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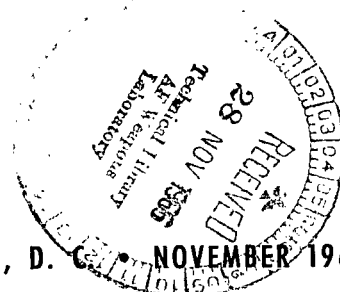
DESIGN AND USE OF DISPLACEMENT GAGE FOR CRACK-EXTENSION MEASUREMENTS

by Douglas M. Fisher, Raymond T. Bubsey, and John E. Srawley

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SUMMARY

A double-cantilever displacement gage was designed for use in plane-strain crack-toughness tests of through-cracked plate specimens. The gage magnification was approximately 750, with 10-volt strain-gage bridge excitation and bridge output recorded on a 0.5-millivolt-per-inch scale. The linearity of the gage was within 0.0001 inch over a range of 0.200 to 0.250 inch.

The design considerations necessary for the determination of the mechanical features, the strain-gage circuit, and the registry aspects of the gage are presented. With suitable strain gages, the instrument can be used at cryogenic temperatures.

Load-displacement slopes were determined for a range of crack lengths in bend specimens. The ratio of major span to specimen width was 4, and results were obtained for both three- and four-point loading with special fixtures designed to minimize friction effects. The results show the relation between displacement per unit bending moment and crack length in dimensionless form.

INTRODUCTION

Precise measurement of the relative displacement of two gage points as a function of applied load is the basic method used to evaluate crack extension in through-cracked plate specimens during crack-toughness tests (refs. 1 to 4). The gage points are symmetrically located on opposite sides of the crack. At constant crack length the displacement is directly proportional to the load, if the region of nonlinear deformation around the crack tip is small in relation to the specimen dimensions. In plane-strain crack-toughness (K_{Ic}) tests the specimens used are large enough to ensure that the region of nonlinear deformation remains negligibly small throughout the course of a test (ref. 4).

In a K_{Ic} test, therefore, any appreciable deviation of the load-displacement record from a straight line is an indication of crack extension. The displacement per unit load is a function of crack length, which can be determined by an experimental calibration procedure for any specimen design. From such a calibration it is possible to interpret the load-displacement record from a K_{Ic} test in terms of the crack extension at any stage of the test.

Displacement measurement for the detection of crack extension should not be confused with measurements of specimen compliance (reciprocal stiffness) for determination of strain-energy release rates with crack extension (ref. 5). The intent of a compliance experiment is to determine the work done by the loading forces, and the displacement to be measured must be chosen appropriately. For evaluation of crack extension, the displacement-measurement gage length can be chosen for experimental convenience and sensitivity because the basis of interpretation is empirical.

A displacement gage for crack-toughness testing must be mounted on the specimen in such a manner that it is released without damage when the specimen breaks. At the same time, the output of the gage during the test must indicate very accurately the relative displacement of two precisely located gage points spanning the crack. Exact and positive positioning of the gage on the specimen is essential. The gage output must be highly linear so that any nonlinearity in the load-displacement record obtained in a toughness test can be confidently ascribed to the behavior of the specimen. Finally, the gage should be capable of operating satisfactorily at cryogenic temperatures. To meet these requirements, a double-cantilever displacement gage was designed and constructed with the incorporation of a suitable method of mounting.

Examples of calibrations which relate displacement per unit load to crack length for single-edge crack-bend specimens are also discussed herein. Special bend fixtures were developed to minimize friction and nonlinearity of load-displacement records in these calibrations. The application of such calibrations in K_{Ic} testing is discussed in reference 4.

GAGE DESIGN, CONSTRUCTION, AND OPERATION

Mechanical Features

The design choice for a displacement-measuring gage reflected the need for a device which would be self-supporting when attached to an intact specimen and self-releasing on specimen fracture. A bowed strut with strain gages, similar to the gage described in reference 5, fulfills the attachment, release, and high-sensitivity requirements but does not have a sufficiently linear output. Good linearity of output, however, can be obtained from

a cantilever beam, which exhibits fiber strain proportional to end deflection. Through the use of two opposed cantilevers, the attachment and release facility can be obtained and sensitivity can be doubled over that possible with a single beam.

The characteristics of the double-cantilever-beam gage described herein were specifically selected for plane-strain crack-toughness testing of through-cracked plate specimens with short gage lengths. The general design is versatile, and modifications for other purposes should present no difficulties.

The choices of dimensions and materials for the double-cantilever-beam gage were based on the following important parameters: (1) the sensitivity, that is, the ratio of maximum fiber strain to deflection of the beam ends, (2) the useful measurement range, (3) the slope of the beams from the horizontal when attached to a specimen, and (4) the gage spring or attaching force. The importance of these parameters is obvious, with the possible exception of parameter (3), which limits the geometry of registry between the gage and the specimen.

In order to determine the effect of beam dimensions on the aforementiond parameters, the following relations were assumed:

Maximum fiber strain at O:

$$\epsilon_O = \frac{P\ell h}{2EI} = \frac{3h}{2\ell^2} f$$

Maximum fiber strain at G:

$$\epsilon_G = \frac{Pm\ell h}{2EI} = m\epsilon_O$$

Slope of beam end under load P:

$$\theta = \frac{P\ell^2}{2EI} = \frac{\ell}{h} \epsilon_O = \frac{3f}{2\ell}$$

Displacement of beam end under load P:

$$f = \frac{P\ell^3}{3EI} = \frac{2\ell^2\epsilon_O}{3h}$$

Load at maximum fiber strain:

$$P = \frac{2EI\epsilon_O}{\ell h} = \frac{Ebh^2\epsilon_O}{6\ell}$$

Sensitivity:

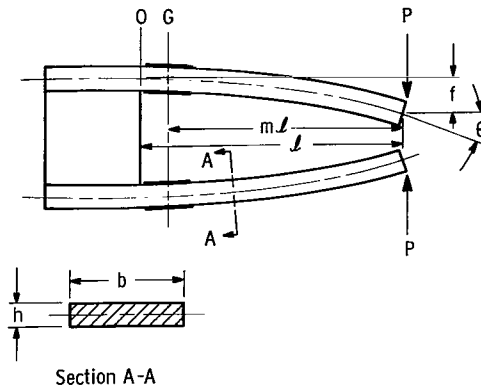$$\frac{d\epsilon_G}{df} = \frac{3mh}{2\ell^2} = \frac{\epsilon_G}{f} = \frac{m\epsilon_O}{f}$$

Figure 1. – Double-cantilever displacement gage model for design-parameter considerations.
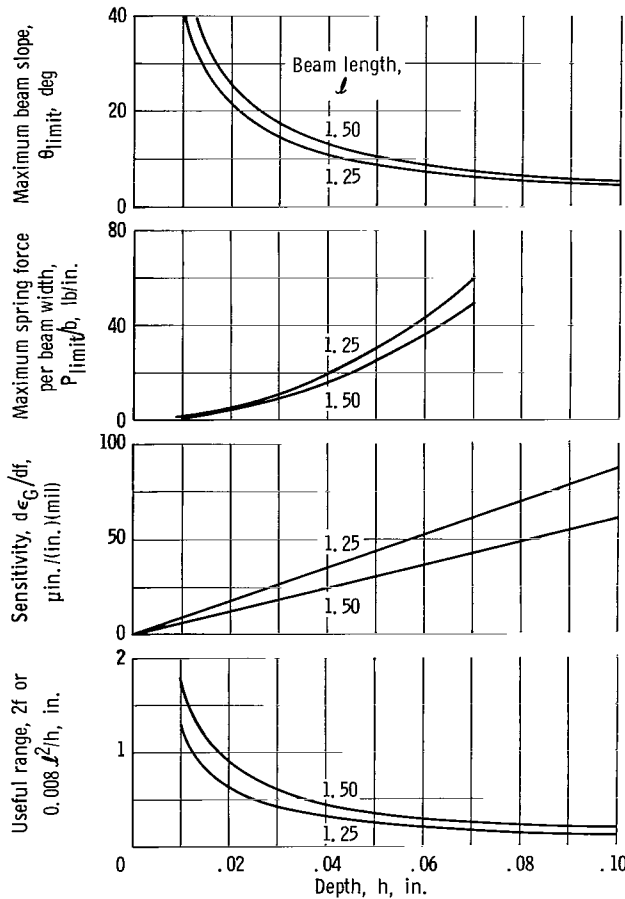

Figure 2. – Important design parameters for double-cantilever displacement gage as function of beam depth.

(All symbols are defined in fig. 1 and the appendix.)

The beam material, chosen for its high ratio of yield strength to elastic modulus, was solution-treated 13 vanadium - 11 chromium - 3 aluminum titanium alloy, with an elastic modulus of 15×10^6 psi and a yield strength of 120 000 psi. The light weight of the titanium was helpful in keeping the gage weight low, but this property is of secondary importance.

To ensure gage operation within the yield strength of the beam material, the maximum fiber strain at the support point ϵ_O was limited to 75 percent of the elastic range or 0.006 inch per inch. Hence

$$2f_{limit} = 0.008 \frac{\ell^2}{h}$$

$$\theta_{limit} = 0.006 \frac{\ell}{h}$$

and

$$\frac{P_{limit}}{b} = 15\ 000 \frac{h^2}{\ell}$$

The four important design parameters for the values of ℓ of 1.25 and 1.50 inches are provided in figure 2 as a function of beam thickness h. When 1/4-inch-long strain gages are mounted as close as possible to the support point O, corresponding values of m are 0.92 and 0.90 inch, respectively. The four design parameters were taken into account, and a beam thickness of 0.04

inch and length of 1.25 inches were chosen. This choice results in a sensitivity of approximately 35-microinches-per-inch strain per mil of beam deflection and a spring force of 19 pounds per inch of beam width at a double-beam displacement of 0.3 inch. This displacement results in a slope of approximately 11°. The choice of beam width of 3/8 inch determines that a spring force of approximately 7 pounds is necessary for specimen attachment. This force can easily be exerted by the fingers and yet is sufficient to hold the gage firmly on the specimen. Other design parameters are unaffected by the choice of beam width.

Considerable effort was devoted to devising an exact and positive method of mounting the gage on the specimen. Early design attempts mated cylindrical surfaces on the gage ends with V-grooves machined into the specimen edges. High rotational friction, which affected the linearity of the load-displacement record, was encountered with this arrangement. The final design depicted in figure 3 registers 0.005-inch-root-radius 90° notches in the beam ends with 60° knife edges machined into the edges of edge-cracked specimen types. This arrangement produced linearity of gage output as a function of displacement within 0.0001 inch over a range of 0.200 to 0.250 inch. This design had the additional advantage of a clearly defined and easily measurable gage length. It can be adapted simply to center-crack specimens by thè attachment of knife edges to the specimen surface above and below the crack.

Final beam dimensions and mounting features are depicted in figures 3(a) and (c). Spacer-block dimensions are detailed in figure 3(d). Aluminum alloy 7075-T651 was chosen as the block material to minimize gage weight. The 0.400-inch block dimension which determines the distance between the gage beams can be varied to suit any chosen gage length. The beams accommodate a gage length which is 0.2 inch less than the distance between beams; thus, the 0.400-inch spacer block would be used for a 0.2-inch gage length. Stops cemented to the beams, as shown in figure 3(a), prevent overstraining during mounting.

## Strain Gages and Measurement Circuit

The measurement circuit of the displacement gage incorporates four active foil strain gages (figs. 3(a) and (b)). Gages are mounted longitudinally on each side of the beams as close as possible to the beam-spacer block. The four-gage circuit provides temperature compensation in a bridge of maximum possible output. High-resistance (500 ohm) constantan epoxy-base foil gages were chosen for room-temperature applications because the heating of the gages is inversely proportional to the resistance at constant excitation voltage. The gage bonding conformed to the manufacturer's specifications. For cryogenic application, 120-ohm Nichrome V strippable foil gages were used
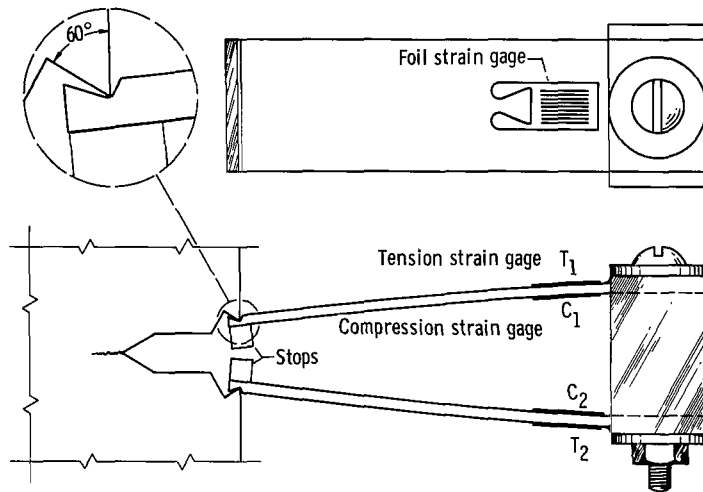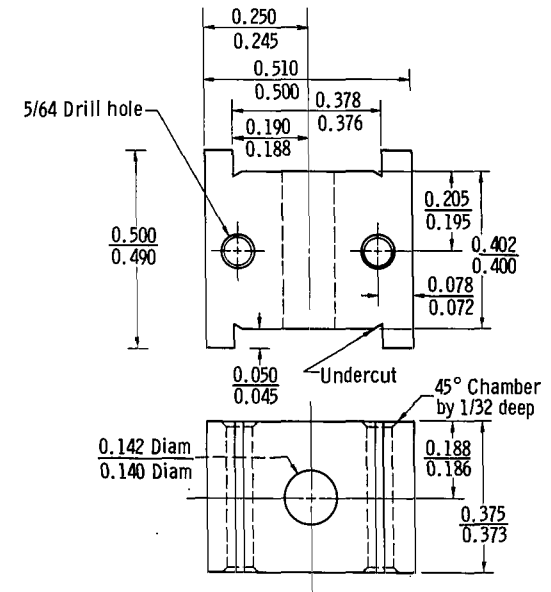
(a) Gage mounted on single-edge-notch tension specimen.
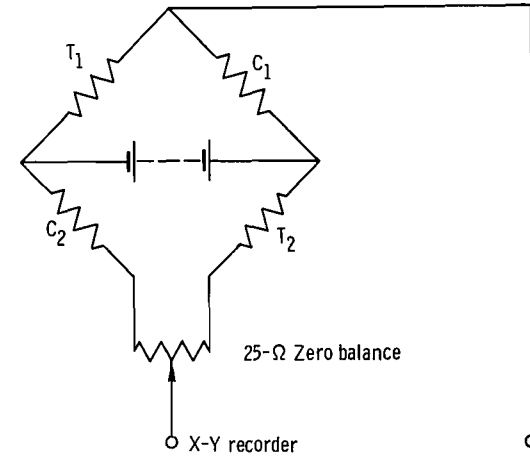
(b) Bridge measurement circuit.
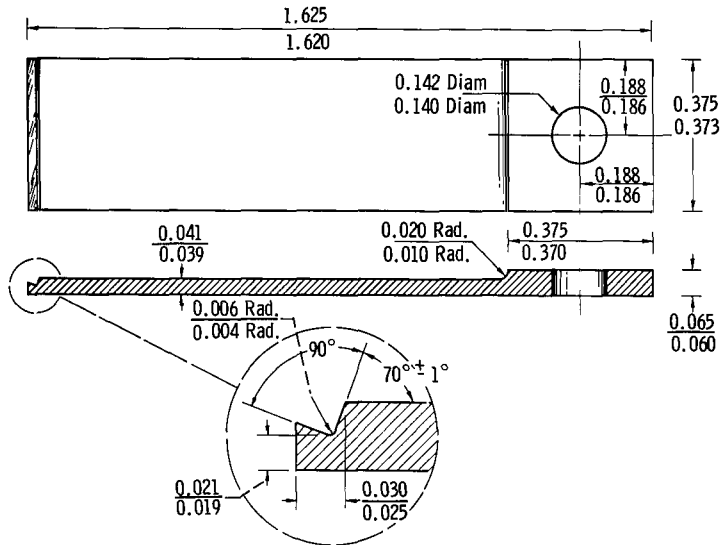
(c) Dimensions of beams.

(d) Dimensions of spacer block.

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Figure 3. – Double-cantilever displacement gage. (All dimension in inches except where noted.)

since this gage type maintains a stable gage factor at temperatures as low as that of liquid hydrogen (ref. 6), and heating effects would not be a problem. The gage must be kept out of the liquid bath, however, to prevent gage agitation by boiling action. Gage bonding for the low-temperature application was performed according to the method detailed in reference 6.

During use of the displacement gage, strain-gage bridge excitation is maintained constant at approximately 10 volts, and the bridge output is recorded on one axis of an X-Y recorder. Original output-signal balancing is implemented by inclusion of a 25-ohm potentiometer in the bridge, as shown in figure 3(b) (p. 6). A load cell supplies the signal to the other axis of the X-Y recorder.

When 2.15 gage-factor strain gages and the beam dimensions detailed in figure 3(c) are used, a sensitivity in the range of 0.0350 to 0.0375 millivolt per volt per 0.001 inch deflection is obtained. This sensitivity results in a magnification of about 750 at a recorder sensitivity of 0.5 millivolt per inch and a 10-volt excitation.
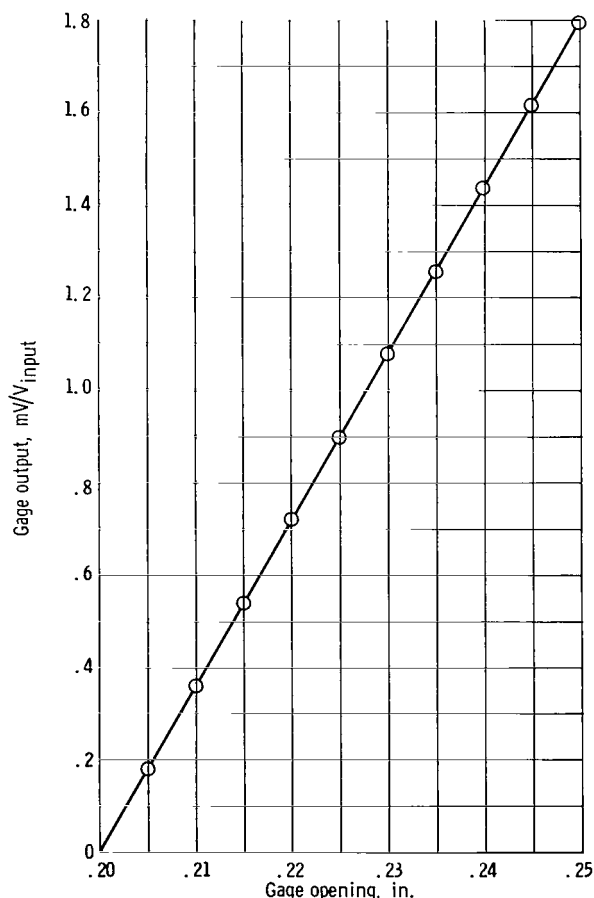

Figure 4. - Typical calibration curve of crack-extension displacement gage.

Gage Calibration and Accuracy

The micrometer system of an optical comparator was adapted to calibrate gages by incorporation of sliding blocks with knife edges. A typical gage calibration curve is shown in figure 4. As previously stated, the gage calibration is linear within 0.0001 inch over the range from 0.200 to 0.250 inch.

Gages can be checked periodically against the original calibration by use of a machined gage block provided with a selected number of individual gage openings. To ensure accuracy of registry, the gage block openings should have knife edges like those used in a specimen for engagement of the displacement gage.

Gage Operation, Protection, and Durability

The excitation voltage is applied for at

least 10 minutes before using the gage to allow the temperature to become stabilized. The gage is readily mounted on the specimen knife edges by depressing the cantilever beams between the thumb and forefinger. The gage output is then balanced to an appropriate X-Y recorder chart location by use of the 25-ohm balancing potentiometer and the recorder-balancing control.

Certain precautionary measures are advisable in the use of the gage. A sleeve of an elastic foam material encompassing the exterior of the strain-gage region of the displacement gage reduces the possibility of damage to a strain gage on the release of the gage during specimen fracture. In bend tests of brittle materials which might fracture completely at the first evidence of crack extension, stops should be placed to prevent the specimen halves from falling onto the gage. With these precautions, the gage assembly should have an extensive service life encompassing hundreds of tests. Gage life is limited primarily by the quality of the bond of the strain gages to the beams. Failed gages can be replaced easily and the displacement gage can be recalibrated for further use.
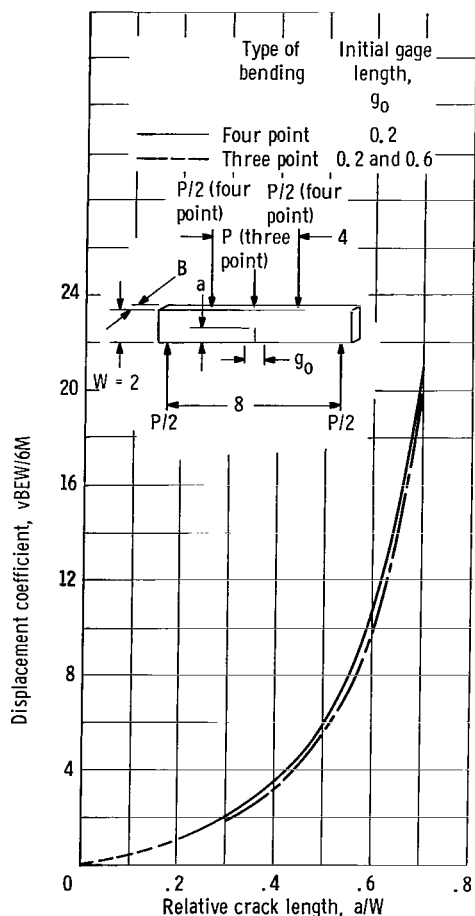

Figure 5. – Conversion of displacement measurements to crack length. Ratio of major span to width, 4; three- and four-point bend specimens.

MEASUREMENT OF DISPLACEMENT COEFFICIENTS OF THROUGH-CRACKED PLATE SPECIMENS

The load-displacement record for a through-cracked plate specimen is linear so long as the crack length does not change (and provided that the specimen dimensions are large in comparison with the size of the region of nonlinear deformation at the crack tip). The slope of the load-displacement record will depend on the crack length, and it is necessary to know the relation between slope and crack length in order to be able to interpret records of K_{Ic} tests in the manner discussed in reference 4. This relation can be determined experimentally for any desired specimen configuration, as illustrated for the bend specimen in figure 5. Relations for other types of specimen are given in reference 4, also. The crack is simulated by a saw cut about 0.01 inch wide, which is extended incrementally after each determination of the load-displacement slope.

It is useful to express the results of such measurements in terms of a dimensionless product called a displacement coefficient. The displacement coefficient used herein for bend specimens is of the form $vBWE/6M$, where v/M is the displacement per unit bending moment, B is the beam thickness, W is the beam depth, and E is Young's modulus. The displacement v is the difference between the gage length g_P at load P and the initial gage length g_O. For through-cracked plate specimens of any suitable thickness which are similar to one another in planar proportions including load distribution and gage length, there is a unique relation between the displacement coefficient and the relative crack length a/W. Once the relation has been determined on a specimen of convenient size and material, it can be applied to any similar specimen, regardless of size and material. The effect of changing the load distribution is illustrated in figure 5 by the curves for three- and four-point bending. The two curves were obtained with the same specimen and the same supporting span. Different curves would be obtained for different ratios of support span to beam depth. The curve for three-point bending in figure 5 represents data for two ratios of gage length to beam depth, 0.1 and 0.3. There was no appreciable difference between the results obtained with these two gage lengths, but if a substantially larger gage length had been used, there might have been an appreciable difference. It is
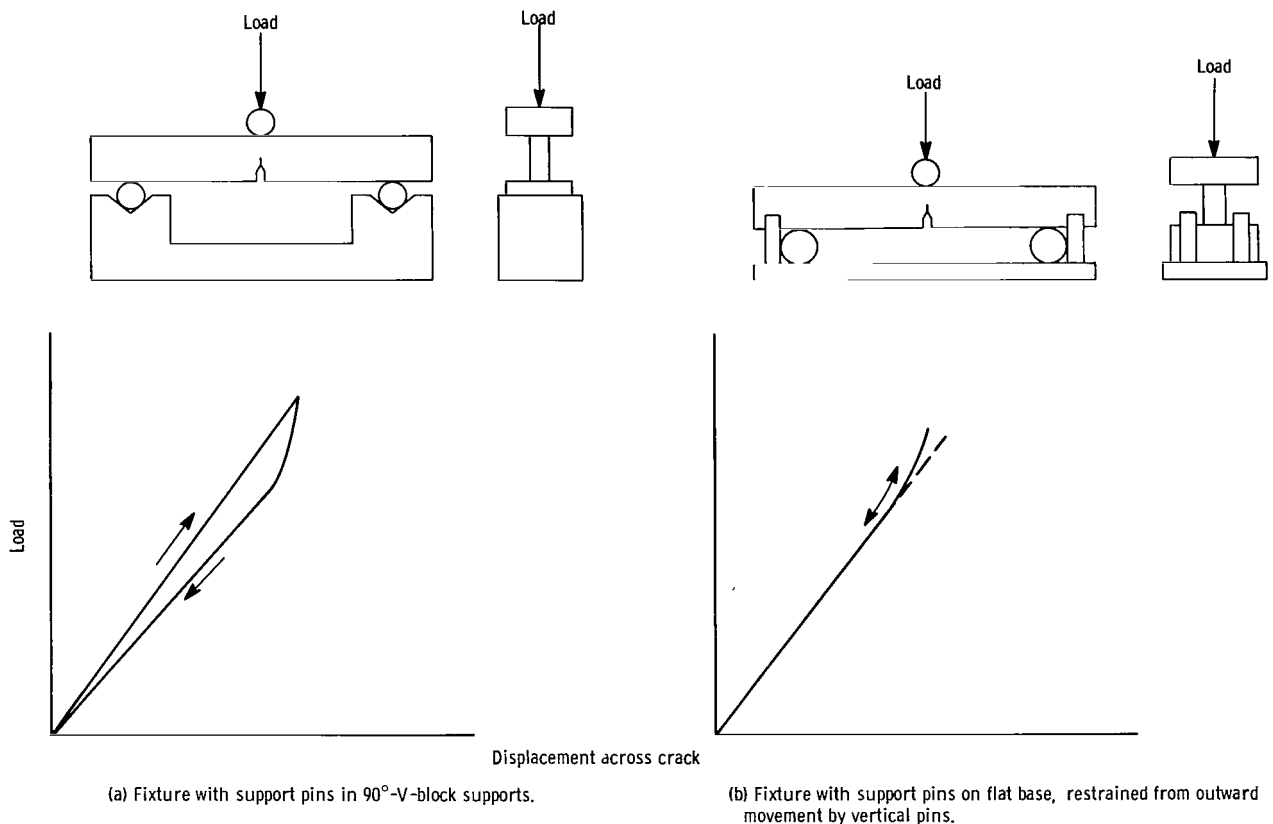

(a) Fixture with support pins in 90°-V-block supports.

(b) Fixture with support pins on flat base, restrained from outward movement by vertical pins.

Figure 6. – Load-displacement records illustrating test-fixture frictional effects obtained with depicted bend fixtures.

probably safe to assume that the displacement coefficient is insensitive to gage length when the gage length is less than the crack length.

REDUCTION OF FRICTIONAL EFFECTS

If a bend specimen is loaded while supported on rollers, the frictional forces exerted on the specimen by the rollers will be appreciable unless the rollers are able to move apart slightly and to rotate. In four-point bending, the frictional effects of the loading rollers, as well as that of the support rollers, can be appreciable. Before the results shown in figure 5 (p. 8) were obtained, some preliminary experiments were conducted to obtain a simple bend fixture which would reduce frictional effects to a satisfactory level.

Figure 6(a) (p. 9) shows hysteresis obtained in the record of a load-unload cycle of a notched specimen in a three-point bend fixture consisting of bare steel support pins in 90°-V-block supports. Nonlinearity, as depicted in figure 6(b), was observed for three-point loading with the 1-inch-diameter support pins on a flat base, restrained from outward movement by 1/4-inch-diameter vertical pins. Hysteresis is also obtained in four-point bending in the same support fixture.
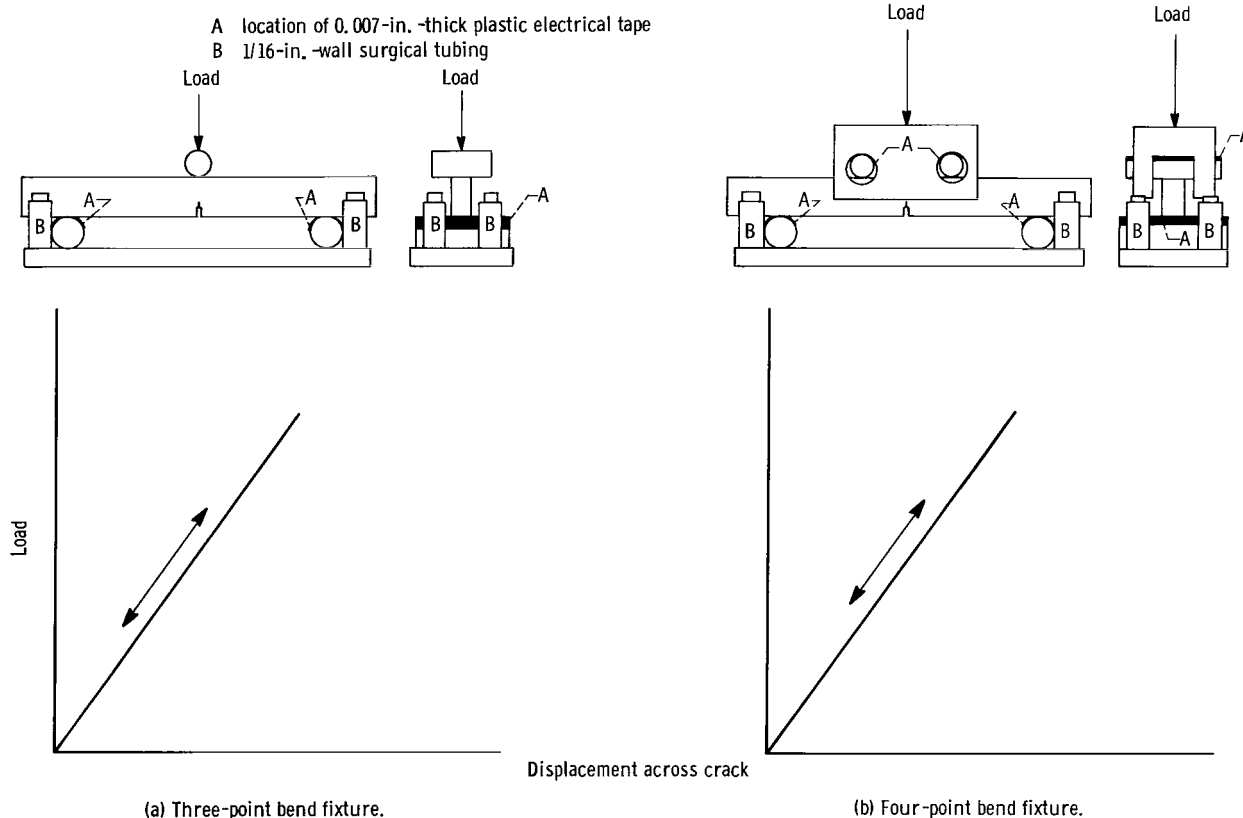

A   location of 0. 007-in. -thick plastic electrical tape
B   1/16-in. -wall surgical tubing

(a) Three-point bend fixture.

(b) Four-point bend fixture.

Figure 7. – Load-displacement records illustrating linearity attained with depicted fixtures.

Minimum pin friction in a fixture of simple construction was obtained in three-point bending by using the previously described flat-plate fixture with 0.007-inch-thick plastic electrical tape applied to the support pin in the area contacted by the specimen and 1/16-inch-thick surgical tubing placed on the vertical pins.

In four-point bending, an additional frictional factor is encountered in the loading pins. This friction was reduced by applying plastic tape between the 3/8-inch-diameter loading pins and the 1/2-inch-diameter holes in which the pins were held in the load applicator. The bend-test fixtures used for both three- and four-point bending are depicted in figure 7 (p. 10). The figure also shows representative load-displacement records, which illustrate the linearity and absence of hysteresis attained with these fixtures.

CONCLUDING REMARKS

A double-cantilever-beam displacement gage incorporating a four-active-strain-gage measurement-bridge circuit was designed for measurement of displacement as a function of load in plane-strain crack-toughness tests. The double-cantilever design provides the features of self-support during a test and self-release on specimen fracture. The gage has high sensitivity and output linearity. A magnification of 750 was obtained when the gage was used with a recorder having a scale sensitivity of 0.5 millivolt per inch. Gage calibrations were linear well within 0.0001 inch over a range of 0.050 inch. The double-cantilever displacement gage has proved to be durable over hundreds of tests. With proper choice of strain gages, the instrument can be operated at cryogenic temperatures.

Load-displacement slopes were determined for a range of crack lengths in single-edge crack-bend specimens. The ratio of major span to width was 4, and results were obtained for both three- and four-point bending with special fixtures designed to minimize friction effects. These measurements provide a means for the accurate determination of crack extension from load-displacement records obtained in plane-strain crack-toughness tests.

Lewis Research Center,
   National Aeronautics and Space Administration,
      Cleveland, Ohio, August 15, 1966,
         731-21-03-03-22.

APPENDIX - SYMBOLS

a   crack length

B   specimen thickness

b   width of gage beam

E   Young's modulus

f   displacement of beam end under load P

h   depth of gage beam

I   moment of inertia

K_{Ic} plane-strain crack toughness

ℓ cantilever length

M   bending moment

m   factor relating position of strain gage to length of cantilever

P   load

v   difference between gage length at load P and initial gage length, $g_P - g_O$

W   specimen width

ϵ_G maximum fiber strain at point G (fig. 1)

ϵ_O maximum fiber strain at point O (fig. 1)

θ slope of beam end under load P

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