Characteristics and Applications of Resistance Strain Gages

U. S. Department of Commerce

National Bureau of Standards

Circular 528

UNITED STATES DEPARTMENT OF COMMERCE • Sinclair Weeks, *Secretary*
NATIONAL BUREAU OF STANDARDS • A. V. Astin, *Director*

Characteristics and Applications of Resistance Strain Gages

Proceedings of the NBS Semicentennial Symposium
on Resistance Strain Gages
Held at the NBS on November 8 and 9, 1951

National Bureau of Standards Circular 528
Issued February 15, 1954

For sale by the Superintendent of Documents, U. S. Government Printing Office
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Foreword

The Symposium on Resistance Strain Gages is one of the twelve Symposia held as part of the scientific program of the National Bureau of Standards in the year 1951, which marks the fiftieth anniversary of its establishment. The subjects of the Symposia represent phases of science and technology in which there is considerable current interest.

NBS activity on resistance strain gages began with the McCollum-Peters carbon-pile telemeter nearly thirty years ago. This was followed by a study of carbon-strip gages in 1936. Work in this field was greatly accelerated with the introduction of strain sensitive fine wires a few years later. Extensive performance tests were made on wire strain gages of different manufacture. Studies were made of applications of strain gages to the measurement of mechanical quantities, such as acceleration, impact force, and dynamic pressure, and calibrations were carried out on a multitude of instruments employing wire strain gages as the sensing element. As in other laboratories, wire strain gages were used in large quantities to determine strain distribution in structures under load. Work is in progress on strain gages consisting of a conducting coating applied by an evaporation technique, on special temperature compensated gages, on gages for strain measurements well beyond the elastic range, and on the application of strain gages to the determination of dynamic properties of materials and to the measurement of very large static forces.

The papers presented at this Symposium represent some of the latest results, both experimental and theoretical, in the study of resistance strain gages by many leading institutions in the United States and abroad.

The cooperation of the Office of Naval Research in making possible this Symposium is gratefully acknowledged.

A. V. Astin, *Director*,
National Bureau of Standards.

Contents

1. Poisson-Ratio Determinations for Elastic and Plastic Strains of Tensile Specimens

By Irwin Vigness [1] and T. E. Pardue [2]

A question exists as to the permissibility, for isotropic metals, of assigning two constant values for Poisson ratio. One value would apply for elastic components of strain, that is, the quotient of the stress and the elastic modulus, and the other value would apply to the plastic component of strain. The latter would be expected to have a value near 0.5. If this procedure is proper, then the value of Poisson's ratio can be easily calculated for any value of strain, provided the stress and the values of the two constants are known. In order to determine the validity of this assumption, circumferentially and longitudinally oriented wire strain gages were wound onto tensile specimens of a variety of materials. The results indicate that the assumptions are permissible within the accuracy of measurements. The experiments are limited to tensile stresses of magnitudes that do not involve necking of the specimens at the section studied.

Introduction

As a metal is strained through elastic into plastic states its value of Poisson-ratio changes from a value near 0.3 to a value approaching 0.5. It has been suggested by Nadai [1] [3] and others that a fixed value of Poisson's ratio be assigned for elastic strains of a given material and another fixed value be assigned for plastic strains, and that these two values be constants of the material. The variable value of Poisson's ratio determined for strains beyond the yield point is regarded as a function of these two constants and the relative amounts of elastic and plastic strain.

A value of Poisson's ratio of 0.5, which requires no change in density of the material under strain, has been assumed to be approximately true under plastic conditions. Under conditions of plastic working of a metal, some decrease in density can be measured [2], but the effects are generally not sufficiently great to cause a decrease of the plastic value of Poisson's ratio by more than a few percent. Swainger [3] has reported values of Poisson's ratio considerably less than 0.5 for plastic strains, but it is probable that the bonded-wire-type strain gages used by him did not perform properly under the large compressive strains encountered. Experiments reported at this time indicate causes of probable errors encountered.

The present experiment requires the simultaneous measurement of stress and transverse strain as a function of longitudinal strain, for tensile specimens, so that the experimental value of Poisson's ratio can be determined and compared with calculated values. Although uniaxial stresses and isotropic materials are required for this study, it is probable that the results can be generalized for other conditions by assigning proper Poisson-ratio constants for each axial direction.

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[3] Figures in brackets indicate the literature references on p 8.

Calculation of Poisson's Ratio

Stang, Greenspan, and Newman [4] have determined Poisson's ratio for a variety of structural alloys subjected to large strains. They have defined the ratio as

$$\mu = -\epsilon_t/\epsilon_l, \tag{1}$$

where ϵ_t is the total transverse strain, and ϵ_l is the total longitudinal strain caused by a stress acting in the longitudinal direction. They have considered engineering values of strain rather than true strain. Under these circumstances a material that is perfectly plastic [4] after a small amount of elastic strain will not attain a ratio value of 0.5 for plastic strains involving no density change but will approach this value for small strains following yield, after which the value will decrease assymmetrically to zero for very large strains.

It is generally more convenient for stress analysts to define Poisson's ratio as the slope of the curve of transverse strain versus longitudinal strain or as

$$\mu = -\Delta\epsilon_t/\Delta\epsilon_l. \tag{2}$$

The per unit change in volume of a tensile specimen can be shown to be approximately

$$\Delta V/V = \epsilon_l(1-2\mu), \tag{3}$$

which requires μ to be 0.5 if the density, or volume, change is to be zero.

If the strain is divided into its elastic and plastic components, with the additional subscripts e and p distinguishing these conditions, such that

$$\epsilon_l = \epsilon_{lp} + \epsilon_{le}, \tag{4}$$

and

$$\epsilon_t = \epsilon_{tp} + \epsilon_{te}, \tag{5}$$

then eq (2) becomes

$$\mu = (\mu_p \Delta\epsilon_l - \mu_p \Delta\epsilon_{le} + \mu_e \Delta\epsilon_{le})/\Delta\epsilon_l. \tag{6}$$

Assume that

$$\Delta\epsilon_{le} = \frac{\Delta\sigma}{E}. \tag{7}$$

Where σ is the stress and E is Young's modulus, then

$$\mu = \mu_p - \frac{1}{E}\frac{\Delta\sigma}{\Delta\epsilon_l}(\mu_p - \mu_e). \tag{8}$$

All the factors contained on the right-hand sides of eq (2) and (8) are obtainable from curves of stress and transverse strain versus longitudinal strain. The value of μ_p is arbitrarily assigned as 0.5. The elastic ratio, μ_e is obtained from the elastic linear region of the transverse-strain curve. Experimental values of μ_p are best obtained by straining the specimen plastically and releasing the load. The ratio of transverse to longitudinal strain under conditions of no load constitutes a plastic value and is termed the "residual value."

[4] A perfectly plastic material as here defined has a stress-strain curve that rises linearly to the yield point after which the stress remains constant as the strain increases indefinitely. The condition of plasticity, of course, exists only after that yield point.

Experimental Procedures

Tensile specimens, of a type shown in figure 1.1, were machined from round bar stock having the chemical composition and treatment indicated in table 1.1.

TABLE 1.1. *Chemical composition, heat treatment, and other history of tensile specimens*

Material	Composition										
	C	Si	Mn	P	S	Sn	Cu	Ag	Cr	Mi	Mo
Cold-drawn mild steel (fig. 1.7). %--	0.26	0.25	0.82	0.019	0.033	--	----	-----	----	----	----
Cold-drawn aluminum (fig. 1.5). %--	----	----	----	----	61	--	----	-----	----	----	----
Bronze (phosphor) grade A: 1, cold-drawn (fig. 1.4; 2, heated to 900° F for 1 hr, and furnace-cooled (fig. 1.8). %--	95.0	----	----	----	-----	5.0	----	-----	----	----	----
Copper (soft) (fig. 1.6)--%--	----	----	----	----	-----	0.1	99.9	Trace	----	----	----
Steel, heated for 1 hr at 1,550° F, oil-quenched, tempered for 4 hr at 1,250° F, and furnace-cooled (fig. 1.9). %--	0.56	.31	.72	.14	0.015	--	----	-----	0.90	1.90	0.20

Initially Baldwin SR–4 type AX–5 gages were used for measuring strain. These were two-element rosette gages, with the elements of the two gages alined at right angles to each other. The gage length of both units was ½ in. Specimens were pulled in a Baldwin Southwark 60,000-lb tensile machine, and strain measurements were made by usual bridge arrangements and galvanometers. Tuckerman gages were occasionally used to check the values of longitudinal strain.

For longitudinal tensile strains of the order of 1 percent (or compressive transverse strains less than ½ percent) consistent results were not obtainable from the transverse gage elements as determined by comparison among presumably identical tensile specimens. Figure 1.2 illustrates the cause of these inconsistencies. The strain-gage bonding material was not able to sufficiently constrain the gage wires to prevent buckling. In addition, the sharper curvature of the transverse gage wires at the ends of the gage length, as compared with the corresponding location on the longitudinal gage, is probably caused by compressive forces repositioning the wire. Examination of the gage under a binocular microscope revealed voids

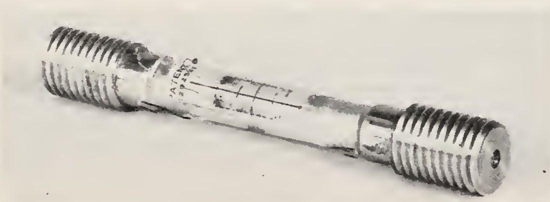

FIGURE 1.1. *Specimen with strain gages.*

The specimen has a diameter of 0.500 in. and length of 2.5 in. for the uniform active gage length.

caused by the motion of the strain-gage wire through the bonding media. Gages used in compression would be improved by using a stronger bonding cement, by using strain-gage wires of low elastic modulus, and by making the wires straighter.

In order that the compressive transverse strains be accurately measured, strain-gage wires were wound around the circumference of the specimen. Insulation was provided between the wire and the specimen, and the wire was wound under tension. The tensile

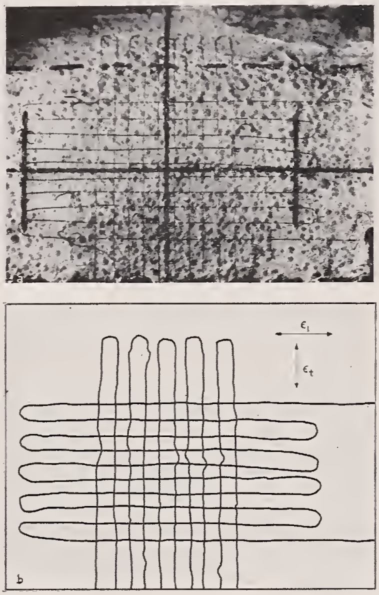

FIGURE 1.2. *Gage wires after about 1-percent longitudinal tensile strain and ½-percent transverse compressive strain.*

Part b is a tracing of the gage wires photographed in part a.

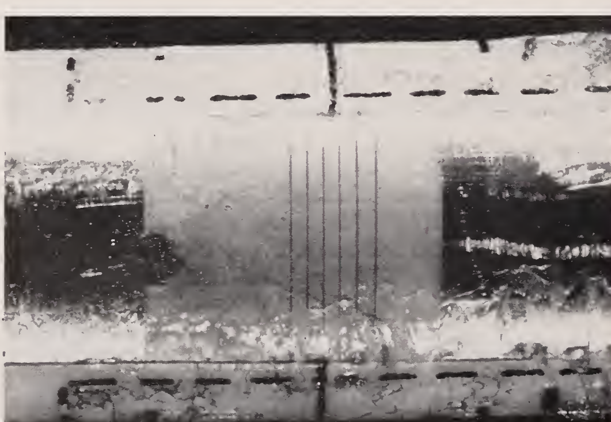

FIGURE 1.3. *Central section of test specimen with enlarged view of a part of the transverse gage.*

This gage disappears under the longitudinal gages at the upper and lower parts of the figure. The protective felt has been removed from the gages with a few fibers remaining in the cement.

stress in the gage wire not only allowed greater specimen transverse strains to be measured before failure of the bond between the gage wire and cement occured, but caused the gage wire to be perfectly straight in its windings. Advance wire was used for these gages. The gage width was ⅛ in., resistance 250 ohms, and the gage factor was determined as 2.06 by measurements of its resistance change as a function of strain. The method used for this measurement was similar to that previously described by Kammer and Pardue [5]. Baldwin SR–4 strain gages, type A–5, were attached and centered over the circumferential gages. Two such gages were used on each specimen. They were placed on opposite sides of the specimen and connected in a bridge circuit so as to cancel all bending strains. Figures 1.1 and 1.3 illustrate the gages on a specimen. With gages attached in this manner, consistent results were obtained for the transverse strains.

Results

The results of these experiments are graphically presented in figures 1.4 to 1.9. The curves for the stress and transverse strain are plotted as a function of the common longitudinal strain. The curve for Poisson's ratio, μ, was obtained by two methods: the first, represented by open circles, was determined from eq (2) or the slope of the transverse strain curve; and the second, represented by filled circles, was calculated by means of eq (8). It was generally found to be more accurate to use the differences in the original numerical values of transverse strain to determine Poisson's ratio by the first method, rather than to determine the slope of the curve, as the points were more accurate than the reading of the curve position. An exception to this is in the initial linear elastic region, where the slope was determined from the plotted line; generally no points are shown for the Poisson's ratio curve over this region. Figures 1.4 to 1.6 for cold-drawn bronze, aluminum, and for soft copper, respectively, indicate a transition of the value of Poisson's ratio from its elastic value to the

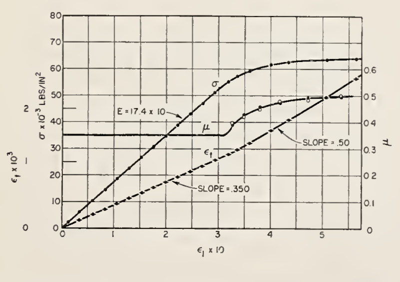

FIGURE 1.4. *Stress, transverse strain' and Poisson's ratio versus longitudinal strain for a cold-worked bronze specimen.*

The open and solid circles on the Poisson ratio curve represented the values of the ratio of $\Delta\epsilon_t/\Delta\epsilon_l$ and the values as determined from equation (8), respectively. μ_p residual is 0.501±0.005.

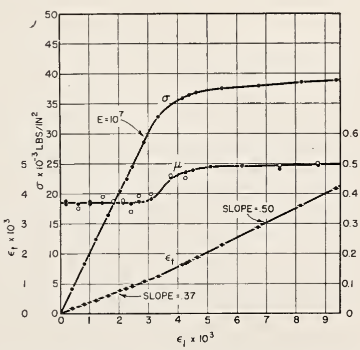

FIGURE 1.5. *Stress, transverse strain, and Poisson's ratio versus longitudinal strain for a cold-worked aluminum specimen.*

The open and solid circles on the Poisson ratio curve represented the values of the ratio of $\Delta\epsilon_t/\Delta\epsilon_l$ and the values as determined from equation (8), respectively. μ_p residual is 0.505±0.005.

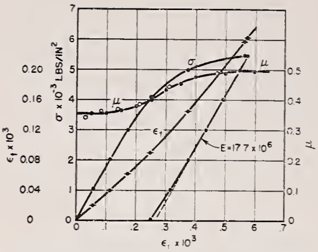

Figure 1.6. *Stress, transverse strain, and Poisson's ratio versus longitudinal strain for a soft copper specimen.*

The open and solid circles on the Poisson ratio curve represented the values of the ratio of $\Delta\epsilon_t/\Delta\epsilon_l$ and the values as determined from equation (8), respectively. μ_p residual is 0.498±0.005.

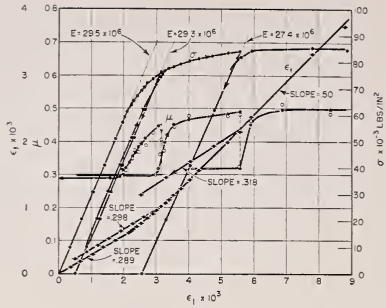

Figure 1.7. *Simultaneous readings of stress, transverse strain, and Poisson's ratio, for several stress cycles for a cold-worked mild-steel specimen.*

Residual is 0.477±0.005.

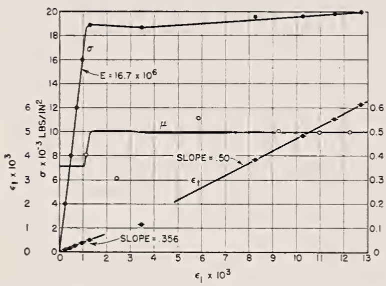

Figure 1.8. *Heat-treated bronze specimen with a slight drop in load after initial yield.*

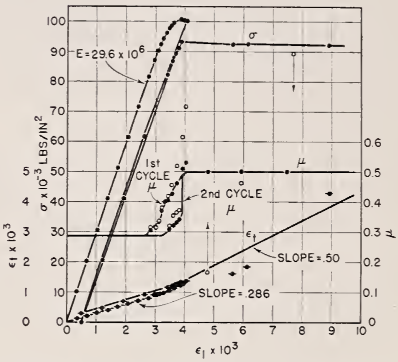

Figure 1.9. *Heat-treated steel with a pronounced drop in load after yielding.*

plastic value of 0.5. There were no significant differences between the measured values as determined from eq (2) and the values calculated from eq (8). Figure 1.7 represents a cold-drawn sample of mild steel that has been subjected to several cycles of strain involving plastic deformations. In this case there is an appreciable decrease in the elastic modulus, as the amount of plastic strain is increased, and there is a slight increase in the elastic value of Poisson's ratio. It appears, however, that the value of the ratio changes percentagewise by about the same magnitude as the elastic modulus and that either may properly be called a constant of the material.

A purely plastic value of Poisson's ratio is placed in the caption of each figure 1.4 to 1.7 for the metal concerned. This plastic value was obtained by stressing the material beyond the yield point, removing the load, and determining the ratio of transverse to longitudinal strain under conditions of no load. These values are equal to 0.50 within the limits of accuracy of the experiment.

Materials with a pronounced yield point, or a drop-in-load characteristic, do not behave in a suitable manner over the strain region involving the falling load to allow Poisson's-ratio determinations. It has been shown by Warnock and Taylor [6] and Miklowitz [7] that the strain is nonuniform over the length of a tensile specimen during initial plastic deformations. In particular, this is true for materials exhibiting a drop-in-load characteristic, or possessing a long plateau in the stress-strain curve following yield. After the stress-strain curve resumes a rising characteristic the strain again becomes reasonably uniform along the length of the specimen. The strain remains uniform along the length until the maximum load is reached. In the present types of measurements, as the width and specimen coverage of the transverse gage was different from that of the longitudinal gage, it was possible to get quite unrelated strain measurements in the case of nonuniform straining. The great spread in the experimental points, for the transverse strain and the Poisson-ratio curves in figures 1.8 and 1.9 in the region following yield, is due to nonuniform straining of the specimen. For the heat-treated bronze specimen, figure 1.8, the strain quickly becomes uniform, as is indicated by the linear transverse-strain curve of slope 0.50 for longitudinal strains in the order of 1 percent. However, for the heat-treated steel specimen of figure 1.9, the slope of the transverse-strain curve was made equal to 0.5 for the plastic area without consideration of the scattered points. The value of Poisson's ratio as calculated from the slope of the stress curve, that is, from eq [8], is represented by the curve for μ in figure 1.8, with the points omitted. Equation [8] breaks down as the slope of the stress-strain curve becomes negative. However, for small values of this slope as compared to the value of the elastic modulus, it is permissible to use its absolute value.

Conclusions

The following generalizations are indicated from the experiments performed:

1. For isotropic materials a Poisson's ratio for elastic strains exists as a fundamental constant for the material.

2. A Poisson's ratio for purely plastic strains has a value very nearly equal to 0.50 (a condition for no change in density) for loads less than the ultimate supportable by the material.

3. The actual value of Poisson's ratio for any value of strain may be calculated from a knowledge of the above elastic and plastic ratio constants and the relative amounts of elastic and plastic strain.

4. It was incidentally indicated that for strains, in the order of ½ percent or greater the compressive strains, as determined by means of bonded-wire strain gages, are generally lower than the correct value.

It is probable that the first three conclusions could be further generalized for nonisotropic materials by the assignment of proper values of elastic ratio constants to each of the coordinate directions.

A paper by Gerard and Wildhorn [8] describing a study of Poisson's ratio in the yield region of several aluminum alloys has belatedly been brought to the attention of the authors. Although their experimental evidence is somewhat doubtful because of the scatter of points, they conclude that the value of the ratio can be calculated from an elastic and a plastic value.

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Discussion

Prof. George Gerard, New York University, New York, N. Y.: We have worked on this same problem, and our results are contained in NACA TN 2561, "A Study of Poisson's Ratio in the Yield Region," by G. Gerard and S. Wildhorn. The results we obtained were on aluminum-alloy specimens loaded along three orthogonal axes in both tension and compression. In most cases, the value of the plastic Poisson's ratio was not 0.5. Although this result may possibly be due to buckling of the strain gages, I do not think this factor is responsible because we tested our specimens both in compression and tension, and the results in compression were quite consistent with those obtained in tension. Therefore, I think there is some question as to the effects caused by buckling of the gage.

We attributed the fact that the values of the plastic Poisson's ratio was other than one-half to the anisotropy of our specimens, which were cut from rolled and extruded bars. Since isotropy is apparently of considerable influence, the question I would like to raise is, how sure are you in the case of the specimens you tested that the material was isotropic?

Dr. Vigness: Not entirely certain. The only assumptions that we would make in that respect, or the only justification for the assumptions, would be that we used specimens not cut from plates or from square bars but from material drawn through circular dies, and we could see no reason for any dissymetry perpendicular to the axis—which was our only concern. However, we have not made any tests to check that.

I realize that if you get nonisotropic materials, the Poisson's ratio will be practically anything. I would not be able to justify the statements that these materials were perfectly isotropic, because I do not know beyond the fact that we selected the specimens in the above-mentioned manner.

Mr. R. G. Boiten, National Council for Industrial Research, Delft, Holland: In the first place, I can remark that the same kind of experiments have been carried out in our laboratory. Later, some students working at the university in Delft under the supervision of Prof. Koch tried to verify the statements of Dr. H. Brandenberger, and from experiments performed in the same way as you did, they got similar results, the value of μ_D proved to be exactly one-half.

The buckling of the wires of the grid is quite interesting. When we started manufacturing strain gages, the first ones had grids of very poor quality. Besides that, the variations in the gage factor were something like ±3 percent, and that was not so good either. It was then suggested that there might be some definite connection between the shape of the grid and the actual gage factor, which we determined by test. We made radiographs of the grid, enlarged them, and studied the pictures in various ways, trying to predict the gage factor from the geometrical shape of the grid. We found that there were gages with poorly shaped grids that gave fine test results and there were gages with fine grids that showed much larger deviations than the bad ones, so I believe that at this moment there are far more factors influencing the behavior of the strain gage than the shape of the grid alone.

Dr. Eugene E. Lundquist, National Advisory Committee for Aeronautics, Langley Field, Va.: The speaker stated that he wrapped the transverse wire strain gage around the specimen. He also stated that he attempted to have an isotropic material. If by chance the material were not isotropic, I would expect that Poisson's ratio would be different in the two transverse directions. Yet measuring the transverse strains with a wrap-around type of gage would give an average of the Poisson's ratio for the nonisotropic material. This method of measuring strains with a wrap-around gage is, therefore, limited only to isotropic material.

Mr. Pardue: While it was considered that the materials were isotropic in the cross-sectional plane, the wrap-around gage would give an average value of Poisson's ratio which should be 0.5 for no volume change.

Dr. Lundquist: I do not question the fact that your material was isotropic. Materials that engineers use, however, are probably more frequently nonisotropic than isotropic. Take rolled plate, for example. For nonisotropic material the wrap-around gage would give some average of the properties that apply to such material.

Prof. Joseph Marin, Pennsylvania State College, State College, Pa.: I was wondering whether for some materials the value of Poisson's ratio would be influenced by strain rate and creep?

Dr. Vigness: I do not believe that it would, inasmuch as creep would be a plastic phenomena. If you would get into strain rate where you might increase the yield point, you would merely have a greater amount of elastic strain, but you could still divide these two into elastic and plastic components. These two components might be differently proportioned if one applied the load at different rates when observing creep phenomena.

2. Cementing and Waterproofing of Resistance Strain Gages

By R. G. Boiten [1]

The cementing of strain gages in the normal way is discussed with remarks on heating and drying under difficult outdoor conditions. Techniques for waterproofing gages with molten wax, special plastic covers, and rubber bags are described. For special purposes, the use of gages cemented beforehand on thin steel or brass sheets, which are soldered to the structure by means of soft solder, are discussed. A number of practical measurements, including measurements under sea water, inside pressure vessels, on concrete structures, etc. are mentioned.

Introduction

In continental Europe, the electric-resistance strain gages began to be used shortly after the end of World War II, but in the United States the strain gage was already a common device, commercially available, and with an established working technique. So when the first strain gages became available in Europe, it seemed a good practice to start with the working methods described in the American literature. However, after a rather successful start, many difficulties arose, and at Delft a few years were spent in a broad research program to study the behavior and properties of the strain gages. It was soon realized that the techniques used in the United States were not generally suitable for the climatic conditions in the Netherlands. Therefore, techniques had to be modified and new solutions found. Some of our results are described. Most of them were obtained in the laboratory of the TNO Organization, Panel for Experimental and Theoretical Stress and Vibration Analysis.

Cementing of Strain Gages

Basically, a strain gage consists of a length of fine resistance alloy wire, laid in a zigzag fashion on a thin paper base and secured to this base by means of a cement layer. For measuring strains, this combination is glued to the surface of the object under investigation, the strain causing an elongation of the wire, resulting in a resistance change of the gage, which can be measured.

The cement is very important and has to fulfill a number of requirements, such as (1) it must have good mechanical properties, including high strength, and little or no cold flow, which would result in hysteresis and zero drift, (2) the cement must have good dimensional stability, (3) it must possess good electrical properties, namely, a high resistivity and a low power factor, (4) the cement must adhere

[1] Chief Engineer, Panel for Experimental and Theoretical Stress and Vibration Analysis, National Council for Industrial Research, Delft, Holland.

firmly to the surface of the test object, (5) it must retain its mechanical properties over a wide temperature range, (6) the cement must have a good chemical resistance and a low water adsorption. Small quantities of moisture in the cement are detrimental, because (a) the electrical and mechanical properties of the cement decrease rapidly with increasing moisture content, (b) the swelling of the cement due to the penetration of moisture causes deformation of the filament grid and consequently a relatively large zero drift. The decrease of the resistivity often has a much smaller effect on the zero point, and (c) metallic surfaces under the cement may start oxidizing. The result is that the bond between cement and metal is destroyed and the strain gage with its cement comes off easily, (7) the application of the cement should be as easy and simple as possible.

At this moment, there is no cement available that satisfies all the above requirements. In common use are two types of cements, a solution of thermoplastics and a mixture of thermosetting resins. For special purposes (high temperature) inorganic ceramic cements are sometimes applied. In table 2.1 a number of plastics, used as adhesives, are presented with a comparison of some of their properties [1, 2, 3].[2]

Phenolic resins have, generally speaking, good properties. Their disadvantage lies in the fact that they require a baking cycle for curing. Therefore, a thermoplastic solution is more appropriate for general stress-analysis work. All the plastics mentioned in table 2.1 were tried, and their behavior was tested. The cements were prepared according to well-known formulas [4]. They have the following general composition: (a) Plastic, (b) resin, (c) solvent, and (d) plasticizer. The resin (damar, Santolite MHP, Gelva) is needed to improve the mechanical properties, and the plasticizer (camphor, dibutylphtalate, tricresyl phosphate, etc.) to prevent cracking or brittleness of the cement layer.

All the cements were tried on strain gages. The most important result was that as the bonding between the gage and the metal decreased, the electrical and moisture-resistant properties increased. It is known that there are plastics with strong polar groups and with feeble polar groups. Metals are polar, and it has been shown that strong bonds to polar surfaces can only be made with polar adhesives [5, 6]. From table 2.1 it follows that cellulose nitrate has the largest dipole moment, whereas polystyrene and polyethylene have no dipole moment at all. As water is also polar, it becomes evident that adhesives that give strong bonds to metallic surfaces necessarily must adsorb water, and vice versa. For that reason, the bond with cellulose adhesives is excellent, and, therefore, they are used nearly exclusively. The manufacturers of strain gages provide or recommend a specific cement, the same as that used in the fabrication of the strain gage. Various comparative tests have indicated that there is not much difference between the various makes and their recommended cement, which should be used whenever possible. In the United States (Baldwin), nitrocellulose seems to be preferred, whereas in Europe (Philips) ethyl cellulose is employed. In using a suitable cement, other factors influence the ultimate quality of the bond [7].

Smoothness of surface. A perfectly smooth surface is undesirable. The bonding force is proportional to the real surface area, which may

[2] Figures in brackets indicate the literature references on p. 29.

Table 2.1.

	Modulus of elasticity	Tensile strength [a]	Cold flow	Heat distortion point	Resistivity [a]	Power factor [a], 1,000 cycles	Dielectric constant [a], 1,000 cycles
	kg/cm^2 [a]	*kg/cm*^{2}		° *C*	*Ohm/cm*		
Phenolic resin [b]	40 to 80×10^3	500 to 570	Small	120	5 to 12×10^{11}	0.03 to 0.08	4.5 to 6.0
Araldite [b]	30 to 35×10^3	650 to 800	do	120	10^{10} to 10^{17}	0.08	3.6
Cellulose nitrate	15 to 30×10^3	350 to 500	Large	60 to 80	10 to 15×10^{10}	0.08 to 0.11	6.0
Cellulose acetate	12 to 20×10^3	360 to 520	do	55 to 80	10^{10} to 10^{12}	0.01 to 0.06	3.5 to 7.0
Ethyl cellulose	15 to 35×10^3	200 to 560	Fair	70 to 100	10^{11} to 10^{12}	0.008 to 0.015	3.0 to 3.8
Polyvinyl acetate	20 to 30×10^3	±500	do	90 to 100	----------	0.008 to 0.010	3.0 to 3.2
Polyvinyl chloride acetate	25 to 35×10^3	300 to 500	do	70	10^{14} to 10^{15}	0.01 to 0.12	----------
Polystyrene	12 to 35×10^3	200 to 550	Small	90 to 105	10^{17} to 10^{19}	1 to 3×10^{-4}	2.5 to 2.7
Polyethylene	800 to 1,000	100 to 200	Fair	65 to 70	10^{10} to 10^{17}	3×10^{-4}	2.25 to 2.3

	Dimensional stability [a]	Dipole moment	Water absorption (24 hr)	Chemical resistance	
				Resistant	Nonresistant
		Debye unit	*Percent*		
Phenolic resin [b]	Excellent	1.56	0.5 to 0.8	Weak alkalies and acids, organic solvents.	Strong alkalies and acids.
Araldite [b]	do	--------	0.1 to 0.15		
Cellulose nitrate	Fair	3.9	1.5 to 3.0	Water, hydrocarbons, dilute acids, and alkalies.	Ketones, esters, lower alcohols, strong alkalies.
Cellulose acetate	do	2.8	2.2 to 4.0		
Ethyl cellulose	Good	1.56	1.2 to 1.8		
Polyvinyl acetate	Fair	2.8	2.0	Water, dilute acids, and alkalies	Organic solvents.
Polyvinyl chloride acetate	do	--------	0.15		
Polystyrene	Excellent	0	0.05	Water, acids, alkalies, salts	Do.
Polyethylene	Poor	0	0.01 to 0.03	Water, acids, alkalies	Boiling solvents, as benzene, toluene.

[a] These properties are tested at room temperature.
[b] Thermosetting; the others are thermoplastic.

be considerably larger than the apparent surface area if the latter has a three-dimensional shape due to fine cracks, scratches, pores, etc.

Homogeneousness of cement layer. Calculations made after a test have sometimes shown that the breaking strength of a cement layer was actually less than the value that could be expected from the tensile strength of the basic solid plastic. This proved particularly true for thick cement layers deposited from a cement solution. The explanation lies in the fact that the evaporation of the solvents may cause gas bubbles and voids if the diffusion velocity of the solvents in the plastic is too small. The volatility of the solvents, as well as the thickness of the layer, is important. The bubbles and voids decrease the strength of the cement material, and a good bond should, on macroscopic or microscopic examination, show no irregularities.

Removal of remnants of solvents and moisture. Traces of solvents and moisture diminish the strength of the bond and increase the cold flow. The removal of these traces is often very difficult and may require a long time at room temperature, or may only be possible at some elevated temperature.

In considering the requirements for a suitable cement, the following remarks may be made with respect to the cellulose adhesives referred to: (1) When perfectly dry, the mechanical properties are fair. (2) The dimensional stability is poor without special treatments. The cement layer must be kept in the same (if possible, perfectly dry) state with regard to moisture content. Although the plasticizers have a low vapor pressure, some of it will evaporate in time. Either this must be prevented by sealing off the layer, or the cement layer must be kept for several hours at a temperature near to the heat-distortion point to drive out as much plasticizer as possible, so that the loss of plasticizer, which would have taken months or years at room temperature, is forced to occur immediately. (3) When perfectly dry, the electrical properties are adequate. (4) The adherence to metal surfaces is excellent. (5) The temperature range is limited to temperatures of about 40° to 50° C. (6) The chemical resistance is fair (not for organic solvents). The water adsorption is great. (7) The application is sufficiently easy.

Phenolic resins have a wider temperature range and greater mechanical stability. Their curing cycle is somewhat difficult, due to the fact that on polymerization, water is liberated. Therefore, the temperature must rise in gradually increasing steps to prevent the formation of voids resulting from trapped vapor bubbles. The curing takes a relatively long time. Less difficult in treatment and equally good are the Araldite cements (Ciba, Basel) [8]. They produce no volatile components during baking, and therefore, they may be cured in an hour's time without any risk of bubble formation. There are Araldite mixtures under development now that cure at room temperature. Their mechanical properties are still inadequate. A cold-setting Araldite type of cement with the properties of a heat-setting phenolic cement probably would be the solution for general stress-analysis work with strain gages.

In using strain gages, it is necessary to decide what accuracy and stability is actually needed. For measuring instruments, dynamometers, weighing cells, etc., the requirements are very high and can only be met at the cost of much time and labor. Most problems in experimental stress analysis, however, do not need such an elaborate treatment.

The strain gages are attached in accordance with the established instructions of the manufacturers [9]. Briefly, the various steps are [10]: (1) Cleaning the surface at the measuring point by scraping and the use of suitable solvents (fig. 2.1). (2) Application of a thin precoat of cement on the surface of the test object over an area somewhat larger than the strain gage itself. This layer must dry at least 15 min, depending on the ambient temperature. It is to be noted that the evaporation of the solvents causes a temperature drop of the cement layer. Some water vapor may condense on the cement, especially when the relative humidity of the air is high. This can be noted from a milky-white clouding of the cement, which should otherwise remain quite transparant. A white-cement layer is definitely spoiled and should be renewed. The remedy is simple and consists in a preheating of the measuring area up to about 25° C (drying lamp or electric hair drier). (3) Application of a thin coat of cement to the underside of the gage (fig. 2.2). (4) Placing the gage at the desired location. (5) Drying the gage 1 hr under pressure (fig. 2.3) by using weights or special devices (fig. 2.4). (6) Checking the resistance of the strain gage (maximum allowable difference with the statement of the manufacturer ±1 percent) and the insulation resistance (at least 10,000 ohm) (fig. 2.5).

Figure 2.1. *Cleaning of the surface before the application of a strain gage.*

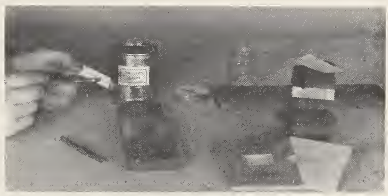

Figure 2.2. *Application of a thin coating of cement to the underside of the gage.*

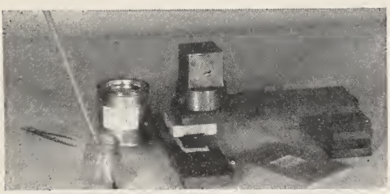

Figure 2.3. *Drying of the gage under pressure.*

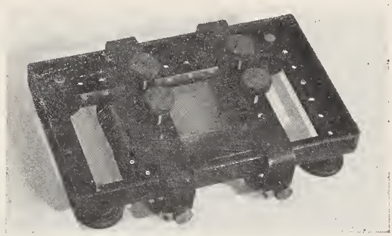

Figure 2.4. *Clamping device with four rubber suction caps for use on vertical planes, etc.*

Figure 2.5. *Checking the resistance of the strain gage.*

Drying of Gages

This can be performed in several ways.

(1) Air drying at room temperature. Except in very hot and dry weather, the last remnants of moisture and solvents will not be removed. The drying time may be 1 to 3 days, depending on the ambient temperature and the thickness of the gage. The stability of gages treated in this way is rather poor and only sufficient for tests of very short duration. It has been found that with an ambient temperature near or below the freezing point, the gages will never become dry.

(2) After a short drying period (exposure to air 6 to 24 hr), the gages are force dried.

(a) The gages are connected to a low-voltage power source (battery or a low-voltage transformer). A current is sent through the gages, increasing in the following way: For 24 hr, a current equivalent to the measuring current prescribed by the manufacturer is sent through the strain gages. Then the voltage across the strain gages is doubled, so that four times as much heat is generated in the gages. This can be continued for 48 hr. If possible, the voltage is doubled again so that the heat generated in the gages is 16 times greater than that under normal working conditions (24 to 48 hr). Not all types of gages can stand this and in this case three times the measuring current or less must suffice. For most applications the gages are sufficiently dry after this treatment.

(b) The gages are dried in an artificial atmosphere. This can be done by keeping them in an airtight box, in which are enclosed some adsorptive chemicals. The most suitable reagent has proved to be perfectly dry silica gel, as it adsorbs readily both moisture and remnants of solvents. Even at room temperature a remarkable state of dryness can be obtained (see Appendix I).

(c) The gages are dried by means of artificial heating. This can be done by radiant heating (drying lamp or equivalent). A recommended procedure is as follows: 24 hr of drying at a temperature of between 30° and 40° C, followed by another period of 24 hr between 50° and 60° C.

The highest stability is needed in measuring instruments. With instruments, all the time periods mentioned above are doubled or tripled, and the final heating takes 24 hr at 85° C. This last treatment serves to stabilize the cement, to relieve the internal stresses developed in the cement during the evaporation of the solvents (shrinkage), and to age the resistance wire. During the drawing of the wire, an appreciable amount of residual stresses are developed in the wire. These stresses diminish automatically as time goes on, accompanied however with changes in the resistance. This process can be shortened notably by giving the wire a suitable heat treatment for at least 24 hr, the temperature being 120° to 140° C with manganin 80° to 100° C with constantan (advance) [11]. Strain gages with thermosetting cements receive this treatment automatically, and for this reason they are often considered as being better for applications in instruments; the experience of the TNO Laboratories, however, shows that the properties and stability of the gages, cemented with cellulose cements, can be equally good when treated as mentioned above. Often, the optimum results are obtained by a combination of all the methods mentioned.

Waterproofing of Gages

As it is impossible to employ moisture-proof cements, the dry gages have to be protected against atmospheric conditions. There exist several practical methods.

Protection of gages with grease, wax, or plastic. The easiest way is to use the "cold" method. A pastelike material is smeared over the surface of the gage and the surrounding area. The materials in common use are:

VASELINE.—It is easy to work with, but gives only very limited protection.

SILICONE-GREASE.—This looks very similar to Vaseline, but has a better resistance against temperature variations. The protection is good (water-repellent), but when submerged in water this property diminishes rather quickly. The price is very high.

DI-JELL.—A soft mixture of microcrystalline waxes. It adheres well to cold surfaces.

Application of molten materials.

MICROCRYSTALLINE WAXES.—These materials are available in a number of compositions, for example, Petrosene wax and Cerese wax (Baldwin). The waxes have melting points between 50° and 90° C. They adhere satisfactorily to the metal surface if the latter has a temperature of at least 50° to 70° C while applying the wax. They must be cooled rather slowly (fig. 2.6). According to W. R. Campbell, it has been found that the wax is really improved by admixing 0.1 to 0.5 percent by volume of aluminum powder consisting of small flakes. These form a kind of overlapping pattern in the wax. This mixture has proved its value, particularly with outdoor measurements.

BEE'S WAX, CERESINE, ETC.—These materials must be applied in the same way as the microcrystalline waxes; their properties are inferior.

PITCH COMPOUNDS.—The properties are generally good. However, they usually result in a messy job.

RUBBER COATINGS.—Their application is rather laborious, but their protection is very good.

PLASTIC COVERS.—A suitable and simple protection can be built up from sheets of guttapercha paper. This paper consists of very pure guttapercha with a thickness of about 0.1 mm. At a temperature of about 55° C it becomes tacky and then adheres perfectly to metal

FIGURE 2.6. *Covering a strain gage with molten wax.*

FIGURE 2.7. *Protection with guttapercha paper.*

First piece put into place.

and other surfaces. Furthermore, it is very pliable and can be shaped in any desired form. A good technique is the following: First, five rectangular pieces of guttapercha are cut with increasing dimensions so that the smallest piece is somewhat larger than the area of the strain gage (fig. 2.7). This piece is pressed over the gage, the electrodes penetrating through the sheet (after the surface of the structure has been heated to about 60° C). Then the electrodes are bent backward and soldered to the leads, which preferably must be provided with a rubber insulation cover. The remaining sheets, beginning with the smallest, are put successively over the gage and the surrounding area. If the temperature of the structure is too low for the guttapercha to become tacky, the sheets may be heated by means of hot air. Another suitable method is to moisten the sheets with a trace of gasoline; they immediately will become sticky and adhere as well to the structure as to each other (fig. 2.8). The resistance of this cover against moisture is excellent. Its application is simple but requires some experience.

It is seldom possible to apply a plastic cover by starting with a solution of the plastic because nearly all the solvents for plastics are also solvents for the cement used for the gage, and therefore would destroy the bond entirely. Consequently, a plastic cover must be made from the plastic in its solid form. A suitable material has been found in Prestik. This is sold in the form of a spooled tape with a width of about 50 mm and a thickness of about 3 mm. At room temperature it is pliable, adheres strongly to metal surfaces (notably after it has been pressed down for a short period), and is soluble in acetone or ethyl acetate. A proved technique is to start by cutting two pieces of the tape, each about 80 mm in length (depending on the dimensions of the gage). A rectangular slit is made with a knife in one of the pieces, its dimensions corresponding with the dimensions of the strain gage (fig. 2.9). After having moistened the underside of this frame with acetone, it is pressed upon the metal surface around the strain gage. The leads (plastic or rubber covered) are placed on the frame and pressed down a little. The insulation of the wires is removed over a short length, falling in the slit. The electrodes of the strain gage are soldered to the wire tips, the soldered joints being protected with oiled silk or plastic sleeving. The space over the gage is filled with a soft microcrystalline wax (Di-Jell), the thickness of this layer must correspond to the thickness of the plastic frame. Thereafter the upper side of the frame is moistened with acetone, and the second piece of tape is placed over it. The assembly is pressed

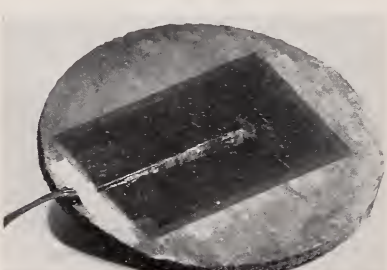

Figure 2.8. *Finished guttapercha protection.*

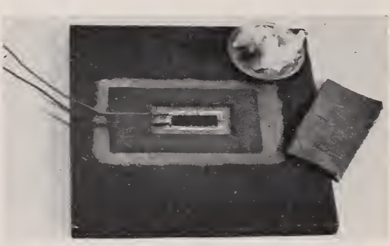

Figure 2.9. *Protection with a plastic cover.*

First rectangular frame put into place

down a little, and by rubbing movements the boundaries are spread out to obtain a gradual change in thickness from the surface of the structure to the cover (fig. 2.10). This protection is very useful under water or with heavy outside pressures.

Protection with ready-made rubber caps. The foregoing methods show a few general disadvantages. The strain gages must be absolutely dry before applying the cover, as any moisture still present will be shut in by the cover, resulting in a permanently defective state. Also, perfect drying of the gages is often very difficult, or even impossible, and requires extensive labor when a great number of strain gages are to be treated, especially if measurements are to be made in the open.

To overcome these troubles and to provide an easy, effective protection, a special rubber cap was developed (fig. 2.11). First, a layer of rubber cement (Ty-Ply S. C. or Pliobond) is spread out with a brush all around the strain gage immediately after the 1-hr drying period under pressure has been completed. While this cement is drying for a few minutes, the flat edges of the rubber cap, with two-core flex vulcanized into it, are cleaned with benzene or chloroform (which gives a better adhesion) and are given a coat of rubber cement. When the cement has become sticky, the back of the rubber cap is stuck on, and the rest of the cap turned back. It remains in this position owing to its special shape. The electrodes of the gage are then quickly soldered to the end of the cable that is vulcanized into the cap (fig. 2.12). In the pocket provided for the purpose is placed a small linen bag containing dry silica gel. Then the cap is turned and pressed down firmly around the edges for a few minutes. This completes the mounting of the strain gage (fig. 2.13). With this method the work involved in cementing and mounting a strain gage takes a little more than an hour.

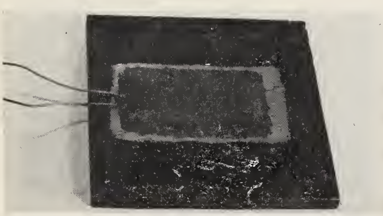

FIGURE 2.10. *Finished plastic cover.*

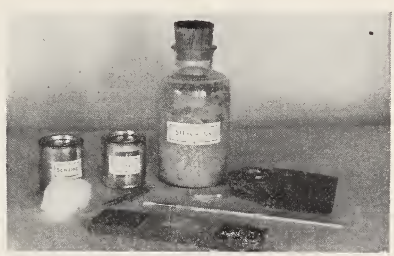

FIGURE 2.11. *Materials for fixing a protective rubber cap over the strain gage.*

FIGURE 2.12. *Soldering the electrodes to the lead vulcanized in the cap.*

A bag of silica-gel has been slipped into the pocket underneath the cap

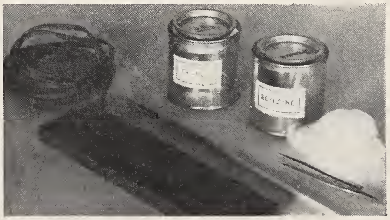

FIGURE 2.13. *Finished rubber protection cap.*

The gage must be left a few days to dry thoroughly. Better results are obtained if the gage is heated by passing an electric current through it, and since all the connections are already made, it can at once be connected to a low-voltage power source. The best results originate in a combination of the three drying methods mentioned. As soon as the rubber cap has been pressed down over the gage, it begins to function as a moisture barrier so that even in a pouring rain the results of the measurements will not be affected.

Sometimes the bond will be improved by cyclization of the rubber surface through application of concentrated sulfuric acid. This may be done by putting the cap in a glass tray in which there is a thin layer of sulfuric acid. After about 5 min., the cap must be rinsed thoroughly with running water (1882, a patent application of Ch. Woodward). Further particulars concerning the protection with a rubber cap, filled with silica gel, will be found in Appendix I.

Control of Insulation Resistance

The last control of the strain gage deals with the determination of the state of dryness. No method has yet been found for determining directly the humidity of the layer of cement in a simple way, but there is a very useful indirect method. The fact is that the higher the moisture content, the greater is the conductivity of the cement, so that by measuring the insulation resistance between the filament of the gage and the metal surface of the test object, an indication of the humidity is obtained. Owing to the risk of dielectric breakdown, however, the voltage used for the test must not exceed 25 to 30 v. As no entirely suitable apparatus was available, a new device (fig. 2.5, background) was developed by the Electronic Department of TNO with a range of 0.5 to 50,000 megohms (see Appendix II). For short tests, the leakage resistance should be at least 100 megohms, but values of 5,000 megohms or more are normally to be preferred. However, with rubber caps the leakage resistance is usually higher than 50,000 megohms, even in underwater applications.

Soldered Gages

Despite its many advantages, there are a few objections to the use of resistance strain gages. The principal disadvantages are (1) an appreciable amount of time must elapse after cementing the gage before it can be used, and (2) the gages cannot be calibrated beforehand (the gage factor is given by the manufacturer, who has estimated this value by statistical methods from samples out of the running production).

With regard to the first point, it may be noted that there are quick-drying gages available with a very thin paper base. For measurements on structures these gages generally are to be preferred as they need no clamping devices and dry at least two times faster than the normal ones. Another method, which requires some experience, works as follows. The surface of the object is heated to a temperature of about 40° C before the first cement layer is applied. This layer must be very thin, as it dries quickly. The layer on the gage, which must also be thin, is allowed to dry a few minutes and when nearly dry, is put onto the precoat layer and pressed down firmly with the fingers for about 2 min. If the moment is estimated correctly, the gage will adhere immediately without the formation of gas bubbles or voids. In this way, many gages (A–5, A–7, and A–8) were put down in difficult spots without any appreciable error or disadvantage. An attempt to overcome both difficulties was made a few years ago. The basic idea is to cement the gage in the ordinary way onto a piece of brass or steel sheet having a thickness of about 0.03 to 0.05 mm. The gage is protected in some suitable way and the whole combination soldered onto the metal surface by means of a low-melting solder.

Most often Bakelite-bonded strain gages are used for this purpose, but good results have been obtained with ethyl cellulose-bonded gages. As a protective cover for the gage and the solder connections (fig. 2.14), a nearly solid semicircular piece of rubber has been used. The rubber is cemented to the metal sheet by means of Ty-Ply. A two-wire cable is vulcanized into the rubber cover. The underside of the metal sheet is covered with a layer of the low-melting solder (fig. 2.15). The alloys listed in table 2.2 may be used as solders.

TABLE 2.2. *Low-melting alloys*

Alloy	Composition				Melting point
	Lead	Tin	Bismuth	Cadmium	
	%	%	%	%	°C
Woods	25.0	12.5	50.0	12.5	60
Lippowitz	26.7	13.3	50.0	10.0	70
Roses	25.0	25.0	50.0	--------	94
Newtons	------	26.0	53.0	21.0	103

The Woods and the Lippowitz alloys are quite satisfactory. The surface of the test object is heated with a soldering torch and a layer of the solder applied to it. Sometimes a soldering flux has to be used to get good adherance (Tricene). The gage assembly is pressed onto the molten alloy, the pressure being applied until the solder has hardened, which takes a few minutes. Immediately after the structure has been cooled down to room temperature, the strain measurements may be carried out. It has been found that strains up to $\pm 1{,}500 \times 10^{-6}$ may be measured without difficulties. The absolute absence of hysteresis is remarkable, even after the first loading. Care must be taken that the stiffness of the gage assembly does not interfere with the characteristics of the test object; its wall thickness must not be too small.

FIGURE 2.14. *Components of the soldered strain gage.*

Left, the rubber protection cap with a two-core flex vulcanized into it; right, the brass sheet with a cemented strain gage (A–1).

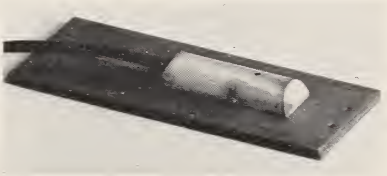

FIGURE 2.15. *Soldered strain gage put into place upon a steel strip.*

After the test, the gages can be removed easily by tearing off the solder layer or by reheating the soldering spot. All the possibilities of this method are not yet explored; the main advantages are that the gages can be used several times so that they can be calibrated, and that the lapse of time between the fixing of the gage and the measurements is very short. The construction just described can only be used on relatively flat surfaces that can be heated up to about 80° C.

Measuring and Testing Methods

All tests with strain gages, various cements, and drying methods were carried out in the laboratory. The gages were cemented onto a bar and tested in pure bending (fig. 2.16). The bars were placed vertically in the loading frame and loaded by putting weights on the end of the crossbar (fig. 2.17). By putting the weights on either the left or right side, the same gage could be tested in tension and in compression. For long-duration tests, the weights could be left on for any desired length of time, so it was possible to study the hysteresis, the drift of the zero point, and cold flow of the cement.

The commercially available indicators were not suited for the most accurate measurements as their accuracy and stability proved to be insufficient. Therefore, a Wheatstone bridge, with precision (wire wound) resistors and a galvanometer as zero indicator, was developed (fig. 2.18). D and K are the two strain gages. The fixed resistors, R, are wound on a common brass tube. Resistors Z can be varied corresponding to a strain of $10{,}000 \times 10^{-6}$ (for a gage factor, $\gamma=2$), and resistors T by amounts corresponding to a strain of $1{,}000 \times 10^{-6}$. All the resistors are made from manganin wire to very close tolerances. The mirror galvanometer (Tinsley) has a resistance of 50 ohm, a deflection of 23 mm/μA, and a damping resistance of 600 ohm. The strains can be determined with an accuracy of 1 part in a million. The stability of the bridge has not changed during a period of several months, and the zero point changed less than 5×10^{-6}.

The effectiveness of the various waterproofing techniques has been tried in the open on the roof of the laboratory building. The first important researches were carried out during the winter of 1947–48. The loading apparatus consisted of a bending bar (fig. 2.19) loaded with weights at the free end. The active and dummy gages were cemented onto this bar, the dummy gages being on an unloaded part of the bar. The indicator was inside the laboratory, the connection between the gages and the apparatus was made by means of a 16-wire rubber cable. The rubber caps and various kinds of microcrystallin waxes (fig. 2.20) were tested during the entire winter (6 months). Measurements were taken each morning, when the weights were removed for a moment to check the zero point of the gages (except during a fortnight, when the weights were frozen together). The changes in the zero point and the value of the drift were at most

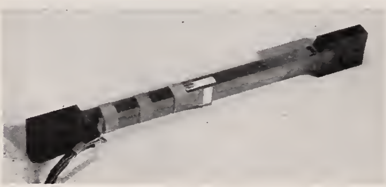

FIGURE 2.16. *Calibration bar with two strain gages.*

(Philips, GM 4473)

FIGURE 2.17. *Loading frame for the calibration of strain gages.*

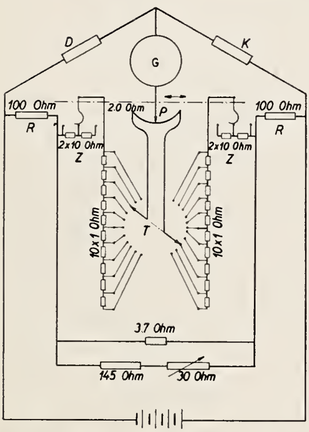

FIGURE 2.18. *Diagram of precision Wheatstone bridge.*

FIGURE 2.19. *Loading apparatus on the roof of the laboratory building.*

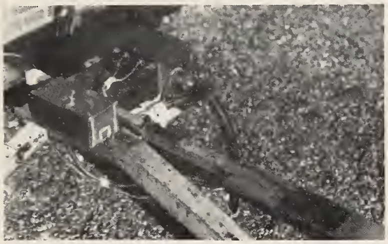

FIGURE 2.20. *Detail of the loading apparatus.*

$\pm 20 \times 10^{-6}$ during this whole period, for either the caps or the wax-covered gages.

Practical Applications

Measurement on steel structures in the open air. For these measurements the rubber caps have proved to be almost indispensable. They are used during winter and summer under all climatic conditions. In most instances they are dried only by means of a current through the filament. Successful measurements were carried out on the loading masts of ships (fig. 2.21), building structures, railway carriages, floating derricks, etc.

FIGURE 2.21. *Loading mast of a ship with rubber cap protected strain gages.*

Measurements on ships. Inside the ships the rubber caps were employed; outside on the hull, the plastic covers (Prestik) were used. This latter protection proved to be effective in sea water for relatively long periods. (The rubber caps can also be used under water, but at greater depths the air under the cap is compressed, and the resulting deformation of the cap may easily cause breakage of the leads).

Measurements inside of pressure vessels: The easiest way is to fill the vessel with oil instead of water. If a pure transformer oil is employed (free of acids and water), the common cellulose type of strain gages can be used without any protection. These gages give correct readings for a period of about 2 weeks after their immersion in oil. After that period, the cement of the gages is gradually destroyed. Investigations have shown that the oil can act as a plasticizer of cellulose derivatives, and this causes a slow deterioration of the cement, with a decrease in mechanical strength and an increase in cold flow. On the other hand, Bakelite-bonded gages can be kept in contact with transformer oil indefinitely without noticeable changes. For long-duration tests, either transformer oil and Bakelite gages or some protection of the gages must be employed. This can be a plastic cover, for example, Prestik (suitable for water, gasoline, oil, etc., but not for organic solvents), which can be used up to very high pressures if care has been taken that no air is trapped under the plastic cover. Reinforced rubber caps can also be used up to pressures of about 50 kg/cm^2 (suitable for water and fluids, which do not attack the rubber).

Two ways of reinforcement have been found successful: a, Filling all the space under the cap with a mixture of fine sand and powdered dry silica gel; b, putting a steel box over the gage before the cap is applied. The outer dimensions of the box should fit accurately the inside dimensions of the cap. The bottom of the box must be open. Successful measurements were carried out on pipe-flange connections, ship models, large containers, etc.

Measurements on concrete structures. In measurements on concrete, there generally are three possibilities.

SURFACE MEASUREMENTS. The following difficulties are encountered: Effect of the moisture in the concrete; difficulties with the bonding; and the needed gage length, which must be large with respect to the components of the concrete. To prevent moisture from penetrating the gage, a barrier must be formed on the surface of the concrete. The following solutions have been tried: (1) Covering the concrete with a layer of pitch compound or bitumen, onto which the gage is cemented.—(Objection: The plasticity of these rather heavy layers causes false readings of the gages.) (2) Covering the concrete with a metallic layer—On concrete specimens, layers of zinc and other metals were sprayed (Schoop process). After polishing the metal surface, the gages were attached in the normal way. (Objection:

Because of the high temperature at which the molten metal is applied, the concrete dried out and pulverized, so that the bond between the concrete and the metal layer proved to be insufficient.) (3) Treating the concrete surface with a plastic.—The selected plastic must have a good resistance against moisture. Nitrocellulose, polyvinyl acetate, and polystyrene were chosen for the tests. They were dissolved in a mixture of acetone and benzene and applied with an airgun. Three or four layers were applied, each layer about 15 min after the previous one. If the concrete was dry, the depth of penetration was appreciable, at least 20 to 30 mm. The gages were cemented to the concrete surface in the normal way and covered with molten wax. This technique worked well in the laboratory with dry test objects but was not suitable for measurements on structures in the open. A modification of this method has been published [12], whereby a 0.25-mm-thick piece of celluloid was inserted between the strain gage and the concrete surface. The strain gages should have a gage length of at least 5 in. (Baldwin, A–9). (Objection: This technique gives reliable results only when applied to concrete with a very low moisture content. In damp weather, the method cannot be used on concrete structures in the open.)

Measurements Inside Concrete Structures. With regard to the difficulties encountered in cementing strain gages to concrete, it is often preferable to apply the gages inside the concrete. The best way is to make use of a hollow steel cylinder, in which a gage is cemented in an axial direction, while the dummy is put in a tangential direction (fig. 2.22). The unit must not be too small. To obtain a true indication, the elasticity of the measuring part must be equal to the elasticity of the replaced concrete. If the modulus of elasticity of the steel is E_s and of the concrete E_c, the outer diameter of the cylinder, D, and the wall thickness, d, the following condition must

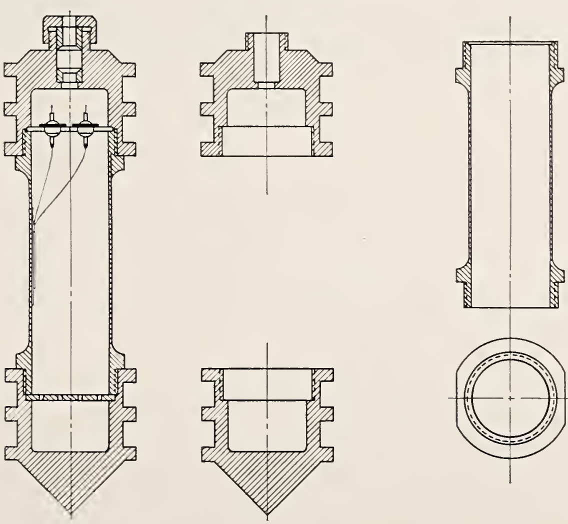

Figure 2.22. *Strain gage for measurements inside concrete structures.*

be fulfilled:

$$d=\frac{D}{2}\left(1-\sqrt{1-\frac{E_c}{E_s}}\right)\cong\frac{D}{4}\cdot\frac{E_c}{E_s}.$$

Good results have been obtained with these instruments. In most instances they can be used only once. Therefore, the use of more simple and less expensive devices has been tried. An inexpensive solution is to use strain gages embedded between two sheets of metal [13], although the gage length may be too short and the elasticity different from the replaced concrete.

Measurements on the Reinforcing Bars. Unless they are too thin, the gages can be put on in the normal way. The waterproofing must be very good. A suitable method is to cover the gage with molten wax and to wrap oil-silk tape around the bar while the wax is still soft. Finally, an outside covering of some pitch compound or bitumen may be applied. Another method was used rather successfully on a shell roof. After the gages were dry, they were wrapped with guttapercha tape (5 or 6 layers). The cover was melted into a solid mass. The final protection was a cover of oil silk over the guttapercha.

Although much work has been done on strain gages, users have the feeling that their possibilities are not yet exhausted and that they are still in the development stage. A fruitful collaboration and an exchange of ideas and results between research workers and employers will be of benefit.

Appendix I

Water vapor and also the vapors of the cement solvents used, such as acetone, ethyl acetate, amyl acetate, benzene, alcohol, etc., are usually present in strain gages. These vapors must be removed to obtain effective drying. Hydrophylic and hydrophobic adsorbents are available for the drying of strain gages. Silica gel and charcoal are to be preferred, and table 2.3 [14, 15] lists some of the properties of these adsorbents.

Table 2.3.

Adsorbent	Type	Specific gravity	Grams of adsorbed liquid per grams of dry adsorbent[a]	
			Water	Benzene
		g/cm^3		
Silica gel	Hydrophylic	0.5 to 0.75	0.35	0.10
Charcoal	Hydrophobic	0.1 to 0.4	------	.20

[a] Values at 18° C.

If the main constituent is water vapor, silica gel should be used as it also adsorbs organic solvents. However, if the water content of the vapor is high, not much of the organic solvent is adsorbed and eventually the organic solvents are released. Charcoal, on the other hand, adsorbs mostly organic liquids and vapors, and, in a less effective way, water. Therefore, if the cement of the strain gages contains small amounts of solvent, the use of silica gel suffices, but if the solvent content is high, a mixture of charcoal and silica gel (equal parts) is to be preferred. Silica gel can adsorb water up to 35 percent by weight. In the "dry" state, it always contains 6 percent of water.

Figure 2.23 shows the vapor pressure in the presence of a specific type of silica gel as a function of the temperature for various degrees of saturation [16]. Calculations have shown that under normal conditions a Baldwin A–1 gage contains

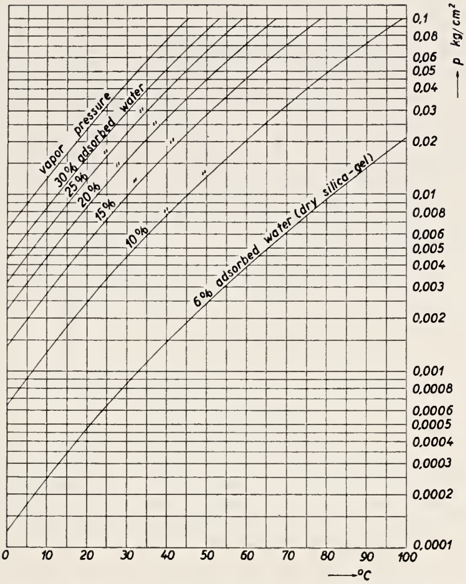

FIGURE 2.23. *Vapor pressure of silica-gel as a function of temperature and of percentage adsorbed water.*

about 0.03 g of solvent and 0.01 g of water after a drying time of 1 hr. A quantity of 8 cm^3 of silica gel can be put under the rubber cap, corresponding to about 5 g. If the silica gel is perfectly dry, it contains 0.03 g of water, so that after some time the total water content is 0.04 g, corresponding to 8 percent of adsorbed water.

At 20° C the vapor pressure, p_0, under the cap will be about 0.0015 kg/cm^2 (relative humidity about 6 percent). As time goes on, water vapor will diffuse through the rubber cap and be adsorbed by the silica gel, resulting in a rise of the vapor pressure, p, inside of the cap. The diffusion is governed by the equation

$$\frac{dV}{dt}=\frac{Q.A}{d}(P-p). \tag{1}$$

V=volume of diffused vapor in cm^3, reduced at 0° C and 76 cm Hg.
Q=coefficient of permeability=$10\cdot10^{-6}$ for rubber.
A=area in cm^2 of the membrane.
d=thickness in cm of the membrane.
p=vapor pressure in kg/cm^2 under the cap.
t=time in sec.
P=vapor pressure outside of the cap (kg/cm^2).

The volume, V, of the diffused vapor may be expressed in terms of its weight, G:

$$V=aG. \tag{2}$$

As a first approximation, the ratio between the vapor pressure and the moisture content (in percent) of the silica gel, f, may be estimated as linear.

$$p=mf+c=m\left(\frac{G}{g}100+i\right)+c. \tag{3}$$

m,c=parameters of the function.
g=weight of the dry silica gel in grams.
i=initial percentage of moisture in the silica gel.

From eq (2) and (3) it follows:

$$\frac{dV}{dt}=a\frac{dG}{dt}, \tag{4}$$

$$\frac{dp}{dt}=\frac{100m}{g}\cdot\frac{dG}{dt}=\frac{100m}{ga}\cdot\frac{dV}{dt}. \tag{5}$$

By substituting this expression in eq (1), we find

$$\frac{dp}{dt}=\frac{100mQA}{gad}(P-p)=C(P-p). \tag{6}$$

In solving eq (6), we get (keeping P constant)

$$p=De^{-Ct}+P, \tag{7}$$

For the boundary value $t=0$, $p=p_0$, we find

$$p=(p_0-P)e^{-Ct}+P. \tag{8}$$

Putting $p=\alpha P$, we get

$$e^{-Ct}=\frac{(\alpha-1)P}{p_0-P},$$

or

$$t=\frac{1}{C}\ln\frac{(P-p_0)}{P(1-\alpha)}. \tag{9}$$

At 20° C and a relative humidity of 70 percent, $P=0.0166$ kg/cm². For p_0 we already found 0.0015 kg/cm². As $Q=10\cdot10^{-6}$, $A=35$ cm² (area of the rubber cap), $d=0.25$ cm (thickness of the cap), $g=5$ g, $a=1.24\cdot10^3$ (water vapor), $m=6.2\cdot10^{-4}$ (at 20° C), the value of $1/C$ becomes $1/C=71.5\cdot10^6$ sec. In table 2.4, t is presented as a function of α for these values.

TABLE 2.4.

α	0.1	0.2	0.4	0.6	0.8	1.0
t (months)	0.6	3.9	11.7	23	42	Infinite.

In practice, the relative humidity of the air will vary somewhat from 70 percent for long periods, and often the temperature is not 20° C (day and night), so that the protection will be sufficient for at least half a year, as has been found with practical applications.

Appendix II

The megohmmeter is visible in figure 2.5 (background). Its working principle follows from figure 2.24.

By means of the neon tube, N, a constant voltage of 85 v is maintained over the voltage divider R_5-R_6-R_7. The testing voltage across R_6 is about 25 v. The unknown insulation resistance, R_x, is put in series with one of the precision resistors R_1, R_2, R_3, or R_4 parallel to resistor R_6. The voltage over the precision resistor is measured with an ordinary vacuum tube voltmeter, consisting of two pentodes. The indication instrument, M, is put between the two anodes. The potentiometer, P, enables the balancing of the amplifier. The instrument has four ranges: 0.4 to 50, 4 to 500, 40 to 5,000, and 400 to 50,000 megohm. The accuracy is about 5 percent. Voltage variations of ±10 percent have an influence of less than 0.1 percent on the indication.

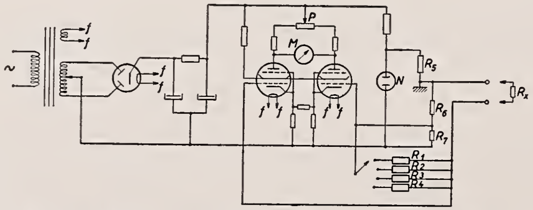

FIGURE 2.24. *Diagram of electronic megohmmeter.*

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Discussion

Mr. Coleman Raphael, Republic Aviation Corporation, Farmingdale, N. Y.: In most instances where we have seen these applications so far, there has been a lot of room around the gage for wax and rubber pads and coatings. At Republic we have typical installations where we might want to put a strain gage on a thin aluminum cantilever beam, and in that case we install ¼-in.-long gage, such as the A–7 or A–8. We cover the gage with wax after wiring it, and then we find that oil attacks the wax, so we cover the wax with glyptal. By the time we have finished, the weight that we have added to the beam changes its natural frequency as well as practically overloading it.

I am wondering if there is anything that anybody here might know of, or that you, Mr. Boiten, have worked with, where you would just spray a thin liquid or put something similar over the gage that would insulate it and not add a lot of weight and make it very bulky.

Mr. Boiten: The problem you mention is common to us, too. The easiest way would be to put some liquid insulation on it, but unfortunately the only suitable things are solutions of some plastics, and the solvents for the plastic are also solvents for the cement, so you certainly would run into trouble. But, for example, we have used the following techique for concrete reinforcing bars. We wrap a few layers of guttapercha tape around the gage and then heat the guttapercha cover with a blowtorch, so that it melts to form a solid mass and afterward, if necessary, protect it with oil silk. We have used this method extensively on measurements in concrete with good results. I should advise you to try something similar. It works quickly, and the mass of guttapercha is very small.

Mr. Harry Stern, Allegany Instrument Co., Cumberland, Md.: We have been using one of the 3 M adhesives made by the Minnesota Mining & Mfg. Co. with excellent success. The particular one that we use is a liquid, and it is baked on after air drying. The cement forms such a good bond to the steel that it is removed only with considerable difficulty.

Mr. K. H. McFarland, Ames Aeronautical Laboratory, NACA, Moffett Field, Calif.: There is a Dow Corning grease sold as DC–4, which is thermally stable and has the consistency of Vaseline.

We have found trichloro-ethylene successful in cleaning the surface. It is a very active degreasing agent, and we use it hot. If the part to be cleaned is immersed in the hot vapors, a grease-free surface can be obtained.

Mr. Edwin J. Mickevicz, Naval Ordnance Laboratory, Washington, D. C.: Mr. Boiten, I would like to ask you what procedure you recommend for waterproofing gages to be used under water at pressures of 1,000 lb/in.^{2}.

Mr. Boiten: I should advise you to try the method based on a plastic cover. We have used it for water pressures up to 700 m. There is no difficulty if you are careful to avoid trapping air underneath. The space over the gage is filled with wax. Tests have shown that it will stand up under 100 atm. We could not go to higher pressures because our pressure vessel became overloaded. The protection is sufficient for a period of at least a fortnight. I am afraid it would not stand for years, but for tests of moderate duration at high pressure I think it will behave satisfactorily.

Mr. Mickevicz: Do you restrict yourself in that case to using a plastic-insulated cable or a rubber-insulated cable?

Mr. Boiten: Normally it does not matter very much, but with regard to the plastic cover and the sealing problem, I prefer plastic-insulated cable because the plastic is more easily connected and embedded in the plastic frame than rubber would be. For other applications the cables we use are nearly always rubber cables, as plastic cables give more trouble with changes in capacity due to temperature changes or bending movements, which alter the capacitive balance of the bridges.

Mr. Richard L. Zenker, Packard Motor Car Co., Detroit Mich.: I wonder if you or anyone else considers it necessary to protect gages against hot oil, say 300° F, and if so, what would you consider the easiest and quickest way of protecting these gages.

Mr. Boiten: In that case I would try a wax with a very high melting point, which is not soluble in oil. I had some specimens of a wax that has been developed by a New York firm (Glyco Products Co. Inc., 26 Court Street, Brooklyn 2, N. Y.). It was tar black and had a melting point of nearly 200° C. I found it was not seriously attacked by water or oil, and it seemed to work satisfactorily on Bakelite gages. The wax was in an engineering publication a few months ago.

Mr. Zenker: Then you do consider it necessary to protect the gages in hot oil?

Mr. Boiten. Not in all cases, only if you are using a kind of oil that has a high water content.

Mr. Zenker: This is transmission oil. I was not so sure about protecting the gages from hot transmission oil.

Mr. Boiten: This protection is not necessary. We have among other things performed tests inside the crankcase of a combustion engine, and it worked all right for about a fortnight with type A gages and very much longer with type B gages, within their temperature range, of course.

3. Unbonded Resistance-Wire Strain Gage

By Louis Statham [1]

A resistance-wire strain gage of the unbonded type is described. This instrument contacts the specimen by means of knife edges and exhibits electrical characteristics similar to those of the cemented strain gage. Other examples of the application of unbonded strain-sensitive resistance wire are described, including incorporation into instruments for the measurement of force, pressure, displacement, and acceleration. Reference is made to energy relationships which display special advantages of the unbonded strain gage in certain instrument types. Pertinent electrical and elastic properties of the more commonly used strain-sensitive wire are discussed.

Introduction

The advent of the resistance-wire strain gage gave to industry a new tool and marked a revolutionary stride in the promotion of the art of stress analysis. This new instrument made possible the rapid measurement of strain at remote points with almost unlimited resolution. The recording of strain at multiple points became commonplace. The instrument was simple and inexpensive. It consisted of a grid of fine resistance wire, usually of the class known as constantan, cemented to a piece of thin paper which was to be cemented in turn to the specimen at the point where strain was to be measured. The success of the new instrument was immediate, and the strain-gage bridge became a familiar sight in laboratories and in the literature everywhere.

Since the resistance-wire strain gage was in reality a transducing element by which a mechanical motion was caused to exhibit electrical expression, it seemed reasonable that the use of the same principle should find profitable application in the measurement of mechanical quantities other than strain. There had always been need for more accurate and more simple methods for transforming into electrical signals such quantities as force, displacement, pressure, acceleration, and the like, so that they might be recorded conveniently or indicated remotely. The resistance-wire strain gage looked particularly attractive because of its enormous inherent advantage of being operable by direct current. Almost any other system that could be said to possess accuracy suitable for quantitative measurements needed actuation by alternating current. The alternating current had first to be produced, and then to be unscrambled again before any recording. The resistance bridge, on the other hand, could be supplied from batteries, and its output could be recorded at once.

In any mechanical-to-electrical transducer element, something has to move. If the movable system possesses any stiffness at all, its movement will store energy, and this energy must inevitably be supplied by the subject under investigation. The variable-capacitance bridge and the variable-inductance bridge do not necessarily

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[1] President, Statham Laboratories, Los Angeles, Calif.

have inherent mechanical stiffness other than what flexure members may be necessary to guide the moving system or to contain the subject itself. For this reason, such transducing systems find wide application in spite of their inconvenience in being essentially alternating-current devices. The resistance bridge is simpler, but the bonded resistance-wire strain gage must be bonded to some sort of member, and the resulting assembly has considerable energy storage at maximum displacement. The member to which the strain gage is bonded must, for practical reasons, be far more massive than the resistance wires; hence the energy that the transducer stores will be largely in the member, and very little of it is needed for the wires.

The unbonded resistance-wire strain gage was conceived as a transducer element of high efficiency. In this device, mechanical energy goes only into producing strain in the wires. This transducer thus achieves the low-energy advantage of the capacitance and inductive bridge transducers, and has the simplicity of the strain-gage bridge. At the same time, the developers of the unbonded strain gage introduced the idea of incorporating four active bridge arms in the instrument and balancing the bridge in assembly. Thus a complete transducer was produced having four terminals and needing no additional bridge elements. A battery could be connected to two of the terminals and a galvanometer or oscillograph to the other two. Subsequently, the same idea has been incorporated in some transducers of the bonded-gage type.

A basic form of the unbonded strain-gage transducer sensing element is shown in figure 3.1. The transducer consists of a frame, E, supporting a movable armature, F, by two thin cantilever plates. Four sets of strain-sensitive filaments, A, B, C, and D, are strung under initial tension between the frame and armature in the manner shown. When the armature is displaced longitudinally, two of the sets of filaments will be elongated, and the other two sets will shorten. The elongated filaments will increase in electrical resistance, whereas the resistance of the shortened filaments will decrease. The change in electrical resistance of the filaments will be proportional to their change in length. The transducer is so wired that the filaments are connected in a Wheatstone-bridge circuit, as shown in figure 3.2. The resistance change of the filaments alters the electrical balance of the bridge so that an electric current is caused to flow in the output circuit.

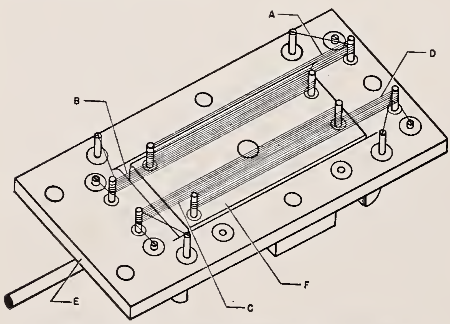

FIGURE 3.1. *Basic transducer element.* Top view.

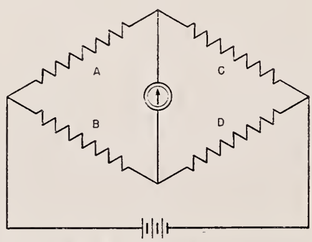

FIGURE 3.2. *Transducer wiring schematic.*

The resistance of the transducer can be controlled through the choice of wire and the number of loops in each element. Resistances from 60 to 5,000 ohms are readily achieved. In a recent telemetering application, an unbonded strain-gage accelerometer was built with a bridge resistance of 54,000 ohms, to provide a full-scale output swing of 4 v when supplied with 400 v. Each active bridge arm contained 22 ft of wire, 0.00037 in. in diameter.

Since the inception of manufacture, 8 years ago, some 25,000 transducers of the unbonded strain-gage type have been built. The following breakdown shows the distribution among three basic categories: Accelerometers, 7,000; pressure transducers, 15,000; dynamometers, 3,000.

Accelerometers

The accelerometer demonstrates most clearly the need for the unbonded strain gage. Accelerometers are seismic instruments used to measure or record motion far below the natural frequency of the instrument. In this region,

$$x=-\frac{A}{n^2}, \tag{1}$$

where x is the relative displacement between the seismic mass and the surrounding case, A is the acceleration to which the case is subjected, and n is 2π times the natural frequency of the instrument. A sensing element to record the relative position of the mass inside the case makes this instrument an accelerometer.

The reverse side of the transducer element is shown in figure 3.3. G is the cantilever plates supporting the armature; H is the linkage pin by which movement is transmitted to the armature; I is a stud attached to the armature; and J is a bar attached to the frame. The square hole in the bar, J, is accurately sized so that the stud, I, will limit the movement of the armature to 0.0015 in. in either direction. The movement limit serves to protect the filaments against mechanical overload damage. The resistor, K, is a trimmer placed in series with

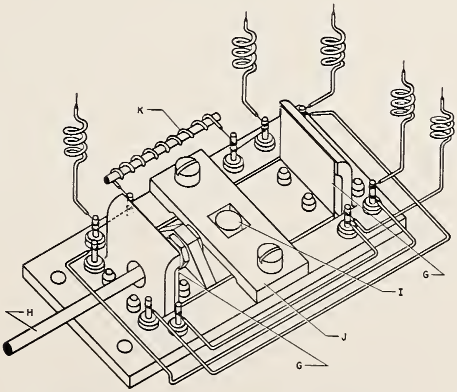

FIGURE 3.3. *Basic transducer element.*
Bottom view

one of the bridge elements. It is adjusted after assembly of the transducer to equalize the resistance of the four elements of the bridge. If the bridge is balanced at zero output before the displacement is applied, the unbalanced electrical output of the bridge will bear an accurate, linear relationship to the displacement.

The transducer element just described is a complete instrument when housed in a suitable case that permits linkage pin H to protrude. Force or displacement applied longitudinally to the linkage pin produces an electrical signal in the receiving instrument. When a bellows or diaphragm is attached to the linkage of the transducer element depicted in figures 3.1 and 3.2, the element becomes a pressure transducer. The basic element becomes an acceleration transducer when a mass is attached to the armature.

The transducer must, of course, be connected to a receiver. The type of receiver is dictated by the nature of the problem. If steady-state physical phenomena are to be measured, the output of the transducer may be connected directly to a microammeter. Recording of steady-state phenomena is accomplished by connecting the output of the transducer to a recording potentiometer of the type used for temperature recording with thermocouples or resistance bulb thermometers. For dynamic studies, the transducer may be connected to a cathode-ray oscilloscope or to a galvanometer-type photographic recorder. Most cathode-ray oscilloscopes contain sufficient amplification. In the galvanometer-type recorders, amplification is usually not required.

If the accelerometer is to be of reasonable dimensions and weight, the mechanical characteristics of the sensing element itself must be considered carefully. A useful design formula will now be derived.

We know that the kinetic energy contained in the vibrating accelerometer mass is $T=\frac{1}{2}MV^2$, and $T_{\max}=\frac{1}{2}MV_{max}^2$. For simplification, we may neglect the damping for the moment. Because the natura mode of the mass is sinusoidal, $V^2=x_{max}^2n^2$. Hence, $T_{\max}=\frac{1}{2}Mx_{max}^2n^2$.

If the undamped mass and spring are free to oscillate at their natural frequency, and are set into motion by an initial displacement, there will occur during the sinusoidal oscillation of the mass a continuous transfer of energy from kinetic energy of motion of the mass to potential energy of spring displacement, and back again. As the mass goes through its neutral position, it possesses maximum kinetic energy, whereas the spring possesses zero potential energy. When the mass reaches an extremity of its travel, it will possess zero kinetic energy, and the spring will have stored in it its maximum potential energy. The kinetic energy plus the potential energy must at all times be equal to a constant, this constant being equal to the amount of energy that was put into the system to start it vibrating. The maximum potential energy in the spring is equal to the maximum kinetic energy in the mass. Then $P_{\max}=T_{\max}=\frac{1}{2}Mx_{max}^2n^2$. Combining this equation with (1),

$$T_{\max}=\frac{1}{2}\frac{MA_{max}^2}{n^2},$$

or

$$M=2T_{\max}\frac{n^2}{A_{max}^2}. \tag{2}$$

Equation (2) is of prime importance to anyone contemplating the design of an accelerometer. Ordinarily, the sensing element may play an important part in establishing the value of T_{max}. If a strain-gage sensing element is to be used, the strain gage itself often constitutes the stiffness of the mechanical system and, therefore, is the sole determinant of T_{max}. If M is to be held as small as possible, it is clear that the natural angular frequency, n, can be high only if T_{max} is low. In other words, we cannot afford to store much energy in the elastic suspension. In the unbonded strain-gage accelerometer, the strain-sensitive resistance wires themselves constitute the sole support of the seismic mass. The wires are not bonded to a cantilever beam, which would constitute an additional potential energy reservoir of many times the capacity of the strain wires themselves. As we are concerned only with work done, it is obvious that no trick of leverage or mechanical advantage can alter this situation.

The strain-sensitive wires used in unbonded strain-gage accelerometers are as small as design considerations will permit in order to minimize the work that must be done to strain them. Wires as small as 0.0004 in. are often used. Constantan strain-gage wire of this size possesses a resistance of about 1,400 ohms/ft. A force of 0.00509 lb will strain the wire 0.0015 in./in. A 1-in. length of wire would, therefore, have a spring rate of 40.7 lb/ft, or 1,310 poundals/ft. The potential energy that will be stored in a 1-in. length of this wire when it is strained 0.0015 in./in. will then be

$$P=\int_0^x Kxdx=\tfrac{1}{2}Kx^2=10.23\times 10^{-6} \text{ poundal ft.}$$

Since the strain-gage-type accelerometer possesses the advantage that it may be connected directly to a recording galvanometer, it is convenient to select a strain-gage-bridge circuit of such resistance that it will serve as the correct damping shunt for the galvanometer. Many commercial oscillographic galvanometers require a damping shunt of about 300 ohms. The accelerometer, then, might advantageously possess a bridge resistance of 300 ohms. It is convenient to place all four active elements of the bridge in use as strain wires inside the accelerometer. Because the resistance of the wire is 1,400 ohms/ft, a total of 10.3 in. of wire will be needed to constitute the complete bridge. As each inch of the wire will absorb 10.23×10^{-6} poundal ft of potential energy when it is strained to its safe limit of $\pm .0015$ in./in., the total bridge will require 105.4×10^{-6} poundal ft of energy.

Let us suppose that the strain gage described in the preceding paragraph is to be incorporated in an accelerometer of range ± 10 g, or ± 322 ft/sec^2, and natural frequency 200 c/s. Direct substitution into eq (2) shows that such an accelerometer will require a suspended mass of 0.00321 lb, or approximately 0.05 oz. Obviously, the geometrical configuration of the mass and strain wires is dictated by eq (1). In the case just taken, the mass will undergo a full-scale movement of $\pm .000204$ ft, or $\pm .00244$ in. Under this condition, the strain-sensitive wires must be strained 0.0015 in./in. The length of the individual wires will dictate what mechanical advantage is needed between this motion of the mass and the strain-sensitive wires to produce the required strain of 0.0015 in./in. Figure 3.4 shows an accelerometer

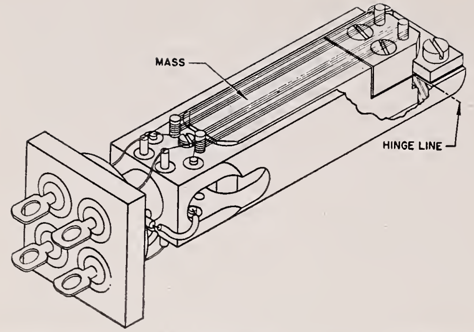

Figure 3.4. *Accelerometer, hinged mass suspension.*

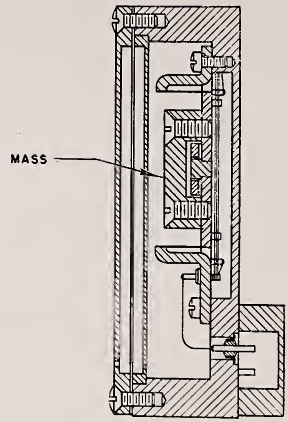

Figure 3.5. *Accelerometer, direct mass suspension.*

design that permits the use of mechanical advantage between the suspended mass and the strain-sensitive wires. The accelerometer shown in figure 3.5 is so arranged that the mass strains the wires directly without mechanical advantage. Cantilever flexure plates are used in both designs to restrain the mass to a single degree of freedom. The stiffness of the cantilever plates is kept low so that the principal stiffness of the mass support lies in the strain-sensitive wires themselves.

The awkward system of units that I have chosen for the foregoing analysis is to satisfy expediency. The cgs system is, of course, neater, but as a practical manufacturer I am denied that luxury. Unfortunately, our English heritage demands that all our machine tools be calibrated in inches. We have to purchase our metal stock by the pound and in inch sizes. Purely theoretical analysis may well use the preferred decimal system, but we are faced with the problem of moving from theory to practice and back again without having to stumble over conversion factors at each turn. Den Hartog would prefer the "Engineer's System", in which I must regard my weight as 6⅓ slugs rather than 200 lb., but I prefer to be relegated to his category of "hardly anybody".[2]

Angular accelerometers present the same energy-level problem as linear accelerometers but with even greater force. So little energy is available to drive any angular accelerometer of popular range that, even with the advantages of the unbonded strain gage, these instruments are likely to be of shocking size and weight. Design data for an angular accelerometer of range 10 (radians/sec)/sec and natural frequency 10 c/s are given here briefly: Bridge resistance is 350 ohms; wire diameter, 0.0007 in.; active wire length, 32 in.; $T_{\max}$, 0.00100 poundal ft; moment of inertia of rotor, 0.0804 lb/ft ^{2}; (cylindrical) rotor diameter, 4.5 in.; and rotor mass, 4.57 lb.

[2] J. P. Den Hartog, Mechanics, 1st ed., 2d Imp., pp. 177–178 (McGraw-Hill Book Co., Inc., New York, 1948).

Pressure Transducers

The unbonded strain gage has found wide use as the sensing element in many types of pressure transducers. Where space is important and sensitivity and natural frequency must be high, it is essential to keep the mechanical-energy level of the transducer low. An example of what can be done with the unbonded strain gage is shown in figure 3.6. This instrument is a subminiature pressure transducer, available in a wide range of sensitivities. Typical performance data are range, 0 to 100 psi; full-range open-circuit output, 22 mv; maximum input voltage, 9 v; and natural frequency, 4,000 c/s. The diaphragm of the model shown displaces a volume of 2×10^{-5} in.^{3} in its full-range travel of 600 μin. The instrument is built almost entirely of stainless steel, yet its weight is only 18 g. An exploded view of the internal assembly is shown in figure 3.7.

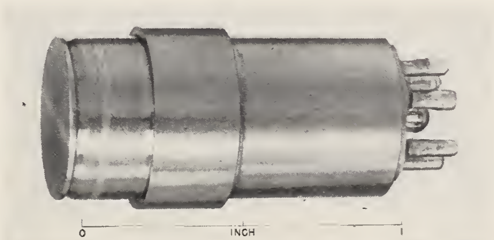

FIGURE 3.6. *Subminiature pressure transducer.*

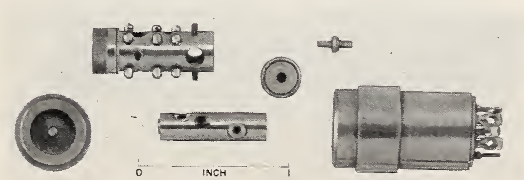

FIGURE 3.7. *Subminiature pressure transducer.* Exploded view.

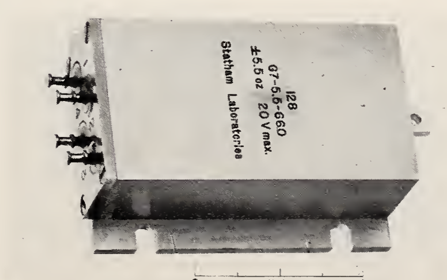

FIGURE 3.8. *Dynamometer.*

Dynamometers

The unbonded strain gage is packaged for laboratory use in measuring small forces with small displacement. Typical design data for the dynamometer shown in figure 3.8 are force range, ±0.15 oz; displacement range, ±0.015 in.; full-range open-circuit output, 12 mv; and maximum input voltage, 6 v.

Strain Gage

Paradoxically, the so-called "unbonded strain gage" was used in its adaptation to instrumentation for years before it was used for the measurement of strain. The techniques that have been developed at Statham Laboratories for the construction of moving-armature-type instruments employing strain-sensitive resistance wire have finally resulted in the development of a strain gage for the measurement of tensile and compressive strains in structural and specimen stress analysis.

The instrument shown in figure 3.9 is provided with knife edges for engagement with the specimen. Two strain-wire elements are actuated through the motion of an armature driven by one knife edge, relative to the frame that supports the reference knife edges. The armature is hinged by crossed flexure strips, as illustrated in the cutaway drawing, figure 3.10.

The design makes possible the provision of an auxiliary gage length

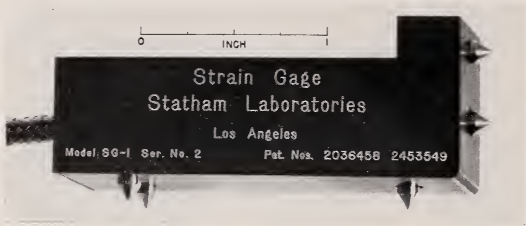

Figure 3.9. *Strain gage.*

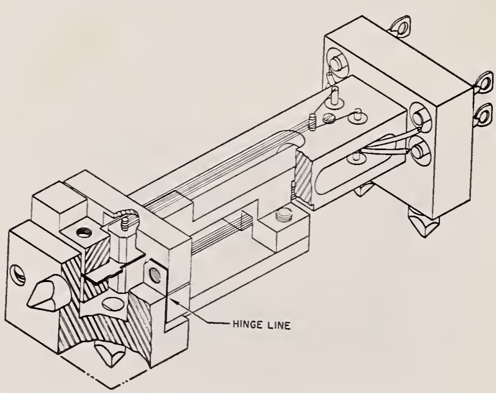

Figure 3.10. *Strain gage schematic.*

of 0.375 in. for use on curved surfaces, in addition to the basic gage length of 1.5 in. The former is suitable for the measurement of strains up to ±0.003, and the latter, ±0.012.

Discussion

Mr. Harry Stern, Allegany Instrument Co., Cumberland, Md.: Can you make pressure gages in higher ranges, say 10,000 or 20,000 lb?

Mr. Statham: We can and do.

Mr. Stern: What is the natural period of vibration of those gages in that range?

Mr. Statham: Probably around 5,000 c/s.

Question: I wonder if you could tell me something about the acceleration sensitivity of the pressure pickup?

Mr. Statham: Any pressure pickup has a mass that will move. For example, the mass can be determined easily for this little one, which has a natural frequency of 4,000 c/s and moves 600 μin. at full scale. You can compute very quickly its sensitivity as an accelerometer and discover it to be extremely low. However, some that we make in the very low ranges may be appreciably sensitive to acceleration.

Mr. Lathan E. Baker, Research Engineer, General Motors Corp., Detroit, Mich.: You said that you had an accelerometer with the range of 10 *g*. Do you have a unit with a range of 1 *g*?

Mr. Statham: Yes, we do.

Mr. Baker: What is the frequency response of that unit?

Mr. Statham: Well, the 10 *g* accelerometer has a natural frequency of about 200 c/s, and the natural frequency would go down as the square root of the range, so the natural frequency of the 1 *g* accelerometer would be something like 50 c/s.

Mr. Baker: Do you make units that are more sensitive than 1 *g*?

Mr. Statham: Yes. We make them 0.1 *g*.

Mr. Carleton M. Fields, The Glenn L. Martin Co., Baltimore, Md.: There is one problem we have with your A5A accelerometer, and I would like to know the life expectancy of it. You require a 5-v maximum, but we require more sensitivity, so we up it to 12 v. Now, I would like to know what range we can expect in lifetime over the accelerometer.

Mr. Statham: Well, if it does not burn out in the first second, its life will not be reduced.

Mr. Fields: We have had 10 of them so far running on 12 v.

Mr. Statham: They will do that, all right, but if we label them 12 v, somebody will put 25 on them.

Mr. David Vandeventer, Leeds & Northrup Co., Philadelphia, Pa.: How successfully can you cool your gages by forced circulation or some such technique and thereby up the capacity or the voltage?

Mr. Statham: Forced air cooling is not effective. We actually try to reduce natural convection with the use of baffles because the wire resistance changes unevenly with convection. Improved cooling can be obtained in certain cases where a low-pressure helium atmosphere can be maintained. With helium the current rating can be improved about four to one.

Mr. L. G. Hoxton, University of Virginia, Charlottesville, Va.: You said some of the pertinent electrical properties of the wire used were going to be discussed.

Mr. Statham: I ran out of time. There is not too much to be said except that we have been using constantan and a new alloy, 479, put out by Sigmund Cohn Corp. with a good bit more strain sensitivity.

Mr. Hoxton: The other was constantan. Is there any appreciable difference between that and what they called "advance"?

Mr. Statham: Not at all. Constantan wire is sold under the name Alloy 45 and other names. Various users swear by one or the other, depending on how successful they happen to be in using it at a particular time. We have drawn our own wire in order to get it very small; however, we do not draw all of it.

Mr. Hoxton: Alloy 479 has a slightly higher sensitivity?

Mr. Statham: It is about twice as sensitive. It is as good as isoelastic wire, and its temperature stability is much better.

4. An Embedded Bonded-Wire Resistance Strain Gage for Measuring Internal Strain in Concrete

By Rudolph C. Valore, Jr.[1]

A description is given of the development of and design criteria for a strain gage that may be embedded in concrete during the fabrication of a structural member or test specimen. The gage utilized an element 6 in. in length or shorter bonded-wire strain gage for sensing. A thermosetting adhesive was used to bond the element on both sides to the inner surfaces of an envelope made from 0.001- or 0.002-in. brass shim stock. The adhesive was cured at 160° F. Transfer of strain from concrete to gage element was provided by the bond of the cement-water paste in the concrete to the metal-foil gage covering after the concrete had hardened. The gage constant determined by the manufacturer of the element remained unchanged for the waterproof gage.

Results are given showing satisfactory performance of internal gages in stress-strain determinations made upon cylindrical concrete, plaster of paris, and mortar specimens in compression, and in measurements of shrinkage of concrete prisms dried for 100 days.

Introduction

The use of bonded-wire electrical-resistance strain gages has greatly facilitated and extended experimental stress analysis in recent years. The relatively high sensitivity, simplicity, and expendability of these gages have brought about their widespread use in the testing of concrete, despite the fact that the gages have been designed primarily for bonding to metals.

Concrete, initially a wet mixture, loses moisture only gradually upon exposure to dry air, and is often reexposed to moisture in curing or in service. It has been necessary, because of the well-known vulnerability of the bonded-wire gages to moisture, to partially dry a concrete test member before bonding gages to its surface. Because even a brief drying treatment produces nonuniformity in concrete, it was desirable to provide means for testing a member in the uniformly moist condition attained by storage under water or in a fog room.

A strain gage suitable for testing moist concrete could be used for evaluating not only the stress-strain behavior, but also the moisture-dependent characteristics of concrete, including the shrinkage and swelling during transitions between the moist and dry states and dimensional changes resulting from freezing and thawing [1].[2]

The easiest method of attaching a satisfactorily waterproofed strain gage to moist concrete appeared to consist in embedding the gage within the concrete at the time of casting of a specimen or structural element. A number of advantages, apart from those to be gained in the testing of uniformly moist concrete, would accrue from the use of embedded gages: a single gage alined along a desired axis of strain would suffice where 2 or 4 surface gages were previously required; once

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[1] Materials Engineer, National Bureau of Standards, Washington, D. C.
[2] Figures in brackets refer to literature references given on p. 61.

safely embedded, the gage would be protected from mechanical damage; and the specimen would be ready for testing without the period of preparation necessary for drying the specimen surface, attaching the gages, and curing the gage adhesive. An additional advantage would be the possibility of determining the distribution of strain within structural members.

Design of the Gage

In order to satisfactorily embed a bonded-wire resistance gage in concrete a protective covering was required that would completely waterproof the strain-sensitive element, and which would be of a material that an adhesive or frictional bond would be formed between the covering and the cement-paste matrix of the surrounding concrete. The method chosen for waterproofing and for providing an effective medium for the transfer of strain from concrete to the strain-sensitive element was to enclose an SR–4-type gage element in a metal-foil envelope, bonding it to the inner sides of the envelope by means of a thermosetting adhesive.

Concrete consists of a mixture of fine and coarse aggregate held together by portland cement-water paste. The aggregate, particles of crushed stone or sand and gravel up to 1 in. or more in diameter, may constitute 70 percent or more of the volume of concrete. The elasticity, plastic flow, thermal expansion, and drying shrinkage of the aggregate and of the cement-paste matrix will generally be different. In order that an embedded gage might indicate correctly the strain in the concrete, the gage should be of sufficient length that possible irregularities in strain in the vicinity of large aggregate particles might be averaged out. Several types of SR–4 gages, including the A–9, were used in the present study. Of the hundred or more types of bonded-wire gages now commercially available, only the A–9 has a gage length exceeding 1 in. The A–9 consists of a single loop of 0.001-in.-diameter advance wire, about 6 in. long, bonded to a paper backing by means of a nitrocellulose adhesive. This gage has negligible transverse sensitivity and appears well suited for use in uniform strain fields (in the measurement of shrinkage and thermal expansion, for example), as well as for measuring the strain due to uniaxial stress in materials of uncertain Poisson's ratio.

Rolled-brass shim stock (70 copper-30 zinc), in 0.001- and 0.002-in. thicknesses, was found satisfactory in most respects as a gage covering. The brass could be bent, folded, and soldered without damage, and appeared to be impermeable to water vapor. The only disadvantage was a high coefficient of thermal expansion, 10×10^{-6} per deg F, or about 60 percent higher than a value commonly obtained for siliceous aggregate concrete. Steel matched concrete fairly closely in coefficient of thermal expansion, but was not used because of rusting and because the 0.001-in. stock cracked when folded. Electrodeposited copper foil was used with some of the first gages prepared, but was found to provide unsatisfactory protection from moisture over long periods of time.

The most satisfactory adhesives for bonding the SR–4 element to the inner surfaces of the brass envelope were the epoxy thermosetting resins.[3] Epon VI, the epoxy resin used in the present work, could be

[3] Epoxy resins are condensation polymers of bisphenol with epichlorhydrin.

cured at room or elevated temperatures (requiring only 2 to 3 hr at 160° F), with only contact pressure between the parts to be bonded, and necessitated no evaporation of solvent. The resin bonded equally well to paper- or Bakelite-type gages, to metal, and to rubber or other types of lead-wire insulation.

Resistance to the penetration of moisture is just as important for the lead wires that pass through the concrete as it is for the gage itself. Gages having No. 24 solid copper lead wires with natural rubber covering ⅛ in. in diameter showed an average leakage resistance exceeding 10,000 megohms after 60 days in water. Neoprene-covered solid copper wire is probably superior to natural rubber, especially over long periods, and metal tubing offers outstanding protection to lead wires, but the wall thickness must be small to avoid reinforcing the concrete. Todd [2] in England has made gages in which the resistance element and the lead wires were protected by metal and he has obtained leakage resistances of the order of 100,000 megohms.

Preparation of the Gage

Procedure

The A–9 gages were obtained from the manufacturer without the customary felt covers. Each of the elements, which were unprotected on one side, was first covered by a strip of ordinary typewriter bond paper, which was bonded to the base paper by nitrocellulose

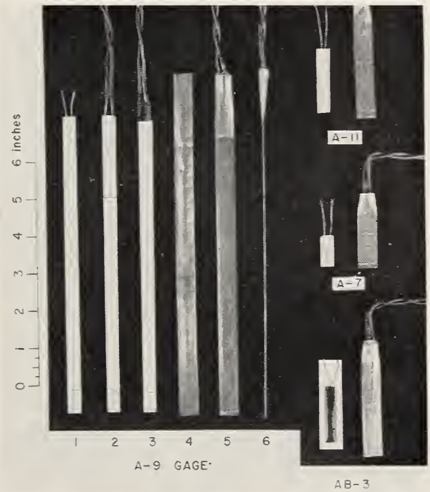

Figure 4.1. *Brass-encased, waterproofed, SR–4 strain gages.*

The steps in the preparation of the A–9 embedded gage are (1) paper-covered A–9 element, (2) rubber-insulated leads soldered to element, (3) soldered joint insulated, (4) empty envelope of 0.001-in. brass foil, (5) finished gage, and (6) edge view of finished gage less than 0.01 in. thick. Plain and brass-covered A–11, A–7, and AB–3 gage elements are also shown.

adhesive. Care was taken to avoid lateral displacement of the strain-sensitive wire because the solvent in the freshly applied adhesive softened the adhesive applied by the manufacturer to secure the element to the base.

Best results were obtained when only a very thin layer of adhesive was used; excess adhesive was removed easily with the finger before placing the cover paper. After curing the individual elements at 150° to 160° F for 24 hr they were trimmed to the size ⅜ by 8 in., as shown in 1 of figure 4.1.

The rubber-covered lead wires in suitable lengths were then lap-soldered to the leads of the gage (2 in fig. 4.1); the soldered joints were cleaned and then covered with electrical insulating tape (3 in fig. 4.1).

The gages were next given an additional 24 hr of curing at 150° to 160° F and were then stored in a desiccator over a suitable desiccant, such as silica gel, for at least 2 weeks prior to covering with brass foil. It was essential that no moisture was sealed into the gage.

Thin rectangular envelopes, ½ by 9 in., were formed by folding lengthwise degreased brass-foil strips 1¹⁄₁₆ by 9 in., with about ¹⁄₁₆ in. overlap at the seam; the seam was closed by soldering, and one end of the flat tube thus formed was folded over and soldered closed.[4] The other end of the envelope was left open for insertion of the gage and the lead wires. Each envelope was tested by forcing air into it while it was almost completely immersed in water. The envelopes were finally degreased by storage in clean solvent for several days, followed by several rinses, each time in clean solvent. Vapor degreasing with trichloroethylene is probably a better procedure. Careful degreasing was essential for proper adhesion. The finished envelope is shown in 4 of figure 4.1.

Both sides of the paper-sandwiched gage element were next coated with Epon VI or other epoxyresin adhesive, and the gage was inserted into the brass envelope so that a portion of the rubber-covered lead wires as well as the insulated soldered connections were inside the envelope. After manipulation to remove entrapped air from the envelope, the gage assembly was placed between two sheets of ¼-in.-thick rubber. The rubber sheets were backed by thick plywood boards, which were clamped so that the rubber sheets pressed against the flat sides of the brass-covered gage. The clamps near the closed ends of the envelopes (a number of gages are prepared at one time) were tightened first. After allowing time for the excess adhesive to move toward the open ends without bursting the envelopes, the remaining clamps were tightened. About 1 in. at the open ends of the envelopes was not covered by the rubber sheets; the excess adhesive moved into this region to form a solid thickened covering over the soldered lead connections and also allowed sufficient space inside the end of the envelope for final waterproofing. Although only contact pressure was required for adhesion, rather large pressures were applied to the gages through the cushioning layers of rubber in order to make the adhesive layer as thin as possible and to obtain a gage of uniform thickness.

The clamped gages were cured for 3 or 4 hr at 150° to 160° F. Waterproofing of the gages was completed by filling the space in the open end of the envelope with hot microcrystalline wax, a drop at a

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[4] Seamless thin-wall tubing may also be used.

time, and allowing each drop to harden before placing the following drop.

The finished gages (5 and 6 of fig. 4.1) were stored under water for at least 1 week with the ends of the lead wires kept dry. When any of the gages showed a low leakage resistance between the resistance element and the water, or a decrease in leakage resistance during immersion, the gage was discarded. Although leakage resistances exceeding 10,000 megohms were generally obtained, and a high value is desirable for a continuous test covering a long period of time (such as a shrinkage test), good results have been obtained in short-time tests (such as stress-strain measurements) with gages having relatively low leakage resistances (50 to 100 megohms). A decrease in leakage resistance during the period of immersion appeared to be a better indication of trouble ahead than a low but stable or increasing value.

The detailed steps outlined for waterproofing the A–9 gage were applicable to other types of SR–4 gages, including the AB (Bakelite) as well as the paper-base A types. The A–7 (¼-in. gage length), the A–11 (1 in.), and the AB–3 (1³⁄₁₆ in.), which have relatively low transverse sensitivities, were waterproofed by the procedures described above, as shown in figure 4.1. The AB–11 (⅞ in.) has also been waterproofed. Additional care was required with some of these shorter gages because they are not designed for bonding on both sides. The paper or Bakelite covering of the gage lead wires was frequently too thin to prevent short-circuiting when the gage was bonded to the inner walls of the brass envelope. The trouble was eliminated when the vulnerable area was insulated by covering with thin, tough paper (such as graph paper), using an epoxyresin for Bakelite gages, and an epoxyresin or nitrocellulose cement for the paper-base gages.

Adjustment of Young's Modulus of the Gage

It may be desirable to prepare gages having a known equivalent Young's modulus of elasticity in order to evaluate approximately the shear stresses at the bonded surface of an embedded gage. Figure 4.2 is an idealized representation of the cross section of an A–9 gage covered with 0.001-in. brass showing one of the two cross sections of 0.001-in. advance wire which forms a single, long strain-sensitive loop. The equivalent modulus of elasticity was the weighted mean of the moduli of all components of the gage structure, based upon the proportion of the total cross-sectional area comprised by each component.

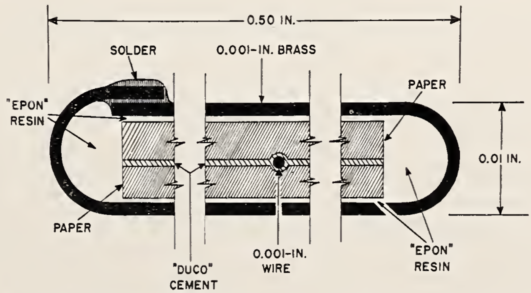

FIGURE 4.2. *Cross section of A–9 brass-encased strain gage showing one of the two cross sections of strain-sensitive wire of the 6-in. long "loop".*

The brass covering had a modulus that was high 17×10^6 psi) in relation to the moduli of the other materials of the gage assembly (less than 0.5×10^6 psi for paper and adhesive). The modulus of the gage could be increased by using a thicker brass covering, or it could be decreased by adding layers of paper and adhesive in such a way as to build up the thickness of the gage.

Young's moduli were determined directly in tension tests for brass strips of several thicknesses and for a few of the brass-covered gages. Values for the gages were also calculated, on the basis of the average thicknesses of the gages and the gage components, and were found to be in good agreement with the directly measured values. Average thicknesses of the gages were calculated from the volume of liquid displaced, which was determined by weighing the gage in air and with the sensitive portion of the gage immersed.

Behavior of Embedded Gages

Elastic Incompatibility of Concrete and Gage

The ideal gage for measuring strain within a concrete element might be an included solid body, perfectly bonded over its entire surface to the surrounding concrete, and having elastic, thermal, and moisture properties identical with those of the concrete. Unfortunately, the stress-strain behavior of concrete makes it impossible to design an internal gage that will be elastically compatible with the concrete. The typical stress-strain curve for concrete decreases in slope as the stress increases, and the modulus of elasticity must be defined—usually as the slope of a secant drawn through the origin and a point on the curve corresponding to a predetermined value for stress or strain. The secant modulus will vary with the rate of loading of the concrete, due to the relatively high degree of time-dependent flow that characterizes solids containing portland cement. The modulus will vary with the moisture condition and will depend upon the degree of hydration of the cement particles, and therefore will depend upon the age of the concrete and the conditions of curing. In addition, the shape of the stress-strain curve will be affected by the previous loading history. The modulus also will be influenced by the mix proportions, the type of aggregate, the type, and even the brand of cement used.

Relation to Previous Work on Inclusions

Nils Hast of Sweden, in a comprehensive study of the stresses and strains in solids [3], examined the effects of gage dimensions and of the ratio of Young's modulus of the gage to that of the concrete, E_g/E_c, upon the behavior of cylindrical stress gages embedded in concrete; Monfore [4] and Loh [5] performed similar studies in this country. In each case the gage was embedded with its axis parallel to the direction of loading. The load was transmitted from the concrete normally to plane, rigid end surfaces of the gage. Precautions were taken to prevent bond with the curved gage surface. It was necessary, in some cases, to prestress the gages in order that they might function in tensile, as well as compressive, stress fields. Hast derived equations, which were based upon the work of Boussinesq [6] in the field of stress concentrations, relating the ratio of stresses in an embedded gage and the surrounding concrete to the modular ratio, E_g/E_c, the gage slenderness ratio, L/R, and Poisson's ratio for the concrete, μ. Loh modified the relationship and gave the following equation for calculating the theoretical error in strain indicated by long, slender, cylindrical embedded gages:

$$\text{Error} = \frac{\epsilon_{\text{ind.}} - \epsilon}{\epsilon} = \frac{\left[1 - \frac{E_g}{E_c}\right] \frac{\pi R}{L} \frac{1-\mu^2}{2 - \frac{R}{L}(1-\mu^2)}}{1 + \frac{\pi R}{L} \frac{E_g}{E_c} \frac{1-\mu^2}{2 - \frac{\pi R}{L}(1-\mu^2)}}$$

Theoretical errors based on Loh's equation were calculated for brass-covered gages, A–9 (L/R=170 to 240), A–11 (L/R=35 to 50), and A–7 (L/R=20 to 28), for modular ratios ranging from 0.1 to 10.0, and are plotted as the family of curves in figure 4.3. R was calculated as the radius of a circle equal in area to the cross-sectional area of the gage, and μ was assumed to be 0.17. The loading of the brass-covered gage was essentially a shear load received by the lateral surfaces of the gage embedded with its axis parallel to the direction of load applied externally to the concrete, whereas the loading of the gages of Hast, Monfore, and Loh was a compression or tension normal to the end surfaces of the gage. The transfer of strain from concrete to the brass-covered gage was effected by the bond between the brass covering and the cement paste in the concrete.

The problem of evaluating stresses and strains in and around inclusions of various shapes has received mathematical treatment by Goodier [7], Donnell [8], Edwards [9], and Robinson [10]. Solutions are indicated for cases in which the axes of the inclusion are parallel to the principal stresses in a surrounding infinite solid, and for the case in which an infinite solid and inclusion are subjected to a change in uniform temperature. Solution of the thermal problem indicates the approach to solving the problem for inclusions (that is, gages) in a solid deformed by causes other than a change in externally applied load, for example, drying shrinkage and plastic flow in concrete. Robinson's treatment of the strain energy, stresses, and strains in the ellipsoidal inclusion is the most general because, by selecting appropriate relationships among the three elliptic axes, it may be made to cover inclusions in the shape of a sphere, and, approximately, in the shapes of a long, circular cylinder or rectangular strip. The work of Robinson gives due weight to the effect of the ratio of cross-sectional perimeter to area.

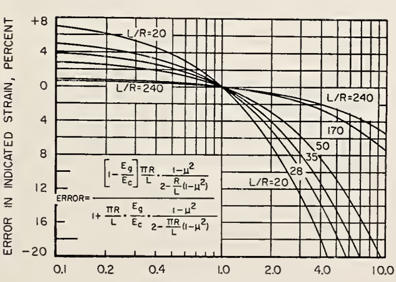

FIGURE 4.3. *Theoretical percentage error in strain indicated by gages embedded in a solid as a function of modular ratio, E_g/E_c, and slenderness ratio, L/R, calculated from the equation shown, due to Loh, using the value of 0.17 for μ, Poisson's ratio, and calculating R as the radius of a circle equal in area to the cross sectional area of the gage.*

Calculation of Bond Stresses

Rather simpler methods are available that yield qualitative criteria for the design of embedded gages. We may utilize the concept of "bond stress" as employed in the analysis of the behavior of reinforcing bars in concrete. When concrete containing an embedded gage is strained in the direction of the length of the gage, the loading of the gage may be assumed to consist of two equal and opposite shear loads, each of which is effective over a half-length of the gage. The average bond stress may be defined as the maximum axial load divided by one-half of the bonded area. Approximate average bond stresses, calculated for a gage strain of 1,000 μin./in., are given in table 4.1 for typical A–9, A–11, and A–7 gages covered with 0.001- and 0.002-in. brass. A strain of 1,000 μin./in. is roughly equivalent to: (a) two times the ultimate drying shrinkage of a small (2 by 2 by 12 in.) unconstrained concrete prism; (b) the difference in linear contraction between brass and concrete caused by a decrease in temperature of 250° F; (c) the plastic flow in concrete under a stress equal to 0.2 times the ultimate compressive stress, sustained over an indefinitely long period of time; and (d) about two or more times the nonelastic component of strain at a compressive stress equal to 0.9 of the ultimate in the usual type of stress-strain determination made upon concrete 28 days old.

TABLE 4.1. *Calculated average bond stresses for typical brass-covered gages*

Gage type	Gage length	Embedded length	Gage thickness	Effective bonded area [a]	Thickness of brass covering	Approximate modulus of elasticity of gage (E_g)	Load on gage	Calculated average bond stress [b]
	in.	*in.*	*in.*	*in.*²	*in.*	*psi*	*lb*	*psi*
A–9	6.0	8	0.007	4.0	0.001	5.0×10⁶	17.5	4.4
A–9	6.0	8	.008	4.0	.002	9.0	36.0	9.0
A–11	1.0	1.5	.007	0.75	.001	5.0	17.5	23.0
A–11	1.0	1.5	.008	.75	.002	9.0	36.0	48.0
A–7	0.25	0.9	.007	.45	.001	5.0	17.5	39.0
A–7	.25	.9	.008	.45	.002	9.0	36.0	80.0

[a] The breadth of all gages was 0.5 in.
[b] Calculated for a strain in the gage of 1,000 μin./in.

The average bond stress for gages of circular cross section equal in area to the cross-sectional areas of the gages of table 4.1 would be about five times the values shown, were E_g to remain unchanged. Because a low value of average bond stress is desirable, the ideal embedded gage will have the highest practicable ratios of length and cross-sectional perimeter to cross-sectional area, and the lowest practicable E_g.

How great a value of average bond stress may safely be tolerated will depend upon the nature of the bond between the embedded gage and the cement-paste constituent of the concrete, and the distribution of bond stress along the length of the gage. It is known that the bond stress will not be uniform along the length of the gage, but will be concentrated largely at the ends [11]. The concentration of stresses in the concrete in contact with the ends of the gage may be sufficient to cause local yielding and end slip, depending upon the shear strength of the concrete. To prevent end slip from affecting the measurement of strain a "dead" region extending beyond the ends of the strain-sensitive element should be built into the gage. All of the brass-covered gages contained a dead region at the ends, which, in the case of the A–9, extended at least ¾ in. beyond the working length of the gage, or about 100 times the minimum gage thickness. It is seen that the longer the gage, the smaller will be the proportion of the gage length that may be adversely affected by stress concentration at the ends.

Effect of Misalinement

Methods of Embedment of Gages

The effect of misalinement of a gage by an angle θ from the axis of compressive of tensile strain, along which measurement is desired, is an indicated strain smaller than the axial strain. As shown in figure 4.4, the indicated strain will be 1 percent lower than the axial strain for $\theta=5°$, about 3.5 percent lower for $\theta=10°$, and about 8 percent lower for $\theta=15°$. If Poisson's ratio differs from 0.17, a value generally assumed for concrete, the error will be changed very little. An error as high as 3 to 5 percent may be tolerated in many tests of concrete.

In using the embedded gage for measurements of drying shrinkage, thermal expansion, and volume changes resulting from freezing and thawing, the effect of misalinement will be negligible because of the relative uniformity of the strain fields in these cases. Even in the case of highly directional shrinkage, etc., the error will be considerably smaller than in the case of stress-strain measurements.

Two methods were used in embedding the gages in concrete. One consisted in orienting the gage within the empty mold or form by a suspension of wires soldered to the envelope and attached to the mold, or by a suspension of waterproof tape. This method is preferred if the aggregate size is small, or if the specimen in which the gage is to be embedded is made of plaster of paris, mortar, or cement-water paste. The pouring of concrete containing large, dense aggregate particles into a mold with a suspended gage may destroy the suspension or damage the gage; the rodding generally performed to consolidate the concrete must be done with extreme care to avoid damaging the suspension or the gage.

The second method, preferred for embedding the long A–9 gages in concrete members, consisted in first fabricating the specimen and then inserting the gage in the fresh concrete, gaging the alinement visually.

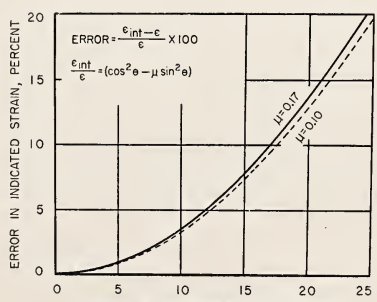

FIGURE 4.4. *Error in indication of strain along an axis of strain due to misalinement of embedded gage with respect to that axis, for two values of Poisson's ratio.*

As will be shown later, this method did not result in satisfactory embedment of the relatively short A–11 gages. Some difficulty was also experienced when this method was used for A–9 gages in the bending or rupturing of the brass envelope as a result of pushing the end of the envelope against a coarse aggregate particle during insertion. This difficulty may be avoided by using an inserter, consisting of a flattened tube, to facilitate placement.

Inherent Errors

Questions have arisen regarding the long-time stability and temperature sensitivity of bonded-wire gages; these questions must be considered in connection with the physical relationship between the strain-sensitive wire and the adhesive and matrix that surround the wire. The degree of mismatch in the physical properties of these elements is far greater than it is in the case of the brass-covered gage as a whole embedded in concrete. The modulus of elasticity of the gage wire is 50 to 100 times greater than that of the matrix and adhesive, and the coefficients of thermal expansion differ to a similar degree.

Much has been written concerning an apparent lack of stability (that is, zero drift and drift under sustained strain) in bonded-wire gages. Faulty preparation of the gage and test surface for bonding and waterproofing, plastic flow in the test object, and unstable instrumentation are the probable causes of instability in many cases. Campbell [12] has shown that appreciable zero drift occurs during the first several cycles of strain or temperature change, and has indicated that preworking of the gages may eliminate this source of trouble. This was accomplished simply with the brass-covered gage by manually straining or temperature cycling the gage several times before embedding it in concrete.

According to Jones [13], the maximum drift due to plastic flow in the adhesive and matrix surrounding the gage wire is 50 μin./in. for a strain of 2,500 μin./in. sustained for 6 months. These values, for paper-backed gages having gage lengths 1 in. or less are about two times the values for Bakelite gages. Jones states that the effect of plastic flow in the adhesive is to alter the stress distribution at the ends of the gage winding, affecting very little the working length of the wire. The smaller the proportion of the winding subjected to the disturbing end conditions, that is, the greater the gage length, the smaller will be the effect. The error in indicated strain should be well under 1 percent in a gage 6 in. long (A–9) subjected to a strain of 1,000 μin./in. sustained over a long period of time.

Errors due to the sensitivity of bonded-wire gages to changes in temperature may, in the laboratory at least, be cancelled out. If a gage identical to the gage embedded in a test specimen is bonded to a material having the same coefficient of thermal expansion as the test specimen, its use in a Wheatstone bridge compensates automatically for changes in temperature. An a-c bridge indicator, such as the Baldwin or Young models, satisfactorily minimizes thermoelectric effects.

Tests of Concrete Specimens with Embedded Gages

Each of 34 concrete specimens contained an embedded gage (table 4.2). Four of these were drying shrinkage prisms, 2 by 2 by 12 in., each with a different type of embedded gage: A–9 (6 in.), A–11 (1 in.), A–7 (¼ in.), and AB–11 (⅞ in.). All other concrete specimens were 6- by 12-in. cylinders, a standard size for compressive-strength tests. In each case the gage was embedded after placing and consolidating the concrete and was alined as determined visually at midheight (or midlength in the prisms) along the long axes of the specimens.

TABLE 4.2. *Mix proportions, strength, and modulus of elasticity of concretes*

Concrete	Proportions, by weight				Compressive strength	Secant modulus of elasticity, E_c[a]	Number of cylinders	Number of prisms
	Cement	Sand	Gravel	Water				
					psi	*psi*		
A	1	2.9	4.1	0.77	3,900	3.3×10^6	3	------
B[b]	1	2.8	2.7	.63	[c] 5,600	4.5	6	[d] 4
C	1	3.3	4.4	.72	3,000	3.9	12	------
D	1	2.3	3.3	.53	4,500	4.4	12	------

[a] Calculated as slope of secant drawn through origin and point on stress-strain curve corresponding to stress of 1,500 psi for concretes A and C, and 2,500 psi for concretes B and D.
[b] Contained high early-strength cement and ⅜-in. gravel. All other specimens contained normal portland cement and 1-in. gravel.
[c] Tested at age of 72 days; all other cylinders were tested at age of 28 ±2 days.
[d] Used for drying-shrinkage measurements from age 10 to 110 days.

Shrinkage Measurements

The shrinkage prisms, made with concrete B (table 4.2), were removed from the molds 24 hr after fabrication and stored under water at 73° ±2° F; initial gage readings were taken when the specimens were 10 days old, after which the specimens were allowed to dry in air at 73° ±2° F and 50-percent relative humidity for 100 days. A Baldwin type A strain indicator was used in making the shrinkage measurements; normal and reversed-leads readings were averaged to

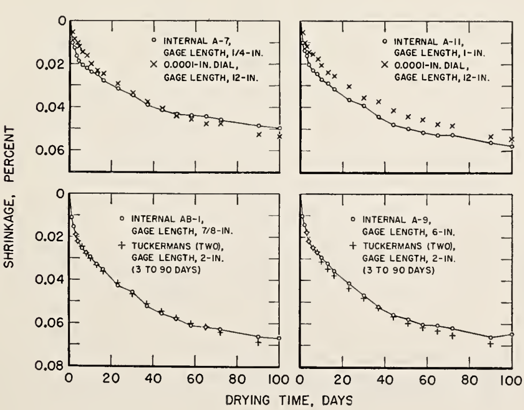

FIGURE 4.5. *Shrinkage during 100 days of drying of four 2- by 2- by 12-in. prisms of concrete, as indicated by embedded strain gages and by dial comparators and Tuckerman optical lever extensometers.*

The concrete contained 6 bags of high-early strength cement per cubic yard, sand, and ⅜-in. gravel; the prisms were removed from water storage at 10 days and dried at 73° ±2° F and 50 percent r. h.

minimize indicator drift. Compensating resistances were obtained from 0.1- to 1,000-ohm four-decade resistance boxes, which were checked monthly against primary standards in the Resistance Section of the National Bureau of Standards. Comparative measurements were made with a 0.0001-in. dial comparator (prism length, 12 in. as gage length), and with Tuckerman extensometers of 2-in. gage length [14]. The shrinkage curves for 100 days of drying are shown in figure 4.5.

Stress-Strain Determinations for Concrete

The concrete cylinders were removed from the molds 24 hr after fabrication, cured in a fog room at 73° ±2° F for a minimum of 21 days, and then stored in laboratory air (73° ±2° F) until tested. Concretes A, C, and D were tested at 28 ±2 days, and concrete B at 72 days.

Surface strains were measured in the axial direction with two A–9 gages and two 6-in. Tuckerman extensometers spaced uniformly about the circumference of each cylinder. (A–1, 1-in. gages were used in one case in place of the A–9 gages.) Lines connecting the centers of the two Tuckerman gages and of the two A–9 gages intersected at right angles at the midheight center of cross section. The Tuckerman gages were removed when the average strain reached 800 to 1,000 μin./in.

Table 4.3. *Secant moduli of elasticity of Concretes C and D*

Concrete	Number of speci-mens	Embedded gages			Secant modulus of concrete (E_c)[a]	
		Type	Gage length	Modulus of elasticity (E_g)	Embedded gage	Surface gages[b]
			in.	*psi*	*psi*	*psi*
C	2	A–9	6	5.0×10⁶	3.74×10⁶	3.78×10⁶
				3.3	3.72	3.94
				8.8	3.89	4.05
				6.0	3.89	3.93
				Mean	3.81	3.92
D	2	A–9	6	5.0	4.26	4.43
				4.2	4.32	4.39
				8.8	4.52	4.42
				6.0	4.51	4.55
				Mean	4.40	4.45
C	1	A–11	1	5.0	3.73	4.01
				4.5	3.94	4.03
				9.0	3.72	3.77
				6.0	4.07	3.95
				Mean	3.86	3.94
D	1	A–11	1	5.0	4.16	4.42
				4.5	4.49	4.39
				9.0	4.47	4.38
				6.0	4.34	4.42
				Mean	4.37	4.40

[a] Calculated as slope of secant drawn through origin and point on stress-strain curve corresponding to stress of 1,500 psi for concrete C and 2,500 psi for concrete D.
[b] Calculated from mean strain indication of 2 Tuckerman gages and 2 A–9 gages, all having a gage length of 6 in.

Each specimen was loaded by continuous compression at a rate of 500 psi/min in a hydraulic testing machine. The indications of all gages were obtained simultaneously as the load for each reading point was attained.

Stress-strain curves for cylinders with A–9 embedded gages are shown in figure 4.6 for concretes A and B and in figure 4.7 for concretes C and D; curves for cylinders of concretes C and D with embedded A–11 gages are shown in figure 4.8. The positions of surface and embedded gages are shown in insets in the figures. Values of E_c are listed for each cylinder of concretes C and D in table 4.3. Two values of E_c were calculated for each cylinder—from strains indicated by the embedded gage and from the mean strain indication of the surface gages (2 Tuckerman's and 2 A–9's).

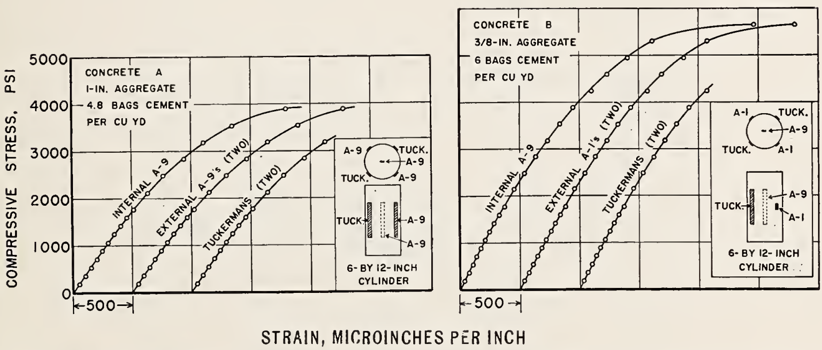

FIGURE 4.6. *Stress-strain curves for 6- by 12-in. cylinders of concrete containing embedded A–9 (6-in.) gages and external Tuckerman optical lever and A–9 or A–1 gages.*

Concrete A was 28 days old and concrete B, 72 days old at time of testing.

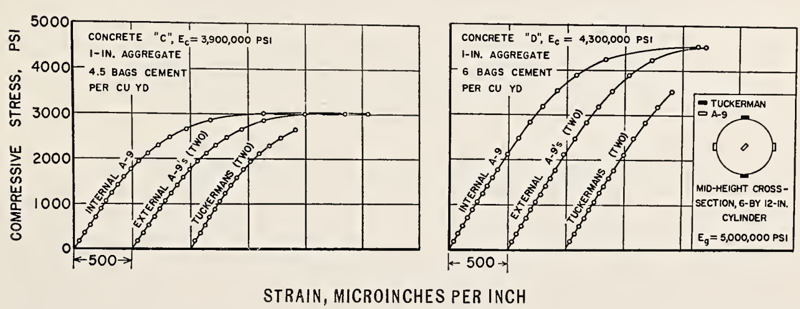

FIGURE 4.7. *Stress-strain curves for 6- by 12-in. cylinders of concretes C and D showing typical behavior of embedded A–9 (6-in.) and external Tuckerman optical lever and A–9 gages.*

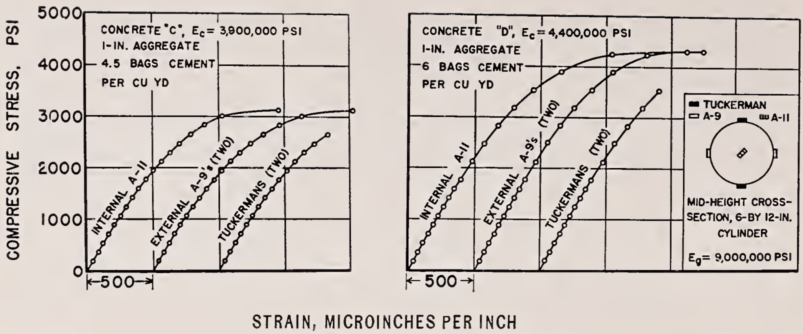

FIGURE 4.8. *Stress-strain curves for 6- by 12-in. cylinders of concretes C and D, showing typical behavior of embedded A–11 (1-in.) gages and external Tuckerman optical lever and A–9 (6-in.) gages.*

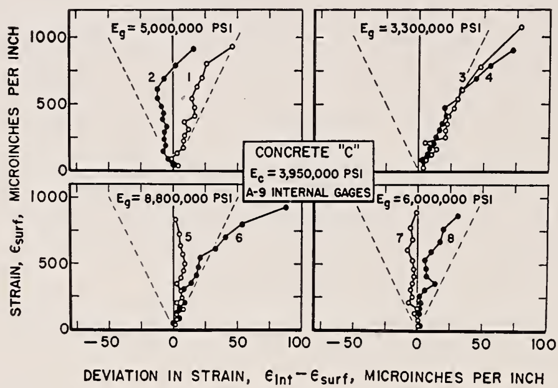

FIGURE 4.9. *Strain-deviation data for 6- by 12-in. cylinders of concrete C with A–9 (6-in.) embedded gages, tested in compression.*

The deviation is defined as the strain indicated by the embedded gage minus the average strain indicated by four surface gages (two Tuckerman optical lever and two A–9 gages). Broken lines define deviation of ±5 percent. Moduli of elasticity for each gage, E_g, and the average for the concrete cylinders, E_c, are also shown.

Strain Deviation Data for Concrete Specimens

Figures 4.9, 4.10, and 4.11 show strain-deviation data for the 24 cylinders of concretes C and D. The deviation is the difference between the strain indicated by the embedded gage and the mean strain indicated by the four surface gages, $\epsilon_{int} - \epsilon_{surf}$, and is plotted against ϵ_{surf}. Mean values for E_c for each group of specimens and approximate values for gage moduli, E_g, are also shown in figures 4.9, 4.10, and 4.11.

The data shown in figures 4.9, 4.10, and 4.11 have been corrected for misalinement according to figure 4.4, and the corrections are listed in table 4.4.

The longer A–9 gages were generally better alined than the A–11 gages, as shown in table 4.4; the misalinement of gages in specimens

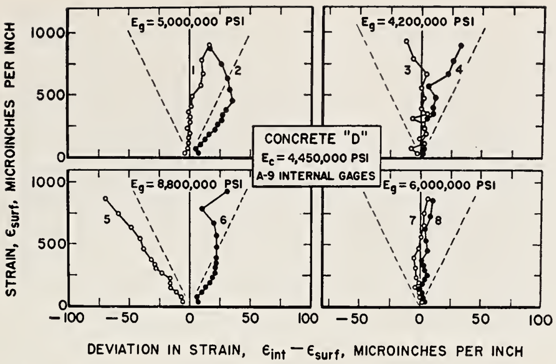

FIGURE 4.10. *Strain-deviation data for 6- by 12-in. cylinders of concrete D with A–9 (6-in.) embedded gages, tested in compression.*

The deviation is defined as the strain indicated by the embedded gage minus the average strain indicated by four surface gages (two Tuckerman optical lever and two A–9 gages). Broken lines define deviation of ±5 percent. Moduli of elasticity for each gage, E_g, and the average for the concrete cylinders, E_c, are also shown.

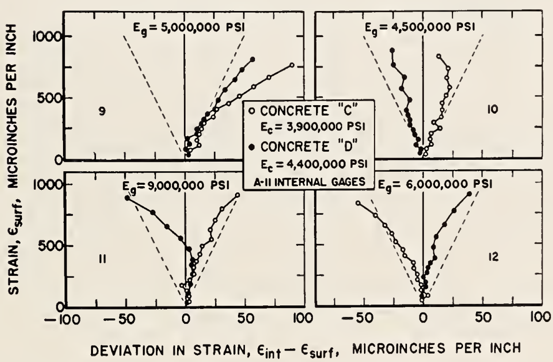

FIGURE 4.11. *Strain-deviation data for 6- by 12-in. cylinders of concretes C and D with embedded A–11 (1-in.) gages, tested in compression.*

The deviation is defined as the strain indicated by the embedded gage minus the average strain indicated by four surface gages (two Tuckerman optical lever and two A–9 gages). Broken lines define deviations of ±5 percent. Moduli of elasticity for each gage, E_g, and the average for the concrete cylinders, E_c, are also shown.

3 and 5 of concrete D was caused by a buckling of the gage during insertion when the end of the gage was apparently pushed against a piece of coarse aggregate. The use of the previously discussed flattened-tube inserter would eliminate this difficulty. It may be seen that the deviations in strain for specimen 9 of concrete C and specimen 9 of concrete D would have been smaller had the corrections for misalinement not been made.

Figure 4.12 shows portions of two broken 6- by 12-in. cylinders, one with a properly alined, and the other with a misalined A–9 embedded gage.

Strain-deviation data are summarized in table 4.5 for 24 cylinders

FIGURE 4.12. *Broken concrete cylinders with properly alined (left) and misalined (right) embedded A–9 (6-in.) gages.*

TABLE 4.4 *Corrections for misalined gages.*

Specimen number	Concrete	Embedded gage	Misalinement	Correction [a]
			Deg	*Percent*
7	C	A–9	9	2.9
9	C	A–11	11	4.3
10	C	A–11	17	10.0
11	C	A–11	15	7.8
3	D	A–9	15	7.8
4	D	A–9	10	3.5
5	D	A–9	16	8.9
9	D	A–11	13	5.9
10	D	A–11	7	1.9
11	D	A–11	13	5.9

[a] From figure 4.5.

TABLE 4.5. *Mean strain deviation data for strains compared at 200, 400, 600, and 800 microinches per inch* [a]

Embedded gage type	Concrete	Number of specimens	Deviation of mean				Mean deviation			
			$\frac{\epsilon_{int}-\epsilon_{surf}}{\epsilon_{surf}}$	$\frac{\epsilon_{int}-\epsilon_{A9}}{\epsilon_{A9}}$	$\frac{\epsilon_{int}-\epsilon_{T}}{\epsilon_{T}}$	$\frac{\epsilon_{A9}-\epsilon_{T}}{\epsilon_{T}}$	$\frac{\epsilon_{int}-\epsilon_{surf}}{\epsilon_{surf}}$	$\frac{\epsilon_{int}-\epsilon_{A9}}{\epsilon_{A9}}$	$\frac{\epsilon_{int}-\epsilon_{T}}{\epsilon_{T}}$	$\frac{\epsilon_{A9}-\epsilon_{T}}{\epsilon_{T}}$
			%	%	%	%	%	%	%	%
A–9	C	8	+2.3	+1.7	+3.3	+1.6	3.1	3.4	3.9	2.5
A–9	D	8	[b] +0.7	+1.4	+0.4	+1.5	3.1	4.7	4.1	5.6
A–11	C	4	+2.4	+2.8	+1.8	−1.0	4.6	5.3	3.8	2.7
A–11	D	4	+0.8	+2.2	−0.4	−2.8	3.3	4.4	1.6	4.1
Grand average		24	+1.6	+1.9	+1.4	−0.6	3.4	4.3	3.5	3.8

[a] Strains indicated by embedded, external A–9, and Tuckerman gages are denoted by symbols ϵ_{int}, ϵ_{A9}, and ϵ_T, respectively. ϵ_{surf} denotes the mean surface strain indicated by 2 Tuckerman and 2 external A–9 gages.

[b] Includes deviation −8.5 percent for specimen number 5; largest other negative deviation for A–9 embedded gages was −1.6 percent. Mean value would be +2.3 percent for 7 specimens, omitting specimen number 5.

of concretes C and D. The deviations for each cylinder were averaged for internal gage strains of 200, 400, 600, and 800 μin./in. The strains indicated by the embedded gages averaged 1.6 percent higher than those indicated by the external gages, as shown by deviations of the means in table 4.5. The mean of the absolute individual values of these deviations, as shown by the mean deviations in table 4.5, was 3.4 percent, or slightly lower than the average deviation of the strains indicated by the Tuckerman gages from those indicated by the pairs of surface A–9 gages. The uncertainty in Tuckerman readings was somewhat higher than the ±1 percent associated with the SR–4 gage factors, because of the method of attaching the Tuckerman extensometer. The knife edges of the extensometers were seated on two brass strips, about 3/32 in. wide, which were cemented to the concrete 6 in. apart, and which introduced an uncertainty in gage length of about ±1.5 percent.

The embedded A–9 gages showed higher strain than the surface gages in 12 of 16 cylinders; in only 1 of the 4 other cylinders did the surface strain differ by more than 1.6 percent from the internal strain, and that was in the case of specimen 5 of concrete D, in which the deviation was −8.5 percent. The deviations did not vary significantly with strain in the range 200 to 800 μin./in. At higher strains the pattern gradually developed toward that shown at failure, at which point the internal strain averaged about 20 percent higher than the external strain. The average internal strain at failure was about 2,100 μin./in.; in view of the very high rate of straining near failure, this value must be regarded as an approximation.

The difference between internal and external strain at very high strains is shown in the stress-strain curves for specimen 2 of concrete C in figure 4.13. As occasionally occurs in concrete of this type, the specimen did not shatter at failure (maximum stress) but continued to deform as the testing machine head continued to travel and as the indicated load decreased. At the last point for which meaningful data could be obtained from the surface gages, before the concrete to which they were attached fractured away from the remainder of the specimen, the internal strain was more than 1,000 μin./in. greater than the external strain. The stress could not be evaluated for the very high internal strains because the effective cross section of the specimen had been reduced by an unknown amount. The loading for which data are shown was the second for this particular specimen,

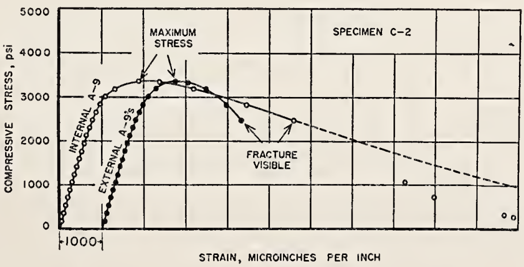

FIGURE 4.13. *Stress-strain curves for specimen of concrete C showing strains indicated by embedded and (two) surface A–9 (6-in.) gages after the occurrence of "failure" (maximum stress).*

accounting for the relatively straight stress-strain relationship during early loading.

The tests of the standard 6- by 12-in. concrete cylinders with embedded gages provided satisfactory results despite limitations inherent in that type of specimen. The low slenderness ratio made it quite difficult to obtain uniform strain around the circumference of the loaded specimen even for the most careful adjustment of the position of the specimen in the testing machine, because of the relatively large proportion of the specimen affected by end constraints.

The inherently variable nature of concrete apparently contributed to observed variations in strain within the stressed specimens; this is shown in table 4.5 by the deviations between strains indicated by the Tuckerman gages and the A–9 surfaces gages, which are comparable with the deviations between internal and surface gages.

Tests of Other Materials With Embedded Gages

In order to examine the behavior of embedded gages in more homogeneous materials, specimens were made of plaster of paris, which generally exhibits a linear stress-strain relationship, and cement mortar. The plaster specimen was a 6- by 36-in. cylinder, the slenderness ratio being sufficiently large to minimize the effects of end constraints upon the midheight of the specimen during testing. The mortar specimen was a 6- by 12-in. cylinder, the mix being proportioned, by weight, of 1 part of concrete sand to 3 parts of portland cement, with a water-cement ratio of 0.60. This specimen was 7 days old and had been air dried at 73 ±2° F for 3 days, when tested.

Each specimen contained seven embedded gages that were oriented to measure the midheight strain in the axial direction. A–9 (6in.), A–11 (1 in.), and A–7 (¼ in.) brass-covered gages were placed near the axis of the specimen (fig. 4.14). Four brass-covered A–9 gages were em-

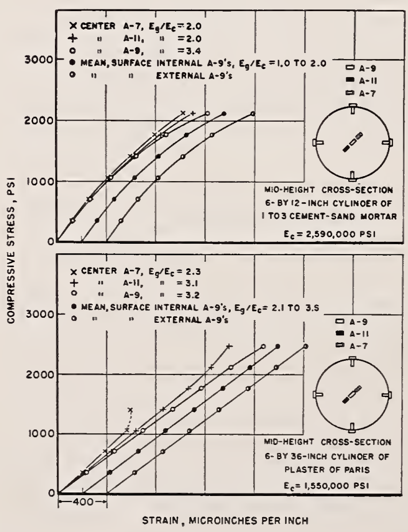

FIGURE 4.14. *Stress-strain curves for a plaster of paris 6- by 36-in. cylinder and a cement mortar 6- by 12-in. cylinder, as indicated by embedded A–9 (6-in.), A–11 (1-in.), and A–7 (¼-in.) gages at the centers of cross section, and by four A–9 gages embedded near the surface and four A–9 gages bonded externally to the surface of the specimens.*

Moduli of elasticity of the specimens, E_c, and gage/solid modular ratios, E_g/E_c, are also shown.

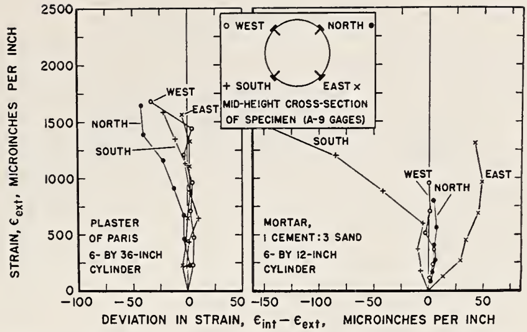

FIGURE 4.15. *Strain-deviation data for plaster of paris and cement mortar specimens for which compression stress-strain data are shown in figure 4.14.*

The individual deviations shown are defined as the strain indicated by a gage embedded near the surface minus the strain indicated by a gage bonded to the surface directly over the embedded gage.

bedded near the surface, and over each of these a paper-backed A–9 element was bonded to the specimen surface with nitrocellulose cement. This arrangement permitted comparison of the behavior of each of the gages embedded near the surface with that of its companion external gage; examination of the effect of gage length and comparison of the internal strains at the center and near the surface of each specimen were also made. Figure 4.14 shows stress-strain curves obtained from each of the center gages, and curves of the average strains indicated by the 4 external and by the 4 embedded surface gages. Comparisons of individual embedded and external surface gages are shown in figure 4.15. For the plaster specimen the deviations were within the ±1-percent manufacturer's tolerance in gage factor for virtually all readings; the mean deviation was negligible to a strain of 1,000 μin./in., despite values for E_g/E_c as high as 3.5:

The mortar specimen showed a variation in strain about the circumference and large individual deviations in strain at two of the gage stations (fig. 4.15). The mean deviation of the strain indicated by the 4 embedded surface gages from that indicated by the 4 external gates was 1.8 percent, averaged for readings taken at 9 increments of loading. The embedded gage at south station showed large negative deviations at 900 to 1,500 μin./in. which, it was established upon unloading, were due to a slipping of the gage during loading of the specimen.

Table 4.6 shows modular ratios and dimensions for the center gages, and calculated theoretical errors in gage indications as obtained from figure 4.3, as well as deviations of the strains indicated by the individual center gages from the average strains indicated by the four external gages. Data are shown for the plaster and mortar specimens, and also for a 6- by 36-in. cylinder of neat cement paste, for which additional data were not obtained. It may be noted that the short A–7 gage embedded in the plaster specimen did not function for strains greater than 600 μin./in., apparently because of a breaking of adhesion between the brass covering and the plaster.

TABLE 4.6. *Effect of modular ratio, E_g/E_c, and slenderness ratio, R/L, on behavior of embedded strain gages*

Specimen	Embedded-gage type	Gage length	Modulus of elasticity of specimen, E_c	Modular ratio, E_g/E_c	Slenderness ratio of gage, R/L	Deviation in strain $\frac{\epsilon_{int}-\epsilon_{surf}}{\epsilon_{surf}}$ [a]	
						Experimental	Theoretical [c]
		in.	*psi*			*Percent*	*Percent*
Plaster of paris (6- by 36-in. cylinder)	A-9	6	1.5×10^6	3.2	240	+2	−1.5
	A-11	1	1.5	3.1	45	−5	−6.5
	A-7	0.25	1.5	2.3	21	[b]−15	−9
Neat cement (6- by 36-in. cylinder)	A-9	6	1.9	2.4	220	+1	−1
	A-11	1	1.9	2.2	40	−2	−4
	A-7	0.25	1.9	2.1	23	−17	−6.5
Cement mortar (6- by 12-in. cylinder)	A-9	6	2.6	3.4	220	+4	−2
	A-11	1	2.6	2.0	45	+3	−3.5
	A-7	0.25	2.6	2.0	25	−2	−6

[a] Strain indicated by embedded gage is denoted by ϵ_{int}, and the average of the strains indicated by 4 external A-9 gages, by ϵ_{surf}.
[b] For indications unaffected by slip.
[c] From figure 4.3, using Loh's equation.

Conclusions

It has been demonstrated that a bonded-wire resistance strain gage, waterproofed by a thin brass covering, may be used successfully in the interior of moist concrete and other materials. It has been shown that the differences between strains indicated by embedded gages of this type and by surface gages bonded in the conventional way are of the same order of magnitude as differences between Tuckerman and paper-backed SR-4 gages bonded to the surface of concrete specimens. In some cases differences between internal and external gages were believed to be due to real differences in strain between the center and the surface of the specimen.

The brass-covered gage was designed according to outlined qualitative criteria, which show that internal strain may be indicated most reliably by an embedded gage having the largest practicable ratios of length to thickness and of perimeter to cross-sectional area, and the lowest practicable Young's modulus. Of the bonded-wire elements currently available, the 6-in. A-9 SR-4 gage best fulfilled dimensional requirements. References to work showing possible quantitative design criteria have also been given.

Further work is necessary to develop methods of embedment to assure alinement of the gages in a predetermined direction.

It appears desirable that additional work be done to determine the applicability of the waterproof strain gage in the continuous measurement of drying shrinkage, elastic and plastic strains, thermal expansion, and the dimensional changes resulting from the freezing and thawing of concrete over indefinitely long periods.

The use of the gages in concrete structural members and plaster models of structures is also an application yet to be studied.

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Discussion

Mr. R. G. Boiten, National Council for Industrial Research, Delft, Holland: In the first place, I compliment Mr. Valore on his paper, and, in my opinion, the excellent results he obtained with such a difficult material as concrete. In what way did you correct for temperature changes in the gage itself? We have found during work on large concrete blocks that the heat inside the structure can be appreciable.

In measuring the internal stresses developed during hardening, it would be necessary to take temperature into account. I showed a slide this morning very quickly because I had no more time. We had pickups of a type that were basically like my figure 2.22. They consist of hollow steel cylinders of certain lengths, and the wall thickness of the cylinders is chosen in such a way that they have the same stiffness as the replaced concrete. We get 28 percent extra output from the tangential gage, and the temperature compensation is all right.

Our latest design has another interesting feature. Two active gages are cemented on the inner surface of a cylinder in the direction of the axis, and they form, together with two dummy gages on a steel strip inside the pickup, a complete Wheatstone bridge for measuring strain. Another strip of bimetal inside the cylinder also carries 4 gages, 2 on each side of the strip, forming a Wheatstone bridge for measuring the temperature. To improve the heat conduction, the pickup is filled with silicon or transformer oil. A 6- or 8-core lead cable comes from the top of the instrument. We are thus able to measure the strain and the temperature with accuracy simultaneously. It seems to be a very nice instrument, especially in large concrete structures. If the temperature rise is too great, it affects the strain in the concrete.

Mr. Valore: The question of compensation for differences in temperature has not been approached as yet. You will recall that our immediate purposes in working with this gage were for use in research and testing in the field of concrete, particularly freezing and thawing, in which case external temperature compensation can be used.

5. Properties of Concrete Under Impact as Measured With Bonded-Wire Strain Gages

By David Watstein [1,2]

The effect of the rate of application of load was investigated with bonded-wire strain gages in compressive tests of two concretes having approximate compressive strengths of 2,500 and 6,500 psi. The concrete was tested in the form of 3- by 6-in. cylinders at rates of straining ranging from 10^{-6} to about 10 (in./in.)/sec. The higher rates of straining were obtained by loading the concrete specimens in a drophammer machine. The rate of loading in the drophammer machine was controlled by placing rubber buffers of appropriate thickness and hardness on top of the concrete specimens.

The compressive strength of the concrete increased markedly with the rate of loading. The maximum ratio of dynamic to static compressive strengths was about 1.8 for a rate of straining of 10 (in./in.)/sec. The values of the secant moduli of elasticity increased significantly with the rate of application of load; the maximum ratio of dynamic to static modulus was 1.47 for the "weak" concrete and 1.33 for the "strong" concrete. Resistance of the concrete to impact as measured by its ability to absorb strain energy also increased with the rate of application of load.

Introduction

In designing a structure subject to impact loading, the engineer faces the twofold problem of determining the peak loads on the structure and ascertaining the mechanical properties of the structural material. The present report is concerned with the latter problem, that is, the determination of the strength and elastic properties of plain concrete under impact.

In the field of reinforced concrete the designer has to know the properties of two distinctly different materials: steel reinforcement and concrete. While a number of investigators have studied the properties of structural steel and other metals under impact, the study of the effect of loading rate on the elastic properties of concrete has been confined to date to the relatively low testing speeds employed by Abrams [3] and Jones and Richart.[4] It was the purpose of the present study to extend the speed of testing of concrete into the range that has been made possible by the recent advances in the technique of measuring stresses and strains with bonded-wire strain gages.

The study included two concretes having approximate compressive strengths of 2,500 and 6,500 psi at 28 days. These concretes were designated as "weak" and "strong" concretes, respectively. Standard 6- by 12-in. cylinders served as control specimens and the dynamic tests were made on 3- by 6-in. cylinders.

Three series of dynamic tests were made with weak and strong concretes. Each series consisted of several sets of 4 cylinders, of

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[1] General Engineer, National Bureau of Standards, Washington, D. C.

[2] This paper was presented for Mr. Watstein by Mr. Walter Hunker.

[3] D. A. Abrams, Effect of rate of application of load on the compressive strength of concrete, Proc. Am. Soc. Testing Materials **XVII,** part II, 364 (1917).

[4] Paul G. Jones and F. E. Richart, The effect of testing speed on strength and elastic properties of concrete, Proc. Am. Soc. Testing Materials **XXXVI,** part II, 380 (1936)

which 2 were tested statically and 2 dynamically. There was a minimum of 6 and a maximum of 9 sets in the 6 series of tests carried out.

The approximate duration of the dynamic tests carried out in a hydraulic testing machine was about 0.9 sec. The duration of the impact tests, which were made in a drophammer machine, ranged from 0.004 to about 0.0003 sec.

Concrete Test Specimens

The materials used in the concrete test specimens were normal portland cement and White Marsh (Md.) aggregates. The aggregates were a siliceous sand and ⅜-in. gravel.

The proportions used in the weak and strong mixes are given in table 5.1.

Table 5.1

Concrete	Test series	Proportions, by weight			Water-cement ratio (by weight)
		Cement	Sand	Gravel	
Weak	W1	1	3.6	2.9	0.90
Do	W2	1	4.1	3.4	.90
Do	W3	1	4.1	3.4	.90
Strong	S1	1	1.5	2.0	.50
Do	S2	1	1.5	2.0	.50
Do	S3	1	1.5	2.0	.44

The test specimens used in dynamic and companion static tests were 3- by 6-in. cylinders. A set of four 3- by 6-in. specimens was cast in a four-cylinder gang mold, and one 6- by 12-in. control cylinder was cast from the same batch of concrete to represent a given set of four smaller cylinders.

The 6- by 12-in. control cylinders were fabricated in accordance with standard procedure; the 3- by 6-in. cylinders were made in a similar manner, except that a smaller tamping rod was used to consolidate the concrete. A pair of each set of 3- by 6-in. cylinders was tested statically, and one pair was tested dynamically.

The concrete was mixed in a tilting-drum mixer of 1-cu-ft capacity. The water, gravel, cement, and sand were added to the mixer in that order, and the mixing was continued for 2 min after the mixer was charged.

All concrete cylinders were moist cured for 25 days and dried for 3 days prior to testing. The 3- by 6-in. cylinders were air-dried for 2 days to prepare the surface of concrete for application of bonded-wire strain gages. After application of the gages, the small concrete cylinders were placed in an oven maintained at 60° C for 3 to 4 hr. The specimens were then removed from the oven and were allowed to cool overnight in the laboratory.

The control cylinders were capped with a sulfur-silica capping compound. The 3- by 6-in. cylinders intended for a static test were capped with plaster of paris.

Testing Procedure and Apparatus

Static Tests

The 6- by 12-in. control cylinders were tested in a 300,000-lb-capacity hydraulic testing machine. The load was applied to the specimen at a loading rate of about 30 psi/sec. The controls of the testing machine were adjusted during the initial period of the application of load to correspond to the loading rate as given by the pacing disk, and no further adjustments were made as the specimen began to yield on approaching the maximum load.

In the static tests type A–2 bonded-wire gages were used. These gages had a nominal gage length of 1 in., a resistance of 300 ohms, and a gage factor of about 2. The ratio of the gage length to the maximum size of aggregate was about 2.7. However, in the exploratory phase of the program a few static specimens were tested with A–5 gages having a length of 0.5 in., and no significant difference from the longer gages was observed in the results.

A static specimen under test is illustrated in figure 5.1. The 3- by 6-in. concrete cylinder is shown being tested in a 60,000-lb-capacity hydraulic machine. The load was applied at a straining rate of approximately 1(μin./in.)/sec., and the 2 gages were read simultaneously with 2 strain indicators without stopping the application of load. In applying the load, the rate of travel of the ram was adjusted with the load valve during the initial stage of the test to correspond to a predetermined rate of application of stress as indicated by the load pacing disk. The load valve was then left undisturbed for the remainder of the test; the duration of the test was about 30 min.

Dynamic Tests

Tests made in a hydraulic machine (series 1)

The 3- by 6-in. concrete cylinders of this series were tested in a 60,000-lb hydraulic machine, which loaded the specimens with the ram running at full speed. The speed of the ram was approximately

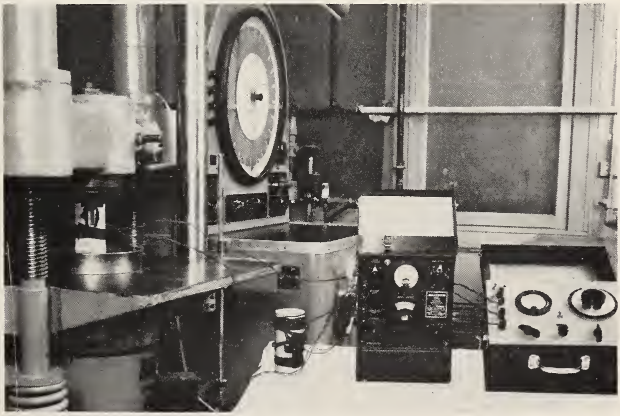


FIGURE 5.1. *Static test of 3- by 6-in. cylinder.*

5 in./min, the duration of test was about 0.9 sec, and the average rate of straining was about 0.003 (in./in.)/sec.

A 3- by 6-in. cylinder under test is illustrated in figure 5.2. The load was applied to the specimen through a 2-in. hardened steel ball interposed between two bearing plates having suitable spherical seats. After the specimen was centered in the machine, a small initial load was applied to it to aline the bearing plate with the fixed compression block in the crosshead of the machine; the crosshead was then elevated several inches, and the lower platen of the machine was pumped up at full speed until the specimen failed.

As can be seen in figure 5.2, the specimen was supported on a dynamometer which measured the applied load. The load indicated by the weighing mechanism of the testing machine was disregarded. The output of the dynamometer and the strain gages mounted on the concrete specimen were fed into the 4-channel carrier-type bridge and recording oscillograph shown in figure 5.2. A block diagram of this equipment is shown in figure 5.3.

Figure 5.2. *Dynamic test of series 1.*

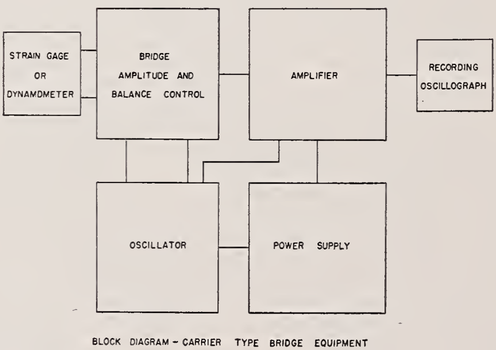


Figure 5.3. *Block diagram of measuring equipment used in tests of series 1.*

The concrete cylinders used in these tests were equipped with bonded-wire gages of type C–3. These gages had a nominal gage length of 1 in., a resistance of 500 ohms, and a gage factor of about 3.4.

Tests made in a drophammer machine (series 2 and 3)

The tests of series 2 and 3 were made in the drophammer machine illustrated in figure 5.4. The machine consisted essentially of a steel anvil supporting the test specimen, a drophammer and a device for catching the hammer on the rebound after the test. The anvil weighed 3,200 lb and was supported on four compression springs. The springs were designed initially to carry the anvil alone, and the natural period of the anvil was then nearly 1 sec. However, the oscillations of the anvil following the impact test were found to be excessive, and the travel of the anvil was limited by inserting 4 shock absorbers and 2 rubber buffers between the bottom of the anvil and the concrete base of the machine.

The anvil was constrained to move in a vertical plane during the impact by means of two sway plates. The sway plates, one at each end of the anvil, were attached through a hinge to the end of the anvil and were anchored to the concrete wall back of the machine through another hinge.

Measurements made with accelerometers attached to the anvil indicated that the displacement of the anvil during the impact was usually less than 0.01 in. After the anvil attained its maximum acceleration at the end of the impact, it continued to travel about 0.25 to 0.5 in. and was brought to a stop with the shock absorbers and rubber buffers.

The specimen shown on the anvil of the machine in figure 5.4 was mounted on a dynamometer. The hammer poised above the specimen weighed 140 lb and was tipped with a flat striking surface. The maximum height of drop that could be obtained in this machine was 5.5 ft, and the maximum velocity of the hammer was about 19 ft/sec.

The concrete test specimen shown in figure 5.4 was set in plaster of paris on the dynamometer and was capped with a steel plate. This

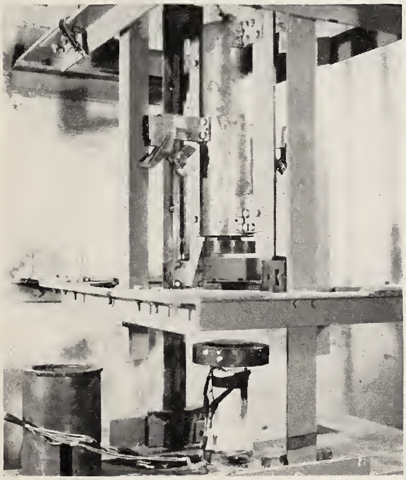


FIGURE 5.4. *Drophammer machine.*

steel capping plate served to distribute the load and to bring the drophammer to a stop after failure of the concrete specimen. During the test the cylindrical steel guard shown on the anvil was placed around the concrete cylinder. With the steel guard in place there was about ¼-in. clearance between the bottom of the capping plate and the rim of the guard having a rubber gasket. After failure of the concrete specimen, the capping plate came down on the rim of the guard and prevented the hammer from following through and damaging the dynamometer. The drophammer rebounded from the anvil and was stopped at the highest point of rebound by a pair of pawls which engaged the racks automatically.

The concrete specimens tested in series 2 and 3 were also equipped with type C–3 gages; the outputs of these gages and of the dynamometer were measured with the equipment illustrated in figure 5.5. The equipment consisted essentially of a pair of potentiometers whose outputs were fed into two preamplifiers. The amplified signals were then fed into a dual-beam cathode-ray oscilloscope. The traces on the tube were photographed with a 35-mm still camera. As illustrated in the block diagram in figure 5.6, the strain gages and the dynamometer formed parts of the two potentiometers, which were powered with batteries producing steady current of about 20 ma for normal operation of the equipment. In several instances the current in the strain gages was increased up to 30 ma to increase the output of the potentiometer. There was no noticeable drift or lack of stability in the cathode-ray oscilloscope after an initial warmup period of about 1 hr.

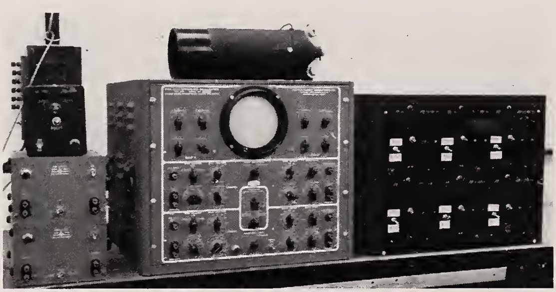


FIGURE 5.5. *Measuring equipment used in tests of series 2 and 3.*

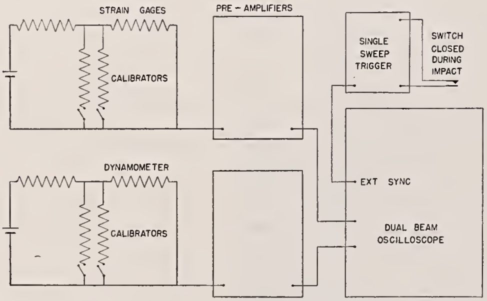


FIGURE 5.6. *Block diagram of equipment used in tests of series 2 and 3.*

The trigger shown in figure 5.6 operated by delivering an external synchronizing pulse in response to the closure of a pair of external contacts by the drophammer. The first closure of the external contacts provided the triggering pulse and all subsequent operations of the contacts had no effect on the output of the trigger. The external switch was mounted on one of the piers of the drophammer machine in the path of the sliding brackets that carried the drophammer along the guiding rails. The elevation of the external switch was adjusted with reference to the plane of contact of the hammer with the buffer placed on the test specimens to initiate the single sweep at a prescribed interval of time ahead of the impact. The duration of this interval was determined in accordance with the anticipated duration of impact, the sweep frequency of the oscilloscope and the velocity of the drophammer.

The duration of impact in the tests made in the drophammer machine ranged from about 0.004 to 0.0003 sec, and the corresponding average rates of straining ranged from 0.5 to 10 (in./in./sec.) The duration of impact was controlled by the type of buffer placed on top of the capping plate; the buffers were made of rubber varying in hardness, and their thickness ranged from 0.5 to 2 in.

Dynamometers

Two hollow cylindrical dynamometers were used in measuring applied forces in the dynamic tests. One dynamometer, made of dural, had a capacity of 50,000 lb and was used to test weak concrete cylinders. That used for testing the strong concrete specimens was made of heat-treated steel and had a capacity of 125,000 lb. The dynamometers were equipped with type C–3 bonded-wire gages. Four of these gages were arranged around the periphery of each cylindrical dynamometer in a manner calculated to compensate for bending of the dynamometer. The gages were attached to the dynamometers with nitrocellulose cement and were dried in air several hours before being cured in an oven at 60° C. Immediately upon removal from the oven, the gages were given a coating of hot cerese wax, which satisfactorily kept atmospheric moisture out of the nitrocellulose cement.

Calibration of Equipment

The dynamometers were calibrated statically at intervals during their period of service; these calibrations consisted in loading the dynamometer in a testing machine and observing the corresponding values of loads and changes in resistance of the bonded-wire strain gages. The calibrations of the oscillographs illustrated in the block diagrams in figures 5.3 and 5.6 consisted in introducing a known change in the resistance in the strain gages mounted on the concrete and those attached to the dynamometers. Actually, the change in resistance was caused by means of calibrating resistors thrown in parallel with the strain gages and the dynamometer, as illustrated in figure 5.6. The contacts of the calibrating resistors within the potentiometers used in tests of series 2 and 3 were made with a hand-operated single-throw three-pole switch. Two of the knives of the switch served to connect the calibrating resistors across the appropriate strain gages, while the third knife initiated the driven sweep in the oscilloscope. The leading edges of the three knives were carefully adjusted by filing to give the desired sequence of contacts.

A typical record of calibrations of the equipment used in the dynamic tests is shown in figure 5.7. In the series 1 tests, calibration of the equipment was made separately for the strain gages and the dynamometer; in the tests of series 2 and 3, the calibrations were made simultaneously. Two calibrating resistors were used in each of the potentiometer circuits to provide a check on the accuracy of the calibrations and test the linearity of response of the equipment to the calibrating signals.

Recording and Reduction of Data

The data obtained in tests of series 1 were recorded on photosensitized paper by galvanometers of type C. The records of data in tests of series 2 and 3 were obtained by photographing the 5-in. screen of a cathode-ray oscilloscope on 35-mm film, with a fixed focus camera having an f:3.5 lens.

Typical records of stresses and strains observed in the dynamic tests are illustrated in figure 5.7. The last frame in each test record shows two test traces obtained with the strain gages and the dynamometer. The strain trace is the signal produced by the two strain gages connected in series and represents the average strain in the specimen. The lower trace produced by the dynamometer represents the stress in the concrete. The time base in the record pro-

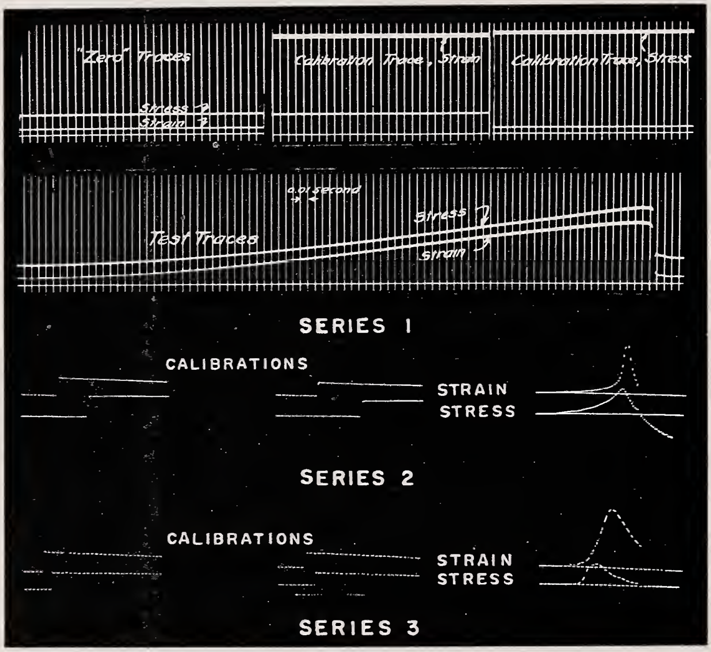


FIGURE 5.7. *Typical calibration and test records.*

duced in the recording oscillograph (series 1) was furnished by the transverse time marks, which were made every 0.01 sec. In the photographic records of the cathode-ray oscilloscope (series 2 and 3) the time base was furnished by an audiofrequency oscillator that modulated the intensity of the beams at a frequency ranging from 5,000 tp 20,000 c/s in such a manner that the traces of the beams became dotted lines.

In the records of data of series 1 a reference line was furnished by a fixed source of light in the recording oscillograph. In the photographic records of series 2 and 3, reference lines were produced by exposing the film to a single sweep of the beams immediately before photographing the test traces.

The data were reduced with the aid of a toolmaker's microscope either directly from the paper record or the 35-mm negative. The microscope had a magnification of 15 diameters. It was equipped with 2 micrometer screws, with which the stage could be transported in 2 mutually perpendicular directions.

Sonic Tests

In addition to determination of the modulus of elasticity in the static and dynamic tests by measuring corresponding values of stress and strain, a dynamic modulus was determined for the 3- by 6-in. concrete cylinders by the nondestructive sonic method. The values of the sonic modulus of elasticity were those computed from the fundamental longitudinal frequency of the cylinders.

The apparatus used in the sonic test consisted essentially of a variable frequency audio oscillator, an amplifier, a driving unit, and a pickup circuit. The amplified power of the oscillator was delivered to the driving unit, which was placed in contact with the concrete specimen. The specimen was supported on a thick pad of sponge rubber so as to permit it to vibrate with minimal restriction. The output of the pickup unit held against the concrete specimen was fed into a cathode-ray oscilloscope to determine resonant frequency of the specimen. The pickup was also used as a probe to identify the mode of vibration set up in the specimen by ascertaining the locations of the nodes along the length of the cylinder.

The sonic modulus was computed from the formula relating the velocity, v, of propagation of sound in the material, its density, ρ, and modulus of elasticity, E.

Results and Discussion

Comparison of the properties of the weak and strong concretes under static and dynamic rates of loading is given in table 5.2. The table lists the average values of data obtained in 6 series of dynamic tests, 3 each for the weak and strong concretes, and the companion static tests. Because only the average data are presented in this table, the coefficients of variation are given in the table as a measure of the dispersion of the data.

Compressive strength

The static compressive strength of the concrete is given in the table for both the 6- by 12-in. control cylinders and the 3- by 6-in. test

TABLE 5.2. *Summary of results of static and dynamic tests*

Test series	Specimens					
	W1	W2	W3	S1	S2	S3
Compressive strength, f_c' (6- by 12-in. cylinders):						
f_c' psi	2810	2370	2400	6390	5500	6730
c[1] Percent	2.2	2.2	3.3	1.2	2.7	2.6
Static (f_s) and dynamic (f_d) compressive strength (3- by 6-in. cylinders):						
f_s psi	2940	2390	2610	6730	6210	7350
c Percent	1.2	1.1	1.7	1.0	1.7	2.6
f_d psi	3210	3730	4830	7620	9430	13240
c Percent	1.8	2.0	1.8	1.0	2.9	2.8
f_d/f_s	1.19	1.57	1.84	1.13	1.53	1.85
c Percent	1.2	2.0	1.8	1.6	2.0	3.0
Modulus of elasticity (3- by 6-in. cylinders):						
Initial tangent:						
Static:						
E_s 10^6 psi	3.00	3.00	3.10	3.83	3.86	5.27
Dynamic:						
E_d 10^6 psi	3.07	3.20	3.49	4.09	4.51	6.55
E_d/E_s	1.02	1.07	1.10	1.06	1.16	1.24
Secant at strain of 0.001:						
Static:						
E'_s 10^6 psi	2.21	2.12	2.29	3.80	3.68	4.92
c Percent	1.1	1.0	1.3	1.2	1.3	1.1
Dynamic:						
E'_d 10^6 psi	2.47	2.80	3.42	4.09	4.30	6.54
c Percent	1.5	2.4	2.8	2.1	2.6	1.9
E'_d/E'_s	1.12	1.32	1.47	1.07	1.17	1.33
c Percent	1.3	2.0	2.6	2.1	2.6	2.8
Sonic:						
El 10^6 psi	3.81	4.40	4.38	5.32	5.20	6.36
E_d/El	0.81	0.73	0.78	0.76	0.86	1.03
Strain at maximum stress:						
Static:						
ϵ_s 10^{-6} in./in.	2300	2050	1990	2610	2660	2190
Dynamic:						
ϵ_d 10^{-6} in./in.	2100	2280	2630	2540	2950	2700
ϵ_d/ϵ_s	0.91	1.14	1.32	0.98	1.11	1.26
Strain energy absorbed by specimens:						
Static:						
W_s in. lb/in.^{3}	4.97	3.70	3.88	11.37	10.74	10.44
c Percent	3.5	4.6	3.5	2.7	2.2	5.4
Dynamic:						
W_d in. lb/in.^{3}	4.47	5.68	8.41	12.09	16.96	21.12
c Percent	7.6	9.0	5.6	5.8	6.0	5.4
W_d/W_s	0.90	1.55	2.23	1.06	1.58	2.17
c Percent	10.0	9.2	8.1	2.6	6.1	7.8
Duration of impact:						
T sec.	0.90	0.0043	0.00025	0.86	0.0010	0.00043
c Percent	2.9	1.3	3.6	1.8	4.0	2.7
Average rate of stressing during impact:[2]						
$\dot{\sigma}_{avg}$ psi/sec.	3570	0.864×10^6	19.1×10^6	8870	9.14×10^6	3.14×10^6
c Percent	1.8	1.5	2.8	1.4	3.8	2.8
Average rate of straining during impact:[2]						
$\dot{\epsilon}_{avg}$ (in./in.)/sec.	0.00364	0.531	10.1	0.00296	2.86	6.69
c Percent	5.4	6.3	5.0	3.9	4.2	4.3

[1] c=coefficient of variation; n, the number of observations, varied from 6 to 18.
[2] $\dot{\sigma}_{avg}$ and $\dot{\epsilon}_{avg}$ are defined, respectively, as the maximum stress and the strain at maximum stress, divided by the duration of the test.

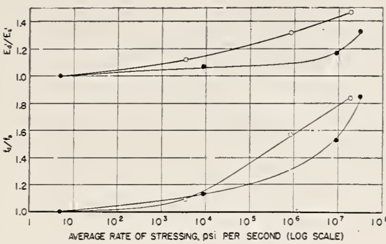


FIGURE 5.8. *Effect of stress rate on the compressive strength and modulus of elasticity of concrete.*

f_d is dynamic strength of concrete; f_s, static strength of concrete; E_d^1, dynamic modulus of concrete, secant value; E_d^1, static modulus of concrete, secant value; ○, "weak" concrete; ●, "strong" concrete.

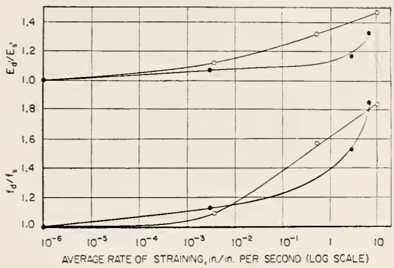


FIGURE 5.9. *Effect of strain rate on the compressive strength and modulus of elasticity of concrete.*

specimens. The average values of the compressive strengths of the weak and strong concretes in the control cylinders were 2,530 and 6,210 psi, respectively, and the corresponding values for 3- by 6-in. cylinders were 2,650 and 6,760 psi. The observation that the smaller specimens developed somewhat higher strengths was in accord with similar results reported by other observers.

The relation between the dynamic and static compressive strengths is given in the table as the ratio of those strengths for the several rates of application of load employed in these tests. The ratios of the dynamic to static strengths ranged from 1.09 to 1.84 for the weak concrete, and from 1.13 to 1.85 for the strong mix. The corresponding durations of impact ranged from 0.9 to 0.00025 sec and from 0.86 to 0.00043 sec for weak and strong concretes, respectively.

The effect of the rate of application of load on the compressive strength of concrete is illustrated in figures 5.8 and 5.9. It will be seen that the effects of varying the rates of stressing and straining on the compressive strength of the concretes was nearly the same.

Modulus of Elasticity

Typical stress-strain characteristics of the concretes observed in the static and dynamic tests are illustrated in figures 5.10 through 5.15, and the average values of the moduli are tabulated in table 5.2. These curves show the relationship between stress and strain up to the maximum load for sets of four cylinders each, which were cast from the same batch of concrete and molded in a single four-cylinder gang mold. Two specimens were selected at random from each set for the impact test. It will be seen that the dynamic modulus for each concrete remained constant for higher values of stress as the duration of impact decreased. The slope of the linear portion of the stress-strain curves also became steeper as the rate of straining increased in the dynamic tests.

It will be recognized that the determination of the initial tangent value of the modulus of elasticity for a material such as concrete represents to a large extent the judgment of the person making this determination. For this reason, the modulus of concrete is usually given as the slope of the secant drawn from the origin to a point on

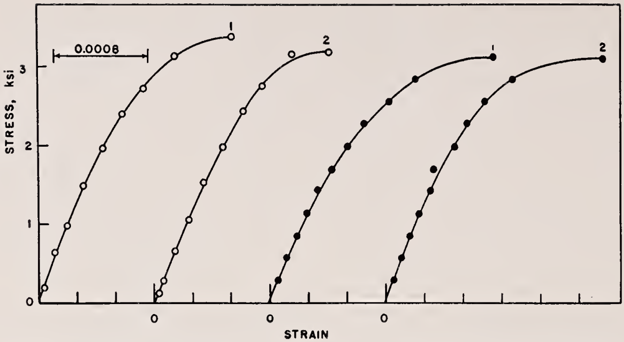


Figure 5.10. *Typical stress-strain graphs, tests of series W1.*

○, Dynamic; ●, static.

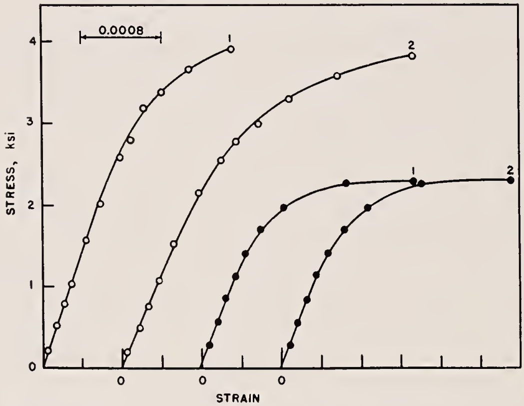
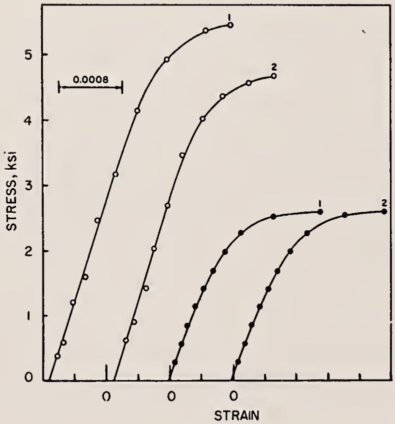


Figure 5.11. *Typical stress-strain graphs, tests of series W2.*

○, Dynamic; ●, static.

Figure 5.12. *Typical stress-strain graphs, tests of series W3.*

○, Dynamic; ●, static.



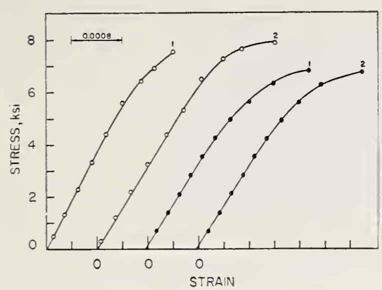


Figure 5.13. *Typical stress-strain graphs, tests of Series S1.*

○, Dynamic; ●, static.

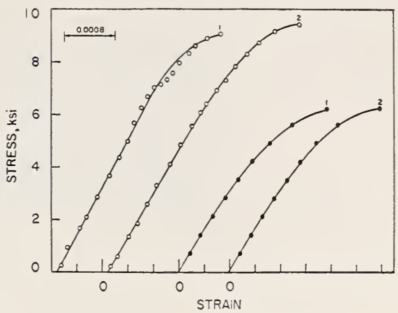


Figure 5.14. *Typical stress-strain graphs, tests of series S2.*

○, Dynamic; ●, static.

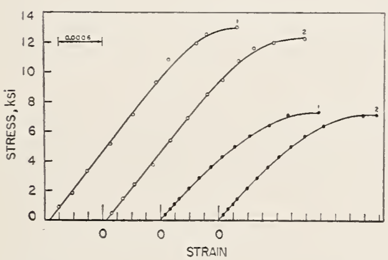


Figure 5.15. *Typical stress-strain graphs, tests of series S3.*

○, Dynamic; ●, static.

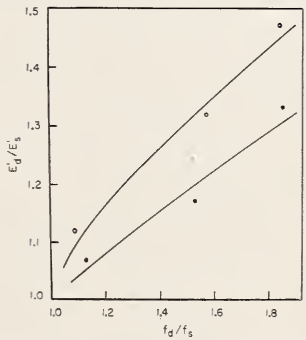


Figure 5.16. *Variation of secant dynamic modulus with dynamic compressive strength.*

E'_d is dynamic modulus of elasticity, secant value; E'_s, static modulus of elasticity, secant value; f_d, dynamic compressive strength; f_s, static compressive strength; ○, "weak" concrete, ●, "strong" concrete.

the curve corresponding to some predetermined value of strain. Table 5.2 gives both the initial tangent and the secant values of the modulus of elasticity, the secant being drawn to a point corresponding to a strain of 0.001.

The variation of the secant values of the dynamic moduli of elasticity with the rates of stressing and straining are shown in figures 5.8 and 5.9, in which the ratio of the dynamic to static modulus, E'_d/E'_s, is plotted against the logarithm of the stress and strain rates, $\dot{\sigma}$avg and $\dot{\epsilon}$avg. These data indicate that the secant moduli of elasticity of both weak and strong concretes increase markedly with increasing rates of stressing and straining.

The ratios of dynamic to static moduli are shown in figure 5.16 plotted against the corresponding strength ratios. It was observed that for the same ratio of dynamic to static strength, the ratio of dynamic to static moduli was significantly greater for weak concrete than for the strong mix

The values of the sonic moduli of elasticity computed from the resonance frequencies of the concrete specimens vibrating longitudinally are also given in table 5.2. The ratios of the initial tangent values of the dynamic moduli to the sonic moduli showed no consistent relationship to any of the other variables in this study.

Strain Energy Absorbed by Concrete

Measurement of strain in both static and dynamic tests was carried out up to the maximum value of stress and in a few tests maximum values of strain were recorded. Thus it was possible to estimate from the areas under the stress-strain curves such as those shown in figures 5.10 through 5.15, the capacity of the concrete to absorb strain energy under impact of various durations.

The values of the ratios of dynamic strain energies to the static values are tabulated in table 5.2 and are shown plotted in figure 5.17 against the corresponding dynamic-static strength ratios. The variation of the strain energy ratio, W_d/W_s, with the strength ratio, f_d/f_s, was nearly the same for both the weak and strong concretes. The values of W_d/W_s ranged from about 0.9 to 2.2 as the ratio f_d/f_s varied from 1.1 to 1.8. Whereas the individual values of W_d/W_s showed considerable dispersion, as can be seen from the values of coefficients of variation given for W_d and W_s in table 5.2, the average values plotted in figure 5.17 are in good concordance with the dynamic-static strength ratios.

It is worth noting that the greater ability of the concrete to absorb strain energy at high rates of loading was due primarily to greater strength and to some extent to the larger values of strain at the maximum loads; it will be recalled that the ability of concrete to absorb strain energy was defined as the area under the stress-strain curve. The ratio of the dynamic to static strain at maximum stress increased with the rate of application of load and the maximum value of this ratio was about 1.3 for both concretes.

There was no significant difference in the manner of failure of the concrete cylinders in the dynamic and static tests. The photographs of typical failures in figure 5.18 show that both the dynamic and static specimens failed in the characteristic manner of brittle material in a compressive test by developing cones at the ends which served to split the cylinders.

Summary

Two concretes of widely different compressive strengths were tested at several rates of straining which ranged from 10^{-6} (in./in.)/sec to about

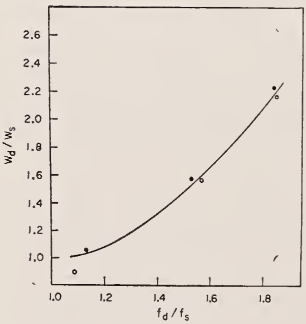


FIGURE 5.17. *Variation of the dynamic-static strain energy ratio with the dynamic-static strength ratio.*

W_d is dynamic strain energy; W_s, static strain energy; f_d, dynamic compressive strength; f_s, static compressive strength; ○, "weak" concrete; ●, "strong" concrete.

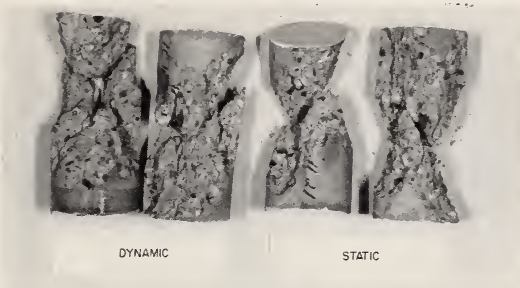


FIGURE 5.18. *Dynamic and static specimens after failure in compression.*

10 (in./in.)/sec. The nominal compressive strengths of the two concretes designated as weak and strong were 2,500 and 6,500 psi, respectively.

The concretes were tested as 3- by 6-in. cylinders under dynamic and static rates of loading. The compressive strains and stresses were measured up to the maximum loads in the dynamic and companion static tests, and the following results were observed:

(1) The compressive strength of each concrete increased with the rate of application of load. The average ratios of the dynamic to static compressive strengths were 1.84 and 1.85 for the weak and strong concretes, respectively, at the highest rate of loading employed in these tests.

(2) The modulus of elasticity of each of the concretes increased significantly with the rate of application of load. The secant values of the dynamic moduli were from 12 to 47 percent greater than the static values for the weak concrete, and from 7 to 33 percent greater for the strong concrete, for the range of loading rates used in this study.

(3) The resistance to impact of each of the concretes, measured by their ability to absorb strain energy, increased markedly with the rate of loading. The average observed ratio of the dynamic to static strain energy ranged from about 0.9 to 2.2 for the range of loading rates used in this study.

(4) The values of strain observed at failure in the dynamic tests for the highest rates of loading were materially greater than the corresponding values in the static tests.

Discussion

DR. IRWIN VIGNESS, Naval Research Laboratory, Washington, D. C.: I was not too sure how you defined the modulus of elasticity when you have a stress-strain curve.

MR. DAVID WATSTEIN: The secant modulus was defined as the slope of the secant drawn from the origin through a point corresponding to a strain of 1/1,000 in./in.

DR. VIGNESS: So the stress-strain curve might not change its slope at the origin, and still you could get an increase in the value of the modulus of elasticity?

MR. WATSTEIN: That is right.

6. A New Strain Gage Without Transverse Sensitivity

By A. U. Huggenberger [1, 2]

Abstract

The properties and design of a new resistance strain gage without paper base, free from transverse sensitivity, and its manufacture were described. The transverse sensitivities of flat grid and helical-type gage windings were discussed for two dimensional states of stress. The new G-H gage is sensitive only to strain parallel to its axis. A transparent plastic base permits visual inspection of bonding conditions. End effects are largely eliminated, and moisture absorption is low. Other advantages of the G-H gage were discussed.

[1] Consulting Engineer, Zurich, Switzerland.
[2] This paper was presented for Dr. Huggenberger by Dr. G. Gustafsson, Chief, Physical Dept., Aero nautical Research Institute of Sweden, Ulvsunda 1, Sweden

7. How to Use G-H Gages

By Gotthard V. A. Gustafsson [1]

Different methods for securing G-H resistance strain gages using various types of cements and the circumstances under which the various cements should be used are discussed. Two new types of strain indicators are described. These indicators give a high measuring accuracy by compensating for minor changes in resistance in the leads and switches connecting the gages to the indicator. Tests on G-H gages are described, and some examples are given of the use of G-H gages for special purposes, for example, measurements on airplane parts and on concrete structures.

Introduction

In 1945 we started to use paper-based wire-resistance strain gages at our Institute, but I must say to start with they were not very successful. In two cases, where the gages had to be applied a couple of weeks before the tests were made, the strains measured were only about 50 percent of what they ought to be, although the readings seemed very stable and reliable. Examination revealed that the paper base could be easily separated so that half the paper adhered to the test surface, and the other half adhered to the wire grid. The fault seemed to be caused by the paper absorbing moisture from the air and so reducing the rigidity of the paper. The gages were not waterproofed, and as we found it too laborious to waterproof hundreds of gages, we decided to try to develop a gage containing no paper. In 1946 we were successful and the first gage of the type, shown in figure 7.1, was manufactured. Since then the materials in the gage have gradually been improved, and the gages are now in common use in Sweden. Since 1948 these gages have also been manufactured in

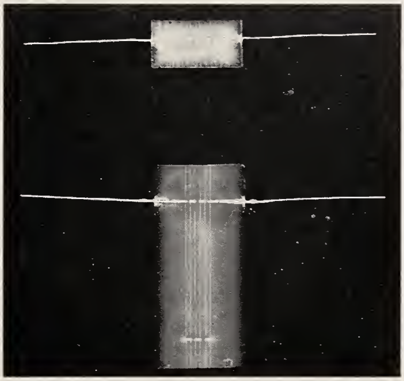


FIGURE 7.1. *Top, 12-strand, 0.06 in. x 0.22 in. strain gage; bottom, 6-strand, 0.6 in. x 0.10 in. gage.*

[1] Chief, Physical Department, Aeronautical Research Institute of Sweden, Ulvsunda 1, Sweden.

Switzerland and sold outside Sweden by Dr. Huggenberger. The gages are named G-H gages after Dr. Huggenberger and the writer. The gages are also named Tepic-gages, and sometimes they are called Sweden-gages.

In a previous lecture during this conference Dr. Huggenberger has described the manufacture of the G-H gages, so I shall now leave the gages themselves aside and give you a few glimpses of our later work in this field.

When using wire-resistance strain gages there are many things to be decided before one can obtain satisfactory results. First, one has to select the type of gage, the size of gage, the type of cement, and finally the most suitable measuring equipment. Only when all these questions are successfully solved can best results be achieved.

G–H Gages and Cements

There are mainly two types of G–H gages, one for use on steel (B-wire) and one for use on aluminium alloys (A-wire). But gages suited for any particular material can be manufactured by combining A- and B-wires or other wire materials in the gage, thereby making the temperature factor low. Almost any size of gage can be manufactured, but certain standard sizes are preferred.

For attaching the gages to the test surface, we use one of three types of cements, called L-, M-, and N-cement. Whenever it is possible to heat the test surface to or above 200° F, we use the L-cement because it gives the best bond and will permit large strains. This cement is thermosetting. When the gage is intended for use up to large strains, the curing should be made at a moderate temperature (200° F) for 4 to 5 hr. If the gage is to have as little creep as possible, the curing should be made at a rather high temperature (up to 300° F) for 2 to 3 hr or more, and also the gage should be allowed to cool down during 1 day or more.

When the test specimen cannot be heated appreciably, we sometimes use M-cement, which is an air-drying cement. This bond is inferior to that of L-cement, and it is necessary to dry the test surface thoroughly before applying the cement. At moderate temperature and humidity the drying time is about 24 hr, but the gage factor has reached about 98 percent of its final value in 10 hr. This cement should not be used at strains larger than about 0.5 percent and not when the creep should be kept low.

The third cement, N-cement, is a room-temperature setting cement, and is of special value when measurements are to be made on surfaces that cannot be thoroughly dried, for example, on concrete. The setting time is about 3 hr. This cement is often used instead of M-cement, as it gives a better bond and a lower creep, but the attaching of the gage is a little more complicated than with L- and M-cement, so we use special accessories shown in figure 7.2. These naturally can be used even when using the other types of cement to save time. Figure 7.2 shows the accessories in the sequence they are used—gage, piece of felt or linen, heating element, piece of brass with felt, and the pressure device consisting of two rubber suction cups and a brass member with a screw to apply the load. The screw and one of the cups are interchangeable so the device can be used when the gage is to be placed in a corner. Figure 7.3 shows the complete assembly of the device.

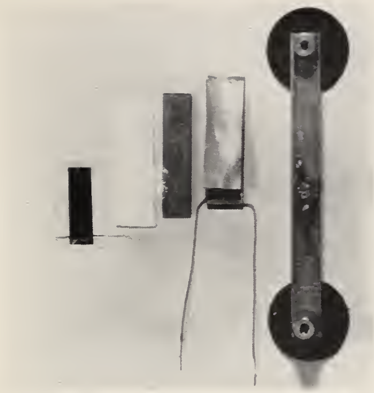


FIGURE 7.2. *Enlarged view of device for attaching gages.*

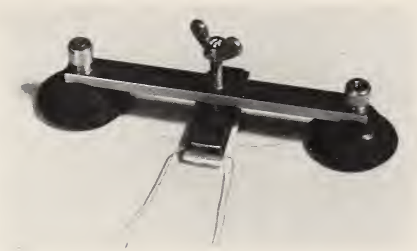


FIGURE 7.3. *Assembly of device for attaching gages.*

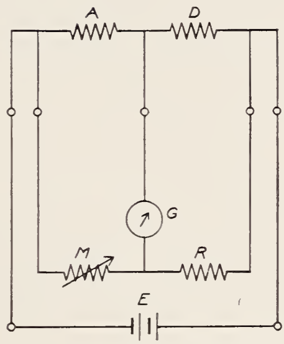


FIGURE 7.5. *Modified Wheatstone bridge (Urwin and Swainger).*

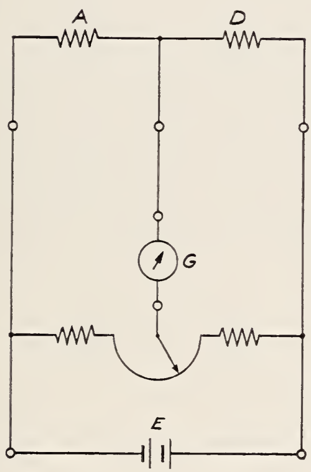


FIGURE 7.4. *General type of Wheatstone bridge.*

Static-Strains Measuring Equipment

Now the gage having been applied, the next step is to measure the resistance changes caused by the deformations of the test surface. This is usually done with some type of Wheatstone bridge (fig. 7.4). This simple bridge can be used very well when measuring only one or a few gages and when the leads are short. Difficulties arise when measuring many gages and when the leads are long. In this case one usually has to use switches in the leads connecting the gages to the measuring bridge, and resistance changes in these switches and leads can seriously affect the measurements. The error is caused by the voltage change in the switches and leads. Hence the lower the current in these leads, the smaller the disturbances from this source. To diminish the influence of resistance changes in switches and leads Urwin and Swainger used a modified Wheatstone bridge (fig. 7.5) having double leads to the gages and high-resistance ratio arms. One lead connects the gage to the current supply (current lead) and the other connects the gage to the ratio arm (potential lead). By this arrangement, the current through the switches in the potential leads is made small and so the error is diminished, but unfortunately the sensitivity of the bridge decreases as the resistance of the ratio arms increases. I have gone one step further in devising a couple of bridges in which the current in the potential leads is made zero, still using low-resistance ratio arms, thereby eliminating the errors from the switches and leads without sacrificing the sensitivity of the bridge. Figure 7.6 shows one of the bridges where two current sources are used, one supplying the gages and the other supplying the ratio arms. The compensation for resistance changes in switches and leads is made by placing a milliammeter in one of the potential leads and adjusting the resistor, R, until the milliammeter indicates zero. Then the milliammeter is short circuited and the common balancing of the bridge can be made. With this arrangement, it is possible to measure strains with an accuracy of about 2μ in./in. (one scale division being approximately 4×10^{-6} in strain). The measuring range of the bridge is equivalent to about 4 percent in strain. The leads can be removed and replaced without any change in the reading. The bridge has 10 range switches, and as can be seen from the wiring diagram, these switches inside the measuring box are placed in the potential leads, thus compensating for resistance changes. Resistance changes in the switches placed in the other leads do not seriously affect the measurements. The only disadvantage of this bridge is the use of two batteries because they seldom change in the same way and therefore the compensation has to be made rather frequently. To avoid the use of two batteries, I have devised another bridge circuit with only one power supply (fig. 7.7), but the advantage has to be paid for by making 2 potentiometer

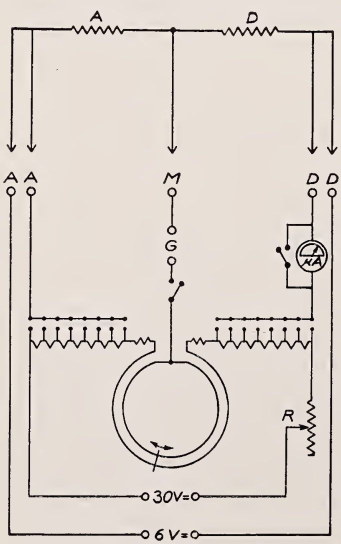


FIGURE 7.6. *Bridge with two batteries.*

(Type used at the Aeronautical Research Institute of Sweden).

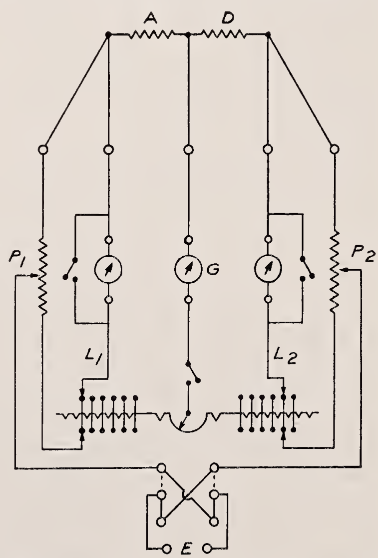


FIGURE 7.7. *Kelvin double bridge.*

adjustments instead of 1. The bridge is a double Thomson bridge, in which means are provided for using a galvanometer in potential leads L_1 and L_2 instead of the keys commonly used. Thereby the tedious work of successively balancing potentiometers P_1 and P_2 and the slide wire is avoided, as only one setting of each is now necessary.

When using the measuring bridge, the galvanometer is first placed in potential lead L_1 and potentiometer P_1 adjusted until the galvanometer indicates zero. Then the same adjustment is made in branches L_2 and P_2. The galvanometer is now placed in the center lead and the bridge balanced by adjusting the slide-wire setting. To increase the measuring range, the resistances in the ratio arms can be changed stepwise, each step being equal to the slide-wire range. In this case there are 50 steps, giving a scale length of 80 ft and a measuring range of about 13.5 percent in resistance change, with a reading accuracy of 2.7 μohm/ohm. With a gage factor of 2.5 this corresponds to a range of 5.4 percent in strain, with an accuracy of about 1μin./in. The accuracy of the bridge can be made even greater if required. The strain reading is within 0.1 percent independent of the resistance value of the dummy gage, but the bridge constant, k, where $\Delta R/R=ku=g\epsilon$, is slightly dependent on the strain reading, u.

Without corrections being made, the bridge can be used to any resistance value of the gage, even if it is as low as a few ohms.

The same principle is used even with self-balancing recorders, thus giving a high accuracy and a rather good speed in measuring.

There are many problems in selecting the best way of measuring or recording strain gage data, but I will now leave this field and show you results of a few tests on G-H gages and also some applications.

Change of Gage Factor With Strain

First, we will see how the gage factor changes with strain. At strains up to about 0.2 percent the gage factor was measured in the apparatus shown in figure 7.8. where the gage is subjected to tension or compression by bending a steel bar. This arrangement gives a rather good accuracy. The results of these tests are shown in figure 7.9. The gage factor is fairly constant in this range but might be a little higher in compression than in tension. At large tensile strains the gage factor decreases, as shown in figure 7.10, to a value of about 2.0. These results were obtained by tensioning a bar 0.16×4×24 in. The

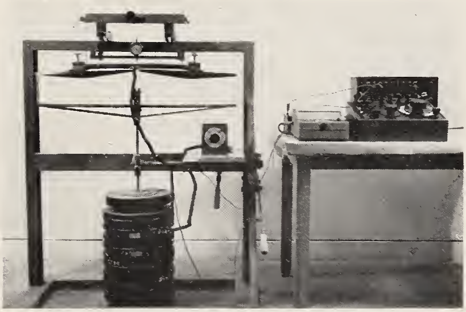


FIGURE 7.8. *Apparatus for applying tensile and compressive strains.*

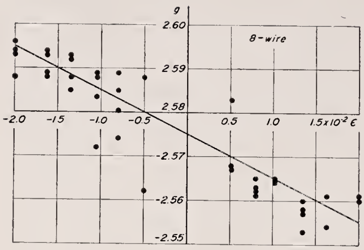


Figure 7.9. *Gage factors at low strains.*

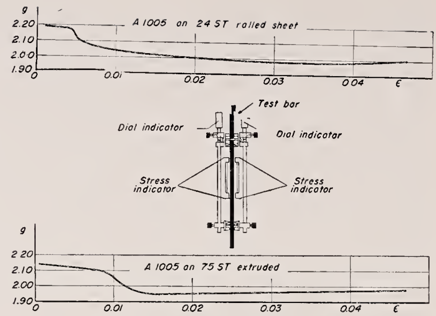


Figure 7.10. *Gage factors at large strains.*

deformation was measured simultaneously by dial gages, tensometers, and G-H gages placed on opposite sides of the test specimen. Two G-H gages with a measuring length of 0.2 in. were attached with L-cement to both sides of the test specimen and coupled in series. The gages were cured at 230° F for 3 hr. At low loads the measurements were made at stepwise increasing loads; but at high loads, when the test material was subject to plastic strain, the measurements were made simultaneously at continuously increasing load. In this test, the strain could be followed only up to about 4-percent strain because of the range of the dial gages, but usually strains up to 8 percent, or even higher, can be measured. The change of the gage factor is dependent on the material in the test surface so the gage factor will change more rapidly in the region where the material starts to flow. Therefore the gage factor change is not a feature of the gage alone but has to be calibrated from tests on the material to be used.

Change of Gage Factor With Temperature

The gage factor will change even with temperature as shown in figure 7.11. This test was done in the calibrating machine already shown, with a heating box placed around the steel bar. The gage factor gradually decreases with increasing temperature. At the same time the resistance of the gage changes with temperature at constant load as shown in the lower curve of figure 7.11. The points denoted by (x) show the changes with increasing temperature and the points denoted by (o) with decreasing temperature. As will be seen, the hysteresis is rather small in both curves.

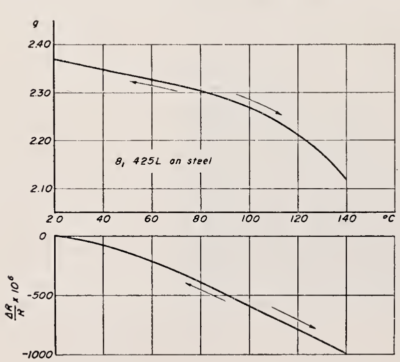


Figure 7.11. *Change in gage factor and gage resistance with temperature.*

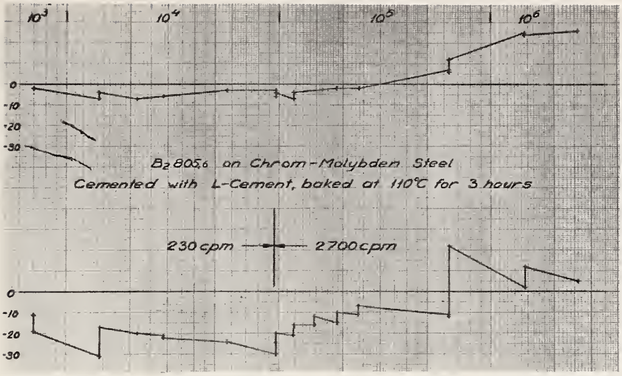


FIGURE 7.12. *Change in gage resistance with repeated loading.*

Change of Resistance and of Gage Factor at Repeated Loads

For repeated loads, there will be a small change in resistance after the first load application. Repeated loads then usually give only small changes of resistance. In one test, two gages were cemented to a sample of steel, which was then repeatedly strained between 0 and 0.19 percent; first at 230 c/m, and then at about 100,000 cycles at 2,700 c/m. At certain intervals the resistance change of the unstrained test specimen was measured. As will be seen from figure 7.12, the changes are rather small, and the gages will stand many cycles without breaking. The numbers on the ordinate axis indicate the corresponding strain in microinches per inch. The test was first stopped at about 600,000 cycles, but 14 days later it was continued for 2 days more. The gage factor was measured several times during the test and always gave the same value. The gages did not break at 2.5×10^6 cycles and showed no visible changes.

Hysteresis and Creep

When using wire-resistance strain gages, hysteresis and creep often are very disturbing, especially in high precision tests. I have, therefore, made a test on gages cemented with various cements to a steel bar, which was then placed in our calibrating machine shown in figure 7.8. The readings were taken with a measuring bridge of the type shown in figure 7.7, using a 2-pole 24-throw switch for the active gages while the leads from the two dummies were connected to the bridge, as the type of active gage changed. Humidity was about 70 percent and the room temperature 68° to 74° F. The results are given in figure 7.13, and tables 7.1 and 7.2. The first 3 rows correspond to 3 G–H gages cemented with L-cement and cured at 300° F for 3 hr, the next 3 rows to gages baked at 250° F for 3 hr, and the next 3 rows to gages baked at 200° F for 5 hr. Then follow 2 gages cemented with M-cement and dried for 48 hr, 2 gages cemented with N-cement allowed to set for 48 hr at room temperature, and finally 2 SR–4 gages, A11 and A7, cemented with SR–4-cement and dried for 48 hr at room

Table 7.1. *Hysteresis and creep.*

Gauge number	P=0	$P=P_o$	P=0	Diff. Hyster.	P=0	$P=P_o$	P=0	Diff. Hyster.	$P=P_o$	Creep 2h	Creep 3h	Creep 20h	Creep 24h	Creep 69h	Creep 93h	Creep 140h
1	4055	5585	4051	-4	4051	5584	4051	0	5585	-1	-2	-2	-1	-1	-1	-3
2	2943	4479	2939	-4	2940	4478	2940	0	4478	-2	-3	-2	-2	-2	-3	-7
3	3097	4630	3093	-4	3094	4629	3093	-1	4629	-1	-2	-2	-1	-2	-3	-5
4	3710	5237	3701	-9	3702	5236	3701	-1	5236	-2	-3	-3	-3	-4	-5	-8
5	3085	4612	3082	-3	3082	4610	3081	-1	4610	-1	-1	-1	-1	-1	-4	-6
6	3159	4687	3158	-1	3157	4685	3156	-1	4685	-1	-2	-2	-2	-2	-4	-6
7	2914	4445	2912	-2	2912	4442	2911	-1	4442	-1	-1	-2	-3	-6	-9	-13
8	5577	7100	5571	-6	5570	7099	5569	-1	7098	-2	-2	-2	-2	-5	-7	-10
9	0591	2123	0591	0	0591	2123	0591	0	2121	-2	-2	-1	-1	-4	-6	-10
10	3164	4676	3146	-18	3148	4674	3142	-6	4668	-24	-30	-69	-77	-122	-134	-149
11	5195	6713	5182	-13	3182	6710	5181	-1	6708	-16	-20	-52	-58	-101	-115	-133
12	4513	6029	4503	-10	4502	6025	4500	-2	6026	-6	-7	-17	-19	-41	-49	-61
13	2540	4057	2522	-18	2523	4055	2520	-3	4054	-2	-4	-6	-7	-15	-17	-23
14	6415	7629	6402	-13	6402	7623	6399	-3	7620	-6	-8	-10	-10	-17	-20	-26
15	6561	7727	6549	-12	6550	7715	6539	-11	7709	-17	-22	-52	-62	-104	-121	-141

Table 7.2. *Gage resistance hysteresis and creep.*

Gauge number	$P=P_o$	P=0	$P=P_o$	Diff. Hyster.	P=0	Creep 24h	Creep 120h
1	5581	4051	5584	3	4049	0	-2
2	4471	2936	4474	3	2936	0	-3
3	4625	3092	4627	2	3090	1	-2
4	5228	3697	5231	3	3695	1	-1
5	4604	3097	4606	2	3075	0	-3
6	4679	3154	4681	2	3152	0	-2
7	4429	2900	4431	2	2899	0	-2
8	7089	5562	7090	1	5561	0	-2
9	2111	0584	2113	2	0580	-2	-5
10	4519	2986	4521	2	2985	22	39
11	6577	5045	6579	2	5044	14	27
12	5965	4442	5967	2	4442	2	0
13	4031	2500	4032	1	2499	2	4
14	7589	6364	7591	2	6364	8	14
15	7568	6380	7569	1	6380	25	40

temperature. The first column gives the initial readings when the bar is unloaded and not having been loaded previously; the next column gives the readings when the bar is loaded to a strain of about 0.16 percent; and the third column gives the readings when the bar is again unloaded. The permanent change in readings are shown in column 4, one unit corresponding to about 1×10^{-6} in strain for the G–H gages, and for the A11- and A7-gages to about 1.25×10^{-6} and 1.3×10^{-6}. The same readings were made 1 hr later, showing no appreciable changes, column 5; then the bar was loaded for the second time, column 6; and again unloaded, column 7. The permanent changes are show in column 8. In order to investigate the creep, the bar was then loaded again and kept at constant load for several days. The changes in readings taken at various time intervals are shown in fol-

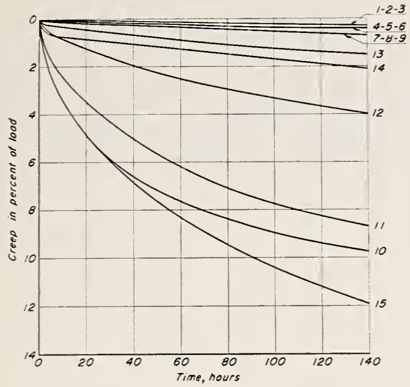


Figure 7.13. *Gage resistance creep.*

lowing columns. The whole creep lapse after applying the load in column 9 is shown in figure 7.13, where the creep is given in percentages of the change in readings at the loading.

After a creep time of 140 hr the bar was unloaded, table 7.2, column 2; then loaded again, column 3; the permanent change being shown in column 4. The bar was unloaded again, column 5; and finally, the creep with the bar unloaded was observed for 5 days.

Applications

The next figures illustrate a few applications. Figure 7.14 shows a test on a stressed-skin structure where gages were placed at different points inside and outside the skin in pairs opposite each other to measure mean stress and curvature when the structure is subjected to a bending moment giving compression in the top skin and tension in the bottom skin of the structure. The strains in three pairs of gages numbered 5, 20, and 36 are shown in figure 7.15. At low loads all gages indicate compression, but when buckling occurs, the gages on the convex sides indicate a rapid change into lower compressive strain or tensile strain. The mean value of strain for each pair of gages decreases when buckling occurs, indicating a lower stiffness of the construction. The measured curvature was in fairly good agreement with deflection measurements made simultaneously.

The Structures Department of our Institute also has made many tests on the materials used in aeroplane construction. The next two figures show the behavior of an Alclad plate (75S–T) when loaded in tension (fig. 7.16) and in compression (fig. 7.17). The longitudinal,

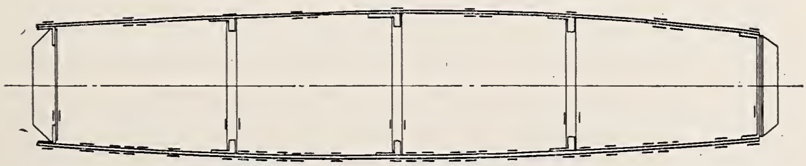


Figure 7.14. *Diagram of stressed-skin structure showing layout of gages.*

TABLE 7.3. *Strains in concrete prism at different loads.*

Load kg	Stress σ kg/cm^2	Side I $\varepsilon_{extens} \cdot 10^6$	Side I $\varepsilon_{gauge} \cdot 10^6$	Side II $\varepsilon_{extens} \cdot 10^6$	Side II $\varepsilon_{gauge} \cdot 10^6$
0	0	0	0	0	0
1000	13.3	48	60	40	52
2000	26.7	102	112	74	78
3000	40.0	153	164	107	117
4000	53.3	207	211	147	155
5000	66.7	255	268	181	190
6000	80.0	310	320	221	224
6950	92.7	364	380	262	255
8000	106.7	431	440	308	298
7000	93.3	398	406	278	259
6000	80.0	357	354	255	246
5000	66.7	310	315	218	203
4000	53.3	265	268	181	181
3000	40.0	221	224	144	138
2000	26.7	173	173	104	95
1000	13.3	115	112	60	60
0	0	54	48	17	17
1000	13.3	102	104	54	52
2000	26.7	153	151	90	95
3000	40.0	204	216	134	130
4000	53.3	255	259	171	164
5000	66.7	306	311	214	203
6000	80.0	354	363	251	233
7000	93.3	401	406	285	268
8000	106.7	452	462	325	311
7000	93.3	415	419	302	285
6000	80.0	374	380	271	250
5000	66.7	333	328	235	220
4000	53.3	289	289	198	182
3000	40.0	241	238	158	147
2000	26.7	194	190	117	99
1000	13.3	136	130	74	52
0	0	71	61	30	26

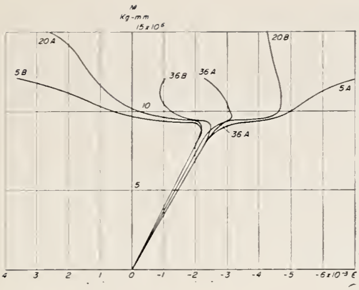


FIGURE 7.15. *Strains as a function of the load.*

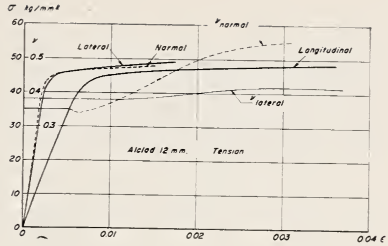


FIGURE 7.16. *Strains for different stresses for Alclad specimen in tension.*

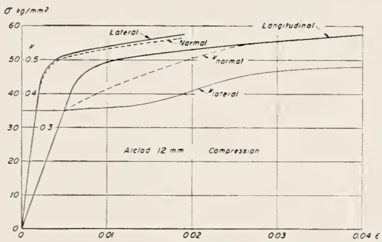


FIGURE 7.17. *Strains for different stresses for Alclad specimen in compression.*

lateral, and normal strains are measured with G–H gages and from these the two Poisson's ratios ν_{lateral} and ν_{normal} are computed.

Finally, table 7.3 shows the results of a test on a concrete prism in compression, where gages of 4-in. length, cemented with N-cement, were used together with extensometers of 4-in. gage length. The prism with the applied gages was then kept under water for a week and the same loading cycle repeated, giving almost the same results. The gages did not flake off from the concrete, even if kept under water for several months without even being waterproofed.

The gages are customarily used without waterproofing. If the gages are to be exposed to rain or used under water for 1 or 2 weeks, we usually cover the gage and its leads with a mixture of wax and clay (modeling clay), which is easily applied. Under severe conditions we cover the modeling clay with a thin sheet of aluminum or brass, so that only the edge of the modeling clay is exposed to water.

The main features of the G–H gage may be summarized as follows: 1, It contains no paper, thereby being less sensitive to humidity; 2, has the same gage factor whatever its size; 3, has a very low cross-sensitivity; 4, can be used up to high strains; 5, can stand many load cycles; 6, the gage factor is determined for each gage during manufacture; 7, the temperature factor can be determined for each gage during manufacture; and 8, it is transparent, and therefore air bubbles are easily discovered on application and thus are easily avoided.

Discussion

Dr. Harold F. Allen, Dept. of Aeronautical Engineering, University of Michigan, Ann Arbor, Mich.: You mentioned curing the cement on some of your gages at 300° F. Can the cured gage be used at such temperatures afterward?

Dr. Gustafsson: Yes, but you must remember that the gage factor decreases at higher temperatures. The change in resistance with temperature must be considered, too, if you intend to measure strains originating from the temperature change. As both changes are rather well reproduceable, it is possible to make measurements at temperatures up to about 300° F.

Mr. R. G. Boiten, National Council for Industrial Research, Delft, Holland: You may know that we have done some work on the normal paperbacked gages. I obtained samples of your gages from Sweden and carried out tests according to your directions, but our results, which I am sorry I do not have with me, indicate just the opposite. Just before I left Holland, I met Dr. Fink of the Max-Planck-Institute. We compared our results, and they were much alike.

That means we found, even following your directions, much larger errors than you show here. You seem to be able to get fine results with your gages, but I have not succeeded in getting as good a stability as with the A–7 gage, which you considered somewhat inferior, although we have used them in great numbers for the construction of pickups without any troubles whatsoever. Another thing is that your gages are truly much less sensitive to moisture than the other gages.

I might make a remark concerning the reading instrument. It seems too complicated to me for this purpose. Basically, there are three Wheatstone bridges, namely the measuring bridge, consisting of the gages A and D, the stepped ratio arms and the potentiometer P_3, and two auxiliary bridges, serving the purpose of keeping the current from flowing through potential leads L_1 and L_2. The required condition is, that with no current in the galvanometer lead, the ratios of the potentiometers P_1 and P_2 are proportional to the ratios between A and the left fixed arm and D and the right fixed arm of the bridge, respectively.

We have made a rather extensive theoretical and experimental study of this bridge circuit, called the Thomson bridge, and have found, that resistance changes in the leads or the switches amounting to 1 or 2 percent of the value of the resistance of the gage do not have any appreciable influence on the zero point of the measurement bridge, even if the potential leads are carrying a small current. With normal gages the difference in the nominal resistance value is small, as well as the resistance change due to the measured strain. The potentiometers P_1 and P_2 may be replaced by two fixed resistors, fulfilling the ratio conditions mentioned before. Now only the balancing potentiometer, P_3, needs to be adjusted. For strain-gage work this simplification does reduce the accuracy of measurements.

Dr. Gustafsson: I do not know anything about your measurements, as I have not given you any gages nor any instructions, but I know that Dr. Fink has made tests on these gages, and his results with the air-drying cement are close to those shown here. In his tests with the temperature-setting cement the results are quite different because he has not followed the instructions. Anyhow, in Sweden most consumers have stopped using the paper gages, although some of them are much cheaper, which shows that many other people have learned to use the G–H gages properly and have obtained better results.

Regarding the bridge, I prefer to have your fixed resistors adjustable, because I then can use gages of any resistance and select the dummy and active gages as I wish. The difference between this bridge and the Thomson bridge is that I switch the galvanometer into the compensating leads and adjust potentiometers P_1 and P_2 in one step only. It does not take much time to do this, and the accuracy is as good as that of a normal Thomson bridge, which requires a very much longer balancing time.

Mr. John C. New, Naval Ordnance Laboratory, Washington, D. C.: This is a question that might apply to several of the papers. There has been considerable discussion on waterproofing gages. Now, that is fine when you are merely dealing with water that may splash on the gage, high humidity, or even putting the gage under a few inches of water, but I want to go down to the equivalent of about half-a-mile in the ocean, let us say 75 atm. My question is, has anyone determined whether there is a pressure effect on resistance gages when working at these high pressures?

Mr. Boiten: I can say that there is not. There is a secondary effect. We carried out some measurements inside pressure vessels to study strain distribution in thick walls at pressures up to 150 kg/cm^2. We attached gages on little pieces of steel inside the vessel. Then we put another outside and compared the two. Actually, it turned out that the differences between these two gages was 25 μin. at 150 atm. There was nearly no difference at all. So I believe that with gages A–1 and A–5 the influence will be very small and cause no serious difficulties.

Mr. R. C. Valore, National Bureau of Standards, Washington, D. C.: I am surprised that Mr. Tatnall has not answered this question. I think one of the answers appeared in a recent SR–4 news-letter describing work done at the University of Illinois. I hope somebody will correct me if I am wrong, but I believe the figure given was 2 to 5 (μin./in.)/1,000 psi for the Bakelite gages, and 10(μin./in.)/1,000 psi for the paper-backed gages.[1]

Mr. A. W. Brunot, Thomson Laboratory, General Electric Co., West Lynn, Mass.: About 5 or 6 years ago we made a test similar to this under oil, inside a pressure vessel. The same problem arose, and we put dummy gages on blocks submerged in the oil at pressures up to 1,500 lb/in.^{2}, and 16 to 30μin./1,000 psi was all the strain found due to pressure.[2]

[1] M. C. Steele, Bakelite gages under high fluid pressure, Testing Topics **6**, 10 (April, May, June 1951 (Baldwin-Lima-Hamilton Corp., Philadelphia 42, Pa.).

[2] A. W. Brunot and W. G. Schmitter, Stress study of a fabricated steam chest, Proc. Soc. Exp. Stress Anal. **4**, 49–55 (1946) (General Electric Co.).

8. Bonded-Wire Strain Gage in the Field of Instrumentation

By Arthur C. Ruge [1]

The widespread and rapidly increasing application of the bonded-wire strain gage to the field of instrumentation as distinguished from the field of stress analysis in which it first met with universal acceptance is discussed. The distinction between the two fields is defined, and limits of accuracy are investigated. Following a brief review of the basic types of bonded-wire strain-gage transducers, examples are given to show the wide scope of usefulness they are finding in the industrial world as the basis of instrumentation for measurement and control. The paper is intended to serve as a factual report on the state of the art—excursions into the realms of theory and prophesy are deliberately avoided.

Introduction

It is an honor and a very real pleasure to address this gathering of outstanding engineers and scientists who are attending this Symposium as guests of the National Bureau of Standards. As many of you know, my association with the bonded-wire strain gage goes back to 1938, and consequently I have had the privilege of intimately watching the role of the gage advance from an idea which was received with marked skepticism on all sides into a widely accepted tool which is now regarded as commonplace but essential by many thousands of engineers and research workers. Like many revolutionary ideas, the bonded-wire strain gage gained acceptance very slowly at first. So slowly, in fact, that I doubt if a gathering such as this could have been successfully held 10 years ago, even under the auspices of this eminent Bureau.

Most of you are familiar with the bonded-wire strain gage as a testing device. Quite naturally, it was in the field of testing that the gage first found acceptance. The wide and rapidly growing use of the bonded-wire strain gage in the field of instrumentation is not so familiar to many of you, and it is this use of the gage that I propose to discuss today.

Before doing so, however, I should like to pause a moment to express my own appreciation of the wonderful work the National Bureau of Standards has done in testing and appraising the bonded-wire strain gage both as a stress analysis device and as a component of instrumentation. The work carried out by Messrs. Wilson, Tate, and Campbell under the direction of Dr. Ramberg is of inestimable value and has been a very important factor in the rapid advance of the strain gage art as we know it today. I am sure that my appreciation of this work is shared by all of those who use the gage and know the part the National Bureau of Standards has played in its development as a truly quantitative measuring tool. Because of its long interest and active work in the field of strain gages, dating back to the fine work of such investigators as Doctors Whittemore and

[1] President, Ruge-deForest Inc., Cambridge, Mass.

Tuckerman, I think it is particularly appropriate that the Bureau has seen fit to include this strain-gage symposium as one of the series celebrating the fiftieth anniversay of this great institution.

It is not my purpose today to discuss technical or theoretical aspects of the bonded-wire strain gage. Rather, I propose to tell you something about what this gage is doing in the field of instrumentation as contrasted with the field of stress analysis. One can think of the field of application of these strain gages as being divided broadly into two parts. The part that is most commonly thought of by engineers is devoted to experimental stress analysis. The other part is devoted to instrumentation. Quite naturally, there is a considerable zone over which these two parts overlap and it is frequently difficult to determine whether or not some applications are to be classified as stress analysis or instrumentation. Broadly speaking, however, the stress-analysis side of the field is concerned with the employment of the strain gage to acquire knowledge of stresses and strains associated with the operation and use of devices and structures, the primary concern being to test the correctness of design or to provide information upon which design may be based. On the instrumentation side of the field the strain gage serves merely as a pickup or transducer, that is, a means of generating a signal that can be translated in terms of the magnitude of some quantity other than a strain. For example, we may employ a strain gage as a transducer to measure load, acceleration, fluid pressure, torque, etc. When so used, the strain gage is truly applied in the field of instrumentation.

We might consider one of the many cases in which the strain-gage application lies in the overlap zone where it is difficult to define its use. When a strain gage is applied to the alighting gear of an airplane so that it may be used during alighting and take-off tests to determine the forces transmitted from the ground to the airplane, and when the relationship between the output of the gage and the force acting on the alighting gear has been determined either by calibration or calculation, the strain gage has entered the zone of overlap between the two broad fields of stress analysis and instrumentation. Up to the point where the relationship between gage output and force acting was determined in some way, the strain gage was truly a stress analysis tool which could be used to gather data as to the state of stress in the alighting gear. The mere fact of establishing a relationship between gage output and force has converted the strain gage into a dynamometer and it has, therefore, moved over into the field of instrumentation as I have defined it. Thus it is readily seen that the transition from a makeshift transducer such as this to a true piece of instrumentation such as I shall describe later is not sharp. It is merely a matter of refinement—application of sound design principles to the transducer to give it high accuracy, ruggedness, permanence, and uniqueness of relationship between output and the particular quantity it is designed to measure.

In contrast to the experimental stress-analysis applications of the bonded-wire strain gage where inaccuracies as high as ±20 percent are frequently quite tolerable and where ±1 percent is closer than the design engineer can make use of, we find in the field of instrumentation that the strain gage is often required to meet inaccuracy tolerances of ±0.1 percent or better. There are a few instrumentation applications where an absolute inaccuracy of ±5 percent is tolerable, provided reproducibility is good to ±1 percent. When speaking of instrumentation inaccuracies, it has to be remembered that the inaccuracy tolerances are frequently expressed in terms of percentage of the quantity being measured rather than percentage of full scale, as is common in the field of stress analysis. For example, in a precision strain-gage weighing device, such as a platform scale, it may be necessary to meet an inaccuracy limitation of ±0.1 percent of actual weight from 10 to 100 percent of rated capacity of the scale. This means that at the lower limit the tolerable inaccuracy of weighing would be 0.01 percent of full scale!

Because of the limitations of publication space, I have selected only a few typical examples which will serve to show the kind of work being done today with strain-gage devices of the bonded-wire type. These are true instrumentation applications which are in every day use. None of these devices I shall show you today can be classed as experimental. They are all commercial instruments of proved performance.

Typical Transducers

Figure 8.1. shows a family of load- and pressure-measuring cells, or transducers, as they are frequently called. In the rear, reading left to right, are three compression-type load cells ranging from 2,000- to 200,000-lb rated capacity. The 200,000-lb capacity cell is 7 in. in diameter by 10 in. high. Next in line are three universal-type load cells adapted for tension and compression loading ranging from 50,000- to 500-lb rated capacity. There are, of course, many intermediate sizes not shown, and ranges actually covered by commercial-load cells of these general types run from 50 lb to several million pounds. Other forms of load-measuring cells are used to measure loads as low as 1- or 2-grams full scale.

In the foreground of the picture is a family of fluid-pressure measuring cells. The cylindrical-shaped cells are made in ranges from 200 to 50,000 psi as standard items. The rectangular-shaped cell at the right is a 10-psi rated-capacity cell. This type of cell is made in ranges up to 100 psi. Fluid-pressure cells are made also as differential pressure devices used for measuring flow, pressures on models in wind tunnels, etc.

Figure 8.2. shows a simple form of tension-type-load cell which comprises a threaded rod with a strain-gage section in the middle protected and sealed against moisture. The standard capacities shown range from 10,000 to 100,000 lb. The 100,000-lb unit at the

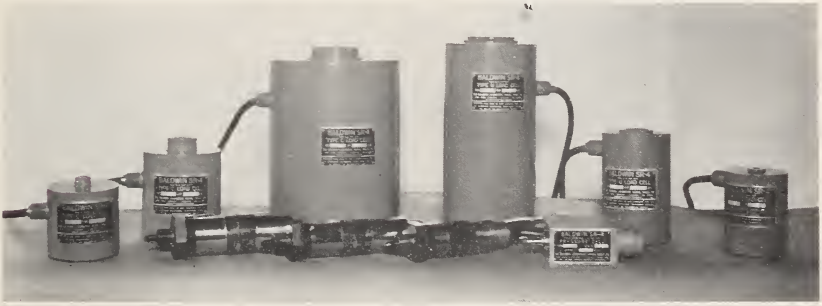


FIGURE 8.1. *Family of load and pressure measuring cells.*

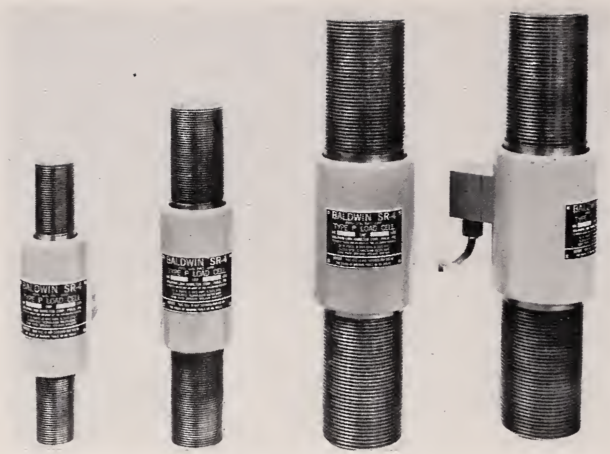


FIGURE 8.2. *Tension type load cells for loads from 10,000 to 100,000 lb.*

FIGURE 8.3. *Cantilever force-beam employing strain gages to measure the degree of bending under load.*

FIGURE 8.4. *Wire strain gage torque pickup for measuring the torque transmitted by a rotating shaft.*

extreme right has a 3-in. thread and is 15 in. in over-all length.

Another common form of weighing device is shown in figure 8.3. This is the so-called force beam, which is a simple cantilever beam employing strain gages to measure the degree of bending under load. The beam-type pickup is especially well suited to the measurement of loads below 1,000 lb and has been used successfully from 5,000-lb to

2-grams full scale. Advantages of this device are extreme simplicity and wide range of capacity-load adjustment by varying point of load application.

Figure 8.4. shows another form of strain-gage pickup in very common use. This is a device for measuring the torque transmitted by a rotating shaft. Bonded-wire strain gages are used to sense the torque; and brushes and sliprings are provided to bring out the signal to the indicating or recording instrument. The pickup shown in figure 8.4 is a 25-in./lb-capacity unit having a rated speed of 3,000 rpm. This particular unit is used for measuring stirring effort in a small-scale mixing operation. Bonded-wire strain-gage torque pickups of standard design range from 25 to 30,000 in./lb. As specials, they have been built up to 18-in.-diameter shaft size.

Force Measurement

Following are some typical applications of the bonded-wire strain gage to force-measurement problems (as distinguished from weighing applications). Figure 8.5 shows a 20,000-lb tension load cell used to measure cable tension in oil-well surveying work. The instrument, which is electronically operated, has two force-indicating dials. The dial at the left will selectively indicate 0 to 5,000 lb or 0 to 10,000 lb (pull on line equals one-half the tension on cell). The dial on the right is a sensitive incremental pull indicator having a scale of 0 to 500 lb. With this scale, the user can detect very small variations in line pull such as occur when the surveying equipment bottoms or begins to catch in the hole. Over 400 of these units are used in regular oil-field service by the Schlumberger Oil Well Surveying Corp., Houston, Tex.

Figure 8.6 shows the application of a force-measuring cell to a papermaking operation. The load cell is mounted between an air cylinder and the pressure roll which squeezes the wet paper as it goes through the machine. Formerly, force measurement was done by means of air-pressure gages, which gave rise to considerable inaccuracies as a result of piston and packing friction. The two electronic instruments indicate and record the forces on the roll at the front and back of the machine. The air-pressure gages were found to give highly erroneous indications of the roll pressures at times. It was found that the paper-quality control improved markedly when the force-measuring cells were used to control the operation of the machine.

Figure 8.7 shows the application of a force-measuring cell to a

FIGURE 8.5. *Load indicating instrument for cable tension load cell.*
20,000-lb tension load cell for measuring cable tension.

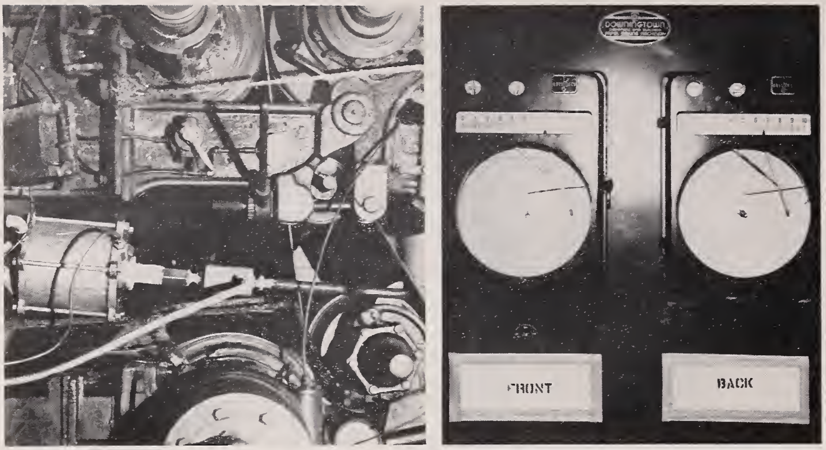


FIGURE 8.6. *Application of a strain gage force measuring cell to a paper-making operation.*
Electronic instruments which indicate and record the forces on a paper roll at the front and back of the machine.

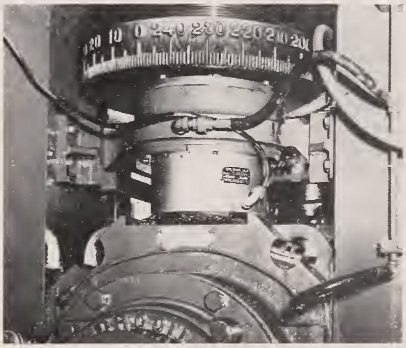


FIGURE 8.7. *Application of a force measuring cell to a rolling mill operation.*

rolling-mill operation. In this case, the cell measures the screw-down pressure on a foil rolling machine in a plant of the Aluminum Co. of America.

Weight Measurement

The measurement of weight by means of bonded-wire strain gage devices usually calls for a higher order of accuracy than the measurement of force, as illustrated in the previous examples. Figure 8.8 shows application of strain-gage-load cells to a pair of crane scales in the Pittsfield, Mass., Transformer Plant of the General Electric Co. The illustration at the left shows a detail of the hook-block arrangement. The load cell is located between the thrust bearing and the hook block and carries the load in compression. The load cell is in the form of a hollow cylinder, and the 7-in. shank of the hook passes through the cell and threads into the thrust nut above. It was possible to construct these scales for 150-tons capacity each by sacrificing only 7 in. of the head room of the crane. The load-

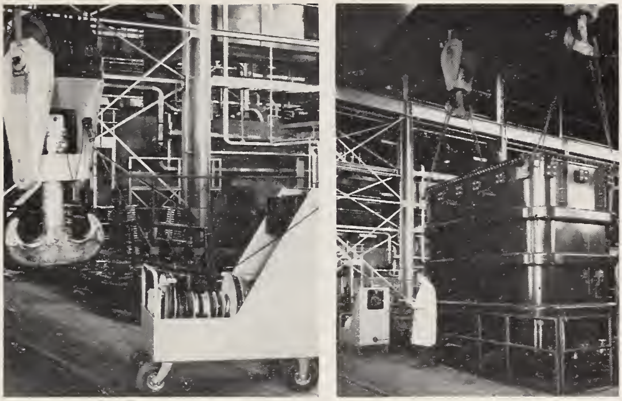


FIGURE 8.8. *Left, application of a strain gage load cell to a crane scale; right, crane scales in operation lifting large transformer.*

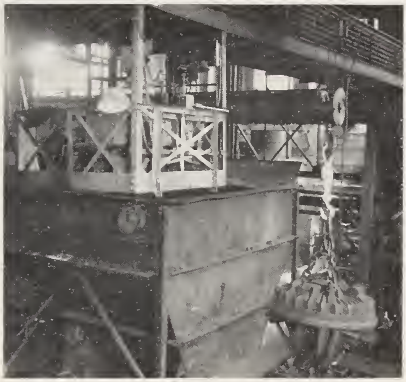


FIGURE 8.9. *On-the-hook type of crane scale used in scrap weighing operation.*

indicating instrument and two cable reels are mounted on a dolly. A selector switch in front of the instrument enables the operator to read the load on either of the twin crane scale units. The picture at the right shows the two units in operation lifting a large transformer. Smaller transformers are lifted with a single hook while the other crane is busy elsewhere. Advantages of such a crane scale are: (1) weighing is performed during a necessary lifting operation, thus eliminating the usual operation of lifting the object, carrying it down a runway to a platform scale, weighing, relifting, and repositioning, (2) no valuable floor space is tied up for a platform scale. In some crane-scale applications the instrument is placed in the operator's cab for added convenience and time saving. In such cases, the cable reels are mounted on the crane bridge. Digital printers are also available for weight printing, and the printer may be either in the cab or on the floor.

Figure 8.9. shows an on-the-hook type of crane scale used in a

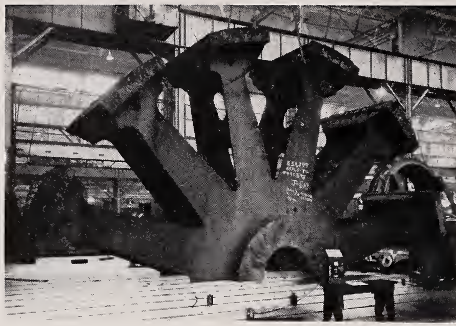


FIGURE 8.10. *Three 50,000-lb load cells being used in the shop weighing of a large casting.*

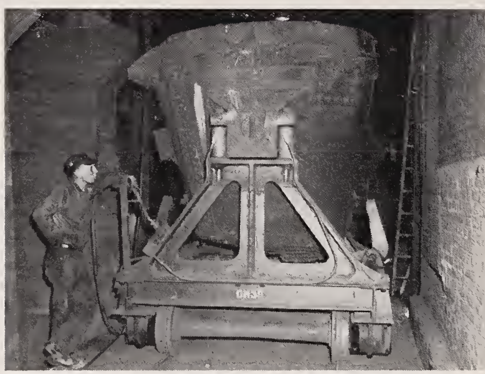


FIGURE 8.11. *Application of load cells to ladle weighing.*

scrap-weighing operation for furnace charging in a foundry. In this instance, the indicating instrument is in the operator's cab so that he can readily keep tabs on the material being dropped into the charging chute. A slip-ringless cable reel mounted on the cab feeds the cable out to the crane-scale pickup.

Figure 8.10. is a good example of shop weighing in its simplest form. Here, a 70,000-lb casting is being lowered by the crane upon three 50,000-capacity-load cells. In this case, the loads on the individual cells are being measured by a manually balanced battery-operated indicator. This weighing operation, which was performed in a very short time, eliminated the necessity for placing the casting on a flat car and carrying it out to the nearest railroad track scale, following which it would be returned to the shop. For occasional weighing, the elegance of this simple method leaves little to be desired.

Figure 8.11. shows the application of bonded-wire strain-gage load cells to an alloy ladle-weighing operation. The ladle car has been modified to permit the trunnion load to be carried on a pair of load cells at each end of the car. The load cells are connected additively to an instrument (not shown) provided with a wide tare-weight ad-

justment. In operation, the car is first placed under the iron furnace and the cable plugged into the instrument, which is tared out to zero. The desired amount of iron is then measured into the ladle, perhaps 45,000 lbs. The car is next taken to the furnace containing the alloy material, sufficient cable length being provided to cover the required distance. The instrument is again tared out to zero, and, in this case, a "times ten" scale is used so that the alloy weight (which may be in the vicinity of 2,500 lbs.) can be read as accurately as the higher weight was read.

Figure 8.12. shows the first all-electronic railroad track scale, installed some time ago for freight-weighing service at the Eddystone Works of the Baldwin-Lima-Hamilton Corp. The 72-ft bridge comprises two pairs of 36-ft. girders pinned together at the middle and supported on a total of six 100,000-lb-capacity load cells. Cable passing through conduit is brought up into the weigh house to operate the indicating and printing instrumentation. The capacity of this scale is 400,000 lb. The indicator is a 24-in. dial reading 0 to 50,000 lb and having 1,000 divisions. A "drop weight" window shows the amount to add to the scale indication to obtain total weight, the entire operation being fully automatic. The digital printer shown at the right of the indicator prints the weight on a ticket by push-button control, printing by 50-lb increments. Suitable interlocks are provided so that the printing device will not operate unless the scale has come to balance. If the printing button is pushed before

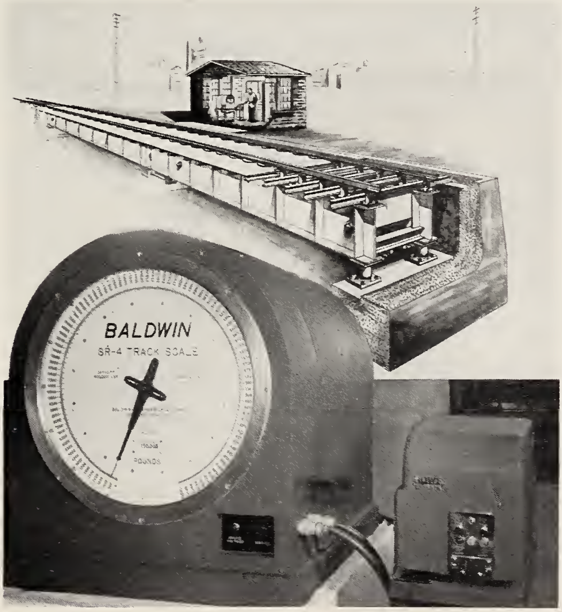


FIGURE 8.12. *An all-electronic railway track scale employing six compression load cells.*

Load indicator and printer for electronic railway track scale.

the balancing operation is completed, the printer will merely wait until a balance signal comes through and then proceed to print automatically. Recalibration after 3 months of service with no adjustments whatever during the period showed the scale to be still within "new scale" tolerances.

Fluid-Pressure Measurement

Illustrative of the wide use strain-gage pressure cells are finding in the industrial world, figure 8.13 shows a battery of fluid pressure cells used in rocket-engine test work by the M. W. Kellogg Co. For reasons of security, the rocket ("jato") engine, which is located to the right of the battery of tubular pressure cells, cannot be shown. Pressure cells are used to determine pressures at a large number of points in the engine and fuel system to obtain design information and to check the performance of complicated valves and other controls. In this same setup can be seen a load cell (left, just below center) that is carrying the thrust of the rocket engine, the engine-supporting platform being so suspended that the entire thrust is transmitted to the load cell.

Strain-gage flowmeters are also used in this type of work to measure the fuel flow. It should be noted that fluid-pressure cells and flowmeters have to carry red fuming nitric acid. Also, the cells and cabling must take the deluge water purge which is employed after each test firing.

The instrumentation shown in figure 8.13 is part of the recording equipment used in a single test cell, of which the company has several in operation. As many as 30 fluid-pressure cells are frequently used in a single test. Some of them are put on strip-chart recorders having a 1-sec full-scale response and others are recorded on high-speed film-type oscillographs. In a single test, a large number of pressures, temperatures, flow, and thrust are simultaneously recorded. Needless to say, a tremendous amount of careful planning and coordination of effort go into each firing test.

Equipment for a strictly industrial pressure-measuring application is shown in figure 8.14. This illustration shows the fluid-pressure cells, electronic console, and the panel indicating meters used in a single pumping station on the 1,200-mile pipeline of the Plantation Pipe Line Co. Here, and in a number of other pipelines, strain-gage pressure cells displace conventional bourdon-type gages and minimize maintenance costs as well as eliminate serious fire hazards. As compared with the necessity of frequent recalibration of mechanical pressure gages, it is found that the bonded-wire strain-gage type of pressure cell retains its original calibration almost indefinitely. The output of each pressure cell in this system is fed into a single tube amplifier that drives the indicating meter. Electrical connections between cells and console and between console and indicators is by cable carried in conduit. On the average, the distance between pressure cells and console is about 75 ft., and console to indicating instrument about another 75 ft. All amplifiers and the power supply are plug-in-type units, and spares of both pressure cells and electronic units are carried ready for immediate replacement in the event of breakdown from any cause. The indicating meters are of the wide-angle type and are installed in graphic panel units.

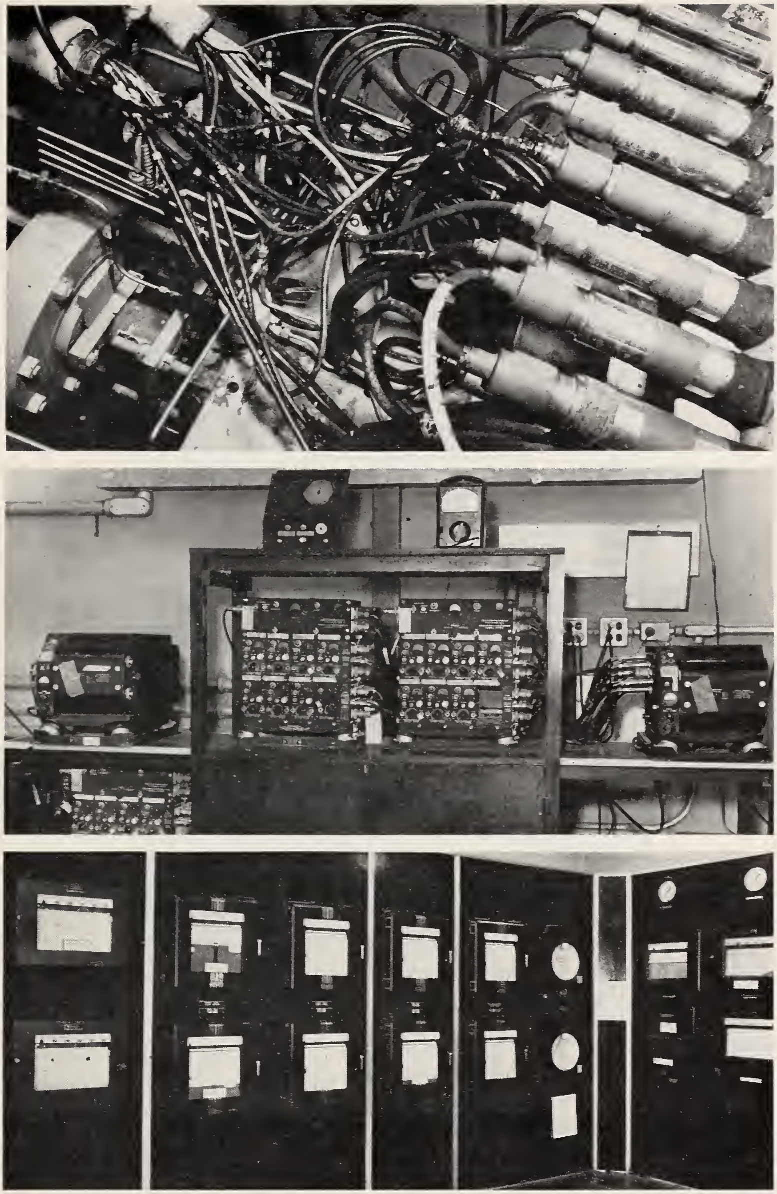


FIGURE 8.13. *Top, battery of fluid pressure cells used in rocket engine tests; center and bottom, instrumentation for recording output of fluid pressure cells in rocket engine research.*

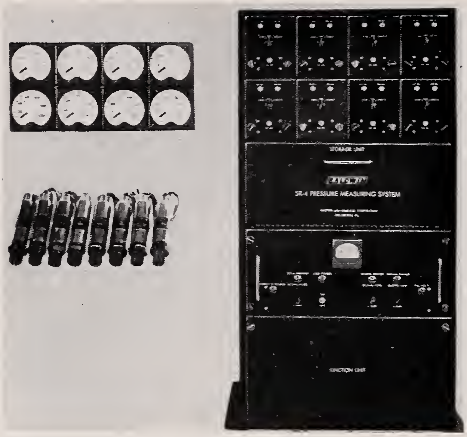


Figure 8.14. *Fluid pressure cells, electronic console and panel indicating meters used in a pumping station on a 1,200-mile pipe line.*

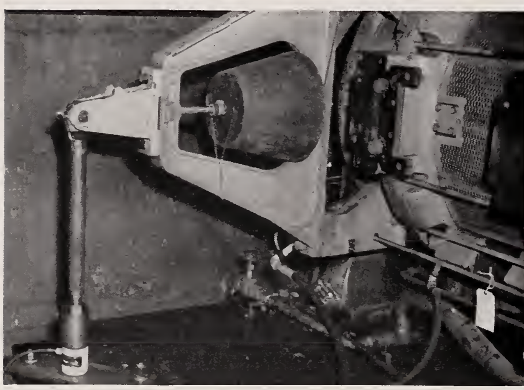


Figure 8.15. *Application of the wire strain gage load cell to the measurement of torque with a large cradle dynamometer.*

Torque Measurement

The bonded-wire strain-gage load cell may be used to measure torque as illustrated in figure 8.15, which shows an application to a large cradled dynamometer. This is part of an engine-test stand for reciprocating engines at the plant of the Wright Aeronautical Corp. The particular dynamometer shown is used for making single-cylinder engine tests, a particularly difficult measurement because of the tremendous torsional pulsations produced by the single-cylinder operation. Here, a load cell and push rod replace the conventional mechanical weighing system. Experience has shown that mechanical weighing systems did not stand up under this kind of service and frequently would not retain calibration from the beginning to the end

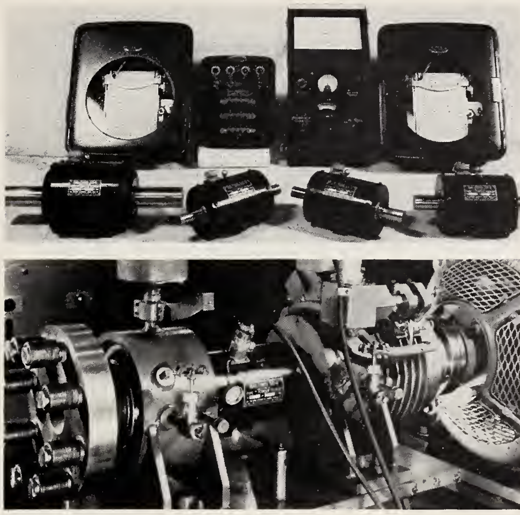


FIGURE 8.16. *Top, typical torque measuring equipment of standard design for use in testing pumps, compressors, engines, etc.; bottom, torque pickup installed in a pump test stand.*

of a single test run. In addition to elimination of mechanical difficulties from vibration, wear, etc., the strain-gage load cell approach in this instance makes it practical to use remote-reading torque indicators conveniently located in the instrument room about 50 ft away where the sound level is greatly attenuated.

Figure 8.16 shows typical torque-measuring equipment of standard design which is widely used in the testing of pumps, compressors, engines, etc. The family of torque pickups shown is part of the production testing equipment for water pumps at the Allis-Chalmers works in Milwaukee, Wis. Capacities shown range from 5,000 to 30,000 in.-lb. Two panel mounting indicator-recorders are shown, and a portable manual-balance torque indicator are shown together with a pushbutton control panel. In actual use, the recording and indicating equipment is conveniently mounted at the operator's console and is so arranged that by pushbutton control the operator can select any pickup to operate into any selected instrument. The photograph at the right shows one of the pickups installed in the production pump-testing stand. The driving motor and electrical tachometer rings are seen at the right. The coupling to the left is a quick-connect coupling for driving the pump under test. The pump to be tested is mounted on a platform, which is hydraulically operated and remotely controlled to give fast and precise adjustment in three coordinates so as to make the matter of coupling the pump for test a very short task.

Figure 8.17. illustrates a high-speed torque pickup in service at the plant of the Wright Aeronautical Corp. The torque pickup shaft with slip-rings mounted on it transmits torque between a turbine and a compressor through spline connections at its ends. The brush assembly shown held in the operator's hand is provided with a solenoid operated brush-lifting mechanism remotely controlled by a switch.

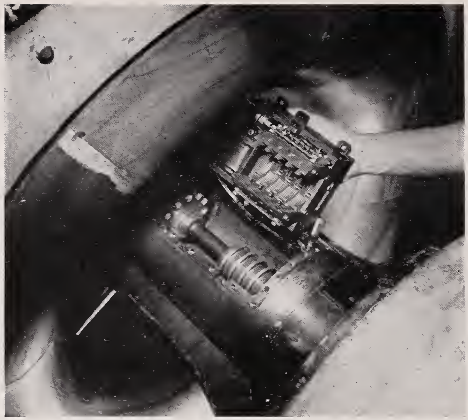


FIGURE 8.17. *High-speed torque pickup for measuring torque transmitted between a turbine and compressor.*

In operation, the brush assembly is installed and a fairing cover completes the enclosure so that the gases can flow directly over the torquemeter housing. The unit operates up to 15,000 rpm with a guaranteed accuracy of $\pm 1/4$ percent of rated capacity torque. Similar units are currently being constructed for service up to 25,000 rpm.

Many other interesting applications of the bonded-wire strain gage have been made to the field of instrumentation, but limitations of space prevent detailed discussion of them. A few might be mentioned briefly in passing, such as the six-component reaction measuring units used in testing models of elaborate piping systems in the laboratory of the M. W. Kellogg Co. in New York City. These were the first six-component strain-gage balances and are the forerunners of the many strain-gage balances that have subsequently been used in wind-tunnel studies in all of the major wind tunnels of the United States. Incidentally, the six-component measuring heads referred to have been in regular service for almost 10 yr without requiring repair or readjustment of calibration.

Another illustration of the versatility of the bonded-wire strain gage in the field of instrumentation is a large size-gaging device built for the Watertown Arsenal at Watertown, Mass. This device makes it possible to gage the inside diameter of gun recoil cylinders and also to determine both ellipticity and out-of-straightness in a fast and simple operation. In this device, the strain gage is mounted on a flexible cantilever which "feels" the diameter of the cylinder and electrically transmits the information to a large dial indicator, which can be read to an accuracy of 0.0005 in. at a distance of 15 ft. In addition, the device is so constructed that it is impossible to scratch the very highly polished surface of the cylinder during the size-gaging operation.

A precision industrial size-gaging device employing the bonded-wire strain gage is manufactured commercially by the Brown and Sharpe

Manufacturing Co., Providence, R. I. This is an industrial comparator having an adjustable sensitivity range from one ten-thousandth inch to one hundred-thousandth inch per division on the indicator. The device is characterized by remarkable ruggedness and stability of measurement combined with extreme simplicity of operation.

It has been rightly said that the range of usefulness of the bonded wire strain gage is limited only by the imagination of the user. While I have here limited myself to a few of the many devices representing application of the gage to the field of instrumentation, it would be a tremendous task to attempt to enumerate the uses to which these same devices have been put by a horde of imaginative users. The bonded wire strain gage has already grown up to be a full-fledged member of the instrumentation family, but I venture to say that the next ten years will dwarf what has been done to date.

The writer acknowledges with thanks cooperation of the following companies in providing photographs and permission to use them: Baldwin-Lima-Hamilton Corp., Schlumberger Well Surveying Corp., Downingtown Mfg Co., Aluminum Co. of America, General Electric Co., M. W. Kellogg Co., Plantation Pipe Line Co., Allis-Chalmers Co., Wright Aeronautical Corp.

Discussion

Dr. Walter Ramberg, National Bureau of Standards, Washington D. C.: Professor Ruge has shown us a fascinating array of industrial applications of the SR–4 bonded strain gage. I would like to ask him if any of these involve exposure of the element to fairly high temperatures?

Mr. Ruge: The only SR–4 devices we have built for high temperature work were made for one of the large aircraft engine manufacturers and they were water jacketed. We built some jacketed cells to be operated in an ambient temperature of 800° F. We do not attempt to subject the strain gage itself to that temperature.

We make a strain-gage load cell and jacket it. In some cases all we need to do is wind a copper pipe around it and circulate a rather small amount of water. It is surprising how easy it is to keep the inside of the cell cool. We normally do not like to subject the inside to very high temperatures, 150° or 200° F. being a reasonable limit for accurate work.

Mr. R. L. Sink, Consolidated Engineering Corp. Pasedena, Cal.: I would like to ask about the ultimate limit of strain gage accuracy. You have indicated that it is possible to attain accuracy in the vicinity of a quarter of a percent, perhaps to a tenth percent of the reading. As I understand it, those accuracies are obtainable only with calibration. Now, if you were to assume a completely accurate measuring instrument, what is the ultimate limit of accuracy of the strain gage itself and under what conditions can that ultimate accuracy be obtained?

Mr. Ruge: Your question would require a good deal of discussion to cover because time and temperature and other factors enter into it. To give you a quick answer, I can tell you that we have agreed to build a precision electric manometer which has a 20-psi full scale, and we have predicted an accuracy of ⅟₁₀ percent of reading over the upper 90 percent of the range. In order to do that, the temperature conditions have to be favorable, let us say within ±15 deg F, because it would be rather difficult to achieve that accuracy, including zero drift over a wide range of temperature conditions. However, we do expect to make our goal. At the lower end of the scale we are talking about 10-percent of capacity—I do not think that is an ultimate limit. It looks like a practical limit today. Three years ago we would not have even talked about trying it. The field of precision measurement is still moving rapidly.

Mr. Coleman Raphael, Republic Aviation Corp., Farmingdale, N. Y.: Have you controlled the manufacture of these gages so that you avoid the zero shift that Mr. Campbell once investigated when you switch from tension to compression?

Mr. Ruge: I can say that it is a great deal smaller—Mr. Campbell was dealing with commercial stress analysis gages and we are dealing here with gages that are built better and with a great deal more care and, of course, they are correspondingly more expensive. I believe there is hardly any comparison between the zero shifts.

Dr. J. M. Frankland, Chance Vought Aircraft, Dallas, Tex.: I would like to ask Mr. Ruge how frequently is recalibration necessary with these high-precision instruments to take care of instrument drift?

Mr. Ruge: I cannot give you history from very far back, Dr. Frankland. I can give you one example of a pressure installation which we put in at the Plantation Pipeline. It was in there considerably over a year and they recalibrated it before they took the trial installation out to put the final one in. They said they could not tell any difference in calibration. I had hoped to show you a picture of a model pipe tester we built for Kellogg Co. in 1942. So far as is known, it has not changed its calibration characteristics. Our history does not go back far enough to give a complete answer. We frequently get load cells back that have had minor damage and we recalibrate them. In general, they are still within the tolerance they had when they went out unless they have been grossly overloaded.

Dr. W. H. Hoppmann II, The Johns Hopkins University, Baltimore, Md.: Remember the very interesting work you did at MIT on earthquake resistance? Did you have an opportunity to use the resistance type gage in that work?

Mr. Ruge: Well, I shall say only that my excursion into the realm of electric strain gages came about directly as the result of an earthquake problem. I was studying the earthquake resistance of elevated water tanks, an important practical problem because they govern the fire fighting when there is a large earthquake. I built myself a tank model. Dr. J. H. Meier was working on it with me at the time. We went ahead and built this beautiful model but could not find anything with which to measure the stresses in the thin shell wall as the tank was shaken. We tried everything available and nothing seemed to work. We tried to make mechanical strain gages and optical gages. Finally in desperation I got into this development. I have never finished that earthquake test.

9. Commercial Weighing With Resistance Strain Gages

By Arthur L. Thurston [1, 2]

Cox and Stevens have specialized in the use of resistance strain gages for weighing aircraft and commercial commodities bought and sold by weight. The paper contains a brief history of the development of the weighing cell and its accompanying instrumentation which apply mostly to the higher-capacity scales. The requirements of commercial weighing are summarized, and how these have been met both in static and motion weighing is described. The paper also covers a recent development where cars and trucks are weighed on the highway at speeds of 60 miles an hour or more.

The concept of the weight of a body is almost as old as history itself, and descriptions or illustrations of scales for weighing occur in the earliest of records. An encyclopedia lists many varieties of scales or weighing machines used in trade and commerce at the present time. These range all the way from locomotive scales to the most delicate of chemical balances capable of weighing a single hair or less.

Weight is important in any field of transportation because revenue rates are generally based on the weight of the goods carried. In air transportation weight is of still more importance because, for safety, the gross weight of an airplane and its cargo must not exceed a certain amount, and the distribution of the weight must be such that the fore and aft center of gravity of the plane falls between rather narrow limits. Weight is also important from the standpoint of economy because a few pounds of additional cargo per trip means an appreciable gain in revenue or goods carried over a period of a year. It is not necessary to weigh a plane before each flight, but periodic weighings are necessary as a check of weight picked up in service, changes of equipment, repairs, etc.

Elaborate scale installations for weighing aircraft have been made at various places, but these require that the plane be transported to the scale. The Cox & Stevens Aircraft Corp., in connection with their extensive work in the weight and balance of aircraft and their development of the load adjuster, recognized the need for, and undertook the development of, weighing equipment that could be easily transported to the plane wherever it might be, rather than the plane to the weighing equipment.

The result of the development is the Cox & Stevens Aircraft Corp. electronic weighing kit (shown in fig. 9.1) of the size and form of an ordinary suitcase, weighing 50 lb complete and having a capacity of 75 tons, or 150,000 lb. The kit contains all the equipment necessary to weigh and determine the center of gravity of an airplane, excepting hydraulic jacks, which are always available at operating airfields.

Basically, the weighing equipment consists of three cells, to be placed on the top of hydraulic jacks between the jacks and jack points of the airplane, and a weight indicator located in the center of a carrying case with a 30-ft extension cord connecting each cell to the

[1] Vice President and Chief Engineer, Cox & Stevens Aircraft Corp., Wantagh, N. Y.
[2] This paper was presented for Mr. Thurston by James J. Heatley, Cox & Stevens Aircraft Corp., Wantagh, N. Y.

FIGURE 9.1. *CS–7 aircraft electronic weighing kit.*
Capacity, 150,000 lb; weight of unit, 53 lb.

indicator. In the cover and along the back of the case are adapters to accommodate the cells to different types of jacks and jack points, and accessories such as level, plumb bobs, leveling bars, 100-ft steel tape, etc. for leveling the plane and making the measurements necessary to determine the center of gravity. The weighing equipment operates from the airplane's 24-v battery or a battery cart, so that a power supply is always available. More recently the electric-weighing kit is being supplied with a 110-v a–c power pack.

An airplane is weighed by supporting it at three points on the cells. These points are usually at each of the main wheel axles and the nose or tail wheel. Wing jacks may be used in place of the main wheel jacks if desired. Although the weight can be determined with the airplane at any angle, it is usually customary to level the airplane in flight position before weighing for the center of gravity determination.

The weight indicator is of the null type with a manually operated weight dial. Controls called "zero set" are provided to adjust each cell to zero weight before loads are applied. All readings on the three cells are taken in succession, the cell in use being determined by a cell selector switch. To eliminate the probability of error in cells, cables and controls are color coded, red, yellow, and blue.

Few people not connected with the scale industry or actual weighing operations are able to realize the important part weighing plays in everyday life. Practically all commodities are weighed at one time or another, and many millions of dollars change hands daily on the basis of weight. As an example, a single stock-yard scale on a busy day may handle as many as 500 drafts of cattle for a total weight of nearly 1 million pounds and a value of over one-quarter of a million dollars, at present livestock rates "on the hoof". A single scale at a coal mine may weigh 300 to 400 cars of coal a day, and when we consider that the transportation costs, as well as the cost of coal, are based on this weight, the total money value may run nearly as high.

Let us consider with what the strain gage has to compete in the general field of weighing. Any electronic system to be competitive must, at the very least, function as well, as long, and with equal accuracy. While strain-gage weighing cells have been in existence for less than 10 yr, it is encouraging to note that if the load cell is adequately protected, we have seen no evidence of deterioration or change that cannot be corrected by simple adjustments. Cox & Stevens Aircraft Corp. has been the sole source to the Air Force and the Navy for some 9 yr in supplying the electronic weighing equipment for aircraft. An Air Force technical order requires the return of these kits yearly to Cox & Stevens for calibration and services. This provides an excellent opportunity, year after year, to study the effects of age on the load-cell strain gage structure. While some cells have given difficulty after several years' service (primarily due to moisture or mishandling), the majority have remained sound for this 8-to 9-yr period.

Scale-accuracy requirements and tolerances are established by various government bodies but, in general, follows very closely the recommendations of the National Bureau of Standards. Without going into great detail, the general requirements of most scales is a maximum tolerance of 2 lb/1,000 lb of weight. In cattle weighing, this is reduced to 1½ lb/1,000 lb and in grain weighing to 1 lb/1,000 lb. For newly installed scales, the tolerances are ½ lb/1,000 lb. For digital printers, the tolerances are increased by one-half the increment between successive prints. Figure 9.2 pictures the four standard Cox & Stevens compression-load cells. The second unit from the left is the most universally used cell as part of the aircraft weighing kit. It is 2¾ in. in diameter by 3¾ in. high. It weighs 2½ lb, and has a weighing capacity of 50,000 lb, or 20,000 times its own weight. The cell is essentially a spring balance of a rather unusual type, where the springs are short steel columns upon which the load rests. Like any other spring under the same condition, this is compressed, and, according to Hooke's law, the compression is proportional to load.

To give an idea of the minute quantities that must be measured, let one consider what this means in terms of deformation, or strain, in the columns and resistances of the gages. These quantities must not only be measured, but also must remain stable and repeat themselves time after time in both the cell and indicator under all conditions of temperature and humidity.

The active length of the strain gage is approximately ½ in. A load of 5 lb will compress this length about 1/10,000,000 of an inch. To

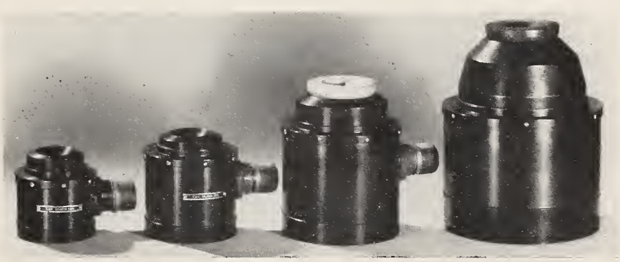


FIGURE 9.2. *Four standard Cox and Stevens compression load cells.*
Capacities in pounds from left to right—10,000, 50,000, 100,000, and 250,000.

measure this strain with a strain gage whose factor is approximately 2, requires a resistance measurement of 1 part in 5,000,000. This means that 200-ohm strain gages would have to be measured to the nearest ten thousandth of an ohm, which is usually done only under laboratory conditions.

All Cox & Stevens cells have the same general construction shown in figure 9.3 and consist of 4 or 6 active columns attached to a base plate. A top plate with a spherical recess rests on the upper surface of these columns and is held in place by a shell and diaphragm assembly. Two shorter columns, called dummy columns, are also fastened to the base plate. The 120-ohm resistance-wire strain gages are bonded to the inside and outside of the active columns, and 480-ohm strain gages are bonded to the dummy columns. The gages are connected in the form of a Wheatstone bridge with four 120-ohm gages in series in each of two opposite arms and the 480-ohm dummy gages in the other two arms. Compensating resistors are also installed in the cell, one which minimizes the change of the indicated load with temperature, and the other which automatically corrects for changes in the modulus of elasticity of the columns with temperature.

While the weighing cell is the heart of the equipment, of no less importance is the instrumentation. All of the Cox and Stevens type indicators are of the null-balance type, that is, an input voltage is applied to opposite corners of the cell bridge and to a potentiometer. A load on the cell unbalances the cell bridge and creates an output voltage proportional to the load. The potentiometer is adjusted either manually or automatically until its voltage exactly equals and is opposite to the cell output voltage and the position of the potentiometer is translated through gearing to indicate the weight directly in pounds. The potentiometer consists of a slide wire or a combination of slide wire and switch.

The basic system is shown schematically in figure 9.4 and in general follows the usual null type method of measuring small potentials.

In addition to the type of instrument used on the electronic weighing kit, Cox and Stevens also manufactures an automatic unit with a printer for permanent installations. In the portable kit the load must be entered manually to compensate for the unbalance of the bridge. The automatic indicator, used for track scales and livestock scales contains an automatic zeroing feature as well.

The automatic equipment shown in figure 9.5 consists of a large visual dial indicator and a digital printer which may be used remotely

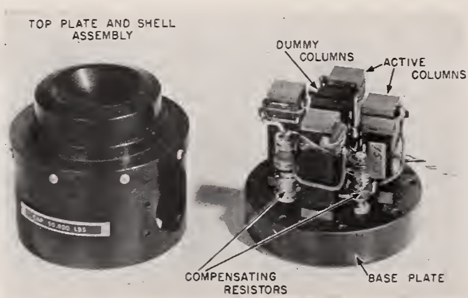


FIGURE 9.3. *Load cell interior construction. 50,000-lb type.*

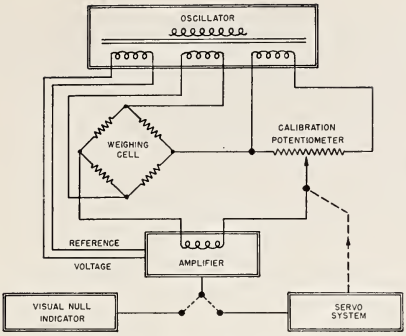


FIGURE 9.4. *Bridge measuring circuit.*

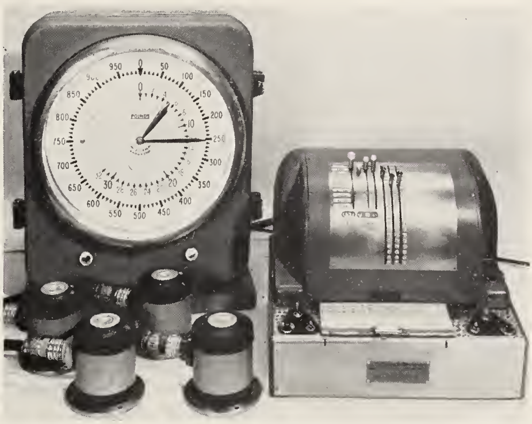


FIGURE 9.5. *Livestock scale showing indicator, 4 cells in waterproofed jackets and printer.* Capacity 32,000 lb.

at any distance from the indicator. It is interesting to comment at this point on the flexibility of electronic equipment. Both the portable, manually operated instrument and the automatic unit may be utilized to indicate individual cell readings or to indicate a total load from a system of two or more cells. A valuable feature of the automatic equipment is the speed of its indication and printing. The indicator will go from 0 to full scale (300,000 lbs) in 3 sec, and then print to 1 part in 10,000. In other words, a 50,000-lb-capacity scale will print to the nearest 5 lb, or a 500,000-lb scale to the nearest 50 lb. Speed is important particularly in motion weighing for obvious reasons. Cattle weighing approaches motion weighing because of the constant milling of the cattle on the scale platform. This constant movement presents a serious vibration damping problem. However, speed of weight indication in the stock yards is not crtitical because considerable time is required to collect the livestock onto the scale platform. The time involved in this operation limits the drafts to about 70 per hour. The slower speed of the indicator eases the damping problem to some extent in this case. The worst condition we have encountered has been in freight-car weighing where the combination of heavy weights, a high-speed instrument, short time on the scale and low-frequency oscillations posed a problem very difficult to solve.

Finally, both electrical and mechanical damping were required.

In June 1949 we installed our electronic equipment in a lever-scale system for the Pennsylvania Railroad in Jersey City, N. J. Eight weighing cells were used of 65,000-lb capacity each, installed in pairs, two at each corner of the scale between the weighbridge and the lever system so that weights could be obtained simultaneously on both the lever system and the electronic system. It is a track-scale installation with a 63-ft-long weigh rail. A record has been kept of the comparative weights of the two systems over the 2-yr period, and the system has been checked periodically every 90 days with test-weight cars. It is interesting to note that after the initial adjustments were made at the time of installation, no further adjustments have been made in either the weighing cells or the measuring circuits. The equipment has been consistently accurate both summer and winter. The deck of the scale has no covering and is exposed to sun, rain, snow, and ice. There is no means of heating the pit in which the cells are located, and while no record has been kept of pit temperatures, it is estimated that these vary conservatively from about 30° F in winter to around 75° F in summer.

Last December a second installation was made for the Pennsylvania Railroad at Cadiz, Ohio. This is similar to the Jersey City scale, except it is on a grade. Between 300 and 400 cars daily are weighed, uncoupled and in motion, as they roll across the scale by gravity. Printing of the weight is done automatically, it being only necessary for the weighmaster to insert tickets in the printer and remove them after the weight has been printed. The automatic printing is governed by three photoelectric cells at coupler height. The criterion for weighing requires that the car has all wheels on the scale simultaneously for three full seconds. This gives the scale time to come up to weight, and also provides a short interval for damping.

The Association of American Railways specifies that the smallest test-weight cars used in adjusting and checking track scales shall not weigh less than 30,000 lb. Most track scales have a weighing capacity of 300,000 lb, and because of the 30,000-lb test-car weight minimum, are not used below 10 percent of total capacity. In comparison, cattle scales of around 30,000-lb capacity do considerable weighing of single animals whose weight will run from 600 to 1,200 lb and are occasionally required to weigh a small calf at 50 or 60 lb.

This is an interesting point; the fact that a 30,000-lb-capacity scale is required to weigh accurately a 50-lb calf. The accuracy of such weighing requires that the modulus of elasticity of the column material remains constant below the elastic limit. It has been a normally accepted belief that at very low stresses the Young's Modulus could not be depended upon to remain constant. However, Cox & Stevens in translating this theory into actual practice has found the contrary to be true. Of course, where a platform is used, the dead weight puts an initial stress in the columns, which in some installations is quite high. However, with the standard 50,000-lb-capacity cell common to the aircraft unit, with no initial preload, weights of 50 lb may be accurately measured. The cross-sectional area of the columns in these cells is approximately 1 in.^{2}, so that in the case of the 50-lb load, the unit stress is about 50 lb/in.^{2}.

An interesting track-scale installation to be made early in 1952 will be in a railroad yard for the Southern Railway System. This will be in what is known as a hump yard where cars are pushed up a grade over a hump, uncoupled at that point, and permitted to freely roll down a grade by gravity over the scale. The novel features of this installation are that the grade will be 3 percent, an unheard of slope for a track weighbridge, the length of the weigh rails, which will be 90 ft, and the closeness of the scale to the apex of the hump. The operation of the system will be wholly automatic and will be controlled entirely by the speed of the locomotive pushing the cars over the hump. This speed has been set at 2½ mph. No car riders will be used. At the hump, the individual cars will separate, and proceed fully on and alone on the scale for 3 sec. This method of operation did not originate with Cox & Stevens; however, our equipment was selected because of its fast operation. Forty-foot cars may be weighed at the rate of 5½ cars a minute. When the Southern Railway System yard is in full operation it is expected that 5,000 cars will pass over the scale each day, with the selective weighing of from two to three hundred.

One of the most interesting recent developments in which Cox & Stevens has had the pleasure of participating is a highway truck-weighing unit. In the spring of this year the installation was made in collaboration with the Bureau of Public Roads. The platform was placed in a busy lane of the Shirley Highway, approximately 25 miles south of Washington. This location is about 4 miles north of a State of Virginia weighing station at Woodbridge. This particular spot provides an excellent research location due to the high density of heavily loaded truck traffic and the smoothness of the road surface. Complete tests were started in June and still continue. Accuracies of indication are constantly being cross-checked with the State of Virginia scale, and the constant monitoring of the installation by Bureau of Public Roads technical personnel has provided a very complete picture of day-to-day performance.

As you may be aware, there is, at present, a considerable amount of interest and activity in the State Highway Departments concerning the limiting of truck-axle weights. A great percentage of road wear may be traced directly to excessively loaded axles and the impact of their concentrated weights.

The highway unit has multiple functions. It will (1) weigh a static load, (2) detect single axles weighing in excess of any given limiting load, (3) record axle weights at any truck speed, (4) record truck velocities, and (5) print the static weight on the platform. To detect overloaded axles with the trucks in motion, a fast, sensitive relay was added to the indicator circuit. Many states limit single-axle loads to 18,000 lb. This figure may be set on the load dial, and if a truck passes over the scale having an axle load in excess of this figure, a bell will ring. This feature has operated at truck speeds to 50 mph.

With the addition of an oscilloscope, a trace may be secured picturing the individual axle weights on the entire truck, figure 9.6. The horizontal sweep of the scope is triggered by a pressure switch stretched across the highway in front of the platform. There is a camera attachment for the oscilloscope to provide a permanent record of the various weight traces. An eyepiece also forms part of the assembly to enable visual observation of the trace.

The average speed of the vehicles crossing the platform in the Shirley Highway is 50 mph. As the length of the platform is but 3 ft, the electronic apparatus must cope with time intervals on the order of 30 to 40 milliseconds.

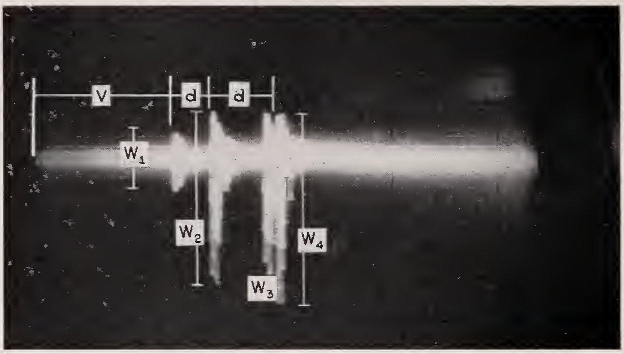


FIGURE 9.6. *Oscilloscope trace photograph of tractor trailer truck at approximately 40 miles per hour over scale.*

V dimension is velocity of truck; d, distance between axles; W_1, front tractor axle; W_2, rear tractor axle; W_3, W_4, rear tandem axle.

FIGURE 9.7. *Highway scale pit showing cell piers, cables, and tie rods.*

Although a single-frame camera only is presently being used, a continuous recording camera is available. Eventually, it may be possible for an operator to visit the highway installation each morning for purposes of checking calibration and to collect the film recording of the complete traffic picture for the previous 24 hr. With this equipment it is anticipated that a complete road load density history may be secured without any interruption to traffic or any knowledge on their part that such an analysis is taking place.

The installation for such a unit is simple and relatively inexpensive. A shallow pit was constructed in the highway shown in figure 9.7. Piers for supporting the weighing were poured simultaneously with the walls. There is one cell pier in each corner. The pit depth is 30 in. The weighbridge, or platform, is a reinforced concrete slab 3 by 10 ft and approximately 1 ft thick. Figure 9.8 shows the platform being lowered into the pit on the weighing cells. The platform slab rests directly on ball adapters on top of the cells, and horizontal check rods

FIGURE 9.8. *Crane installation of highway platform.*

FIGURE 9.9. *Finished highway platform appearance.*

Shirley Highway, Va.

are provided to keep the slab centered. Cables from the cells were run to a small shack about 50 ft off the highway. The final installation is pictured in figure 9.9. The pit and platform were made by and under the direction of the Bureau of Public Roads, and the trueness of approach, slab, and exit surfaces are excellent.

Tests are still being conducted, and, as with a first experimental model, certain problems have become apparent, and certain discrepancies still need explaining. In general, however, we feel safe at this point in saying that there is no evidence we are measuring impact loads rather than axle weights. There appears to be no error due to speed. The errors we are experiencing occur just as frequently at speeds of 10 mph as at 50 or 60 mph.

The weighing problem at Woodbridge, Va., provides an excellent example of the practical value of this type of instrument. At present all trucks are being weighed in order to determine which have overloaded axles. On a busy day, trucks may be lined up 1 mile waiting their turn at the scale. The electronic unit could be placed down the road from the main scale and only those trucks on which overloaded axles are detected need be stopped for enforcement of the overload limit.

In summing up, we at Cox & Stevens feel, after some 10 years of experience with strain-gage weighing, that the future points toward general acceptance by all of this principle for high-capacity scales.

Discussion

Mr. Arthur T. Snyder, Boeing Airplane Co., Seattle, Wash.: On your pressure scales, in what manner do you compensate for incidental lateral loading on the cell, that is, loading other than the vertical which you wish to measure?

Mr. Heatley: Our compensation is mechanical. We have a ball adapter that rests in the top of the unit and depend on that to help center the load. Our cells actually will remain in calibration with up to an 8-deg load inclination. Some of our cells have been collapsed, but that has been due to faulty aircraft-weighing techniques. You may recall the incident at Northwest a short time ago when they collapsed a cell. That was due to poor alinement of the jack.

Mr. Snyder. You say you can misaline your load by as much as 8 deg and still be within the accuracy tolerance of your cell?

Mr. Heatley: Well, no, I would not say that. You can up to 4 deg, within the accuracy tolerance. At an 8-deg angle, the cell will retain its calibration for the next use. I mean it will not damage the cell at the strain-gage bond.

Mr. Merle C. Brady, Consolidated Vultee Aircraft Corp., San Diego Division, San Diego, Calif.: Do you make a small, flat scale onto which the airplane could be taxied or pulled instead of using the load cells you illustrated there under the wing?

Mr. Heatley: Yes, we do.

Mr. Brady: If so, is it immune to or compensated for a temperature condition in which you might have heat from some source acting on the scale but not well distributed, so that you might have a fairly high temperature gradient on the part of the scale containing the weighing element?

Mr. Heatley: That is a rather difficult question to answer not knowing the magnitude of the temperature range, but the cells are compensated within a reasonable range. The fact that one cell was under a different temperature condition than a second cell in the system would not make any difference as far as the indication was concerned, if that was your question. The cells could be at different temperatures.

Mr. Brady: What I had in mind was that with the active gages on one column, as illustrated on your sketch of one cell, and the compensating gages on another column, it appeared that the temperature gradient might introduce noticeable temperature drift.

Mr. Heatley: I do not know.

Mr. K. H. McFarland, Ames Aeronautical Laboratory, NACA, Moffett Field, Calif.: Is there any real reason in temperature compensation to put the dummy gage on an insensitive column? A standard practice is to put Poisson's ratio gages on where you have transverse sensitivity, and so far as I know there are no detrimental effects from that, but you do not do it that way, and I was wondering why.

Mr. Heatley: Technically I am not sure. We have made cells without the inactive columns. Mr. Ruge can possibly answer that.

Mr. Arthur C. Ruge, Ruge-deForest Inc., Cambridge, Mass.: It is purely a practical matter of economics, dollars, and cents. It has 4 or 6 columns by which we could take care of eccentric loading and the number of strain gages goes up to where the economy is seriously affected if you use the lateral gages. We built them both ways in the early days.

Mr. McFarland: Do you use dummy gages?

Mr. Ruge: Dummy gages are made 480 ohms and the active are 120, so you see you cut down the total number of gages. Let us say 420 ohms on active gages and 420 on dummy gages; it simply cuts down costs. Functionally, they do not show any difference.

Mr. McFarland: But they could be put on the active columns.

Mr. Ruge: Yes.

Mr. Harry Stern, Allegany Instrument Co., Cumberland, Md.: I would like to bring up another point. It seems to me another possible source of error comes from the fact that both your modulus correcting resistor and temperature correcting resistor are on a column separate from the active gage. This arrangement could result in zero shifting and change in cell calibration in outdoor measurements where the sun, wind, etc. are causing temperature changes. Lagging your cells will help, but for the accuracies that you claim a temperature difference of 2 deg may make quite a difference. What is your final error, something like 1 percent/100 deg?

Mr. Heatley: I am not familiar at all with those figures. I would appreciate it if Mr. Ruge could answer the questions.

Mr. Ruge: When you say what is the error, do you mean Cox & Stevens' error to compensation or what is the modulus coefficient?

Mr. Stern: What is the error? Is that the same as the Baldwin gage?

Mr. Ruge: No, these cells are in different order of accuracy. Undoubtedly for 100-deg change you would find they do not vary by more than $\pm 1/20$ percent over a 100-deg range. They are exceedingly closely adjusted, and the workmanship has to be very, very careful all the way through.

Mr. Stern: These are for steady state conditions.

Mr. Ruge: That is right. Now, when we have the conditions you speak of, such as in jet-engine work, we get around those effects by lagging the cell with as much—sometimes you might have a couple of inches, and if you are right in under the tail of an engine, you put a reflector there to pick off the radiant energy. You have to be kind to it just like any other delicate instrument and prevent those sudden changes.

Mr. R. G. Boiten, National Council for Industrial Research, Delft, Holland: May I put in a few auxiliary questions? In the first place, coming to the point noted by the two last speakers—the matter of temperature compensation and response—at this moment a few of your kits are in use at the KLM Airport at Schiphol, as you may know perhaps, and they are quite often checked by one of our laboratories. As a matter of fact, they are stored in an office, and when an aircraft has to be weighed it has been observed that it takes about ½ hour for the cell to warm up to outdoor conditions and become stable. The whole temperature compensation, according to your design, responds rather slowly to temperature changes, and so the cells are liable to give larger errors than they should. This seems to be a distinct disadvantage in such applications, especially as the weighing cell is not isolated at all. It responds immediately to temperature changes, and because the heat flow to the columns has to pass rather narrow sections, it takes some time before the new state of temperature equilibrium is reached.

Mr. Heatley: Well, maybe I do not understand your problem, but the temperature compensation in a cell does not have very much to do with the warmup of the indicator or the columns. It is a question of the amplifier and adequate warmup and the temperature stabilization within the amplifier, as well as the cells.

Mr. Boiten: It is not always true, because other cells can be made without temperature compensation and are stable within 5 min. Furthermore, I would ask you what stresses are you allowing in your pressure cells? I mean, how near to yield point of your steel you are going?

Mr. Heatley: We have, I would say, about a 5-to-1 safety factor.

Mr. Boiten: Five to one still? How then is it possible that the instrument is destroyed with such a slight angle of 8 deg?

Mr. Heatley: Well, that failure does not have anything to do with the compressive strength of the columns, but due to the narrow area of the columns, the side load and tipping over. It is not a bending failure.

Mr. Boiten: I see. It is a matter of the construction and design, so to say.

Mr. Heatley: That is right.

Mr. Boiten: I was interested in your remarks concerning the irregularities in the modulus of elasticity at low stresses. There are some very peculiar effects. We have tested quite a number of cells and would like to find an explanation for this effect. It seems to be a good practice to preload the cell to a certain amount to reduce that first 5 percent. Have you been able to find a steel that has a perfectly linear relation between stress and strain?

Mr. Heatley: Well, yes. As I said, we have a 50,000-lb cell, and the steel in the columns of that cell design will weigh 50 lb without any preload and weigh it accurately and repeat many times.

Mr. Boiten: So you have found a special steel which has all those properties?

Mr. Heatley: Well, you might say, yes, but I do not know about the heat treatment.

Mr. Boiten: Is the zero point of your measuring device independent of temperature or not? Most measurements are made over an interval of a few minutes, but sometimes our customers have weighing problems where the weight must be controlled without unloading for a period, for example, of about 2 yr under various temperature conditions. I have had quite a lot of trouble in getting absolute zero stability over these long periods. Naturally, zero drift would immediately cause a corresponding drift in the end results. Are your weighing cells absolutely compensated, and have they a perfectly stable zero point for various temperatures? Or are they to be compensated for the temperature at the moment?

Mr. Heatley: Well, on the aircraft kit we have a zero set, but this is for use under stable temperature conditions.

Mr. Boiten: I know.

Mr. Heatley: On the automatic equipment we have an automatic zero. Of course, it has to be operated with no load on the platform. We have no knowledge of a zero compensation with a load on the scale, over a long period of time, at various temperature conditions. I cannot answer that because we do not attack the problem that way.

Mr. Boiten: Well, we did.

10. Application of Resistance-Wire Strain Gages to High-Capacity Load-Calibrating Devices

By D. R. Tate [1]

The National Bureau of Standards has for many years maintained a program to provide means of verifying the accuracy of tension- and compression-testing machines. These machines, in wide use in industrial plants and laboratories, vary in size from small devices for testing small samples of sheet metal or organic and fibrous materials up to machines capable of testing a steel girder or a concrete cylinder several feet in diameter. Large or small, it is important to know that the test results obtained with these machines are correct.

The construction of suitable precision calibrating devices has heretofore been limited to capacities of a few hundred thousand pounds by practical restrictions of weight and size. The perfection of wire strain gages has opened broad possibilities for the design of lightweight, high-capacity calibrating devices. The National Bureau of Standards has developed a series of such devices which have been constructed in units having capacities as great as 3 million pounds. The work has involved the construction and gaging of load-carrying units and the incorporation of available alternating-current bridges into special instruments to indicate the load.

Introduction

The National Bureau of Standards has been interested for many years in the development of elastic devices for load calibration of tension- and compression-testing machines. The objective has been to produce instruments of adequate accuracy and sensitivity, yet at the same time rugged, portable, and adaptable to a variety of testing conditions. Instruments of this type must be not only accurate, but also of such design that the calibration of the instrument is unaffected by time, rough handling, or operation by relatively inexperienced personnel.

One of the important contributions was made by H. L. Whittemore and S. N. Petrenko of the Bureau, who developed the first proving rings [1].[2] These devices have been improved and refined by the manufacturers and are now widely accepted as standard instruments for calibrating testing machines [2]. The proving ring, shown in figure 10.1, is a specialized device and functions best when used under conditions in which purely axial loads can be applied rapidly and smoothly with a high degree of control. The rings can be used for general load-weighing purposes if these conditions are fulfilled, but they are not satisfactory for the measurement of fluctuating loads or for applications where lateral stability is lacking. Proving rings do not indicate load directly, but give a value on an arbitrary scale, the load being calculated from the scale value multiplied by a factor read from a calibration chart. The design features that insure the excellent stability of the ring tend to prevent adjusting the response to any fixed scale interval.

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[1] Physicist, National Bureau of Standards, Washington, D. C.

[2] Figures in brackets refer to the literature references given on p. 129.

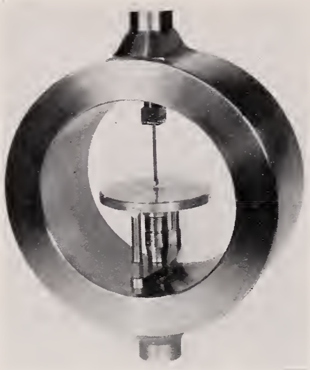

Figure 10.1. *Proving ring for calibrating testing machines.*

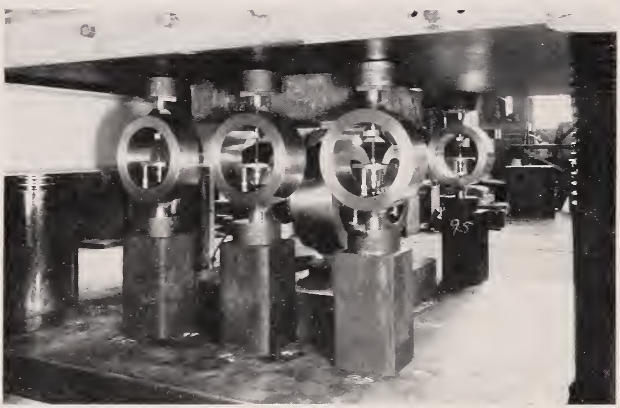

Figure 10.2. *Several proving rings loaded simultaneously in a testing machine.*

Proving rings are supplied in a variety of sizes covering a range of loads from a few hundred pounds up to three hundred thousand pounds. In the larger sizes both weight and machining cost mount rapidly. The ratio of gross weight to capacity for a large proving ring is about one in two thousand; thus a 300,000-lb-capacity proving ring will weigh about 150 lb.

Modern testing machines are made in capacities up to 5,000,000 lb, and a machine having a capacity of 10,000,000 lb has been in service at the National Bureau of Standards for many years. Materials testing specifications currently in force in this country require calibration of a testing machine over its entire usable range. Thus, the widespread use of large machines has provided a real need for the development of calibrating instruments having capacities beyond the present range of the proving ring. Although it is possible to use several proving rings simultaneously in a large machine, figure 10.2, the process is costly and time consuming. The method has been used, however, to calibrate up to about 2,500,000 lb. Practical considerations of space limit the measurement of large forces by this method.

Basic Features of Dynamometers

The invention of the bonded resistance-wire strain gage made possible a new approach to the problem of calibrating these large testing machines. As the gages respond primarily to strain rather than deflection, the use of an efficient, elastic compression element in the form of a column was feasible and opened the door to devices having a much higher capacity per unit of gross weight.

Early applications of this principle appeared in aircraft-weighing kits made by the Cox & Stevens Aircraft Corp. [3] and in the load cells manufactured by Ruge deForest Inc. for the Baldwin-Lima-Hamilton Corp. Experimentation to develop compression dynamometers having capacities of 1,000,000 lb and more was started at the National Bureau of Standards in 1943 at the instigation of Dr. Lyman J. Briggs, then Director. Progress was painfully slow because of limited manpower and funds, but by May 1946 a device having a capacity of 1,000,000 lb had been constructed and calibrated. During succeeding years three more dynamometers of 1,000,000-lb capacity were completed and calibrated, and in addition four 3,000,000-lb-capacity dynamometers of similar design were constructed and calibrated.

The basic principles governing the application of resistance strain gages to an elastic column type of load measuring device have been agreed upon by most workers in the field. Two or more gages are bonded to the column with their axes parallel to the load line, and two or more other gages are attached either on the column with their axes transverse to the load line or on an unstressed piece of metal. These gages are electrically connected to form a complete Wheatstone bridge, the gages parallel to the load line being placed in opposite arms of the bridge. Connections to the four corners of the bridge are then brought out through a cable.

This system offers several advantages, one of the most important being that variations in contact resistance in the cable connections on the order of 1/20 ohm or less do not appreciably affect the balance of the strain gage bridge or the accuracy of the unit. Other advantages of having all four arms of the bridge included in the device are the improved temperature compensation and the relative ease of balancing and matching the device to the indicator. The process of attaching all four arms of the bridge to the same column provides the major part of the temperature compensation, as any expansion of the column from temperature changes affects all four arms of the bridge equally and leaves the bridge balance unaltered.

The degree of unbalance produced in such a strain-gage bridge is usually measured by opposing the output of the bridge with another variable-resistance bridge or a potentiometer circuit. If the strain-gage bridge and the measurement bridge are both brought to the same degree of unbalance so that they produce equal and opposite voltage outputs, no current will flow in the linking circuit. A sensitive galvanometer in the linking circuit would indicate an accurate matching of the two bridges. This arrangement is not feasible in working devices because a galvanometer sensitive enough for the purpose is too slow in operation and lacks the necessary ruggedness. Instead, both bridges are usually supplied with low-frequency alternating current (about 1,000 cps is common), and a low impedance input to a

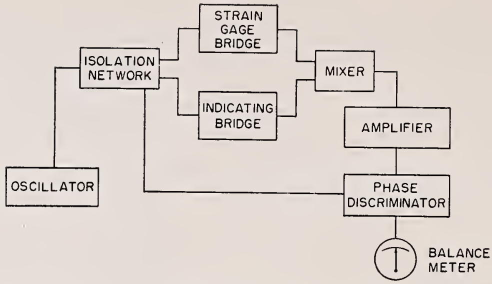

FIGURE 10.3. *Schematic diagram of dynamometer circuit.*

stable amplifier is provided in place of the galvanometer. A simple phase discriminating network at the output of the amplifier permits the unbalance between the two bridges to be indicated on a zero-center d-c milliammeter. Operation of the measuring equipment is then very rapid, and the meter is protected from accidental overloads by the limited current output from the amplifier. A schematic diagram is shown in figure 10.3.

Basically, the electrical system offers several advantages over the mechanical measuring system of the proving ring. First, it permits measurement of load from a remote point. Second, much less skill is required of the operator to obtain satisfactory readings on loads that are changing rapidly or that transmit considerable vibration. Third, the scale indication corresponding to capacity load may be adjusted to match any desired scale interval. There are other advantages besides these and may be equally important.

As might be expected, the system offers a few drawbacks along with its advantages. The more serious of these are the difficulty in producing the required high degree of stability in the strain gages and the measuring circuit and the relative complexity and high cost of the electrical components.

Design of the NBS Dynamometers

In utilizing the principle of mounting strain gages on an elastic column to form a dynamometer, it was recognized that the equipment was inherently somewhat more subject to variations than a purely mechanical system. Furthermore, the need to conserve weight made it necessary to design around a shorter column and a much higher working stress than the best theoretical considerations would indicate. The design does, however, provide practical working units of reasonable weight and dimensions with capacities up to 3,000,000 lb.

In the work at the National Bureau of Standards the design chosen for the elastic column was essentially that shown in figure 10.4. The unit is made of alloy steel, SAE 4340, and heat treated to a hardness of 45 to 50 on the Rockwell C scale (Brinell 425 to 485). This heat treatment gives a tensile strength of approximately 250,000 lb/in.^{2} and a yield strength of about 230,000 lb/in.^{2} The design working stress for the reduced section of the column is about 125,000 lb/in.^{2} The ends of the column are flared to form enlarged integral bearing blocks having an average bearing stress of 60,000 lb/in.^{2} This bearing

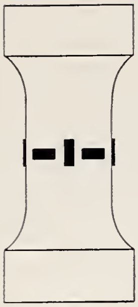

FIGURE 10.4. *Dynamometer column design showing location of strain gages.*

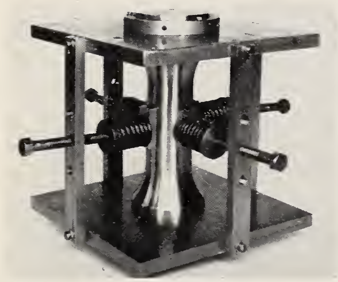

FIGURE 10.5. *Jig for spring loading gages during baking cycles.*

FIGURE 10.6. *NBS dynamometers, capacities 100,000 lb, 300,000 lb, 1,000,000 lb and 3,000,000 lb.*

stress must be reduced further by suitable hardened and ground blocks to avoid damage to a mild-steel testing-machine platen.

The strain gages are arranged in a pattern as shown in figure 10.4. There are four longitudinal and four transverse gages attached to the center section of the column. Each gage is electrically connected in series with the diametrically opposite gage to form one arm of a bridge. The gages, SR–4 type ABD–5, are dual lead gages bonded with phenolic resin, having an advance wire filament with a resistance of 75 ohms. The effective gage length is ½ in.

The gages are attached in the usual manner. Figure 10.5 shows a jig for providing the spring loading to the gages during the baking cycles. The dynamometer being gaged in the figure has a capacity of 300,000 lb. The baking is accomplished in a laboratory oven, or, in the case of the largest dynamometers, in a portable furnace having radiant heaters controlled by thermocouples under dummy pressure pads.

After attachment of the gages, the columns were subjected to repeated applications of a 20-percent overload in order to eliminate hysteresis in the gages or columns. The gage circuits were then adjusted to balance the bridges to zero output at zero load, the gages were waterproofed with Petrosene wax, and the protective cover was installed. Finished dynamometers of various capacities are shown in figure 10.6. The cover is held in place by the upper retaining ring and slides in a recessed groove in the lower ring, making a dust-tight seal, which permits the column to be compressed freely. A sectional view of the dynamometer with its cover is shown in figure 10.7.

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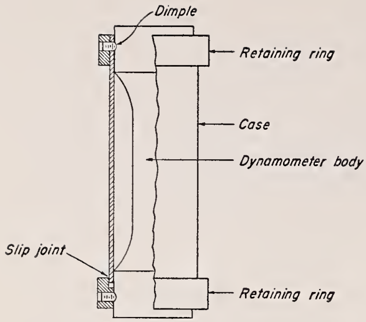

FIGURE 10.7. *Sectional view of dynamometer cover.*

A 1,000,000-lb-capacity dynamometer weighs about 30 lb, and a 3,000,000-lb-capacity dynamometer weighs about 225 lb. The larger dynamometers are provided with a tapped hole in the upper bearing surface to permit attachment of an eyebolt for handling.

Electrical Measuring Equipment

It was decided to utilize the conventional type of SR–4 strain indicator with suitable modifications as the load-indicating device. Although the output of a dynamometer is not linear when compared to the internal bridge of the strain indicator, the indicator is adjusted to approximate the output curve near the upper end of the scale, and a final small correction is made from a calibration curve. In this manner the indicator reads load directly over the entire scale to within 1 or 2 percent and is corrected to a much more accurate figure from the curve.

Modifications to the bridge of the SR–4 indicator included eliminating the gage-factor adjustment, changing the zero-input reading from the center of the scale to the zero position of the range, replacing the graduated slide wire dial, and installing a zero-adjustor circuit. The operation also included extensive electrical realinement of the indicator.

Connections between the modified strain indicator and the dynamometer were by means of a four-wire shielded cable and AN type connectors. In practice, each dynamometer is always used with the same indicator and cable.

The indication for capacity load on the dynamometer is about 1,000 divisions and the reading is estimated to the nearest tenth of a division. Sensitivity is such that an unbalance of one-twentieth of a division on the scale gives an appreciable indication on the balance meter.

Load Calibration

The dynamometers are calibrated by loading them against a combination of smaller capacity elastic devices in the manner currently employed for calibrating large proving rings [2]. In this process three or four devices that have been previously calibrated are placed on the platen of a large testing machine, and a thick steel plate is placed on top of them. The device to be calibrated is placed above the plate in such a manner that loads applied to it will be distributed among the smaller devices in proportion to their capacities.

A load approximately equal to the desired calibrating load is then applied by the testing machine, and readings are taken on all of the devices simultaneously. The true load is calculated as the sum of the loads measured by the smaller devices and is compared to the reading obtained for the dynamometer. In order to obtain a direct comparison of the repeatability of the dynamometer over several calibration runs, the readings for the nominal value of the load are computed by linear interpolation. Any actual test load is usually within ½ percent of the nominal load.

The basic standard for the calibration is the 111,000-lb-capacity dead-weight testing machine in the NBS Engineering Mechanics Section [4]. Three 100,000-lb-capacity proving rings are calibrated in this machine, and by the method described above, are used to calibrate three 300,000- and one 200,000-lb-capacity proving rings. These four rings are then used to calibrate individually the four 1,000,000-lb dynamometers, which in turn are assembled to calibrate the 3,000,000-lb dynamometers.

As each step in this process will theoretically reduce the accuracy of the final calibration, it is apparent that a graduated set of working tolerances for the devices is required. Such a set of tolerances is given in the American Society for Testing Materials Tentative Methods of Verifying Calibration Devices for Verifying Testing Machines, ASTM designation E74–50T [5]. There is at present no U. S. Government specification of a parallel nature. The ASTM tolerances require in essence that the load-deflection curve for the device shall fit a first- or second-degree curve within the following limits:

ASTM E74-50T requirements		
Capacity of device—		Tolerance
Exceeding	Not exceeding	
lb	*lb*	*Percent*
--------	300, 000	±0. 25
300, 000	1, 000, 000	± .3
1, 000, 000	3, 000, 000	± .4
3, 000, 000	10, 000, 000	± .5

Temperature Correction

The dynamometers, like other elastic devices, are affected by temperature in that both the modulus and the dimensions of the elastic column change with temperature. Although it is not a difficult matter to introduce a short length of special wire in thermal contact with the column as a temperature-compensating resistor, this would require a verification test for each individual dynamometer. For this reason no compensation has been applied to the dynamometers constructed at the National Bureau of Standards.

Experiments have been carried out to determine the temperature coefficient for uncompensated devices of lower capacity but constructed of the same steel and gaged with the same type of gages. The coefficient for the dynamometer was found to be −0.00019/deg F, and the coefficient for the indicating instrument was found to vary with individual instruments from +0.00007 to −0.00009/deg F.

Performance of NBS Dynamometers

In presenting performance data for elastic calibrating devices in general, it has been found that a graph showing the relationship between the indication of the device and load is not sufficient to reveal variations on the order of a few tenths of a percent. Instead, a graph showing a quantity called the calibration factor is generally plotted with the indication of the instrument as the independent variable. The calibration factor is defined as the applied load divided by the indication of the device in scale divisions. The calibration factor changes only a small amount throughout the range of the instrument; thus it can be plotted on a magnified scale, so that variations in the factor of the order of one-tenth of 1 percent are readily perceptible.

Such a graph is given in figure 10.8, showing the calibration of a 1,000,000-lb-capacity dynamometer. It will be seen that the observed points fit a straight line of positive slope quite well. The graph shown in figure 10.9 presents the calibration for a dynamometer of 3,000,000-lb capacity. For loads of 1,200,000 lb and greater, this device was calibrated against four 1,000,000-lb-capacity dynamometers. The 300,000-, 600,000-, and 900,000-lb loads were applied through a single 1,000,000-lb-capacity dynamometer.

The graphs shown in figures 10.8 and 10.9 indicate that the calibration factor increases in a nearly linear fashion throughout the range of the dynamometers, although the total change is less than 2 percent. This means that the relationship between the indication

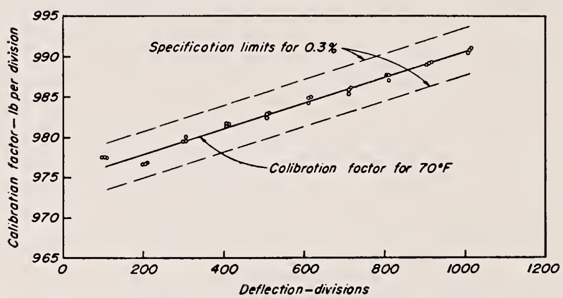

Figure 10.8. *Calibration graph for 1,000,000-lb-capacity dynamometer.*

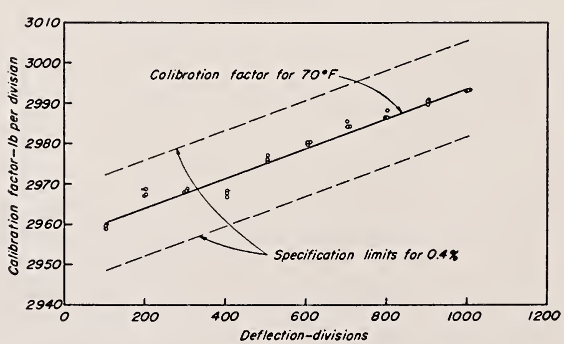

Figure 10.9. *Calibration graph for 3,000,000-lb-capacity dynamometer.*

of such an instrument and load is not linear but follows a second-power law. Had the response been perfectly linear, the calibration-factor graph would have been a horizontal line.

Nonlinearity

The nature of the response of devices such as proving rings, column dynamometers, and other elastic devices is almost invariably nonlinear. The few cases where linear relationships appear may arise either from lack of sensitivity or from a design of device in which the deflection is unusually small compared to the overall dimensions or where compensating sources of nonlinearity tend to cancel each other. The reason for the nonlinearity is not difficult to understand when one considers that the constant of a spring is dependent on the elasticity of the material and on the shape and dimensions of the spring. When the spring is deflected, its shape is changed and the spring constant accordingly changes with load. This is just as true for a compression column or a tensile bar as it is for an elastic ring. As a column is loaded in compression, the lateral expansion causes its diameter to increase so that the sectional area increases with load. In addition, the compression tends to shorten the gage lengths parallel to the load line, so that actual deflections, the product of strain and gage length, progress at a relatively slower and slower rate as the column is loaded.

Conclusions

Load-measuring devices in capacities up to 3,000,000 lb employing bonded-wire strain gages have been constructed and calibrated at the National Bureau of Standards. The combination of four 3,000,000-lb devices is sufficient to calibrate to capacity the largest testing machines in this country. The errors of these 3,000,000-lb devices are believed not to exceed 0.4 percent. The dynamometers are light enough to be handled by two men and rugged enough to permit handling on hand trucks or by crane.

At present the electrical measuring instruments are portable and adequate in sensitivity and ease of handling, but it is thought that there is considerable room for improvement in quality of the electrical measuring instruments and for the design of instruments engineered to the special requirements of this type of service.

The demands imposed in the design of high-capacity load-meauring devices are such that the bonded-wire strain gage can be employed with great advantage in their construction. It is felt that the results obtained with the dynamometers constructed at the Bureau have been satisfactory, and that the dynamometers are a suitable means of calibrating large testing machines.

References

[1] Proving ring. U. S. Patents 1648375 and 1927478 issued to H. L. Whittemore and S. N. Petrenko.

[2] B. L. Wilson, D. R. Tate, and G. Borkowski, Proving rings for calibrating testing machines, Cir. NBS C454 (1946).

[3] A. L. Thurston and R. W. Cushman, Precision determination of weight by means of bonded strain gages, Proc. Soc. Exp. Stress Anal., III, No. 1, 62 (1945).

[4] B. L. Wilson, D. R. Tate, and G. Borkowski, Deadweight machines of 111,000-AS and 10,100-pound capacities, Cir. NBS C446 (1943).
[5] TM Standards, 1950 Supplement, Part 1, Ferrous Metals, 274.

Discussion

Mr. Arthur T. Snyder, Boeing Airplane Co., Seattle, Wash.: I would like to ask, Mr. Tate, what steel you use in your dynamometers and what heat treatment you use on it, and whether you follow the Baldwin Locomotive Works baking-cycle recommendation on application of your gages?

Mr. Tate: The steel we used was SAE–4340, a deep-hardening alloy steel. It was heat treated to give hardness at the surface of somewhere between Rockwell C–48 and –50. We followed the baking cycle recommended by Baldwin Locomotive Works.

Mr. David Vandeventer, Leeds & Northrup Co., Philadelphia, Pa.: Mr. Tate, didn't you have some difficulty with the flatness of the ends of your dynamometers in your testing machines?

Mr. Tate: Yes, that is a problem. In many designs of load-measuring devices a spherical or other curved surface is used on one end of the device. In the case of the dynamometers both ends are ground flat and are loaded against large hardened and ground bearing plates. It has been our experience that uneven bearing may be transmitted through a considerable thickness of bearing.

11. Preliminary Investigation of the Strain Sensitivity of Conducting Films

By William R. Campbell [1]

During recent years conducting coatings and films have been developed for use in printing electronic circuits. While good resistance stability of electrical components is desired in such applications, experience has shown that resistance changes due to mechanical distortions (strain sensitivity) have been troublesome with some film materials. Because strain sensistivity is an important characteristic of resistance strain gages, tests were made to determine the relative strain sensitivity of various materials in the form of thin conducting films.

This paper presents the results of resistance-strain measurements on vaporized films of silver, platinum, aluminum, nickel, palladium, tin, advance alloy, and carbon. Calibrations of sections of resistance tapes and films of carbon-pigmented paints are also discussed. The results indicate the possibility of developing a film strain gage having a relatively high output and a useful strain range of about 18 percent. It is concluded that a fundamental study of the resistance-strain characteristics of pigmented paints is desirable to provide basic data on the performance of conducting films.

In the application of conducting films to printed circuits, it is desirable that resistance materials show a high degree of resistance stability under various atmospheric conditions, and that the resistance of a finished film be relatively insensitive to mechanical deformation, that is, the conducting film should have a low strain sensitivity. While strain sensitivity is an objectionable characteristic in printed-circuit components, it is a prime factor in variable-resistance strain measurements. Hence, a printed-circuit material that is discarded because of excessive strain sensitivity may be considered for possible application to strain measurements, using the variable-resistance principle.

During a recent study of the velocity of propagation of small pulses of strain in prestressed prismatic bars, two wire resistance strain gages attached to a bar were used to trigger an electronic interval timer that indicated the time required for a strain pulse to be propagated from one strain-gage point to the other. The relatively low output of the wire strain gages for the small strain pulses necessitated a high level of amplification that led to numerous instrumentation difficulties. It was apparent that most of the difficulties would be alleviated if, even at the expense of output linearity, the sensitivity of the strain gages could be increased. The carbon strain gage, pioneered by de Forest, and long since superseded by the wire strain gage, seemed well suited to the interval-timing problem, since the carbon gage, apart from many shortcomings, had always exhibited a high sensitivity. It was a simple matter to construct on the test bar two "painted" strain gages, using a film of carbon-pigmented paint as the strain-sensitive element. These gages were so useful in making velocity measurements that it was decided to survey the resistance-strain characteristics of several conducting film materials.

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[1] Mechanical Engineer, National Bureau of Standards, Washington, D. C.

From a survey of the various methods of depositing or producing conducting films and the number of materials available, it was apparent that only a limited number of exploratory tests could be made at the time. Three types of films and 13 coating materials were considered.

1. Films of conducting paints: (a) Colloidal graphite in alcohol, (b) powdered graphite in a solution of cellulose acetate and acetone.
2. Vaporized films: (a) Platinum, (b) nickel, (c) palladium, (d) aluminum, (e) silver, (f) advance alloy, (g) carbon, (h) tin.
3. Resistance tapes: (a) Printed-circuit resistors.

The details of construction of an experimental painted-film gage are shown in figure 11.1. A tissue-paper base was first cemented to a 24S–T aluminum-alloy calibration bar. A mask was placed over the base paper so as to leave a rectangular area 1½ by ¼ in. on which the conducting paint was brushed. Copper-wire leads were then placed in contact with the ends of the test film (after air drying) and cemented with Dupont No. 4817 silver paint. The finished gage was dried 4 hr at 70° C and then coated with hot petrosene wax. A similar procedure was used for gages made from resistance tape, except that

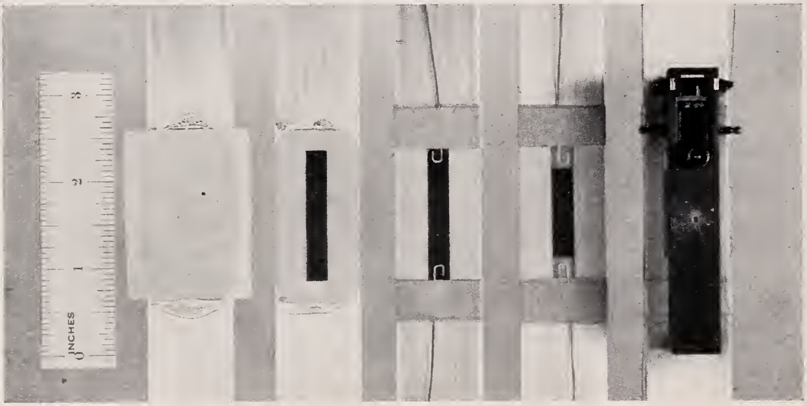

Figure 11.1. *(Left to right) Progressive stages in the construction of a painted film gage.*

Tuckerman optical strain gage is shown spanning completed gage at right.

Figure 11.2. *Sample of vaporized metal deposit on lens paper base (above) and section of resistance tape (below).*

the rectangular area of sensitive material was cut from the tape, figure 11.2, and cemented to the paper base. Vaporized materials were deposited on a sheet of lens paper, figure 11.2, through a mask having a configuration similar to the multistrand wire gage. Electrical connections were made in the same manner as for painted gages.

After the gages had been attached to the calibration bars, a Tuckerman optical strain gage was mounted on the bar so as to span the test gage, figure 11.1, and measure the strains produced by loading the calibration bars. The change in the resistance of the test gage was measured with a conventional Wheatstone bridge. Calibration bars were loaded in tension, and the unit change in gage resistance was measured for increasing values of strain.

Calibration curves for vaporized-metal gages of platinum, nickel, palladium, silver, and tin are shown in figure 11.3. The resistance-strain characteristics of these gages were decidedly nonlinear and offered little promise in the way of performance. This is perhaps not unfortunate because these materials are noted for having an extremely high temperature sensitivity, a factor that is not desirable in strain-measuring devices. The calibration curve for the vaporized-nickel gage is of special interest, however, as it is noted that the curve has a positive slope, that is, a positive strain sensitivity, K, which approaches 35 at the higher strains. Nickel, in the wire form, is known to have a negative strain sensitivity near $K=-11$. This suggests that the resistance changes that take place in the vaporized film might be due to a separation between particles in the electrical path rather than to a deformation of the individual particles, as is probably the case with a strained wire. The possibility that the particles in the film separate from one another to produce an increase in film resistance seems consistent with the fact that the vaporized film is composed of a sprinkling of particles without the benefit of a binder. Although this single observation of the difference between the characteristic

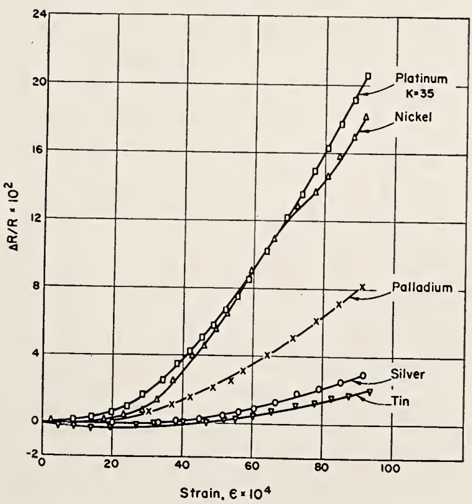

FIGURE 11.3. *Calibration curves for vaporized metal coatings.*

curves for a film of vaporized nickel and for nickel wire is by no means conclusive, it would indicate that the resistance-strain relationships for the vaporized films are determined more by particle size and shape, and the geometric relation between particles, than by deformation of the particles.

Resistance-strain relationships obtained for painted films of colloidal graphite in alcohol (Dag Dispersion No. 154) are shown in figure 11.4. Gages were constructed with resistances ranging from 1,400 to 15,000 ohms, and over this range of resistance the calibration curves appear to be relatively independent of gage resistance. Gage factors approached 42, and output linearity was considerably better than for the vaporized-metal films.

Results obtained with resistance tapes are shown in figure 11.5. These tapes, selected from those being studied in another program, were composed of a furnace black pigment in an unknown binder, with the pigment content varied from 8 to 11 percent by weight. Inspection of figure 11.5 shows that the resistance-strain relationship was nonlinear and that the strain sensitivity was about 30 at the higher strains.

Following the general calibrations of the vaporized metals, colloidal graphite, and resistance tapes, a strain cycling test was devised to test gages for hysteresis and creep. The calibration bar with gage attached was subjected to two complete cycles of the strain sequence in tension 400 to 2,400 to 400 μin., with the strain held constant for 15 min at each strain level. During this test, which required 1 hr for the 2 cycles of loading, the change in gage resistance was measured with time. The ideal result with the cycle test would be to obtain a square wave of $\Delta R/R$ versus time.

The cycling tests yielded very erratic results when applied to the vaporized-metal gages, figure 11.6. Two additional metals, aluminum and advance alloy, were added to the metals tested. Figure 11.6 shows that no gage in the group returned to its original state after the initial

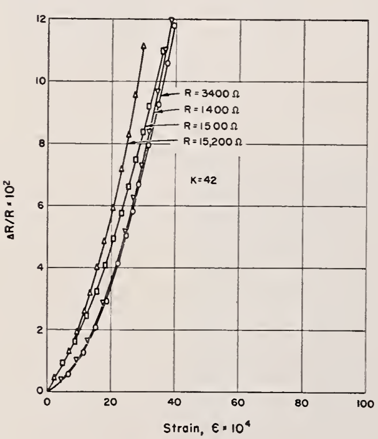

Figure 11.4. *Calibration curves for films of colloidal graphite in alcohol.*

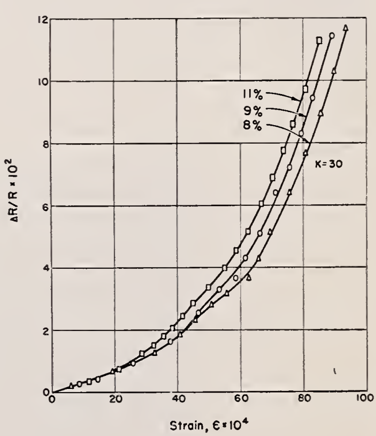

Figure 11.5. *Calibration curves for gages made from sections cut from resistance tapes.*
(Pigment content 8, 9 and 11% by weight.)

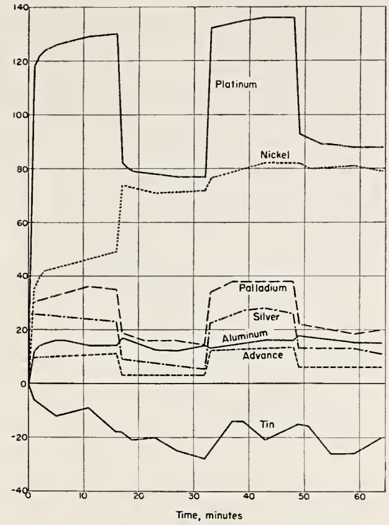

FIGURE 11.6. *Results of strain cycle tests on vaporized metal films.*

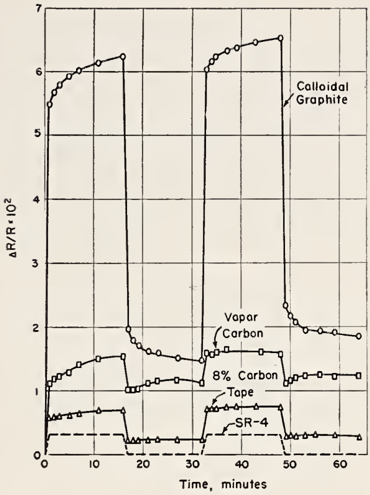

FIGURE 11.7. *Results of strain cycle tests on nonmetallic materials.*

loading. This also is believed to be due to the lack of binding media between the particles of vaporized metal.

Strain cycling tests were made on gages of colloidal graphite, resistance tape, and vaporized carbon. Typical results of these tests are shown in figure 11.7. For convenience in estimating the relative performance of the different gages, the response of an SR–4 wire strain gage is shown in this figure. It is seen that neither the output amplitude nor the symmetry of the curves is especially impressive for the vaporized carbon and the resistance tape. The colloidal graphite gives an output about 18 times that of the conventional wire gage. There is, however, evidence of hysteresis with the colloidal graphite in that the resistance of the gage does not return to its initial value after the first cycle. Also, the curved tops and bottoms of each cycle indicate possible creep or temperature sensitivity.

On the basis of the foregoing cycling tests and the resistance-strain calibrations, it was concluded that the vaporized-metal gages offered little promise in the present form, and no further work was undertaken on this type of gage. Because there was a tendency for the carbon tapes and painted films to show improved linearity at the higher strains, additional calibrations were made on these materials at post yield strains. The results of the high-strain calibrations on vaporized carbon, resistance tape, and colloidal graphite are shown in figure 11.8. It should be noted in figure 11.8 that the initial resistance of a gage is doubled at $\Delta R/R=1$. It is then apparent that the resistance of the vaporized-carbon gage, for example, increased eleven-fold for a strain of 4 percent. Of the three materials tested at high strains, the colloidal graphite gave a surprisingly high degree of linearity, coupled with a strain sensitivity of about 61. The colloidal graphite was the first material to give encouraging results as a strain-sensitive material, and it also functioned well at post yield strains.

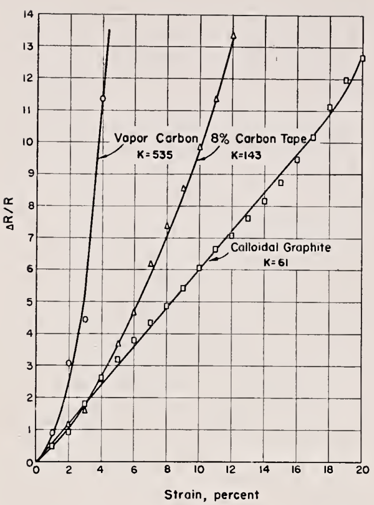

Figure 11.8. *Calibration curves at high tensile strains for vaporized carbon, resistance tape, and colloidal graphite.*

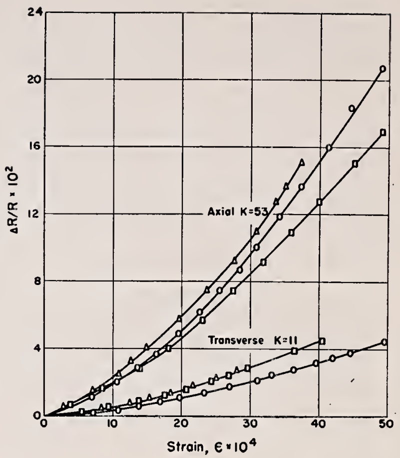

Figure 11.9. *Output curves for two colloidal graphite gages mounted parallel to and transverse to the axis of major principal strain in an uniaxial stress field.*

So far nothing has been said of the behavior of conducting films in a biaxial stress field. Although the film gages shown in figure 11.1 appear to have an axis parallel to the test bar, an isolated element of the film is probably composed of a random placement of conducting particles and does not have a distinct axis, such as the axis of an element of strain-sensitive wire. Thus a film gage might be expected to be equally sensitive to strain in all directions. This was not found to be true experimentally, however, as is evident from figure 11.9, which gives the results of longitudinal and transverse calibrations. For these tests, two gages were attached to a wide test strip with the long dimension of one gage parallel to the center line of the strip and the long dimension of the other gage perpendicular to the axis of the strip. The test bar was loaded in uniaxial tension, and the longitudinal and transverse calibration factors, K_L and K_T, respectively, were determined from the relation.[2]

$$\frac{\Delta R}{R} = K_L \epsilon_L + K_T \epsilon_T,$$

where the subscripts L and T refer to the longitudinal and transverse axes of the gage, respectively, and ϵ is strain. Figure 11.9 shows that the gage mounted transversely on the test strip gave substantially less output, $\Delta R/R$, than the gage mounted parallel to the axis of the strip. Several tests were made on rectangular-shaped gages, and the ratio of axial to transverse strain sensitivity was about 5 in all cases. This ratio was as low as 2 for a few square-shaped gages, but in no case was the strain sensitivity completely independent of strain direction.

[2] W. R. Campbell, Performance tests of wire strain gages, IV—Axial and transverse sensitivities, National Advisory Committee for Aeronautics, TN 1042 (June 1946).

It was concluded that end effects at the lead-in connections and the technique of depositing the films possibly affected the results.

The painted-film gages necessarily have a limited range in compression, since a decrease of the resistance of a gage to zero would correspond to only $\Delta R/R = -1$. Several gages were calibrated on short columns for strains up to about 0.01. The resulting resistance-strain curves showed that gage resistance decreased at a decreasing rate in compression, and as a consequence, the output linearity was very poor. The tendency toward this nonlinearity in compression may be seen in figure 11.10, which shows a calibration curve for a complete cycle of strain, tension and compression, for a strain amplitude of approximately 0.0016.

During the tests of the resistance tapes, vaporized-carbon films, and colloidal graphite films, it was observed that all the calibration curves for these materials curved upward, especially near the origin, and that all of the gages showed a positive hysteresis (fig. 11.7) when repeatedly strained and released. Considerable improvement in output linearity was obtained with a paint consisting of a mixture of Dixon Micronized Graphite No. 200–08 and cellulose acetate. The weight ratio of binder to graphite was varied over the range 5:1 to 15:1. A ratio of 9:1 produced a good mixture for painting and reasonable gage resistances (less than 20,000 ohms). A calibration curve for a gage of micronized graphite is shown in figure 11.11, where it may be observed that the characteristic upward curvature of the resistance-strain curve is confined to values of strain below 20×10^{-4}. At strains above this level, the output linearity is reasonably good, although the strain sensitivity, $K=30$, is less than that of colloidal graphite in alcohol. A strain cycle test was made on three micronized graphite gages, with the result shown in figure 11.12. The hysteresis with this gage material was negative, that is, successive strain cycles in tension produced a gradually decreasing value of the gage resistance, corresponding to zero strain.

The tests with the micronized graphite films demonstrated that, in general, gage characteristics can be altered by varying the in-

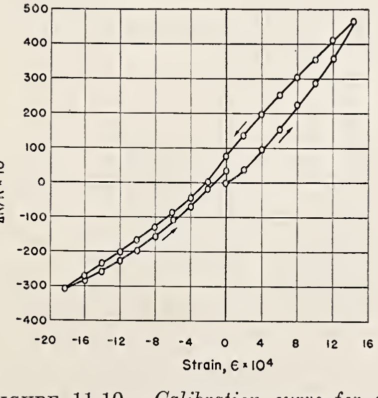

FIGURE 11.10. *Calibration curve for a colloidal graphite gage subjected to a complete cycle of strain, tension and compression.*

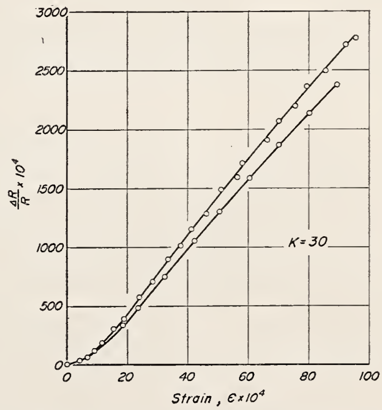

FIGURE 11.11. *Calibration curve for film of micronized graphite and cellulose acetate.*

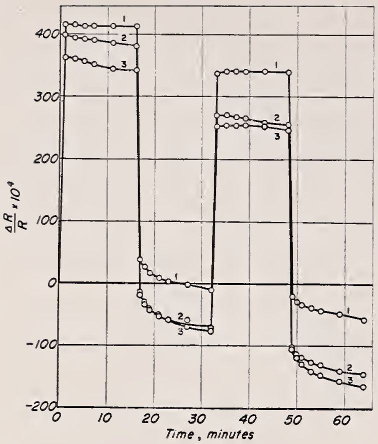

FIGURE 11.12. *Results of strain cycle test on three micronized graphite gages.*

gredients of the conducting deposit. This suggests that further study of the influence of particle size and shape, binders, mix ratios, and depositing techniques on over-all film performance may point the way to useful strain-sensitive films.

It should be stated that while the term "gage" has been used repeatedly in describing these tests on various conducting films, the films discussed here are not resistance strain gages suitable for actual strain measurements. The results of this survey are entirely exploratory and should be supplemented by further study. No mention has been made of resistance stability, temperature sensitivity, constancy of gage factor, gage current limitations, etc. All of these factors should be considered in a more comprehensive study of the electrical characteristics of conducting films. It seems reasonable to conclude that the possibility of developing a high-range, high-output conducting-film strain gage, having somewhat less accuracy than that of the wire strain gage, is not entirely remote.

The author expresses his appreciation to W. G. Brombacher and Benjamin Davis for their cooperation in providing vaporized-metal samples and resistance tapes for use in these tests.

Discussion

MR. ARTHUR C. RUGE, Ruge deForest, Inc., Cambridge, Mass.: I should like to say, if I may, that I think Mr. Campbell has made a very significant contribution, the most significant perhaps in the last 8 or 10 years of the strain-gage art. I have a question I should like to ask regarding the axis of your plots where you put $\Delta R/R$ for the resistance change. I think we ought to adopt a sort of Geneva Convention. Are you plotting the true strain sensitivity at these points?

MR. CAMPBELL: No, $\Delta R/R$ is the relative change in gage resistance from the initial value. The denominator R is the initial gage resistance, not the instantaneous resistance.

MR. RUGE: I have been confused about this in a number of papers printed on that very subject.

Mr. Campbell: Yes, true gage resistance is also used, but in these plots the denominator is the resistance of the gage at the start of the test.

Mr. Ruge: The strain is what?

Mr. Campbell: The strain is the change in gage length divided by the original gage length we are working with.

Mr. Ruge: Mr. Tate brought up in discussing the matter of strain-gage nonlinearity that it seems to be a resistance strain gage characteristic to follow that peculiar law, which you were getting only approximately, of course.

Mr. W. Lavern Howland, Lockheed Aircraft Corp., Burbank, Calif.: I would like to compliment Mr. Campbell on this excellent paper. I think that this is a very fruitful field. We have conducted some tests at Lockheed on conductive coatings. We have evaporated some thin coats, some of them being only a few angstroms thick where you could see through the coating when put on glass or quartz, and some of these very thin coats revealed quite nice electrical strain-sensitivity characteristics. We have made some tests where different specimens would definitely reproduce the same calibration constant, and they would return very close to the same point, that is, zero point. The coatings have to be protected carefully from oxidation because when you evaporate the metal, of course you get an oxide many angstroms thick, and that oxide changes your gage cross section. We have already run tests on conductive paint and had some that displayed quite good characteristics. I am saying that mostly as a word of encouragement. There are a lot of problems, such as making contacts at the end. That appears to be a major problem.

I have evaporated complete bridges in order to eliminate some of this problem. This seems to be one way of solving the contact problem. We still have a hard time making contact with these very thin films.

I want again to compliment you on your fine paper.

Mr. Campbell: Thank you, Mr. Howland. I might say that on the basis of the results of these tests we have planned a more detailed program to study the characteristics of natural graphites, channel blacks, and furnace blacks in conjunction with various binders and solvents. It is hoped that more information on the resistance-strain characteristic of a variety of paints will enable us to make a substantial improvement in linearity.

Dr. J. M. Frankland, Chance Vought Aircraft, Dallas, Tex.: This has been a very interesting paper. It makes me think back a number of years to Prof. de Forest's first interest in resistance strain gages that arose in this very same field. He was intrigued, as I recall it, by some results he had seen in General Electric's laboratories of the remarkable variations in resistance of some carbon-painted surfaces. So he took some of the stuff back to his laboratory and was horribly disappointed when he tried to check its consistency. That was what started him on the resistance strain gages.

I believe that original paint was flake graphite blended in a solution of sulfur in carbon disulfide.

Mr. Campbell: The carbon gage, I think, was just making its exit when I became involved with resistance strain gages. I did not know that Prof. de Forest had used carbon paints. I did know a great many measurements had been made with very thin solid flakes of carbon that had been more or less machined. In any case, there is nothing new in this, for the strain sensitivity of carbon has been known for a long time.

Dr. L. B. Tuckerman, National Bureau of Standards, Retired: I might add a little more background. Going back about, let me say 50 years, we sometimes made high resistances for use in apparatus by coating the inside of glass tubes with a film of carbon in lacquer. That was my first contact with carbon films as resistances. Then came, as Mr. Frankland has said, this report of the strange sensitivity of films. But de Forest went further, and with the Alfred D. Little Co., he turned out those carbon resistance cemented gages and they worked, but they did not work as well as he had hoped, and he then went over to wire gages. The use of a film of carbon in a lacquer goes way, way back. It was certainly over 50 years.

Mr. R. G. Boiten, National Council for Industrial Research, Delft, Holland: I would say that some similar work has been done just before the war, following a suggestion of the Philips Laboratory, and it has been published in some research papers at the beginning of the war. I do not know if these papers have come to this country, but actually we had some experience in our laboratory. It was done in the following way. By using a drawing pen and Chinese black drawing ink, a line was drawn on a slip of paper. If I am not mistaken, it had a gage factor in the neighborhood of 60, but it was dropped because it was enormously unstable due to changes in temperature and moisture.

I do not know how much you have regarded these points. Due to moisture, resistance changes up to 15 or 20 percent are possible, especially on a paper base.

Mr. Campbell: This is very true. We had to waterproof these gages in order to hold such changes down. Temperature effects were avoided by carrying out the calibrations at constant temperature.

U. S. GOVERNMENT PRINTING OFFICE: 1954