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LOAD-DISPLACEMENT MEASUREMENT AND WORK DETERMINATION IN THREE-POINT BEND TESTS OF NOTCHED OR PRECRACKED SPECIMENS

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ABSTRACT

Suggestions for testing of notched or cracked three-point bend specimens are presented which: (1) correct displacement measurement errors resulting from misalignment between the load applicator and specimen; (2) account for coincidental strains not associated with the work of crack extension; (3) simplify record analysis and processing; (4) extend displacement gage range without sacrifice of sensitivity or accuracy. These testing details are particularly applicable to procedures in which the crack extension force J_I is determined from the work done on the specimen.

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SUMMARY

Details for the testing of notched or cracked three-point bend specimens are discussed, namely:

1. A dual-gage load-displacement measurement procedure which corrects for displacement measurement errors resulting from misalignment between the load applicator and specimen. The gage outputs are summed to provide a single signal.

2. A technique to measure and correct for the excess work associated with the coincidental displacement components that are unrelated to specimen crack extension.

3. A means for extending the range of a double-cantilever-beam displacement gage while retaining the short range accuracy and sensitivity.

These testing details are of current interest due to the convenience of the three-point bend test for the determination of crack characterization quantities such as J_I, the non-linear generalization of the linear elastic quantity $\mathcal{G}_I$. Such determinations are needed since ASTM Standard Method of Test for Plane-Strain Fracture Toughness of Metallic Materials E 399-74 is frequently impractical for measurement of crack toughness

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due to size requirements which can exceed the dimensions of the available stock. Determination of J_I requires an accurate load-displacement record so that the work available for crack extension can be determined. The testing details described contribute to the accurate determination of such work, and help to simplify record processing and analysis.

INTRODUCTION

It is frequently impractical to employ sufficiently large specimens to obtain valid K_{Ic} fracture toughness values by ASTM Standard Method of Test E 399-74. Preceding and during crack extension, the materials concerned exhibit sufficient plastic deformation in the crack tip region that the specimen sizes required to approximate the model on which the test method is based exceed the dimensions of available stock.

In alternative fracture test methods which are currently being examined for use on such materials, measurement of displacement of the load, and the subsequent determination of the work done by the load, are critical. A prime example of such a method is that for the determination of a critical value of J_I, the non-linear generalized form of the crack extension force $\mathcal{G}_I$.

At the current stage of development the estimate of a critical J_I value requires the testing of at least 5 replicate, fatigue-cracked, bend specimens. Each specimen is tested to obtain an individual J_I value for a particular amount of crack extension under monotonically increasing displacement. A critical J_I value (J_{Ic}) for the material can then be estimated from a plot of the J_I values versus the corresponding amounts of crack extension.

In the determination of a J_I value for a single specimen, the work relating to crack extension must be established from a load-displacement record. In the case of a three-point bend test on an ASTM E 399-74 designated specimen, J_I can be taken as equal to twice the area under the load-displacement curve divided by the uncracked section area, $B(W - a)$, where B = thickness, W = width (depth), and a = crack length (ref. 1). In reference 1 the general form of the J_I relationship is shown to be:

$$J_I = \frac{\varphi U}{B(W - a)}$$

where U is the applied work available for or consumed in crack extension, and where φ has a practically constant value of 2.00 over the range of a/W from 0.5 to 1.

It is obvious that the accuracy of the load-displacement records and their subsequent interpretation determine both the accuracy of the individual specimen J_I values and the critical value for the material. The precise procedure for the determination of a critical J_I value is currently under development by Task Group E-24.01.09 of ASTM Committee E-24.

This report concerns details of displacement measurement and test record analysis which should assure sufficient accuracy of determination of the work associated with crack extension in three-point bend specimens. These details are equally important in the determination of specimen compliances where strains are limited to the elastic range, or in the development of crack growth resistance curves (R-curves) where the need to measure larger displacements arises. The particular details described are:

(1) A dual-gage load-point-displacement measurement procedure that corrects for displacement measurement errors resulting from misalignment between the load applicator and specimen and that sums the gage outputs to provide a single, average signal.

(2) A technique to measure and correct for the excess work associated with coincidental displacement components which are not considered as contributory to work performed on the specimen for analytical purposes.

(3) A means for extending the range of a double-cantilever-beam displacement gage while retaining its short range sensitivity and accuracy.

DUAL GAGE LOAD DISPLACEMENT MEASUREMENT

The mechanics of a three-point bend test prohibit measurement of the load-point-displacement at the mid-point of the contact line of the applied force where the force might be considered as being concentrated. A common practical location for the displacement measurement is on the extension of the load applicator pin immediately adjacent to the specimen as shown in fig. 1. Displacement is measured using a displacement gage also shown in fig. 1. This gage consists of a double-cantilever clip-in displacement gage (described in ASTM Test Method E 399-74) mounted in a piston-cylinder adaptor. The piston-cylinder device is described more fully in ref. 2. This adaptor has practical merit in that laboratories equipped to run plane-strain fracture toughness tests can easily convert to load-point-displacement measurements with existing instrumentation.

Measurement of displacement on only one side of the specimen will probably contribute to some load-point-displacement error since attainment of absolute alignment of load applicator and specimen is difficult. The error is unlikely to be constant for the specimens of any single test series. Therefore its consideration and compensation is doubly important.

To illustrate an error in measuring displacement at a single point on the loading pin adjacent to the specimen, a specimen was purposely misaligned. The bend test main support block (fig. 1) was shimmed so that the specimen was 0.0025 in. closer to the loading pin at one edge than at the other. The specimen was unnotched, one inch square in cross section, and was tested on a four inch span. Displacement was measured simultaneously on both sides of the 0.5 in. diameter cylindrical load applicator (fig. 1) at positions 0.75 in. from the specimen edges. Separate displacement records were obtained on an XYY' recorder. Measurement of the two load versus displacement areas over an initial 0.005 in. average displacement range showed a variation of ± 9.8 percent from the average. The misalignment conditions were, of course, exaggerated, and the errors were not corrected for coincidental strains (as described later). Errors in actual tests where care in alignment was exercised would be considerably less. Nevertheless, unless proper precautions are taken there is likely to be error from this source.

To minimize such displacement measurement error, dual displacement gages can be employed with output signal summing. Displacement is measured at two points on the load applicator pin, equidistant from each specimen side (fig. 1).

The outputs from the two displacement gages can be connected in series to provide a signal with compensated errors.

MEASUREMENT OF COINCIDENTAL DISPLACEMENTS AND THEIR USE IN CORRECTION PROCEDURES

Several sources of coincidental displacement are included when load-point-displacement in three-point bending is measured from the loading pin relative to the test base. The major errors are due to elastic deformation of the various test fixture components, and to elastic and plastic indentations of the specimen by the loading pin and support rollers. A method for correcting the test record for such coincidental displacements has been discussed by Robinson and Tetelman (ref. 3). We have extended their method so that a load versus load-point-displacement plot of the coincidental displacements is obtained by use of the actual testing fixtures and the specimen used in the test. Such a "correction" record is made for each specimen tested, and is included as part of the permanent test record sheet. Individual correction for each specimen is desirable because the correction plot varies depending upon the dimensional or mechanical property pecularities of the individual specimens.

COINCIDENTAL DISPLACEMENT DETERMINATION

The experimental setup for determining coincidental load-point displacement is illustrated in fig. 2. An insert block of the same width and the same material and material condition as the support block, is inserted into the span gap of the support block. This insert positions the support rollers at the same height from the base as was the case for the test proper. The support rollers are butted together to provide a span that is as close to zero as possible. An undeformed part of the test specimen is then placed in position on the butted rollers with the same orientation as during the test proper. A load versus load-point deflection record is obtained as described in the previous section with the highest load slightly in excess of the maximum load achieved during the bend test. The displacement "correction" record obtained should approximate closely the displacement that occurred during the bend test other than that due to bending, shearing, and cracking of the specimen. This coincidental displacement, thus isolated, can be subtracted from the test record to give the desired plot of load versus load-point displacement. The latter plot then is used to determine the work area used in subsequent data analyses.

There is a minor contribution to the "correction" displacement due to bending and shear of the specimen over the butted support roller span, and some due to the difference in deformation between the roller support base during the test proper and that of the insert block during the "correction" run. Calculations made for the test setup depicted in fig. 2 indicate that the error in the correction displacement would be positive (that is, the magnitude of the coincidental displacement measured in the "correction" run would be slightly greater than that of the coincidental displacement included in the record of the test proper). This positive error was calculated to be no greater than 7 percent of the "correction" displacement at any load.

PROCEDURES FOR THE CORRECTION OF LOAD DISPLACEMENT RECORDS FOR COINCIDENTAL DISPLACEMENTS

The most obvious procedure to correct a load versus displacement record for coincidental strains is a point-by-point replotting of the curve. The original curve at any given load point is decreased by an increment of displacement equal to that displacement at an identical load on the displacement "correction" curve. Although it is tedious, this process is probably the most accurate means for obtaining a "corrected" representation of the test record. Such a representation may be useful, for example, in measuring compliance, detecting changes in slope in the initial portions of the test record, or for studying other variations in the load-displacement record as the situation warrants. This point-by-point method for applying the correction for coincidental displacements is shown schematically in fig. 3(a).

In determining such quantities as J_I, however, the test record is utilized primarily to obtain the area under the load-displacement curve. This area is related to the work associated with crack extension up to the point of unloading of the test specimen (ref. 1). A simple and direct method for determining the "corrected" area under a load-displacement curve is depicted in fig. 3(b). The area under the coincidental displacement curve is simply subtracted from the area under the primary test curve to yield the "corrected" area for the test. These areas may be measured directly from the test record by use of a planimeter or other suitable means. No replotting is necessary in using this procedure, thus conserving much time and effort in analyzing the test data.

This correction method is applicable to tests which have been continued beyond maximum load as well as to tests which have been terminated at or prior to attaining maximum load. It is important that the final load value used in determining the area under the primary data curve is also used to determine the area under the "correction" curve, as shown in fig. 3(b).

A source of error may exist in the "correction" of test records that extend beyond maximum load which is not present in other cases. It is assumed that the loading path of the coincidental displacement between that load at which the specimen is finally unloaded and the maximum load would be retraced on unloading. This may not be the case since some part of the coincidental displacement could be due to plastic deformation of the specimen at the load and support points during loading, and this part would not be recovered on unloading. This part is inconsiderable when the difference between maximum and interrupt loads is small.

EXTENDED DISPLACEMENT MEASUREMENTS

Although much useful fracture mechanics information is obtained from bend tests having relatively small displacements, as in K_{Ic} determinations, there are conditions which require that bend tests be continued through larger displacements, as in the J_I crack extension resistance tests discussed previously or in crack resistance (R) curve determinations. Two related difficulties that arise when bend tests are continued to substantial deflections are: (1) the limitation of the displacement range of the conventional clip gage and (2) the scaling of the total test record to the recorder chart without sacrifice of resolution in the record.

For tests involving large displacements, constricting of the test record is necessary so that the entire record can be included on standard size recorder paper. This reduces the resolution of the test record, thereby making its analysis more difficult. This is a particular problem when close examination of the initial portion of the test record is desired.

A simple addition to the load-point displacement gage arrangement of fig. 1 permits recording at a sensitivity sufficient to define well the early portion of the test, and also permits extended displacements over the remainder of the test to be included on the chart at the same sensitivity.

The revised arrangement is shown in fig. 4. Spacers are inserted between the load applicator pin and the pistons of the displacement gage adaptors. The height of the displacement gage adaptor support blocks must of course be decreased to compensate for the thickness of the spacers so that the proper initial opening (i. e., the "zero" position) of the clip gages will be maintained. The arrangement of fig. 4 shows four spacers in position. In this case, 0. 100 in. (2. 5 mm) thick spacers are shown, for a total increased displacement capability of 0. 400 in (10. 2 mm). In practice, the number of spacers required is determined by the total displacement expected for the test. However, if a series of tests is to be performed, this determination may be more logically based on the greatest displacement expected for the series in order to minimize rearranging of the test setup.

During the progress of a bend test, as the displacement gages or the recorder pen reaches a limit, the topmost pair of spacers is extracted without interrupting the test. The spring force of the clip gages causes each adaptor piston to "reset" an amount equal to the thickness of the removed spacer.

The retaining rods prevent the remaining spacers from sliding forward along with the topmost pair.

As the test progresses, the retaining rods are temporarily withdrawn while a second pair of spacers is moved forward to engage the spacer removal fork. The rods are reinserted through the rear holes of the remaining spacers, and the process may be repeated.

If thicker spacers are more convenient for a particular testing program, it is suggested that their trailing edges be machined to a ramp-type configuration to cause the piston to reset in a less abrupt manner than that allowed with the square-edge configuration shown. Also, if desired, an L-shaped slot in place of the retaining rod feed-through hole at the rear of each spacer would facilitate manipulation of the spacers when preparing for secondary spacer extraction operations.

An example of a test record employing this procedure is depicted in fig. 5. The XY recorder displacement drive reverses and moves the pen back at its slewing rate by an amount proportional to the spacer thickness. This permits the chart to be retraversed as the test continues.

CONCLUDING REMARKS

The methods described in this report for improving load-displacement measurement and record analysis of three-point bend tests of cracked or notched specimens provide improved measurement accuracy and simplify treatment of test records. These are: (1) a summation of two load-displacement signals into a single output signal which reduces displacement measurement error due to specimen and load applicator misalignment; (2) the recording of coincidental load-displacement components which are not considered as contributory to the work performed on the specimen for analytical purposes; and (3) the extension of displacement gage range with the retention of short range sensitivity and accuracy. These test method details should aid in more accurate determination of such crack characterization quantities as J_I.

REFERENCES

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3. Robinson, J. N. and Tetelman, A. S., "Comparison of Various Methods of Measuring K_{Ic} on Small Precracked Bend Specimens that Fracture after General Yield," Engineering Fracture Mechanics, Vol. 8, No. 2, June 1976, pp. 301-313.

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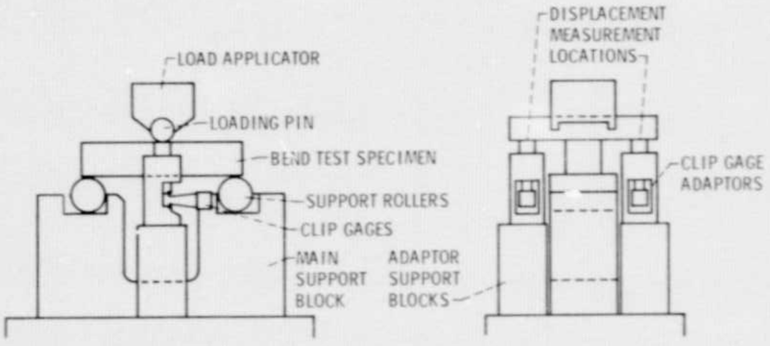
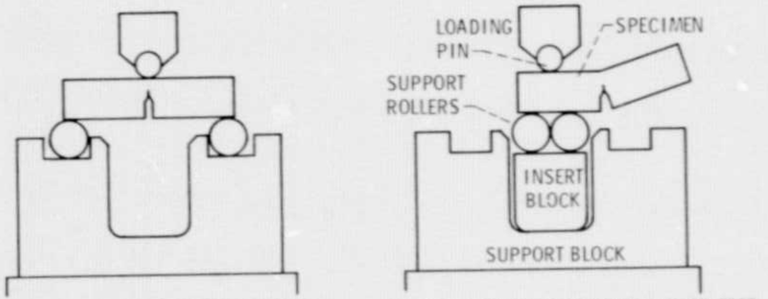


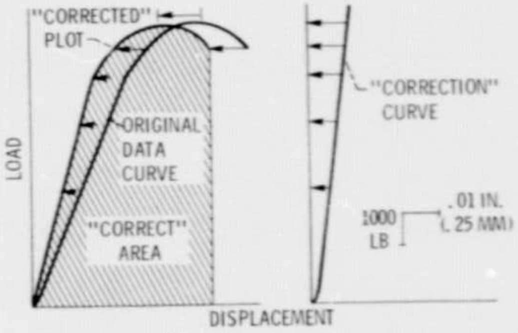
Figure 1. - Schematic of bend test apparatus showing dual displacement gage placement. (A displacement gage consists of a clip gage in its piston-cylinder adaptor.)



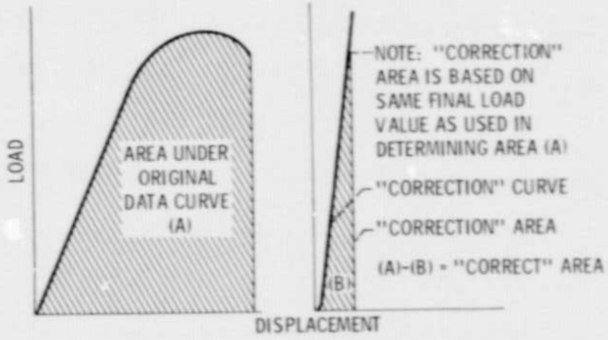
(a) SPECIMEN IN STANDARD TESTING POSITION.

(b) SPECIMEN IN POSITION FOR POST-TEST DETERMINATION OF DISPLACEMENT CORRECTION USING INSERT BLOCK.

Figure 2. - Bend test apparatus with specimen in position for testing and for post-test correction determination. (Displacement gages not shown.)



(a) CORRECTION BY POINT-BY-POINT REPLOTTING.



(b) CORRECTION BY SUBTRACTION OF AREAS.

Figure 3. - Examples of methods of applying correction for coincidental displacement to load-displacement record.

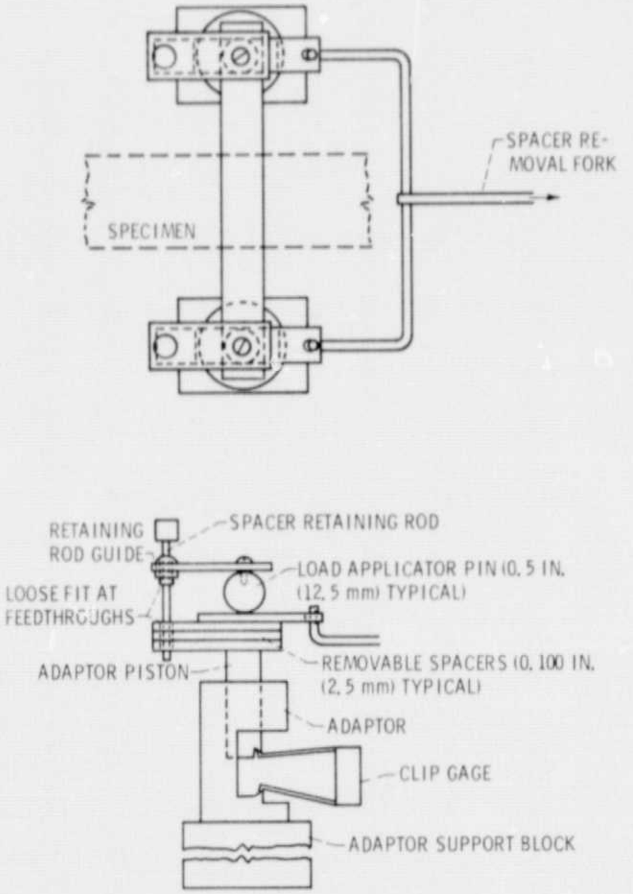


Figure 4. - Schematic showing method of extending range of displacement gages by use of removable spacers. (A displacement gage consists of a clip gage in its adaptor.)

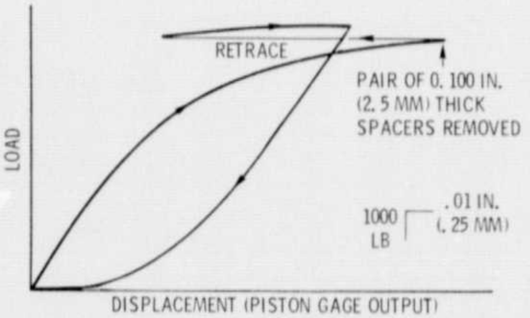


Figure 5. - Example of bend test record obtained using spacer removal technique. Removal of spacer allows piston gage to reset by amount equal to spacer thickness, causing pen to retrace as shown.