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Hole-Drilling Strain-Gage Method of Measuring Residual Stresses

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CONTENTS

ABSTRACT

The hole-drilling, strain-gage method of measuring residual stresses in elastic materials has been termed semidestructive because of the use of holes of very small diameters. The method permits the magnitudes and principal directions of residual stresses at the hole location to be determined. This is accomplished by means of an empirically determined quantitative relation between the magnitudes and directions of the principal stresses and the strain relaxation about the hole as the hole is drilled. This relation was obtained for a nondimensional model of the hole-gage assembly in order to make the results independent of hole size. A generalization was postulated to extend the use of this calibrated solution to the measurement of residual stresses in all elastic, isotropic materials.

PROBLEM STATUS

This is a final report on this phase of the problem; work is continuing on other phases.

AUTHORIZATION

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HOLE-DRILLING STRAIN-GAGE METHOD OF MEASURING RESIDUAL STRESSES

INTRODUCTION

With the exception of x-ray techniques there are no practical nondestructive methods for measuring residual stresses. It is possible, however, to determine residual stresses by drilling a hole in a specimen and measuring the resulting change of strain in the vicinity of the hole (1,2). Recent refinements in strain gage manufacturing techniques have made it possible to obtain strain gages of very small dimensions. Thus a hole only 0.01 inch in diameter and depth may suffice for the measurement. Since this amount of destruction can sometimes be tolerated, this method is called semidestructive. While it would be possible to calculate the relief of strain caused by drilling the hole and to obtain the average strain over the area covered by the gage, an experimental approach is considered more practical. By using nondimensional units and maintaining similitude the experimental calibrations relating the strain gage readings to residual stress can be made to apply to any size hole. Calibrations can be made for the determination of residual stress as a function of depth below the surface. However, sensitivity is expected to limit this depth to a value approximately equal to a hole diameter.

THEORETICAL APPROACH

A hole drilled in a stressed material will change the strain in the surface area surrounding the hole. Consider the strain in a radial direction at a fixed distance from the hole of given diameter and for a uniaxial stress field of known direction. The change of strain as one drills from a depth z to a depth of $z + \Delta z$, as shown in Fig. 1, is

$$\Delta\epsilon_z(\alpha) = K_z(\alpha)\,\sigma_z\Delta z \qquad (1)$$

where σ_z is the stress at depth z, α is the angle (see Fig. 2) between a radial direction from the hole and the stress axis, $\Delta\epsilon_z(\alpha)$ is the radial strain at a given radial distance caused by drilling a distance Δz at a depth z, and $K_z(\alpha)$ is a parameter which is a constant for any given z, Δz, and α. This parameter must be experimentally determined.

For simplicity we will consider only the case where the value Δz is taken as the full depth of the hole, in which case

$$\epsilon(\alpha) = K(\alpha)\sigma \qquad (2)$$

where $\epsilon(\alpha)$ is the radial strain at a given radial position and angle α caused by drilling a hole of a given diameter and depth.

If one considers two principal stresses in a plane parallel to the surface and, of course, orthogonal to each other, then by superposition

$$\epsilon(\alpha) = K(\alpha)\,\sigma_{max} + K(\alpha + 90°)\,\sigma_{min} \qquad (3)$$

where α is measured from the direction of the maximum stress.

Generally the directions of the principal stress axes are not known. Let the angle β (Fig. 2) be the unknown angle between the x-coordinate direction and the direction of σ_{max}.

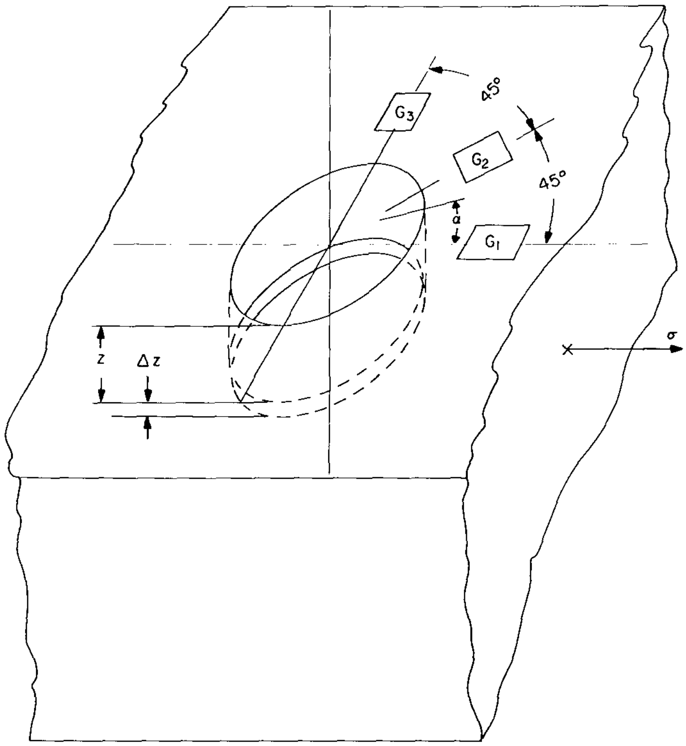


Fig. 1 - Hole in stressed plate with strain gages, (G), located so as to measure changes of radial strain caused by drilling the hole

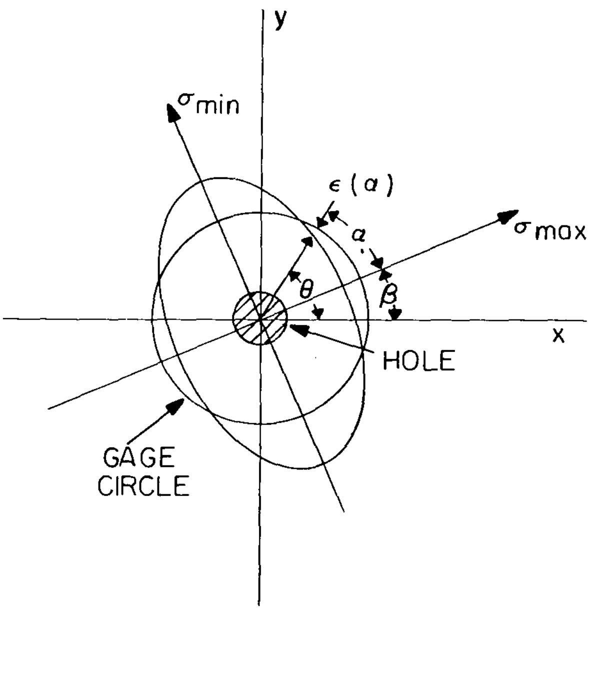


Fig. 2 - Coordinate axes x and y with origin at center of hole. The radial strain is measured on the gage circle at an angle θ from the x-axis. β is the angle between the maximum principal stress axis and x-axis. The radial distance between the gage circle and the ellipse represents the amount of strain at that location caused by drilling the hole.

Strains will be measured along the strain circle at various values of θ, as measured from the x-coordinate. The value of α of Eq. (3) is then

$$\alpha = \theta - \beta. \tag{4}$$

There are three unknowns in Eq. (3): the angle α and the magnitudes of the two principal stresses. The function $K(\alpha)$ can be determined by calibration, i.e., applying known stresses and measuring $\epsilon(\alpha)$. Since there are three unknowns in Eq. (3) it is theoretically possible to obtain solutions of the magnitudes of the principal stresses and the angle α by making measurements of strain at three uniquely different positions. The angle β can be determined from Eq. (4).

However, if $K(\alpha)$ is retained in graphical form and solutions are attempted, the procedures are too cumbersome to be of practical value. Instead, $K(\alpha)$ will be approximated by a relatively simple mathematical expression, even though the solution is still relatively complicated.

Qualitatively the radial strain caused by drilling a hole of diameter d at a fixed distance from the hole is shown in the polar diagrams, Figs. 3(a) and 3(b). Uniaxial stresses in the x and y directions exist in the two respective cases. It can be seen that the $K(\alpha)$ is an even function and can be represented by the series

$$K(\alpha) = \sum_n A_n \cos 2n\alpha , \quad \text{where } n = 0, 1, 2, \ldots . \tag{5}$$

As an approximation only the first two terms are retained, or

$$K(\alpha) = A + B \cos 2\alpha , \tag{6}$$

as shown in Fig. 3(c). Substitution of Eqs. (6) and (4) into Eq. (3) yields

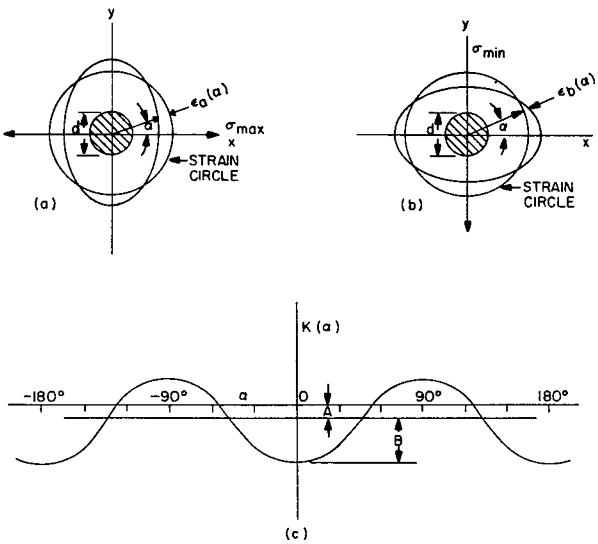


Fig. 3 - Qualitative representation of radial strain caused by drilling a hole in a uniaxial stress field along (a) the x-axis and (b) the y-axis. The strain of diagram (a) is given in diagram (c) in rectangular coordinates. This is proportional to $K(\alpha)$ (see Eq. (2)) and is of the form of Eq. (6)

$$\epsilon(\alpha) = [A + B \cos 2(\theta - \beta)]\,\sigma_{max} + [A + B \cos 2(\theta - \beta + 90°)]\,\sigma_{min}. \tag{7}$$

In measuring the strain at three different locations it is convenient to let the strain gages be located so that ϵ_1, ϵ_2, and ϵ_3 correspond respectively to $\theta = 0°$, $45°$, and $90°$, since these values will simplify Eq. (7). Further simplification is introduced by the substitution

$$-2\beta = \gamma. \tag{8}$$

The three simultaneous equations thus obtained can then be solved to obtain the principal stresses and their directions in terms of the measured strains and the constants A and B. These solutions are

$$\sigma_{max} = \frac{\epsilon_1(A + B \sin \gamma) - \epsilon_2(A - B \cos \gamma)}{2AB(\sin \gamma + \cos \gamma)} \tag{9}$$

$$\sigma_{min} = \frac{\epsilon_2(A + B \cos \gamma) - \epsilon_1(A - B \sin \gamma)}{2AB(\sin \gamma + \cos \gamma)} \tag{10}$$

$$\gamma = \tan^{-1}\left[\frac{\epsilon_1 - 2\epsilon_2 + \epsilon_3}{\epsilon_1 - \epsilon_3}\right]. \tag{11}$$

The constants A and B can be evaluated by applying a known stress. If nondimensional units are used by expressing the dimensions in units of hole diameter, and if similitude is maintained in all important aspects, then the values of A and B will be independent of hole diameter.

The constants A and B contain the material constants E and μ (Young's modulus and Poisson's ratio). If these material constants were separately stated, then Eqs. (9) through (11) would apply to any elastic, isotropic material. The material constants may be separated from the constants A and B in the following manner.

In Eq. (2) the radial strain is described as

$$\epsilon(\alpha) = K(\alpha)\sigma \tag{2}$$

for a uniaxial applied stress. Using a different approach than that previously taken, the maximum and minimum radial strains as measured on a strain circle about the hole can be expressed in terms of the principal stresses and the material constants, provided the proper proportionality constants are included, as follows:

$$\epsilon_{max} = \frac{k_1}{E}\sigma_{max} - \frac{\mu k_2}{E}\sigma_{min} \tag{12}$$

$$\epsilon_{min} = \frac{k_1}{E}\sigma_{min} - \frac{\mu k_2}{E}\sigma_{max}. \tag{13}$$

If we assume for the moment that the direction of the principal stresses in Eqs. (9) through (11) are known, then the strain measuring system can be aligned with its x-axis made coincident with the direction of the maximum principal stress, making β equal to zero. For this condition the strain ϵ_1 equals ϵ_{max} of Eq. (12) and ϵ_3 equals ϵ_{min} of Eq. (13).

Under these conditions, with β and therefore γ equal to zero, Eqs. (9) through (11) may be solved for the measured strains ϵ_{max} or ϵ_1 and ϵ_{min} or ϵ_3. The solutions are

$$\epsilon_{max} = (A + B)\,\sigma_{max} + (A - B)\,\sigma_{min} \tag{14}$$

$$\epsilon_{min} = (A+B)\,\sigma_{min} + (A-B)\,\sigma_{max}. \tag{15}$$

Through comparison of Eqs. (12) and (14) or of Eqs. (13) and (15) it becomes evident that

$$A + B = \frac{k_1}{E} \tag{16}$$

$$A - B = \frac{-\mu k_2}{E}. \tag{17}$$

The constants A and B may then be evaluated in terms of the general constants k_1 and k_2 and the material constants μ and E. These solutions as derived from Eqs. (16) and (17) are

$$A = \frac{1}{2E}(k_1 - \mu k_2) \tag{18}$$

$$B = \frac{1}{2E}(k_1 + \mu k_2). \tag{19}$$

Thus if E and μ are known, one calibration to determine k_1 and k_2 will suffice for all elastic isotropic materials.

EXPERIMENTAL PROCEDURE

The system was simplified for the experimental calibration by making the minimum principal stress be zero and applying a known stress in the direction of the strain gage coordinate system. In Eqs. (9) through (11), σ_{min}, β, and γ were made equal to zero and the equations were solved for A and B in terms of the known stress σ and the measured strains ϵ_1 and ϵ_3. With the hole and gage system aligned as shown in Fig. 4, strain ϵ_1 would be measured by the longitudinal gage and strain ϵ_3 by the transverse gage.

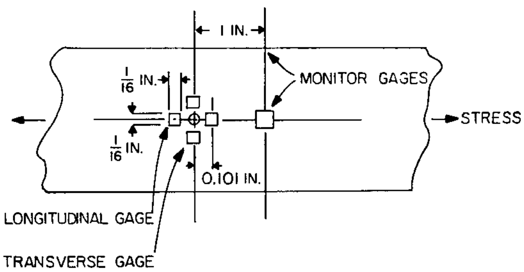


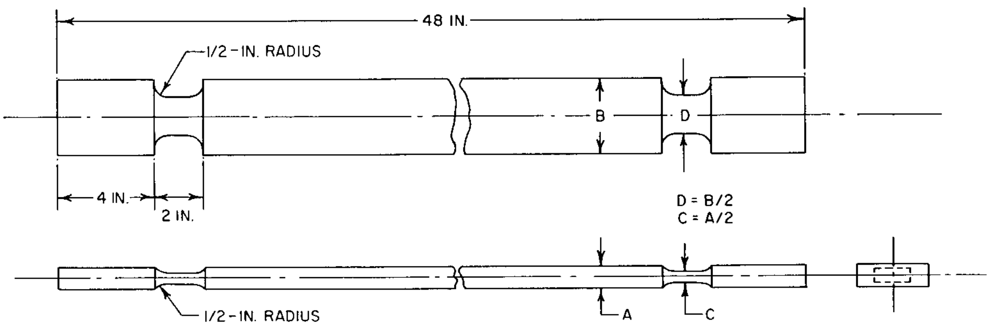
Fig. 4 - Double 0°, 90° strain-gage rosette of the nominal 1/16-in. size. Gages were positioned diametrically opposite the hole in the symmetrical stress field to aid in obtaining data for gages in the optimum gage location. Monitor gages were placed as shown.

The initial work involved the development of the equipment and techniques essential to the operation of a practical measurement system. The details of this effort will be taken up next.

Specimens

In designing the test specimen it was necessary to consider that (a) the applied tensile stress must be uniform throughout the cross-sectional area of the specimen, (b) the applied stress must be of a magnitude sufficient to provide for measurable changes in strain in the material about the hole but not sufficient to produce a plastic flow of the material in this region, and (c) the hole must be small compared with specimen dimensions and must be distant from all boundaries.

As stated in requirement (a) the applied load must produce a uniform stress throughout the cross section of the specimen. Preliminary tests were made with specimens 1-1/2 inches by 2 inches in cross section and 4 feet in length mounted in flat grips in a Baldwin Universal Test Machine of 60,000 lb capacity and indicated the presence of unwanted flexure stresses in the material. The flexure stresses in the test section were reduced to negligible values (0.2% of the applied stress) by machining a reduced section into the bar near each of its ends. Prior to test, sufficient load was applied to the bar to produce plastic flow in the reduced sections and thereby to relieve the machine-induced bending moments. The final specimen design is shown in Figs. 5 and 6.



SPECIMEN NUMBER	A (IN.)	B (IN.)	
1	1-1/2	2	SERIES 1
2	1	2	SERIES 1
3	1/2	2	SERIES 1
4	1/4	2	SERIES 1
5	1	3	SERIES 2
6	1	2	SERIES 2
7	1	1	SERIES 2

Fig. 5 - Specimen design. Prior to test plastic flow was initiated in the reduced end sections to eliminate the machine induced bending moments caused by deflection of the machine head under load.

The test specimens were monitored for flexure stress throughout the test program. Strain gages (those labeled monitor gages in Fig. 4) were mounted on all four sides of the specimen in a cross-sectional plane 1 inch from a cross-sectional plane through the center of the test hole. Comparison of the readings from gages mounted on opposite sides of the specimen provided immediate detection of any change in machine-specimen alignment during test.

There were also residual stresses to consider. How the effects of these were eliminated will be considered in a later section.

Requirement (b) was for an applied stress of sufficient magnitude to produce a measurable strain output from the gages radially positioned about the hole. In general the strain relaxations about the hole will be small in value. The problems involved in the measurement of very small strains could be relieved by increasing the magnitude of the applied stress; however, for the calibration to have meaning (that is, for the strain relaxations to be proportional to the applied or simulated residual stress) the material throughout the hole region must remain elastic. Because of the stress-concentrated region adjacent to the hole, the applied stress must not exceed approximately one-third

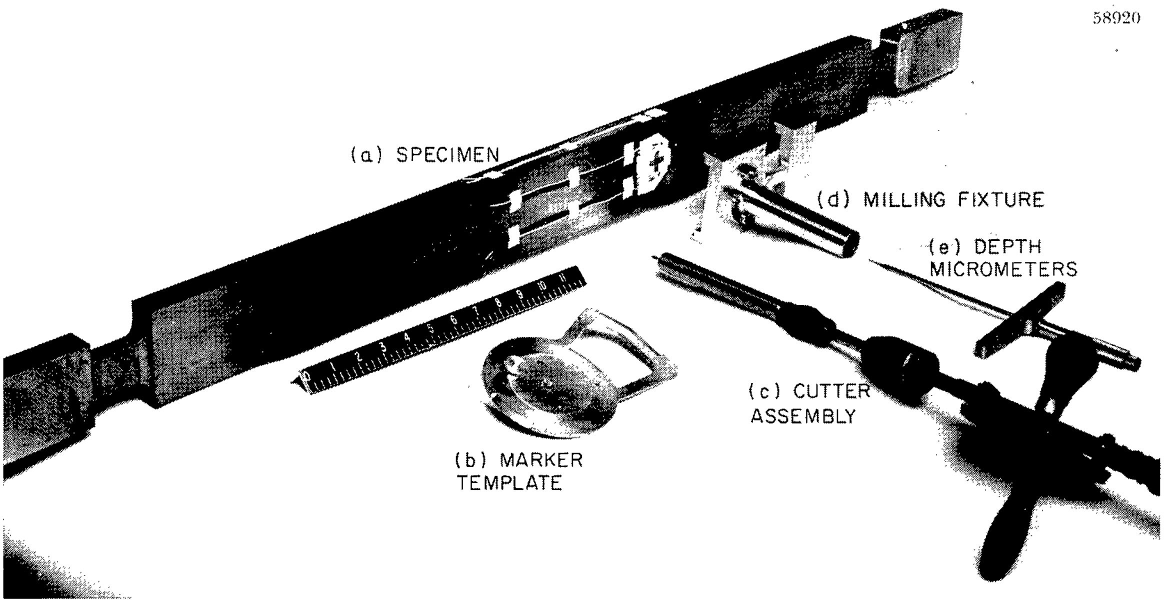


Fig. 6 - Specimen and hole-drilling and gage-mounting hardware: (a) 1 in. x 3 in. cold rolled steel specimen with a double 0°, 90° strain gage rosette and monitor gages in position ready for test, (b) marker template for positioning the gage location lines, (c) cutter, boring bar, flexible coupling, and hand drill assembly, (d) milling fixture to guide the cutter assembly, and (e) micrometers to measure the hole depth

of the yield stress of the material. To help in this situation one may select a test material having a high yield point. Cold rolled steel with a yield point of 70,000 psi was chosen, and this property permitted an applied stress of 16,250 psi to be used, which was sufficient to produce a measurable strain without being sufficient to produce plastic flow.

Requirement (c) for specimen design involved the effect of material removal from the hole upon the average stress through the specimen cross section at the hole. The change in average stress for full depth of the hole must be negligible compared to the initial applied stress. Under this condition the initial stress in areas remote from the hole will remain essentially unchanged throughout the milling operation. The measured strain relaxations will be those produced by the localized nonuniform stress field about the hole, and the calibration may be said to be independent of the specimen size.

The condition could be simply attained by providing a specimen cross section of very large area compared to the cross-sectional area of the hole. However, from a practical standpoint, it would be desirable to determine the maximum allowable approach of material boundaries to the center of the hole and the minimum plate thickness with respect to the depth of the hole. Specimens of different sizes were therefore included in the test program. Tests were initiated on specimens for which the ratio of any significant specimen area to hole area was very large. Specimens having smaller area ratios were then placed under test and the data compared with that of the initial or pilot test to determine the effect of the boundaries.

Two series of specimens were provided as tabulated in Fig. 5. For the first series (specimens number 1 through 4) the width was held constant at 2 in. while the thickness was reduced from 1-1/2 in. to 1 in., to 1/2 in., and to 1/4 in. In the second series, the specimen thickness was held to 1 in. while the width was reduced from 3 in. to 2 in. and to 1 in. All specimens were ground a few thousandths of an inch under their nominal sizes to remove surface blemishes. A length of 48 in. was chosen to provide room for a number of tests in the central portion of each specimen. Test holes were spaced at 2-in. intervals along the bar with no test locations closer than 4 in. from the reduced section on either end of the bar.

Strain Gages and Application Techniques

Two sets of different sized strain gages and milling cutters were selected. The corresponding dimensions of set components were proportionately related, since it was postulated that a single calibration would apply for any size hole provided that similitude was maintained with respect to the critical dimensions of the hole-gage assembly. Verification would require that a minimum of two different sized assemblies be tested. Epoxy-backed, etched-foil strain gages were procured in sizes of 1/16 in. and 1/8 in., and two-lipped end milling cutters were also obtained in both of these diameters.

An effort was first made to apply the strain gages with a contact cement, but the application techniques proved to be difficult. The space restriction imposed by the small radial distance between the gage center line and the hole center line severely hampered the cementing operation. In Fig. 4 the four-gage rosette is shown in the nominal 1/16-in. size with a gage-to-hole space of 0.101 in. These rosettes were assembled from individual gages. During application, the cement from the gage invariably contaminated the adjoining metal surface. A necessary procession of application and cleaning procedures within the confined area proved to be a harsh treatment for both the cement and the gages. Although this cement was finally abandoned in favor of a heat-cured epoxy, the difficulties encountered with the contact cement will be largely eliminated by the acquisition of preassembled, manufactured rosettes once the rosette design is complete. Advantage can then be taken of the speed and ease of application associated with use of the contact cement.

The technique developed for the application of the gages when using the epoxy C-2 cement may be of interest. Gage location lines were first scribed on the specimen surface in order to locate the rosette (Fig. 4) in the exact center of the specimen. After cleaning and neutralizing the metal surface, two strips of 0.002-in. shim stock were taped to the specimen on opposite sides of the gage area. A large drop of cement was then placed to one end of the gage area and between the shim strips. The cement was spread into a flat layer, 0.002 in. thick by sliding a 1/4-in.-diameter glass rod along the spacer strips. It was found that if the rod slid along the strips without rotation, a smooth even layer of cement was formed and the cement was completely free of any of the air bubbles injected during the cement mixing process. The four gages were next placed on the cement layer and, with the aid of optical magnification, positioned precisely over the location lines. The shim strips were carefully removed, and one edge of a square sheet of Mylar tape was attached to the specimen along the side of the gage assembly. The hinged sheet of Mylar tape was not permitted to touch either the gages or the cement during this operation. The sheet of tape was then pulled taut by grasping its two free corners and applying small forces diagonally away from its center. Using the fastened edge as a hinge, the tape was brought straight down upon the gage assembly and pressed to the specimen on all sides of the gage area. A final light pressure applied to the tape over the gages, securely fastened them into the desired position. A pressure of 5 psi was applied by placing a lead weight of the proper proportions on top of the taped assembly. The weighted rosette was then cured in an oven at 200°F for 90 minutes. After curing, the cement layer was measured and found to be 0.0005 in. thick.

Gages applied in this manner exhibited negligible creep. At a stress of 20,000 psi and at room temperature the creep rate generally did not exceed 1 μin./in.-hr. Hysteresis effects were negligible.

Too much emphasis cannot be placed upon the need for a good gage-to-metal bond for this work. The shear strength of the cement must be high and uniform over the entire gage area. Since the gages are placed close to the hole, in a region of high stress gradients, a weak bond, even though local in character, will reflect upon the average strain output of the gage.

Every precaution was taken to check the gage bond prior to test. With the gage leads attached to a strain indicator, the edge of a pencil eraser was pressed lightly against the gage at many points over its surface. An abnormal production of strain indicated a poor bond beneath the eraser tip and the suspect gage was automatically rejected. The bond tests were conducted under load and no-load conditions.

Test specimens and gages were cycled three times prior to test to a stress well above the test stress. They were then held at the test load for a minimum of 20 minutes. Strain readings were recorded throughout these preliminary check runs and the strain response of each gage was compared with that of the monitor gages. These measurements were made both to test the bond of the rosette gages and to assure of the absence of bend stresses in the test specimen. The gage rejection rate was cut from 40% for the contact cement to 10% for the epoxy cement.

The same standards were applied to the construction of the electrical circuits and to the operation of these circuits and of the strain measuring equipment. Wire solder connections were inspected for wetting of the components and for mechanical strength. Switches were avoided in design, except for those already built into the strain indicator. Terminal posts were used in place of switches to eliminate variable contact resistance. All of the switch contacts on the strain indicator were wiped prior to use by rotation of the switch knobs. All terminal post contacts were reset prior to test. The gage area and connecting leads were covered with a moisture resistant coating. Only when all of these precautions were observed was it possible to hold error in strain measurement to ±1 μin./in.

Hole Drilling Method

Hole properties such as location and alignment were controlled through design of the hole milling fixture. The size and shape of the hole and the condition of its wall and bottom surfaces were dependent upon the hole cutter design. It was initially proposed that the hole milling equipment be capable of reproducing straight, untapered holes, perpendicular to the material surface. A hole as small as 0.062 in. in diameter was to be milled in the center of the strain gage rosette with the allowed tolerance on the diameter to be +0.0005 and -0.0000 in. The hole cutter was to remove material from the bottom of the hole in increments of 0.012 in. without disturbing the established hole wall. The cutter was to produce wall and bottom surfaces which would be smooth or free of blemishes or tears. The bottom of the hole was to be flat to permit meaningful measurements of hole depth. Hole depth increments were to be read within the allowed tolerance of ±0.0002 in. The equipment which met these specifications is shown in Fig. 6, and again in an assembled view in Fig. 7.

The boring unit, which included the milling cutter, bar, flexible coupling, and hand drill, was centered on the specimen by the milling fixture. Clearance was provided beneath the milling fixture for chip removal and for strain gage leads. One end of the fixture carried an index mark for centering the unit over the gage assembly in the longitudinal direction. With the unit held to the specimen in the indexed position, a cross bar was placed against the end of the fixture and clamped to the specimen. The cross bar remained on the specimen throughout the test and provided a positive index stop for the fixture. The fixture was clamped to the specimen when an increment of hole was to be milled but was removed when strain gage readings were taken. The boring bar was rotated by hand at a speed of approximately 200 rpm.

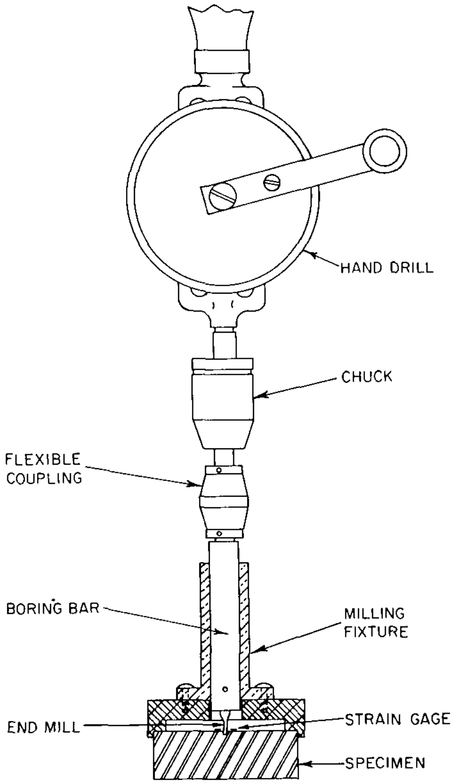


Fig. 7 - Assembled view of the specimen, milling fixture, and cutter-boring bar assembly. The milling fixture was located over the center of the gage rosette and held in position by a cross bar stop which was clamped to the specimen throughout the test. The milling fixture was clamped to the specimen only during a milling operation. It was removed prior to the reading of each set of strain measurements.

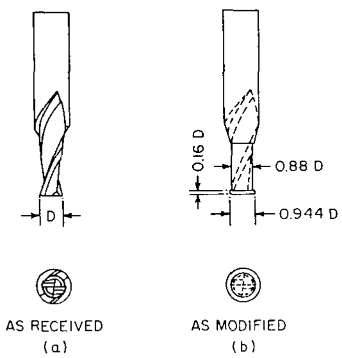


Fig. 8 - End mills as modified by grinding so that only the flat end did the cutting while the sides (to a height 0.16 D) provided a self-bearing feature to control the hole diameter and to eliminate taper in the hole

The milling cutter is shown in Fig. 8. End mills are normally supplied with cutting edges on the end and side of the mill. The mill will cut when provided with either an axial or a lateral feed motion. The cutter, as provided by the manufacturer, will not produce the specified hole. Lateral thrust upon the end of the mill due to grinding imperfections on its two lead cutting edges invariably produced a tapered hole. The unwanted side cutting edges were removed by cylindrical grinding. The cutter diameter was reduced by 5.6 percent to 0.944 times its original diameter. At a point equal to 0.16 diameter back from its leading edge the cutter diameter was further reduced to 0.88 times the original diameter to provide clearance between the cutter and the hole wall. The lead cutting edges on the end mill were ground to cut a perfectly flat bottom in the hole. As ground, the noncutting sides of the short lower section of the cutter acted as a bearing in the established hole and prevented the removal of additional material from the wall. Cutters modified as shown in Fig. 8 consistently produced holes to a diameter of 0.0590 in. +0.0003 and -0.0000 in.

Resumé of Accuracy and Tolerance Requirements

The nature of the investigative problem was such as to impose restrictions not normally encountered in measurements for stress analysis problems. The necessity for precision was so great that the final tolerance on measurements had generally to represent simply the practical limit of accuracy which was obtainable with the currently available instrumentation and skills.

Tolerance for Strain Measurements – The qualitative representation of the strain distribution about the hole as noted in Fig. 3(c) will aid in the description of the tolerances required for strain measurements. The actual strain distribution was to be experimentally determined. The strain relaxations to be measured vary in value with the angular position of measurement from zero to positive and negative maximums. Assuming that the required number of measurements of radial strain will be made if strain gages are placed in successive angular positions which are 22-1/2 degrees apart, it is immediately apparent that for some gage positions the gage output in strain values will be very small. But this is not the most severe restriction to be imposed. Strain relaxations must also be measured as a function of hole depth. The values of strain increase with the hole depth and vary from zero to the maximum value for a given angular position. Only a few preliminary experiments were necessary to indicate that strain increments as small as 3 μin./in. must be resolved. Obviously the allowed tolerance of ± 1 μin./in. for strain measurements was simply the highest degree of accuracy which could be obtained for this measurement.

Effect of Gage-to-Hole Distance Upon Gage Location Tolerance – The final location of the strain gage with respect to the hole had to be a compromise between the requirement that for a reasonable positional tolerance the gage must be placed at some distance from the hole and the requirement that for a maximum of strain sensitivity the gage should be located close to the hole. It was quickly apparent that the degree of precision necessary in locating the gage to a preselected position was related to the radial distance between the gage and hole centerlines. If the gages were located with their leading edge adjacent to the hole, they would encounter extreme differences in stress per unit of radial displacement. In this area of high stress gradient, the strains measured by the gage would be so dependent upon gage position as to render the gage location tolerance prohibitive. It was also apparent that the gage-to-hole spacing could be increased to a point beyond which a measurable strain gage output would not be produced. The radial gage-to-hole distance was experimentally adjusted to equal 0.101 in. (center to center) for the nominal 1/16-in. hole and gage assembly.

Determination of Strain Gage Location Tolerances – Three errors in gage location could occur. The gage could be translated radially or tangentially with respect to the desired location of the strain circle or it could be rotated out of its correct angular position. The allowed tolerance for each of the possible positional errors was determined from the observed experimental effect upon the strain gage response.

For all tests performed, the strain relaxation due to the applied stress of 16,250 psi was measured as a function of hole depth and with respect to a specific gage location and hole diameter. The hole diameter was measured after each increment of material was removed from the hole. The exact location of the gage with respect to the hole was measured with a traveling microscope after completion of the test. Careful study of this data revealed the independent effect of each of the positional errors upon strain sensitivity. When the final tolerances were determined, data was available for gages whose axes were located at 0°, 45°, and 90° to the direction of the applied stress.

When the error in radial position amounted to no more than a few thousandths of an inch, the effect of the change upon strain sensitivity was found to be linear. The strain ($\Delta\epsilon$) values at a hole depth equal to the hole diameter were subject to a change of 3.3%

strain per 0.001 in. of radial displacement of the gage. A similar result was observed for a change in hole diameter at a fixed gage position. Small errors due to tangential displacement of the gage and to rotation of the gage from its correct angular position were not critical for gages located in the 0° and 90° positions, since in these locations the radial strain as a function of angular position had achieved minimum and maximum values respectively. However, for gages located other than at 0° and 90° and in particular for gages located at 45° to the stress axis these errors were important. The tolerance of ±0.001 in. for tangential translation error and ±5 minutes of angle for rotational error was applied in order to limit errors due to this cause to a few percent.

Strain Gage Optimum Position – It was very difficult to consistently locate the strain gage within ±0.001 in. of a specific position. However, advantage could be taken of the fact that strains caused by drilling the hole into the stressed material had radial symmetry. Using the double rosette shown in Fig. 4, many measurements were made with equivalent strain gages on opposite sides of the hole. When the tolerance for an individual gage was exceeded, it was occasionally possible to select two gages on diametrically opposite sides of the hole whose positional errors compensated each other with respect to their effect upon strain sensitivity. Data from these gage pairs were averaged if the positional error of each gage did not exceed the allowed tolerance by more than 0.003 in. and 5 minutes of angle and if the average dimension was within the allowed tolerance. The averaged response of these gage pairs was then accepted as the equivalent of a single gage in the optimum position. The procedure was justified on the basis of the established linear relationship between strain values and gage position for small displacements from the correct gage location.

DETERMINATION OF EQUATION CONSTANTS (CALIBRATION)

General Principles

The project was initiated with the hypothesis that residual stresses in an elastic material could be determined by drilling a hole into a stressed area and observing the strain relaxation in the vicinity of the hole. A set of empirical equations were derived to relate the magnitudes and directions of principal stresses to the strain relaxation values in the vicinity of the hole. In writing these equations it was necessary to assume an approximate relationship between the strain $\epsilon(\alpha)$ and the angle of measurement α. It will be necessary to determine the accuracy of this assumed strain distribution.

The procedure for determining the equation constants, see Eqs. (9), (10), and (11), was simplified by making the minimum principal stress be zero and applying a known stress in the direction of the x-axis of the strain gage coordinate system. As seen in Fig. 9, σ_{min} and β are then made equal to zero. Under these conditions it can be shown that

$$A = \frac{\epsilon_1 + \epsilon_3}{2\sigma} \tag{20}$$

$$B = \frac{\epsilon_1 - \epsilon_3}{2\sigma} \ . \tag{21}$$

The constants A and B may then be determined in terms of the known stress σ and the radial strains ϵ_1 and ϵ_3 as measured at angles of 0° and 90° to the direction of the known stress.

The distribution of radial strain (see Eqs. (6) and (7)) assumed for the derivation must compare reasonably well with the measured strain distribution about the hole. The assumed strain distribution may be calculated by substituting values of A and B into the equation

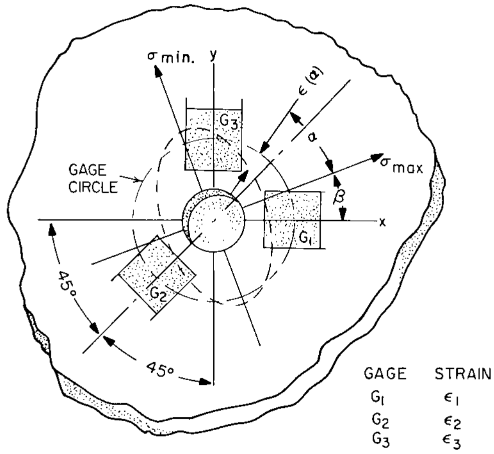


Fig. 9 - The hole-gage measurement system with the 0°, 45°, 90° strain gage rosette referenced to the principal stresses of a biaxial stress field. The hole-gage system is shown in final form as it will be used in the field to determine the magnitudes and directions of the unknown residual stresses. Nomenclature is the same as that used in Fig. 2.

$$\epsilon(\alpha) = (A + B \cos 2\alpha)\sigma \qquad (22)$$

and solving for the values of radial strain $\epsilon(\alpha)$ for various angular positions (α) of strain as located on the strain circle. The variation between these values and the measured values of radial strain (made with a gage of prescribed dimensions centered on the strain circle) will indicate the degree of error caused by the approximation. Because of the double symmetry inherent in the stress field the actual number of gages necessary for this coverage may be reduced to those required in a single quadrant.

Method for Eliminating Effects of Residual Stresses During Calibration

Calibration procedures must take into account the presence of residual stresses in the cold-rolled steel specimen. The change in strain introduced by drilling a hole into the material while the specimen is under load is a function of both the residual and the applied stress. The strains caused by the two stress components were separated by the method illustrated in Fig. 10. The specimen load was first increased until a stress of 16,250 psi was attained at point a. For the 1/16-in. hole and gage assembly a 0.012-in. increment of material was milled from the hole, and the strain relaxation $\Delta\epsilon_T = \epsilon_a - \epsilon_b$ was observed. The load was then decreased to provide a specimen stress of 2000 psi and

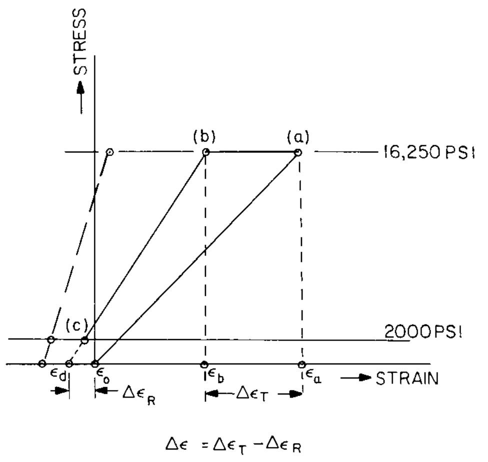


Fig. 10 - Method of separating the strains caused by the applied stress and the rolling (residual) stress. $\Delta\epsilon_T$ is the total strain relaxation caused by both stress components. $\Delta\epsilon_R$ is the strain relaxation caused by the rolling process stress.

strain ϵ_c was noted. Graphical extrapolation of the new stress-strain curve to the zero axis at point d provides a value of strain ϵ_d which is caused by the residual stress. If ϵ_0 is the strain at zero load before drilling the increment of hole depth, then $\Delta\epsilon_R = \epsilon_0 - \epsilon_d$ can be attributed to the residual stress in the material at this depth. Subtraction of the two strain increments $\Delta\epsilon_T$ and $\Delta\epsilon_R$ provides the strain, $\Delta\epsilon$ caused by the applied stress. The drilling process was repeated in increments of 0.012 in. until a hole depth of 0.108 in. was attained.

Effect of Material Boundaries Upon Calibration Accuracy

As previously stated assurance must be provided that the test calibration (the values of the constants A and B) are independent of the specimen size. It should also be determined how close the boundaries can be before the accuracy is seriously affected.

Tests were conducted on two series of specimens as tabulated in Fig. 5. For the first test in each series, a specimen was used which had a very large cross-sectional area compared to the cross-sectional area of the hole. The ratio of areas for these pilot specimens was so great as to provide assurance of a negligible change in strain due to a reduction of specimen cross-sectional area with the advent of the hole.

The nominal 1/16-in. hole and gage assembly was applied in the exact center of each specimen. A hole diameter of 0.059 in. was milled in increments of hole depth of 0.012 in. while a specimen stress of 16,250 psi was applied in every test. Gage rosettes of double 0°, 90° form were aligned as shown in Fig. 4. A number of tests were run on each specimen to secure data from gages in the optimum position. The characteristic curves of strain relaxation as a function of non-dimensional hole depth for the two test series are shown in Figs. 11 and 12.

For hole depths up to one diameter no dependence of strain sensitivity on either plate thickness or on plate width was observed. With consideration given to the data from both test series, the maximum deviation from the average change in strain at the nondimensional depth of 1 was 3 percent for the 0° gages and 6 percent for the 90° gages. The data provides assurance of valid equation constants for plates whose boundaries are at a distance equal to or greater than 8 hole diameters from the hole center line and for plates of 4 or more hole diameters in thickness.

Equation Constants for Different Sized Hole and Gage Assemblies

The equation constants can be made independent of hole size if all of the important dimensions of the hole and gage assembly are made proportional to the dimensions of the calibration model. As long as this principle of similitude is maintained all of the different hole and gage assemblies will be represented by a single nondimensional specification of the calibration model. Such a description is provided in Table 1.

The actual dimensions of the nominal 1/16-in. hole and gage assembly are given on the first row of Table 1. In the second row, the units are expressed nondimensionally in terms of the hole diameter. The third row provides the dimensions of a proportionate system in the nominal 1/8-in. size. The first and third row systems have the same nondimensional values, as stated in the second row.

A single experimental determination of the equation constants will apply to any size hole and gage assembly that has the nondimensional values shown in Table 1 provided the restrictions pertaining to material boundaries as given in the last two columns of the table are observed.

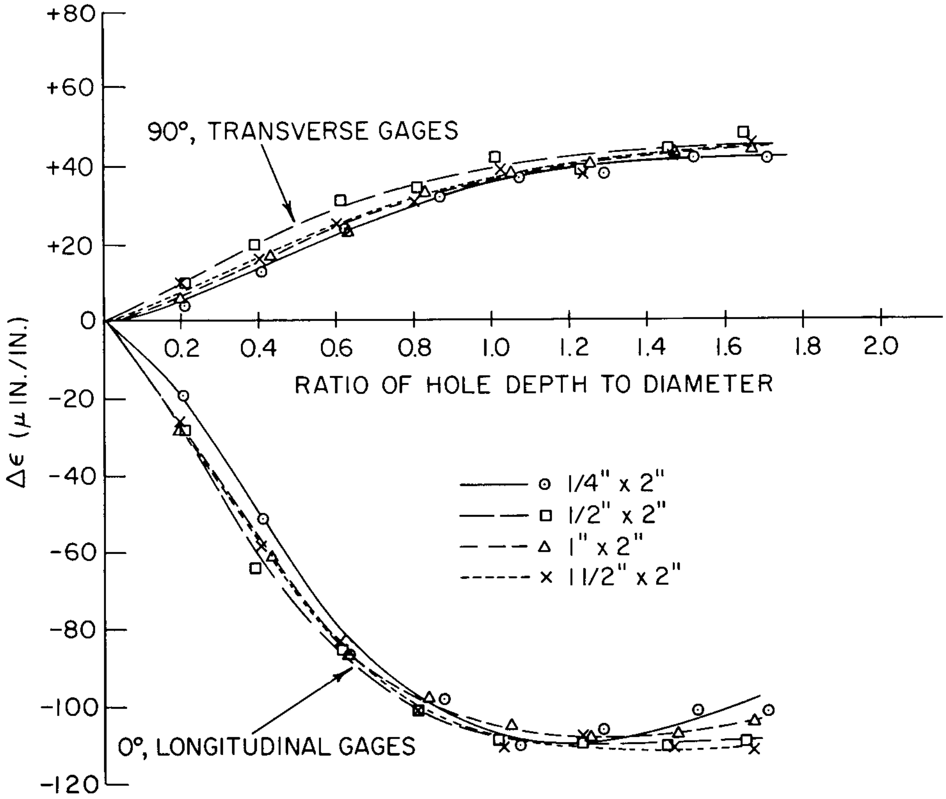


Fig. 11 - The strain relaxation vs hole depth characteristic for four specimens of thicknesses varying from 1/4 in. to 1-1/2 in. No dependence of strain sensitivity upon plate thickness was observed.

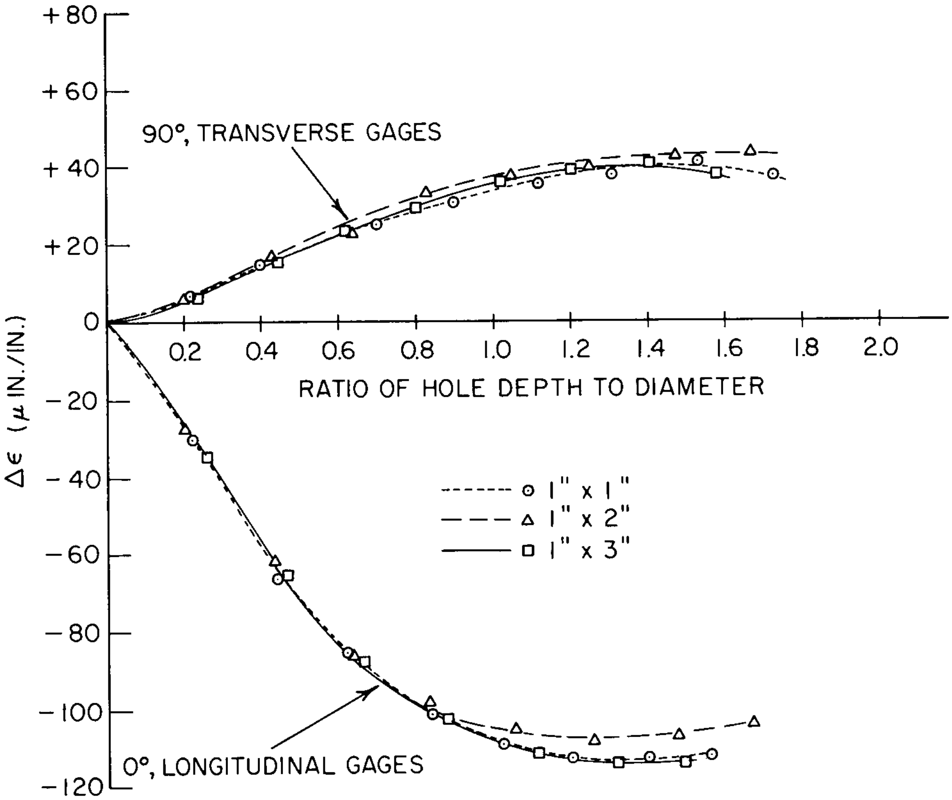


Fig. 12 - The strain relaxation vs hole depth characteristic for specimens of differing width. For nondimensional hole depths up to approximately 1, no dependence of strain sensitivity upon specimen width was observed.

Table 1
Hole and Gage Assemblies as Related to the Nondimensional Model

	Hole Diameter*	Square Gage Side	Distance from Hole Center to Gage Center†	Hole Depth	Minimum Boundary Distance from Hole	Minimum Plate Thickness
Nominal 1/16-in. Assembly	0.059 in.	0.0625 in.	0.101 in.	0.059 in.	0.500 in.	0.250 in.
Nondimensional Model	1.000	1.059	1.712	1.000	8	4
Nominal 1/8-in. Assembly	0.118 in.	0.125 in.	0.202 in.	0.118 in.	1.000 in.	0.500 in.

*Provided by a milling cutter reduced 5.6 percent from its nominal diameter by grinding.
†Strain gages located at 0°, 45°, and 90°.

Strain relaxations ($\Delta\epsilon$) with respect to nondimensional hole depth for gages located at 0°, 45°, and 90° to the stress axis are shown in Fig. 13 for 1/8-in. and 1/16-in. holes.

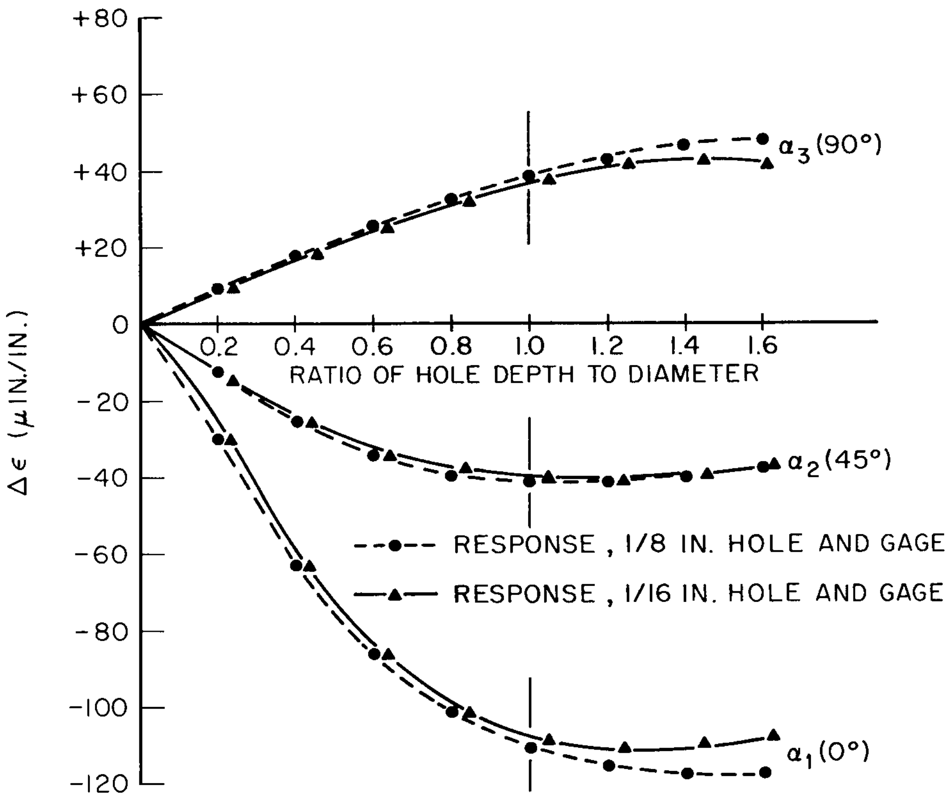


Fig. 13 - Comparison of strain relaxation caused by drilling a 1/16-in. and a 1/8-in. hole into a beam stressed at 16,250 psi

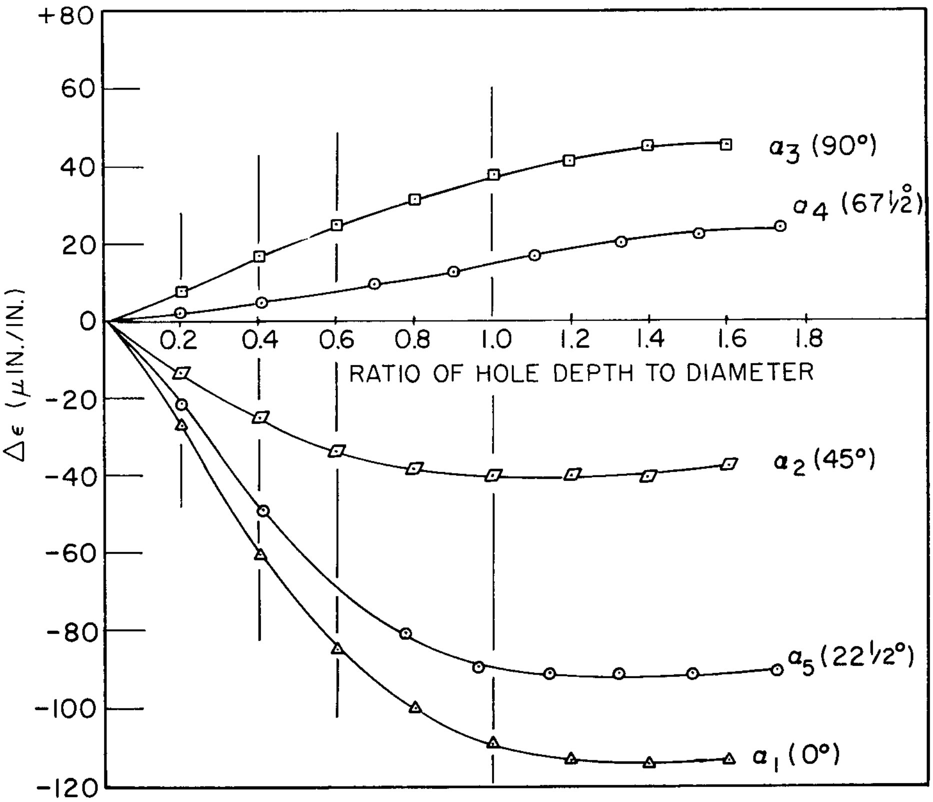


Fig. 14 - Characteristic curves of the strain relaxation as a function of nondimensional hole depth for five angles of measurement varying from 0° to 90°. The curves show the average response of a series of nominal 1/16-in. and 1/8-in. hole and gage assemblies.

The gage response for the 1/8-in. hole compares favorably with that for the 1/16-in. hole at each of the three angular gage positions. The comparisons are best for a hole depth equal to about one hole diameter. These test data indicate that the calibration is independent of hole size.

Equation Constants as a Function of Hole Depth

The final calibration curves are shown in Fig. 14. The data for these curves were obtained from a series of tests on cold-rolled steel specimens using both the 1/16-in. and 1/8-in. nominal hole size. The applied stress in every test was equal to 16,250 psi. The alignment of the strain gage with respect to the direction of the applied stress was varied to provide measurements of radial strains in five angular positions: 0°, 22-1/2°, 45°, 67-1/2°, and 90°. A number of tests were run at each angle of measurement to secure data from gages in the optimum position. The characteristic curves of strain relaxation as a function of nondimensional hole depth are those shown in Fig. 14.

Vertical intercepts were drawn through this family of curves at the hole depths of 0.2, 0.4, 0.6, and 1. For each hole depth, the intersections provided values of radial strain $\epsilon(\alpha)$, for the indicated angular positions. The values of the equation constants A and B were obtained by solution of Eqs. (20) and (21). In these equations, the strains ϵ_1

and ϵ_3 are the experimental values of radial strain at the angles α of 0° and 90° respectively. They were obtained from Fig. 14 for the hole depth of interest. The calibrated constants at the various hole depths are given in Table 2.

Table 2
Equation Constants at Various Hole Depths

Nondimensional Hole Depth	Value of Constant (10^{-8} in.^{2}/lb)	
	A	B
0.2	-0.060	-0.106
0.4	-0.134	-0.235
0.6	-0.183	-0.334
1.0	-0.225	-0.450

COMPARISON OF ASSUMED AND MEASURED STRAIN DISTRIBUTION (PROBABLE ACCURACY OF THE METHOD)

The assumed radial strain distribution about the hole at each hole depth was determined by substituting the appropriate values of constants A and B for the depth of interest (given in Table 2) into Eq. (22). Solutions of this equation provided values for the radial strain $\epsilon(\alpha)$ at intervals over the complete strain circle. The family of curves shown in Fig. 15 by dotted lines represent the assumed or derived strain distribution about the hole for the four hôle depths as noted.

The measured strain distribution for each hole depth is shown by the family of solid line curves in Fig. 15. Data for these curves were obtained from the strain intercept values provided by the curves in Fig. 14. Because of symmetry, the data from a single quadrant can be made to apply to the full strain circle.

The comparison of the assumed and measured strain distributions as shown by the two families of curves in Fig. 15 is generally good. The maximum discrepancy between the curve sets occurs at the angle of 45°. The percent of error decreases with increasing hole depth, and at a nondimensional hole depth of 1.0 the error drops to 8 percent. It is evident that the hole depth of 1.0 should be specified for greatest accuracy. This depth was included in the description of the nondimensional hole and gage model in Table 1.

GENERAL CALIBRATED EQUATIONS FOR A HOLE ONE DIAMETER DEEP

The calibrated values of the constants A and B at the hole depth of 1.0 are

$$A = -0.225 \times 10^{-8} \text{ in.}^2/\text{lb}$$

$$B = -0.450 \times 10^{-8} \text{ in.}^2/\text{lb}.$$

It is to be noted that

$$B = 2A . \qquad (23)$$

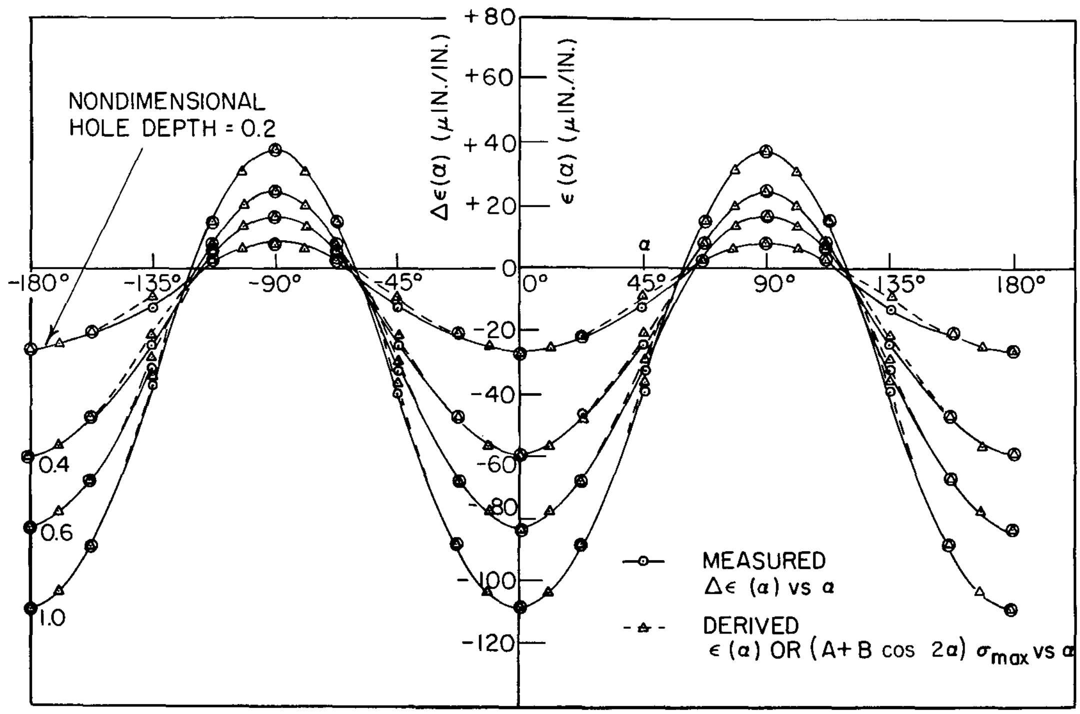


Fig. 15 - The theoretically derived radial strain $\epsilon(\alpha)$ (dotted lines) is compared to the measured strain (solid lines), for four different hole depths. The best fit of the mathematical description to the actual radial strain field occurs at a nondimensional hole depth of 1.0.

The constants A and B contain the material constants E and μ (Young's modulus and Poisson's ratio). It was shown that

$$A = \frac{1}{2E}(k_1 - \mu k_2) \tag{18}$$

$$B = \frac{1}{2E}(k_1 + \mu k_2) \tag{19}$$

where k_1 and k_2 are constants that are the same for all elastic and isotropic materials for the established nondimensional hole and gage model.

The substitution of Eq. (23) into Eq. (19) and the subtraction of Eq. (18) from the result provides the expression

$$A = \frac{\mu k}{E} \tag{24}$$

where $k = k_2$.

The substitution of A and B from Eqs. (23) and (24) into Eqs. (9) and (10) yields the following solutions for which there is but one constant, k, and this constant is the same for all elastic materials:

$$\sigma_{max} = \frac{\epsilon_1(1 + 2\sin\gamma) - \epsilon_2(1 - 2\cos\gamma)}{4k(\sin\gamma + \cos\gamma)}\left(\frac{E}{\mu}\right) \tag{25}$$

$$\sigma_{min} = \frac{\epsilon_2(1+2\cos\gamma) - \epsilon_1(1-2\sin\gamma)}{4k(\sin\gamma+\cos\gamma)}\left(\frac{E}{\mu}\right). \tag{26}$$

The constant k can be evaluated numerically, since the material constants of the specimen material of cold-rolled steel were measured. Thus,

$$k = \frac{E_s}{\mu_s}A = \frac{29.85\times10^6 \text{ psi}}{0.282}(-0.225\times10^{-8} \text{ in.}^2/\text{lb}) = -0.238.$$

Substitution of the value of k into Eqs. (25) and (26) provides the final calibrated solutions:

$$\sigma_{max} = \frac{\epsilon_2(1-2\cos\gamma) - \epsilon_1(1+2\sin\gamma)}{0.952(\sin\gamma+\cos\gamma)}\left(\frac{E}{\mu}\right) \tag{27}$$

$$\sigma_{min} = \frac{\epsilon_1(1-2\sin\gamma) - \epsilon_2(1+2\cos\gamma)}{0.952(\sin\gamma+\cos\gamma)}\left(\frac{E}{\mu}\right) \tag{28}$$

$$\gamma = \tan^{-1}\left[\frac{\epsilon_1 - 2\epsilon_2 + \epsilon_3}{\epsilon_1 - \epsilon_3}\right] \tag{11}$$

where $\gamma = -2\beta$.

These calibrated equations are of course valid only if applied to measurements made by a hole and gage system which conforms to the nondimensional calibration model as described in Table 1.

PREASSEMBLED ROSETTES

Strain gage rosettes can be manufactured in the form shown in Fig. 16. Preassembly of the gages upon a single epoxy back will reduce the tedious effort imposed when gages are separately applied in the laboratory. With gages preassembled the necessary operational skill is reduced to that of locating the cutter in the precise center of the rosette. As an aid in this process, the rosette design includes an annular ring and triangular marker points.

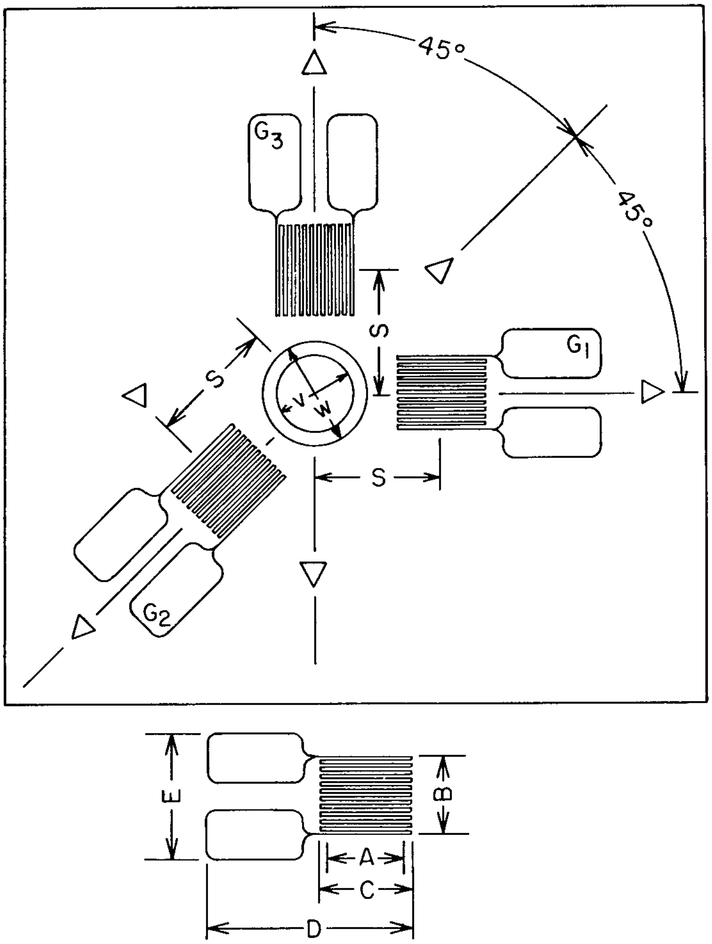
The table in Fig. 16 provides the dimensions for nominal 1/16-in. and 1/8-in. rosettes with the necessary tolerances within which the dimensions must be held.

CONCLUDING REMARKS

Residual stresses in elastic and isotropic materials can be measured in a semidestructive manner by the hole-drilling-and-strain-gage method. Holes as small as 0.059 in. in diameter and in depth were found to be practical.

A single calibration of the measurement system will suffice for holes of many different sizes if similitude is maintained, that is, if the hole and strain gage assembly conforms proportionately to the nondimensional calibration model.

Equation constants were determined which will apply to any elastic and isotropic material provided the elastic modulus and Poisson's ratio for the material are known. Additional work is planned to test and refine this calibration for use with preassembled strain gage rosettes.



Gage Size (in.)	Rosette Dimension (in.)							
	A*	B*	C	D	E	S*	V	W
1/16	0.062 ±0.001	0.062 ±0.001	0.075 ±0.002	0.165 ±0.016	0.100 ±0.005	0.101 ±0.001	0.060 +0.000 -0.002	0.080 +0.002 -0.000
1/8	0.125 ±0.001	0.125 ±0.001	0.150 ±0.002	0.300 ±0.016	0.200 ±0.005	0.202 ±0.001	0.124 +0.000 -0.002	0.164 +0.002 -0.000

*Critical dimensions.

Fig. 16 - Strain gage rosette for residual stress determinations. Dimensions and tolerances for the 1/16-in. and 1/8-in. gages are indicated. The annular ring and triangular center markers are used for alignment of the hole-drilling end mill. (For the work reported here the rosettes were made from individual gages.)

The accuracy of the method for field applications will be directly related to the operator's ability to precisely position the milling cutter in the center of the gage rosette. A device is being developed to aid in this centering process. The final accuracy of the method will probably be in the order of 10 percent of the maximum values.

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13. ABSTRACT

The hole-drilling, strain-gage method of measuring residual stresses in elastic materials has been termed semidestructive because of the use of holes of very small diameters. The method permits the magnitudes and principal directions of residual stresses at the hole location to be determined. This is accomplished by means of an empirically determined quantitative relation between the magnitudes and directions of the principal stresses and the strain relaxation about the hole as the hole is drilled. This relation was obtained for a nondimensional model of the hole-gage assembly in order to make the results independent of hole size. A generalization was postulated to extend the use of this calibrated solution to the measurement of residual stresses in all elastic, isotropic materials.

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