better than in conventional gages, making the task of waterproofing easier. As long as the resistance between the gage and ground remains larger than 10 megohms, the resulting strain error should be less than about 0.5 microstrains.

b. The small size of the gage should facilitate the construction of very small strain-measuring elements, but problems will arise if a large gage length is desired. It appears that the semiconductor gage is best suited to measuring small deformations of a rigid casing and thus its most promising application may be in the field of direct stress measurement. Actually, semiconductor gages have already been used in the construction of pressure transducers[41,42] and some earth pressure cells.[43-45] Potentially, however, the semiconductor gage could replace metal resistance gages wherever high sensitivity is desired but extraordinary length is not mandatory. Indeed, there are several embedded strain meter concepts that require only relatively short sensing elements (e.g. systems with rigid casings similar to those of the Carlson, Monfore, Boiten, or Pilny meters).

c. Due to the large change in resistance occurring in semiconductor meters under strain, and due to their nonlinearity, conventional measuring circuits like the Wheatstone bridge will often not suffice, making new and more expensive circuits necessary.

66. The U. S. Bureau of Mines has reportedly used semiconductor meters for internal strain measurement in rock samples but details of this work are not known. WES has also started some preliminary work in this field but results are not yet available.

Electrical Inductance Meters

67. An electrical inductance meter is a device in which a displacement produces a change in the magnetic field, and, hence, in the impedance of a current-carrying coil. The impedance of a coil depends on its inductance and on its effective resistance; either or both of these quantities can be made sensitive to the displacement to be measured. The inductance that is changed can be either the self-inductance of the coil or its initial inductance with respect to another coil.

68. Electrical inductance meters are classified below according to the method they use for varying impedance (from reference 16).

a. Variable-air-gap meters (fig. 16a) are meters in which the reluctance of the magnetic circuit is varied by changing the air gap.

b. Moving-core solenoid meters (fig. 16b) are meters in which the reluctance of the magnetic circuit is varied by changing the position of the iron core in the coil.

c. Eddy-current meters (fig. 16c) are meters in which the losses in the magnetic circuit are varied by changing the thickness or position of a high-loss element inserted in the magnetic field.

d. Magnetostriction meters (fig. 16d) are meters in which the reluctance of the magnetic curcuit is varied by changing the stress in the magnetic core of the coil.

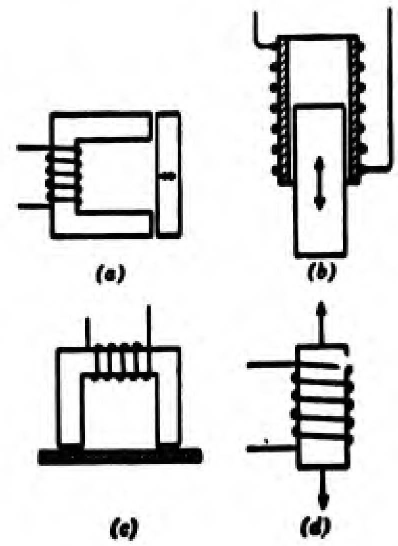


Fig. 16. Basic forms of electrical inductance meters
(a) Variable air gap
(b) Moving-core solenoid
(c) Eddy current
(d) Magnetostriction
(After reference 16)

Since eddy-current and magnetostriction meters appear to hold little promise for our application, they will not be discussed further.

Fundamental relations
(condensed from reference 16)

69. The impedance of a coil to the passage of alternating current is given by the expression

$$A = \sqrt{(2\pi fL)^2 + R^2} \qquad (13)$$

where A = impedance, ohms

f = frequency of current, cycles per second

L = inductance of coil, henrys

R = resistive component, ohms

70. In a coil of high quality factor q, $2\pi fL$ is large compared to R and the impedance varies almost in proportion to the inductance.

71. The action of the variable-air-gap meter is shown by the expression for the inductance of an iron-core coil, the magnetic core of which contains a small air gap:

$$L = \frac{3.19N^2}{\frac{\ell_i}{\mu a_i} + \frac{\ell_a}{a_a}} \times 10^{-8} \tag{14}$$

where N = number of turns in the coil

ℓ_i = length of iron magnetic circuit, in.

μ = permeability of magnetic material at the maximum alternating flux density

a_i = cross section of iron, sq in.

ℓ_a = length of air gap, in.

a_a = cross section of air gap, sq in.

72. If the permeability μ is sufficiently high, equation 14 reduces to

$$L = \frac{a_a}{\ell_a} \times 3.19N^2 \times 10^{-8} \tag{15}$$

The variable-air-gap inductance meter is one of the best known methods of converting small physical displacements into high-energy electric signals. However, equation 14 is only valid as long as the length of the air gap is small relative to its cross-sectional dimensions. For larger displacements, it is better to use the moving-core solenoid meter.

73. The inductance of a long solenoid of small cross section a filled through ℓ inches of its length with magnetic material of permeability μ is approximately

$$L = 3.19\ell n^2 \mu a \times 10^{-8} \tag{16}$$

where n in this case is turns per inch of length. Therefore, to a first approximation, the inductance increases linearly as the core enters the coil. The above equation shows the effect of small displacements of the movable iron on the self-inductance of one coil. Quite often the movement of the iron is used to change the mutual inductance of two coupling coils (fig. 17A). Their inductance depends on the position of their common iron core. If the excitation voltage V of the primary coil is kept constant, the voltage output V_1 of the secondary coil will depend on the position

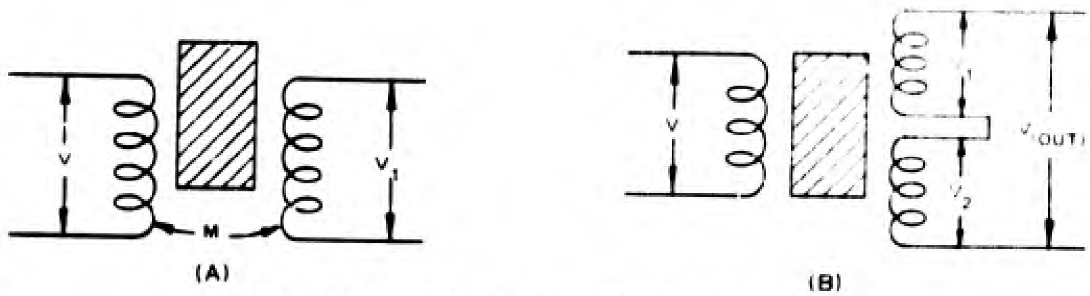


Fig. 17. Double core inductance meters

of the core. In actual application, two secondary coils are used as shown in fig. 17B. The outputs of the two secondary coils are connected in a push-pull arrangement which is generally called the linear variable differential transformer (LVDT).

74. The long-term stability of an inductance meter is inherently better than that of most other systems because (a) the individual parts of the system are not under stress and will therefore not creep, (b) the permeability of the air gap is not affected by the presence of nonmetallic particles, moisture, or oil, and (c) the high output eliminates many sources of trouble found in low-energy systems, such as leakage currents due to moisture, deterioration of insulation, and pickup from stray fields. Moreover, induction meters are capable of covering an extremely wide strain range and a resolution of only a few microinches can be achieved. The effect of temperature is probably less than in most other systems, but to some extent temperature changes will affect the resistance of the windings, the permeability and resistivity of the iron core, and may disturb the phase relation between the output voltages of the two secondary coils. Geometrical dimensions of the meter will also be slightly altered by changing temperatures. The resulting temperature sensitivity of an inductance-type meter is usually small and can be compensated for, but not as easily as in metal resistance meters.

Inductance meters for embedment in concrete

75. To the author's knowledge, no inductance meter for embedment in concrete is presently produced. In fact no references to embedded

inductance meters were found at all. Considering the widespread application of small inductance meters for all kinds of displacement measurements, the lack of an embedded inductance strain meter for concrete is surprising since the inductance systems appear very promising for this application. There would be, for instance, no apparent difficulty in modifying the Philips PR 9312 surface strain meter, or one of the many small LVDT's now being produced in this country for use as an embedded strain meter. A proposed solution is sketched in fig. 18. The contemplated meter would have a measuring length of about 1-1/2 to 3 in., a diameter of about 1/2 to 1 in., and a resolution of approximately 2 microstrains. The relatively high initial cost (about $80 to $200) could possibly be balanced by recovering and reusing the meter several times, a practice that should be feasible with this very rugged instrument in many laboratory applications. A program to develop and test different inductance-type small embedded strain meters is presently under way at WES and first results should be available shortly.

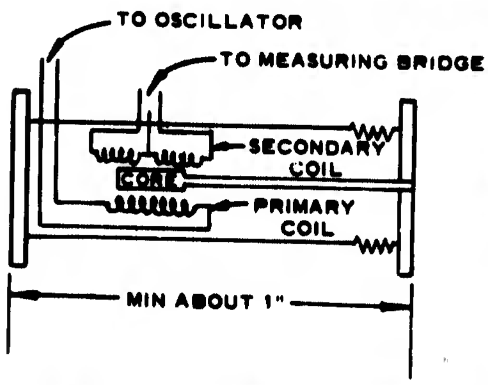


Fig. 18. Sketch of embedded inductance strain meter

76. It is strongly believed at the present time that the inductance system, due to its good stability, high signal output, wide strain range, low modulus of elasticity, and large length-to-diameter ratios, is one of the best systems for internal strain measurement in concrete. The minimum measuring length of an inductance meter is probably around 1 in., making this type of instrument very promising for use in models also.

Electric Capacitance Meters

77. As the name implies, this system expresses physical displacement through changes in electrical capacitance. The capacitance of a parallel-plate condenser is given by

$$C = 0.2248 \frac{KA}{t} \tag{17}$$

where C = capacitance, μμf

K = dielectric constant

A = area of the plate, sq in.

t = distance between the plates, in.

The capacitance of a condenser may thus be varied by changing either A or t, but it is also influenced by any change in K. For internal meters, varying t (variable-gap pickups) is generally preferred. The sensitivity S of a capacitance meter is obtained by differentiating equation 17 with respect to t,

$$S = \frac{dC}{dt} = -0.2248 \times K \times \frac{A}{t^2} \tag{18}$$

and it is seen that the sensitivity increases as t decreases. Therefore, the variable-gap pickup, particularly if air is used as the dielectric, is not linear unless the variation of t is very small. Its linearity can be considerably improved by introducing a thin layer of mica to partially fill the gap between the plates, using, for instance, the following combination:[1]

$$t = \text{total air gap} = 0.001 \text{ in. and}$$

$$t_1 = \text{thickness of mica} = 0.00075 \text{ in.}$$

For this meter, maximum relative displacement of the parallel plates should not exceed 0.0002 in. When the above numerical values are used, the capacitance of the parallel-plate condenser is 600 μμf and the maximum change of the capacitance due to relative displacement of the plates is 20 μμf, which indicates that both the capacitance and the change in capacitance are very small. Thus, the impedance of a capacitance meter, which is inversely proportional to capacitance, is very high. Hence, the system is susceptible to any outside electrical disturbances. The capacitance pickup itself and connecting cables have to be carefully shielded. All measuring cables should be as short as possible and protected from vibrations or cross-sectional deformations. Since the maximum relative displacement between the two condenser plates is limited to 0.0002 in., differential thermal expansion in the mechanical parts of the meter becomes critical, and may induce a large temperature error unless the meter is very carefully designed. Moreover, any moisture changes will affect the dielectric properties of the mica and the air gap, thus making careful waterproofing mandatory. Finally, temperature changes will also alter the capacity of leads, thereby providing another cause for drift in long-term applications.

78. In spite of all these problems, capacitance meters have successfully been used for pressure measurements and, on a smaller scale, for displacement and strain measurements. The only application of capacitance meters for measurements within concrete known to the author was described by Morgan and McLachlan.[46] A cross section of their capacitance strain meter is shown in fig. 19. It appears that temperature compensation, long-term stability, and measuring circuits for this meter presented major difficulties.

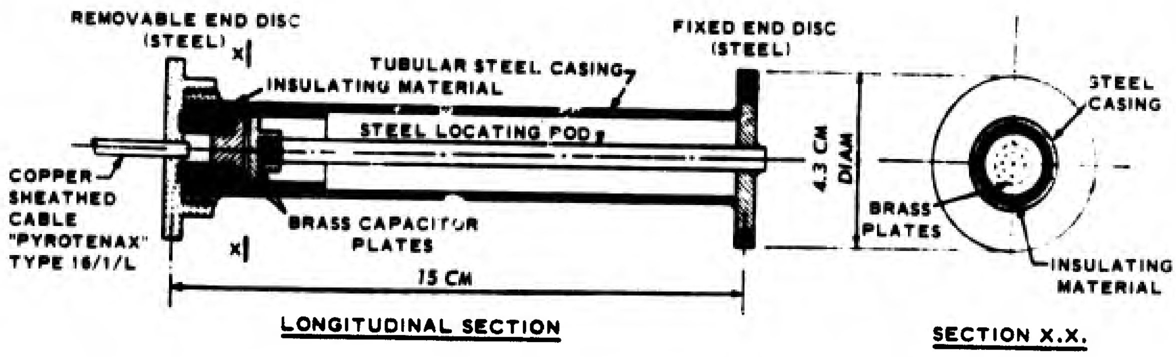


Fig. 19. Capacitance strain meter (after reference 46)

79. Generally, capacitance meters do not appear very promising for long-term internal strain measurement in concrete, but they could conceivably serve as a gaging element in stress meters such as the Carlson or WES stress meters.

80. It might be mentioned here that a very interesting and rather revolutionary soil pressure meter based on the variable capacitance principle was recently developed by B. Prange,[47] Technische Hochschule Karlsruhe.* The cylindrical, 40-mm-diameter (1.6 in.) and 15-mm-high (0.6 in.) meter

* Communication from Professor H. Leussink, Technische Hochschule, Karlsruhe, Germany.

combines a capacitance gaging system with a small high-frequency transmitter, operating on rechargeable batteries, which allows wireless transmission of the measuring signal over a distance of several yards, thereby eliminating the need for troublesome connecting cables. At the present stage of development, the unit is capable of about one week's continuous operation, or half a year of intermittent use if it is switched on and off for readings by an outside radio signal. The pressure range is currently restricted to about 150 psi, and it seems unlikely that the meter could easily be adapted for use in concrete. However, the idea is very striking and deserves to be looked into.*

Piezoelectric Gaging Methods

81. Some asymmetrical crystalline materials, such as Rochelle salt, tourmaline quartz, etc., possess the property of generating electric charges when load is applied to the crystal along its electric axis. The relation between the electrostatic charge generated and the applied load is given[1] by

$$Q = KP$$

where Q = static electric charge generated

K = piezoelectric constant of the crystal

P = total load acting on the crystal

The piezoelectric constants vary for different crystals. For instance, the value for Rochelle salt is about 1000 times larger than that for quartz. But quartz crystals are commonly used for mechanical measurement because of their high mechanical strength and resistance to both heat and moisture.

82. The important disadvantage of piezoelectric meters is their inability to measure static loads. When a static load is applied to the crystal, the charge generated leaks away slowly. Even low-frequency measurements pose such major problems that the meter is essentially restricted to high-frequency dynamic measurements, an area which is of minor interest in the present study.

* Recently very small implanted transducers and telemetry systems have successfully been used for various biomedical measurements.[65]

Acoustic Meters

Vibrating wire meters

83. As early as 1919, a vibrating wire strain meter was employed by O. Schäffer and since then acoustic strain (and stress) meters have found very widespread application, particularly for long-term measurements within concrete dams in various European countries.[7,21,22,49-53*] A vibrating wire strain meter consists basically of a wire stretched between two points. The variation of the distance between these points is measured by the changes in the fundamental natural frequency of vibration of the wire. This frequency f is given by the expression:

$$f = \frac{1}{2L}\sqrt{\frac{\sigma}{\rho}} \tag{19}$$

where L = the length of the wire

σ = stress in the wire

ρ = unit mass of the wire material

When σ changes by $\Delta\sigma$, the variation of the frequency is:

$$\Delta f = \frac{1}{4L}\sqrt{\frac{1}{\rho\sigma}}\,\Delta\sigma \tag{20}$$

and it is seen that the magnitude of the frequency changes increases with decreasing length of the wire and decreasing stress.

84. In most instruments, the steel wire is set in vibration by an electromagnet which also picks up and transmits the vibration to a frequency measuring apparatus. The frequency may be measured directly or by comparison with the vibrating frequency of a wire whose length can be varied by means of a high-precision micrometer screw. Longitudinal sections of vibrating wire strain meters used for measurements in concrete are shown in fig. 20.

85. The main advantages of the vibrating wire meter are good

* Also from communication from M. Rocha, Laboratorio Nacional de Engenharia Civil, Lisbon, October 1966.

long-term stability, high accuracy, and relative insensitivity to moisture. Since the measurement is in frequencies, readings are also independent of the characteristics of the connecting cables. These important advantages have made the vibrating wire meter possibly the most widely used instrument for long-term strain measurements in concrete.

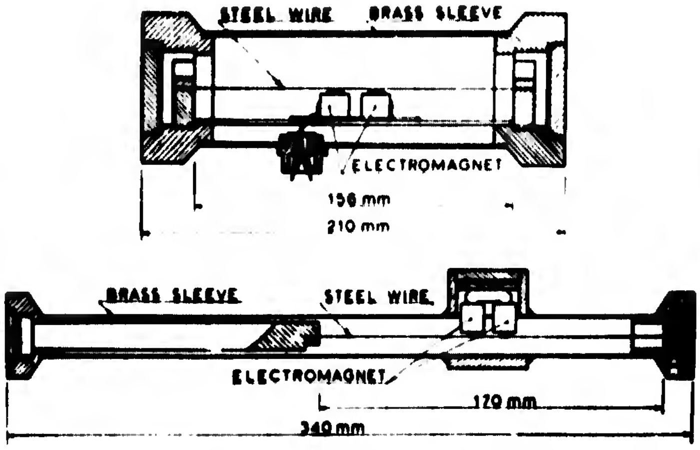


Fig. 20. Longitudinal sections of vibrating wire strain meters for inside measurements (after reference 7)

86. However, there are, of course, a few problems with this meter too. Since the wires are pretensioned to a high stress level, one problem is how to avoid relaxation of the wire, which can give rise to considerable error. For this reason, heat-treated high-strength steel wires are normally used. These wires show practically no creep within the temperature range usually encountered. However, if temperatures exceed about 200 F, relaxation of the wire becomes a serious problem again. Another problem, of a less serious nature, is reliable corrosion protection of the wire, which is usually achieved by electroplating it with silver. Finally, if the meter undergoes significant temperature changes (and in most applications it will), a temperature compensation has to be made, which poses problems similar to those encountered with inductance or capacitance meters.

87. The smallest vibrating wire strain meters currently produced have a measuring length of about 2 in., which makes them usable in larger models. Further reduction of size for application in small models seems difficult. In addition, the average strain range of acoustic meters, which is about the same as that of unbonded wire meters, may be rather narrow for a few special types of studies mentioned previously. The smallest acoustic stress meter is a disk-shaped capsule about 2-1/4 in. in diameter and about 1 in. high, especially designed for use in concrete models (table 3).

88. To the author's knowledge, vibrating wire meters for embedment

in concrete are presently manufactured by five European companies. No commercial manufacturers were found in the United States. Technical date and approximate prices for commercially available meters are compiled in table 3. Besides the vibrating wire meters listed in the table, several meters of slightly different design were developed in different research laboratories, e.g. the Building Research Station,[51,54] the Laboratorio Nacional de Engenharia Civil, Lisbon,[7,52] and others.[53] Of these, the long stress meter developed by LNEC and described by Rocha[7] is particularly interesting. Fig. 21 shows a longitudinal cross section of the meter. It is basically a thick-walled steel cylinder with a height/diameter ratio of about 3 and an equivalent elastic modulus of 17×10^6 psi, i.e. about four times that of concrete. In order to allow the measurement of tensile stresses, the bases have a larger diameter than the body. A vibrating wire determines the deformations in the stress meter, which is empirically calibrated by means of tests made inside concrete prisms that directly yield the ratio of the applied stress σ to the reading of the meter.

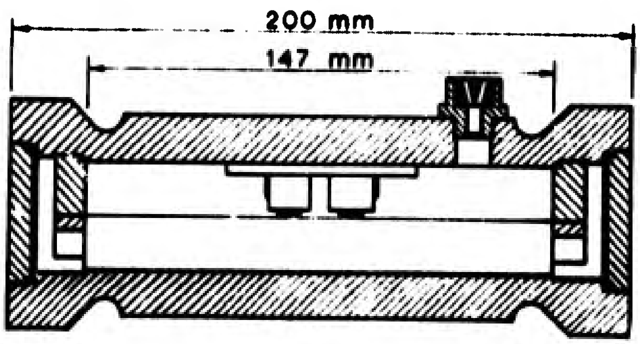


Fig. 21. Cross section of a long stress meter (after reference 7)

Radio-frequency cavity gages

89. Similar in appearance and function to the vibrating wire meter, this new type of meter is a very recent British development. Its general operating principle is described by R. D. Browne and L. H. McCurrich[63] as follows:

> General principles
>
> 29. Radio waves resonate at a certain frequency in a given cavity in the same way as sound waves. If the volume of the cavity changes so will the resonant frequency. In the radio frequency cavity gauge the size of the cavity is reduced and the sensitivity increased by incorporating a capacitor within the cavity.6[64] Strain is obtained from a calibration curve of resonant frequency against strain.

Design and performance

30. [Fig. 22 shows the] general internal arrangement of an available gauge, details of

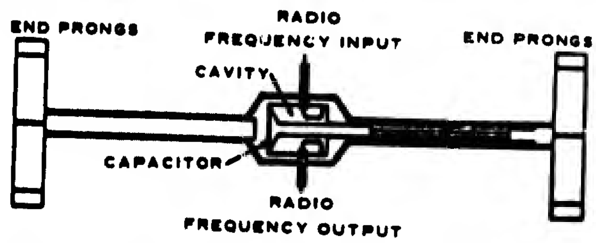


Fig. 22. Radio frequency cavity gauge. General arrangement

which are given in Table 4. At present the gauges are rather expensive and need special equipment for signal generation and frequency reading. In addition, automatic data logging is not practicable. They share with vibrating wire gauges the advantages that changes in the resistance of leads and contacts do not alter their reading. They are suitable for very hostile environments, including strong magnetic fields.

Table 4 Radio frequency cavity gauges

Manufacturer	Type	Overall length in.	Gauge length in.	Elasticity of gauge (E_g) lb/sq. in.	Maximum long-term operating temp. °C	Range micro-strain	Approximate gauge factor	Resolution micro-strain
British Aircraft Corporation Ltd	BT-E22	8.8	8.3	4×10^3	100	3600	Use conversion tables	1.2
	Description: 0.25 in. dia. brass spacer tube separating 2.25 in. dia. radial prongs. Plastic coated to prevent bond of concrete except at ends.							

31. An attempt has been made to design the gauge to have a consistent gauge length, by coating the outside of the spacer tube and cavity with plastic to prevent bond, and tests carried out for the manufacturers have shown the gauge to behave identically in air and concrete. Early gauges were not watertight but a later version has withstood immersion at a pressure of 600 lb/sq. in. (42.2 kg/sq. cm) with no ill effect.

32. Temperature compensation can be built into

> these gauges and they can be made to operate under extremes of temperature. Successful readings have been made when a stainless steel gauge was running red hot (850°C, 1562°F).
>
> 33. Radiation levels in the major portion of [nuclear reactor] vessel should present no problems. The radio frequency cavity technique has been used successfully in irradiated structures and it appears that it will function satisfactorily in conditions experienced in prestressed concrete pressure vessels.

Pneumatic and Hydraulic Gaging Systems

Variable-orifice meters

90. Menneson, in about 1930, was probably the first to use pneumatic flow for measurement of strain. His instrument utilized the pressure differential which exists in an airstream restricted by two successive orifices, one of which varies in size. The instrument has been described as extremely sensitive, accurate, heat resistant, easy to operate, and capable of magnification ratios up to and even exceeding 100,000.[16,40]

91. The principle of operation is rather simple. Fig. 23 shows schematically: (a) the air supply and differential manometer, and (b) an

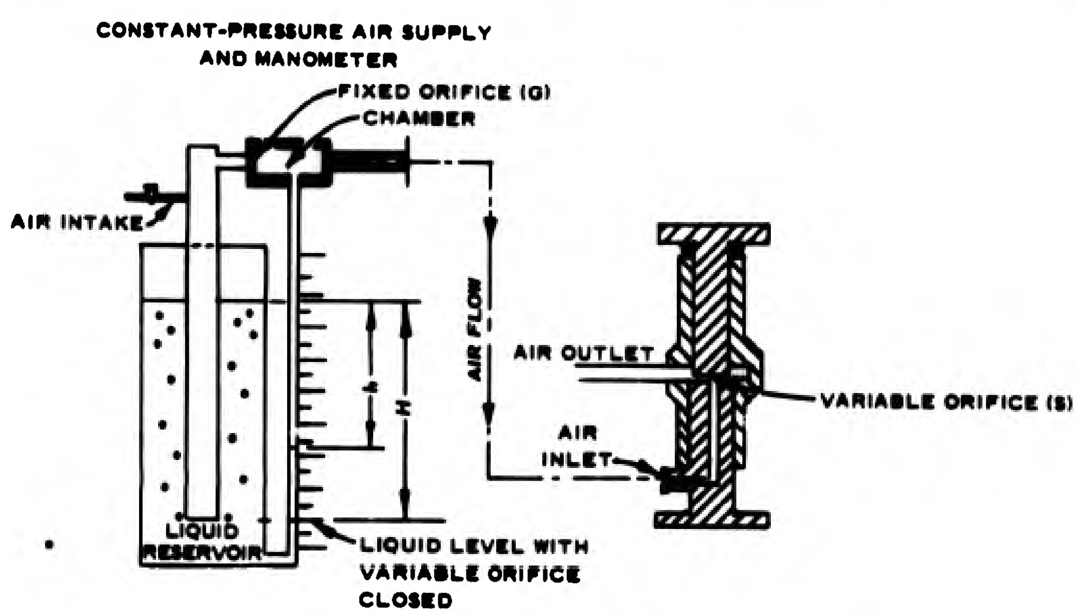


Fig. 23. Pneumatic strain meter for embedment

embedded strain meter based on the variable-orifice principle. Air under constant pressure, H, flows through two orifices placed in series (G and S), the pressure between the two orifices being a function of the ratio of their areas. Consequently, if the nozzle G is of fixed dimensions and the exhaust orifice S is of variable dimensions, the pressure h serves to measure the dimension of S. The theory utilized in this instrument may be summarized briefly as follows: if air is assumed to be incompressible and

G = nozzle orifice area

S = discharge orifice area

$C = C_g = C_s$ = coefficient of contraction, assumed to be the same for both orifices

ρ = density of air

g = acceleration due to gravity

The flow through each orifice is the same, so

$$CG\sqrt{2g(H - h)/\rho} = CS\sqrt{2gh/\rho} \tag{20}$$

where $h = \dfrac{H}{1 + \dfrac{S^2}{G^2}}$

92. Obviously, the function $h = f(S)$ is not linear; however, it has an inflection point when $h/H = 3/4$ or $S/G = 0.58$. Hence, for values in this neighborhood the relation is very nearly linear.

93. An application of the variable-orifice method to the problem of internal strain measurement in concrete is not on record but could well be conceived (see fig. 23), and may indeed hold considerable promise for long-term measurements under adverse conditions. The instrument calls for extremely fine workmanship, which is presumably the reason why pneumatic strain meters have not yet been widely used.

Glötzl pressure cell[7,55-57]

94. A hydraulic, direct stress measuring system based on the

principle of a bypass valve was developed in recent years by F. Glötzl,[57] primarily for use in soils; however, a modified version is available for use in concrete. The meter essentially consists of two disks, A and B (fig. 24), welded together at their edges C , the inward-facing surface of one of the disks being fitted with circular and radial grooves as indicated. Because the disks lie on one another, a force can be transmitted through them without their bending. At the center of disk B is a valve opening D that is kept shut by disk A . At a convenient point E , a fluid such as oil or mercury can be introduced under pressure,

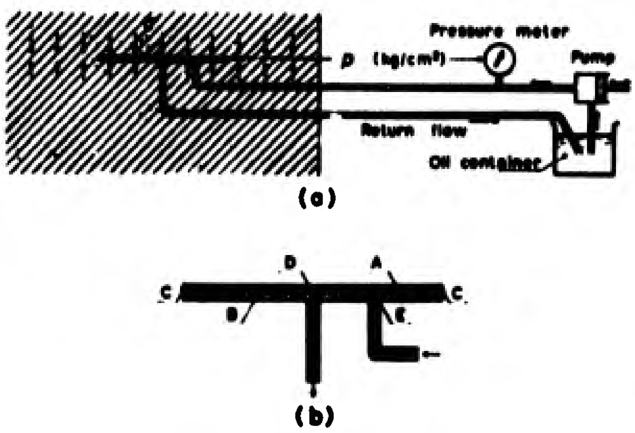
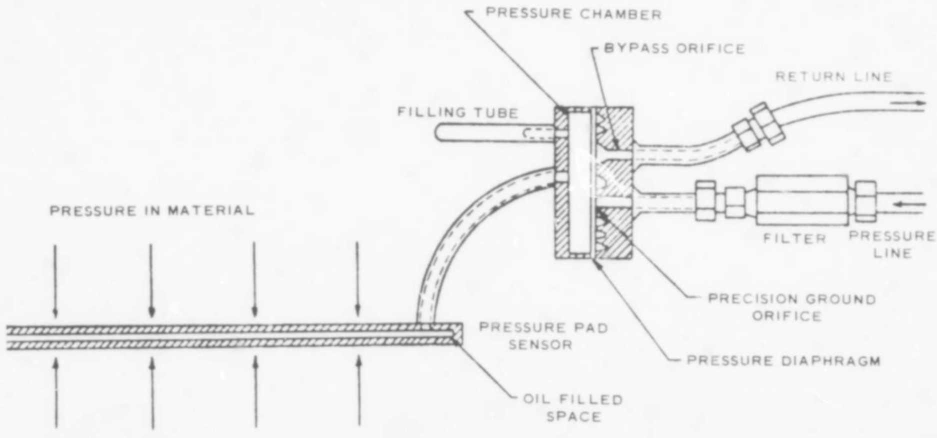


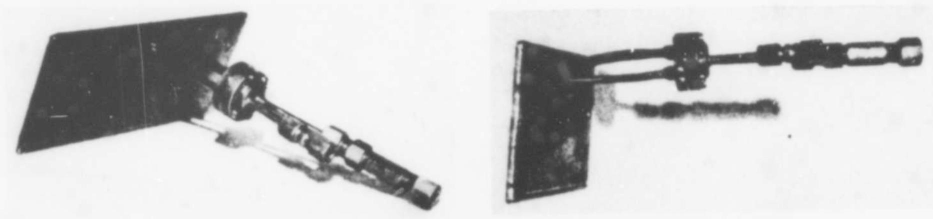
Fig. 24. Sketch of the Glötzl stress meter (after reference 7)

completely filling the free space between the disks. The oil pressure p inside the stress meter rises until it reaches the value of the stress σ acting on the instrument. The disks are so flexible that an extremely small difference between σ and p suffices to force valve D to open and the oil to flow out. Since the oil is continuously supplied by a pump, which delivers a small but steady flow, the valve automatically adjusts itself in such a way that the oil pressure balances the applied stress σ . Relief valve and stress-sensing pad may also be separated as shown in fig. 25.

95. In its standard version, the pad for sensing concrete pressure is 3/32 in. thick and covers an area of 4 by 8 in., or 2-3/4 by 5-1/2 in., resulting in a very favorable height/diameter ratio, which makes the meter rather insensitive to stressless shrinkage deformations or variations in concrete elastic modulus. Smaller measuring pads are, of course, possible; however, reduction of the size of the relief valve would probably be difficult.

96. Although the Glötzl cell has been used very successfully in a





CONCRETE STRESS CELL

Size	- 2-3/4" x 5-1/2" x 3/32" and 4" x 8" x 3/32" (others on request)
Measuring Range	- 0 - 3570 psi
Sensitivity	- 0.15 psi 1.5 psi

The cells can be pre-pressured for readings of cells which are located below the measuring station or areas where slight tensile stresses are anticipated.

Fig. 25. Glötzl stress meter with separated pressure pad and valve (after reference 56)

number of soil pressure measuring programs,[58,59*] the reliability and accuracy of the concrete stress meter are controversial. One difficulty, for instance, arises from the use of mercury as the (noncompressible) hydraulic fluid, which necessitates a careful temperature correction. As far as

* Also Data Sheets SG1/66 and SG5/66 and letter of 3 October 1966 from Deakin Philips Electronic, Ltd., Tilly's Lane, High Street, Staines, Middlesex, United Kingdom.

application in models is concerned, the necessary reduction in size would certainly increase the problems associated with the instrument. Another disadvantage of the Glötzl cell is its high cost ($195 per cell).

PART IV: SUMMARY OF RESULTS AND CONCLUSIONS

97. From an extensive literature review, a worldwide survey covering about 100 meter manufacturers, research laboratories, and universities, and from a few preliminary tests (Appendix A), the following conclusions are drawn.

a. For the vast majority of long-term strain or stress measurements within concrete structures or structural elements, only two gaging systems have been used, namely, the vibrating wire and the unbonded resistance wire systems. Both have proven accurate, stable, and reasonably reliable in numerous laboratory and field applications during the past three decades. Pertinent instrumentation and techniques for measurements in mass and structural concrete are well developed and a variety of meters is readily available, e.g. Carlson meters of various sizes, and various brands and sizes of vibrating wire meters. However, the minimum practical size for both systems appears to be in the range of 2 to 4 in. maximum dimension, which is rather large for application in models. Further reduction of the size seems difficult and may be altogether impractical.

b. The best known, most economical, and most versatile strain measuring system, i.e. the bonded metal resistance gage, unfortunately does not lend itself very readily to application as an embedded meter in concrete for measurements over an extended period. Difficulties arise primarily from zero drifting due to four factors.

   (1) Moisture sensitivity of the gaging system and problems in providing dependable moisture protection.

   (2) Creep in cementing or encapsulating materials.

   (3) Volume instability of encapsulating materials.

   (4) Temperature effects.

   A host of investigators have tried a variety of schemes to utilize regular wire or foil strain gages, and some of these approaches appear very promising for model work. However, at the present no generally accepted and well proven small meter for long-term measurement in concrete or mortar is available. Further research into the stability, reliability, and limitations of various existing bonded wire meters and/or development of new instruments especially designed for model work appears necessary before any particular bonded wire meter can safely be considered satisfactory for use in long-term model studies.

c. A number of existing internal bonded metal resistance strain meters can successfully be used for short-term static or dynamic measurements where zero drifting does not play an important role, e.g. plastic-encapsulated and shimstock meters, Valore meters, and various meters in rigid metal casings (Pilny, etc.), which can easily be reduced in size to make them suitable for model work.

d. Some systems which appear very suitable for internal measurements have been entirely neglected to date. A good example of this is the electric-inductance meter. Since it is felt that embedded electric-inductance strain meters with a measuring length of about 1 in. are feasible, some development work appears justified and worthwhile. Another new system that holds promise for internal measurements in concrete models is the semiconductor meter.

e. Based on the information collected, it is believed that future efforts to select or develop an embedded, small strain meter with good long-term stability for use in concrete model work should concentrate on:

(1) Bonded wire gages on metal carriers or in metal casings, such as the Valore, Philips, Pilny, or Microdot meters.

(2) Semiconductor gages in metal casings.

(3) Inductance meters (LVDT).

(4) Small acoustic meters.

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Table 1

Comparison of Different Gaging Systems

Type of Gaging System	Linearity of Sensitivity	Accuracy of Measurement	Long Period Stability	Suitability for Static Measurement	Suitability for Dynamic Measurement	Environmental Error Due to Temperature	Effect of Humidity	Noise in the Measuring System
Resistance strain gage	Linear	10 μin./in.	Fair	Good	Good	Good if compensating gage is used	Small if waterproofed	Low
Capacitance	Linear for small displacement	0.5 μin./in. (depends on design)	Fair	Fair	Good	Fair	Small if waterproofed	High
Inductance	Linear	1-5 μin./in. (depends on design)	Good	Good	Good for low and medium frequency	Good	Small	Very low
Magnetostriction	Nonlinear	30 psi (depends on preloading)	Poor	Good	Good for low frequency	Poor	Small	High
Piezoelectric	Linear	0.5 lb (depends on design)	Unsuitable	Unsuitable	Good for medium and high frequency	Poor	Large	High
Acoustic	Nonlinear	1 μin./in.	Good	Good	Poor (unless very special techniques are used)[60]	Fair	Small	Low
Pneumatic	Linear for small displacement	1 μin./in.	Good	Good	Poor	Fair	Small	Low
Hydraulic (Glötzl)	Linear	2 psi	Good	Good	Poor	Poor	None	Low

Table 2

Resistance Strain Meters

Meter & Manufacturer	Type	Dimensions	Sensibility Accuracy	Strain Range	Temperature Range	Stability	Suitability for Dynamic Measurement	Limitations and Problems	Comments	Approximate Price Piece
Carlson strain meter R. Carlson & Co.	Elastic unbonded wire	Total length 4-10 in. = measuring length; min diam 1 in.	$\pm 5 \times 10^{-6}$	$+500 \times 10^{-6}$ -1000×10^{-6}	Up to about 150 F	Good	Fair	Not feasible for small meters; somewhat restricted strain and temperature range	Widely used all over world with good success	$35-65
Monfore Standardizing strain gage G. E. Monfore	Elastic unbonded wire	Total length 4 in. plus 2 in. probably feasible; min diam ~1/2 in	About $\pm 5 \times 10^{-6}$ (G.F.* about 2)	About 3000×10^{-6}	Up to about 250 F	Very good	No good	Not feasible for very small meters	Used with good results by PCA	~$80-100
Polyester-mold gage Tokyo Sokki Kenkyujo	Bonded wire resin encapsulated	85 x 13 x [illegible] mm 125 x 13 x 5 mm (smaller sizes pose no problem)	G.F. about 2	About $20{,}000 \times 10^{-6}$	Up to about 350 F	Poor	Should be good	Stability problems due to moisture absorption in resin. Mismatch in thermal expansion and creep	Good results reported by ref 27, less favorable results in PCA and NBS tests.	$3
Other plastic-encapsulated resistance meters (self-produced)	Bonded wire resin encapsulated	Practically all sizes up to 6 in. total length feasible	G.F. about 2	About $20{,}000 \times 10^{-6}$	Depends on strain gage and resin used	Poor	Should be good	Stability problems due to moisture absorption in resin. Mismatch in thermal expansion and creep	Good result in short-time tests	Approximately $2-5 (self-produced)
"Shimstock" meters	Bonded wire resistance on metal carrier	Practically all sizes up to 6 in. total length feasible	G.F. about 2	Elastic limit of metal carrier	Depends on strain gage and cement used	Fair	Should be good	Good moistureproofing and bond essential. Stiffness of metal carrier may influence readings	Not widely used	Approximately $2-5 (self-produced)
Valore brass envelope strain meter Baldwin-Lima-Hamilton	Bonded wire resistance with metal envelope	Standard size 5 x 3/8 x 0.01 in. (overall), smaller sizes feasible	G.F. 2.1	Elastic limit of metal carrier	-50 to +150 F	Fair	Should be good; bond losses possible in cyclic loading	Good soldering of metal envelope, waterproofing of cable inlet, and good bond to concrete essential	Proper embedment and alignment difficult	$15-20
Philips strain meter PR 9239 A. G. Philips	Bonded wire resistance with metal envelope	Standard size 200 x 12 x 0.4 mm (overall)	G.F. 2	2000×10^{-6}	Up to 140 F	Fair	Should be good; bond losses possible in cyclic loading	Essentially the same as for the Valore meter		Approximately $20
Other metal foil envelope meters	Bonded metal resistance with metal envelope	Practically all sizes feasible	G.F. 2.1	Elastic limit of metal carrier	Depends on strain gage and cement used	Fair	Should be good; bond losses possible in cyclic loading	Good soldering of metal envelope, waterproofing of cable inlet, and good bond to concrete essential	Proper embedment and alignment difficult	About $5-10 (self-produced)
Filmy strain meter Dr. G. Wazau, Berlin	Bonded metal resistance meter on prestressed steel	Standard size 4-in. measuring length, 8-in. total length; smaller sizes feasible	$\pm 10 \times 10^{-6}$	$\pm$[illegible],000 $\times 10^{-6}$	-20 to +80 C	Fair	Should be good	Somewhat restricted strain and temperature range	Used with good results at University of Berlin	Not known
Other rigid casing meters	Bonded metal meter in rigid metal casing	Minimum measuring length around 1-2 in.	About $\pm 10 \times 10^{-6}$	Elastic limit of metal casing	Depends on strain gage and cement used	Fair	Should be good	Usually sensitive to bending and lateral loads	Not widely used	Between about $10 and $100 depending on type
Semiconductor meters Several U. S. manufacturers	Can replace bonded metal meters in most of above systems	Length about 0.2-0.5 in.	G.F about 50-250	$+3000 \times 10^{-6}$ $-10{,}000 \times 10^{-6}$	Up to 1500 F	Better than bonded metal meters	Good	Gaging element restricted to 0.5-in. maximum length. More expensive gaging circuits may be necessary	Not yet used	$15-25
Integral lead gage Microdot, Inc. Pasadena, Calif.	Weldable wire resistance encased in stainless steel tube	Length 11/16 to 37/32 in., tube diameter 0.021 in., flange width 1/8 to 3/16 in.	G. F. 1.40-1.80	$\pm 6000 \times 10^{-6}$	-320 F to +650 F	?	Good			About $4-6

Note: All meters listed can probably be built for any practical pressure range.
* G.F. denotes gage factor.

Table 3

Vibrating Wire Meters

(Presently on the Market)

Manufacturer	Model	Special Features	Dimensions: Measuring Length mm	Dimensions: Diam mm	Sensitivity	Strain Range	Temperature Range	Pressure Range	Comments	Approximate Price/Piece
Telemac s.a. (60)* 17 rue Alfred Roll Paris, France	Strain meter F1	Brass casing	313	28	5×10^{-6}	3000×10^{-6}	**	Tested under 10 atm water pressure	Very widely used in European reinforced concrete structures and dams, particularly in France. (52, 22)	About $[illegible]
	Strain meter F2		254	28	$2\text{-}1/2 \times 10^{-6}$	1.500×10^{-6}				
	Strain meter F4		212	28	1.25×10^{-6}	750×10^{-6}				
	Strain meter SF		367	28	8×10^{-6}	4.800×10^{-6}				
	Strain meter C90	Steel casing	120	5	1×10^{-6}	600×10^{-6}			Successfully used in models of prestressed concrete reactor vessels	About $-5
Maihak A. G. (61) Hamburg 39 West Germany	MDS 53		50		3×10^{-6}	1.500×10^{-6}	**	Tested under 15 atm water pressure	Widely used in Europe (49, 50, 42, 54)	$[illegible]
Officine Galileo (62) Viale Eginardo 29 Milano, Italy	EA-SC-150/150		150	25	5.3×10^{-6}	2500×10^{-6}	**	Tested under cycling water pressure of 6 atm	Widely used in Europe, particularly in dams (52, 22)	[illegible]
	EA-SC-150/120		150	25	3.35×10^{-6}	1300×10^{-6}				[illegible]
	EA-SC-300/185		300	43	5.3×10^{-6}	2500×10^{-6}				[illegible]
	EA-SC-300/150		300	43	2.67×10^{-6}					$50
	EA-SC-1000/150		1000	~70	0.5×10^{-6}	200×10^{-5}				[illegible]
	EA-SC-50/50		50	~6	6×10^{-6}	1500×10^{-6}				[illegible]
	Stress meter TEA-C-50	Disk-shaped	Height 110	240	0.2 kg/cm^2	Up to 150 kg/cm^2				[illegible]
	Model stress meter	Disk-shaped E_t = 50,000 kg/cm^2	Height 23	60	Variable					[illegible]
Domain Philips Electronic, Ltd.† Staines, Middlesex England	RBL/A	Acrylic tube	140	6	0.5×10^{-6}	**	Up to 50 C possible	**	Used in many Commonwealth countries	$20**
	RBL/SS	Stainless steel tube	140	6	0.5×10^{-6}	**				$20**
	RBS/E	Temperature measurement possible	140	6	0.5×10^{-6}	**				$30**
	New model meter		76	6	0.5×10^{-6}	**			Used in models of prestressed reactor vessels	[illegible]
Perivale Controls• Telfordway London W3	PC 657	Temperature measurement possible	130	~7	5×10^{-6}	$\pm 1000 \times 10^{-6}$	-10 to +70C	Tested at 75 psi water pressure		**
	PC 65[illegible]		130	~7					Relatively new product	**
	IC 641		[illegible]	~7	1×10^{-6}	$\pm 1000 \times 10^{-6}$	-10 to +600			Approx [illegible]

* Numbers in parentheses are numbers of references in Literature Cited.
** Information lacking.
† Information from data sheets SC-1/66 and SS-5/66 and letter of 3 October 1966.
†† Price in U. K.
• Information from Perivale Controls data sheet C1.

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APPENDIX A: PRELIMINARY TESTS OF BONDED WIRE METERS

Description of Meters Tested

1. A short description of the bonded wire meters tested in the preliminary test series is given in table A1, and all meters tested are shown in fig. A1.

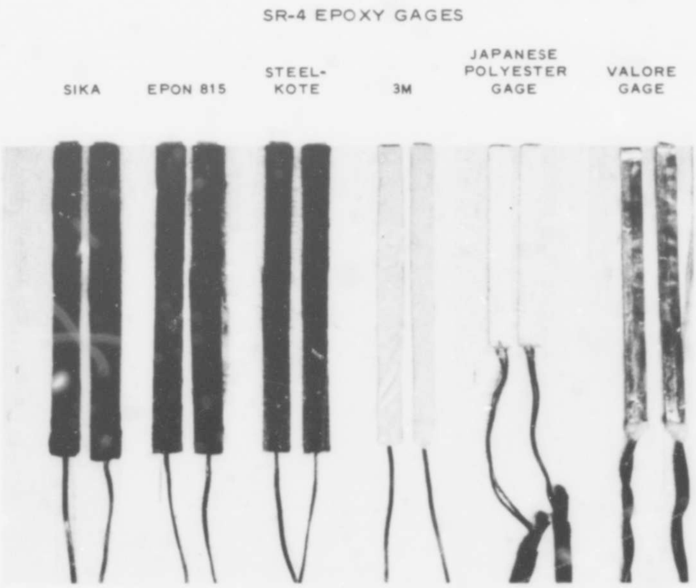


Fig. A1. Encapsulated strain meters tested

Tests

Water-immersion and drying test

2. One of each of the meters described in table A1 was immersed in tap water of 74 $\pm$ 3 F temperature for a period of 40 days and the apparent strains and weight gains were continuously recorded. At the end of the 40-day period, the resistance of the meters to ground was checked, and all meters were taken out of the water and exposed to air of 74 $\pm$ 3 F temperature and 50 $\pm$ 10% relative humidity. Apparent strains as well as

weight measurements were then continued for another 40 days. The results of this test series are shown in fig. A2.

Sand-embedment and subsequent immersion test

3. Another meter of each type was first embedded in dry, loose, quartzite sand of 75 ± 4 F and apparent strains were recorded for the 40-day period, whereupon the sand containers were filled with tap water and the ground resistance of the meters was checked. Strain readings were then taken for another 40 days. Fig. A3 shows the results of this series. Two compensating gages cemented to a small steel plate embedded in dry sand, and an SR-4 strain indicator were used for all tests. Reverse readings taken to check the stability of the measuring circuit were well within about 20 microstrains over the total test period.

Discussion of Test Results

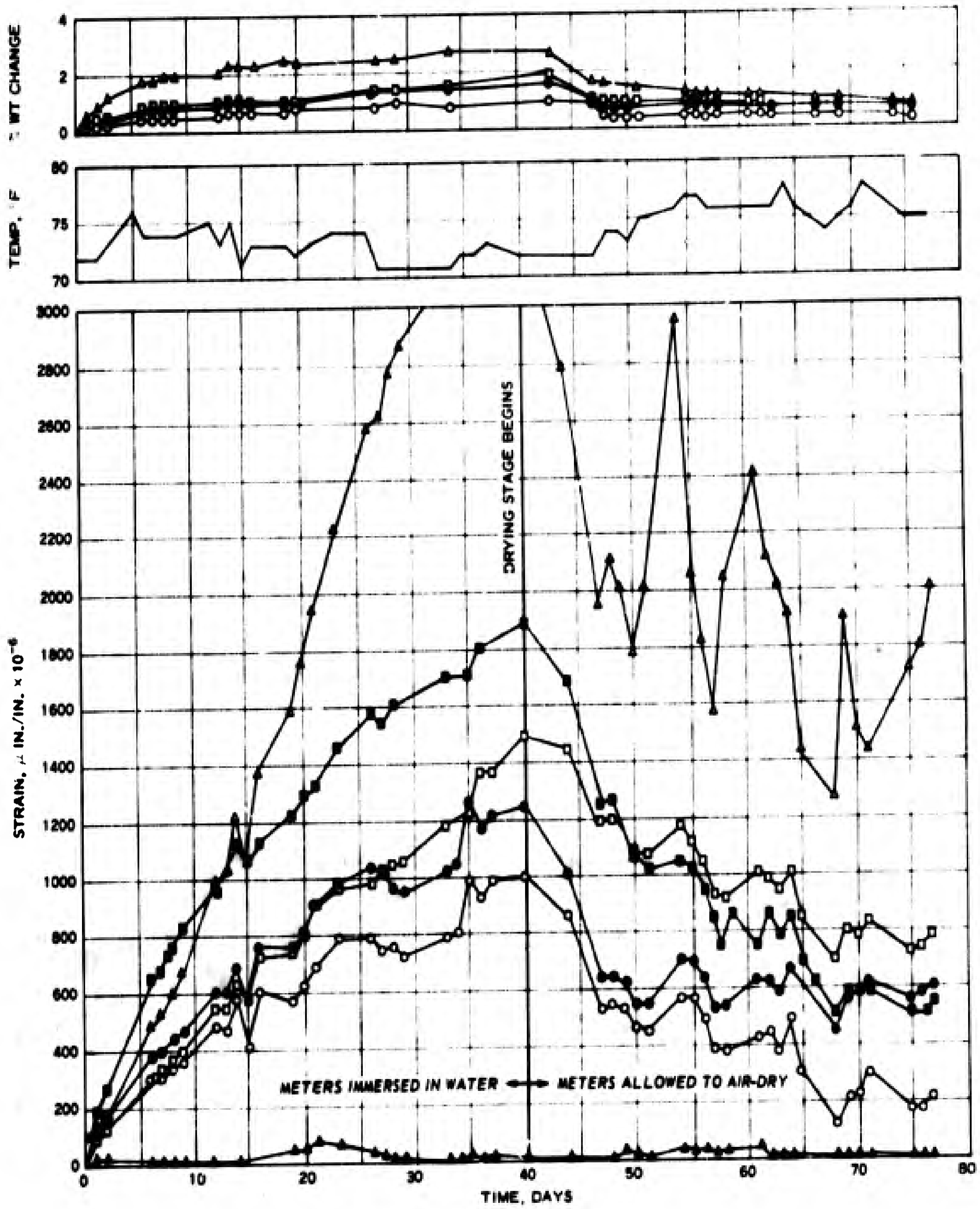
Water-immersion and drying test

4. Fig A2 shows that all plastic-encapsulated meters developed very high apparent tensile strains when immersed in water, exceeding 1000 microstrains within a test period of 14 to 40 days. The rapid growth of apparent strains was accompanied by a continuous weight gain, the magnitude of water absorption being proportional to the apparent strain, i.e. meters with the highest water absorption also showed the greatest drift. Due to the repeated loss of sand grains from its sand-coated surface, the absorption curve for the polyester mold meter was considered erratic and is not shown in fig. A2.

5. After the meters were immersed in water for 40 days, the resistance to ground was checked and found in excess of 20 MΩ for all meters. During subsequent storage in air, the meters gradually lost weight, accompanied by a sharp decrease of apparent strains.

Sand-embedment and subsequent immersion test

6. All meters showed apparent tensile strains in excess of 100 microstrains during the 40-day embedment in dry sand, and it is believed



LEGEND

- ○ EPON 815
- □ 3M EPOXY
- ▲ SIKA
- ● STEELKOTE
- ■ JAPANESE METER
- ▲ VALORE METER

Fig. A2. Results of water-immersion and drying test

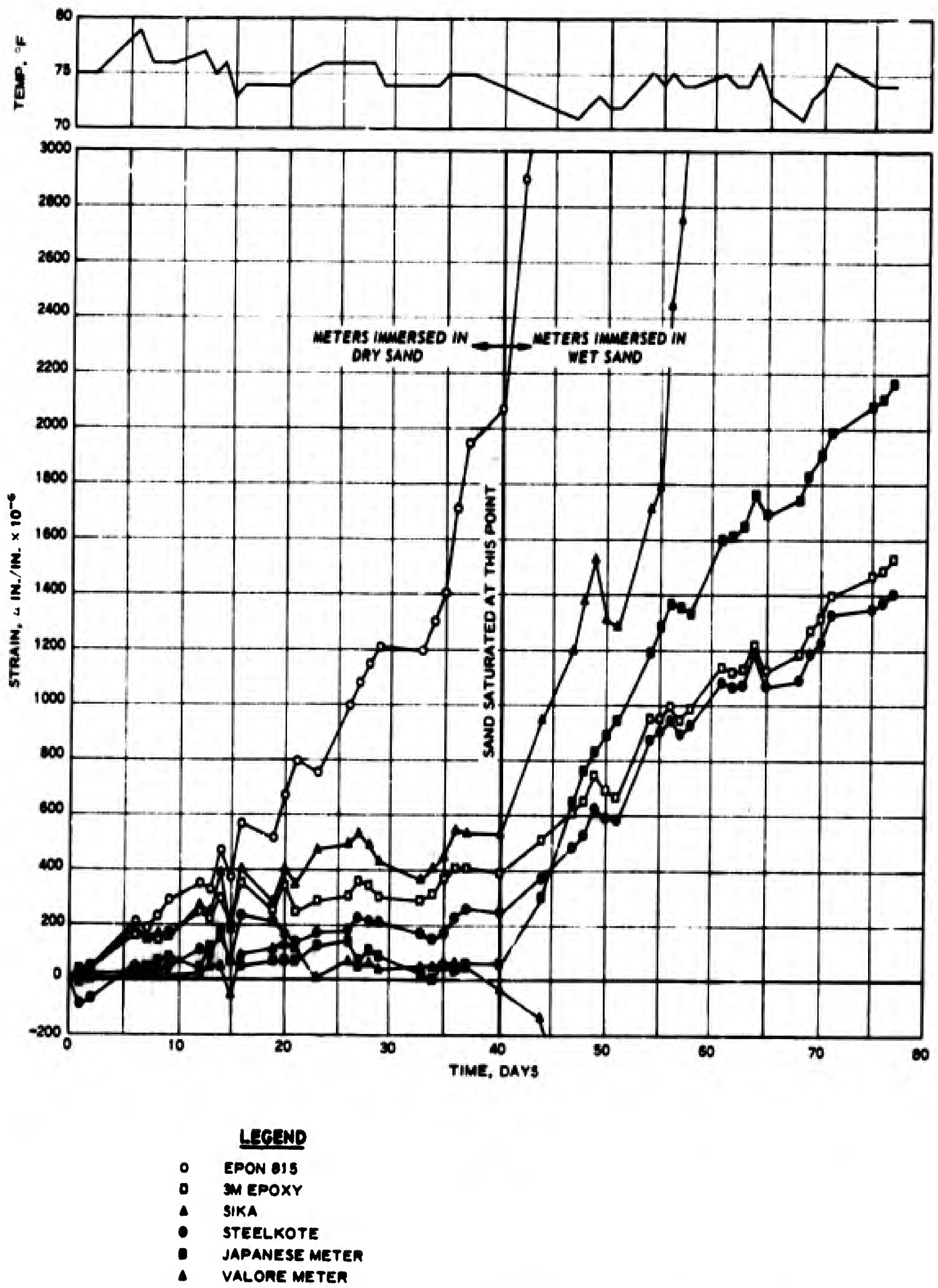


Fig. A3. Results of sand-embedment and immersion test that part of these apparent strains was caused by temperature differences between the active and the compensating gage. However, all the self-made plastic-encapsulated meters (which had been cured at room temperature for 4 to 10 days) had a clear upward-drifting tendency. The Epon 815 encapsulated meter exhibited a puzzling drift of more than 2000 microstrains in 40 days, compared to less than about 500 for the other meters. Following the addition of water to the sand, all plastic-encapsulated meters experienced a sharp increase in apparent strains. In fact, the Epon 815 encapsulated meter swelled so drastically that it finally ruptured the resistance wire after 10 days of immersion. The resistance to ground of all plastic-encapsulated meters, including the Epon meter, at that point was better than 20 MΩ. The Valore meter, however, rapidly lost resistance to ground after immersion in water, apparently due to defective waterproofing, so that the measurements on this meter had to be discontinued.

Conclusions

7. From the two brief preliminary test series, it is concluded that plastic encapsulating materials absorb water and, in the process, undergo volume changes which cause large apparent strains. The conclusion that genuine swelling rather than a shunting effect causes the apparent strain is supported by:

   a. The high resistance to ground that all meters exhibited after 40 days immersion in water.

   b. The fact that one resistance wire within the meter actually broke, an effect that can only be explained by drastic swelling of the plastic capsule.

Table A1

Bonded Wire Meters Tested

Type of Meter	Overall Dimensions	Wire Gage Used	Gage Factor	Resistance ohms	Remarks
BHL concrete embedment gage Valore brass envelope	3x3/8x0.01 in.	SR 4-AS-9	2.1	300	--
Tokyo Sokki Kenkyujo polyester mold gage PML-60	125x13x5 mm	--	2.2	120	--
SR-4 gage encapsulated in shell epoxy Epon 815	7.4x0.7x0.25 in.	SR 4-A-9-6 (BLH)	2.12	300	1 part resin, 0.6 parts catalyst* (DMP system)
SR-4 gage encapsulated in SIKA epoxy (colmadur bonding compound)	7.4x0.7x0.25 in.	SR 4-A-9-6 (BLH)	2.12	300	1 part low viscosity resin (polysulfide), 1 part catalyst*
SR-4 gage encapsulated in 3M epoxy	7.4x0.6x0.15 in.	SR 4-A-9-6	2.12	300	1 part resin EC 1838 B, 1 part catalyst* EC 1838 A
SR-4 gage encapsulated in Steelkote epoxy (Corps of Engineer binder type II)	7.4x0.7x0.25 in.	SR 4-A-9-6	2.12	300	Epoxy I = 10 parts Epoxy II = 5 parts Catalyst DMP 10 = 1 part Catalyst DMP 30 = 1 part

* All meters were allowed to cure at least 3-7 days at room temperature before testing.
BHL--Baldwin-Lima-Hamilton. DMP--Dimethyl Phthalate.

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) U. S. Army Engineer Waterways Experiment Station Vicksburg, Mississippi	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE
STRAIN METERS AND STRESS METERS FOR EMBEDMENT IN MODELS OF MASS CONCRETE STRUCTURES; Report 1, SUMMARY OF INFORMATION AVAILABLE AS OF MARCH 1967

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Report 1 of a series

5. AUTHOR(S) (First name, middle initial, last name)
Helmut G. Geymayer

6. REPORT DATE January 1968	7a. TOTAL NO. OF PAGES 79	7b. NO. OF REFS 71
8a. CONTRACT OR GRANT NO. b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Report No. 6-811 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	

10. DISTRIBUTION STATEMENT
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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Office, Chief of Engineers U. S. Army, Washington, D. C.

13. ABSTRACT This report summarizes the results of an extensive literature review and a worldwide survey to develop information on small, embedded stress meters and strain meters suitable for model work and long-term investigations. Following a discussion of general problems of internal strain and stress measurement in concrete, including a brief review of the advantages and disadvantages of various systems of measurement, numerous particular meters are described in detail, and their applicability to model work is tentatively assessed. Although this report is primarily concerned with internal strain meters, some of the most important stress meters will also be discussed briefly. The information collected reveals a lack of small, embedded meters suitable for long-term model studies, and indicates that in the past primarily two measuring principles were used for long term measurements in concrete; these were the unbonded wire and the acoustic meter. Neither system, however, lends itself well to construction of very small meters (less than about 2-in. maximum dimension). Many methods of utilizing bonded wire strain gages for internal measurements in concrete have been proposed. Several of these methods appear quite satisfactory in applications where drifting is not a problem, yet the long-term stability of embedded bonded wire gages remains unproved. A number of other systems of measurement (inductance-capacitance, semiconductor, hydraulic, and pneumatic meters) that appear rather promising for internal stress and strain measurement in concrete have hardly been investigated to date. Based on the results of this preliminary study, it is concluded that further efforts to select or develop suitable instrumentation for internal long-term stress and strain measurements in concrete models should concentrate on the evaluation and improvement of bonded wire meters, on the development of new inductance and semiconductor meters, and on the use of existing small acoustic meters.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Concrete--Stresses						
Concrete structures						
Engineering models						
Stress meters						
Strain gages						
Strain meters						

Unclassified
Security Classification