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C-SHAPED SPECIMEN PLANE STRAIN FRACTURE TOUGHNESS TESTS

by R. J. Buzzard and D. M. Fisher
Lewis Research Center
Cleveland, Ohio 44135
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16. Abstract

Supplementary information is presented which was obtained during participation in a cooperative program for evaluation of C-shaped specimens for inclusion in ASTM Standard Method of Test E 399 for Plane Strain Fracture Toughness of Metallic Materials. Observations are reported on: specimen preparation and dimensional measurement; modifications to the standard ASTM E 399 displacement gage, which permit punch mark gage point engagement; and a measurement device for determining the interior and exterior radii of ring segments. Load-displacement ratios were determined experimentally which agreed with analytically determined coefficients for three different gage lengths on the inner surfaces of radially-cracked ring segments.

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by R. J. Buzzard and D. M. Fisher

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 41135

SUMMARY

As a consequence of participation in a cooperative program for evaluation of C-shaped specimens for inclusion in ASTM Standard Method of Test E-399 for Plane Strain Fracture Toughness of Metallic Materials, much supplementary information was obtained beyond that required for the program coordinator's report. The documentation of this supplementary information is important for those investigators who will use the C-shaped specimen.

The information reported here includes observations regarding specimen preparation and dimensional measurement, modifications to displacement gage design, and development of dimensional measurement devices. Particularly, a means for determining interior and exterior radii of ring sections is detailed. A modification of the ASTM E-399 standard displacement gage is described. This modified gage incorporates points which seat in center punch indentations on the specimen. This method of attachment permits specimen and gage machining savings over knife edge type specimens and gage mounting. Use of the gage modification in those C-shaped specimens where it is applicable gave K_{Ic} results comparable to those obtained using knife edge mounted gages.

In addition to providing fracture toughness results for the cooperative program, the specimens were used to establish load-displacement slopes for the determination of displacement coefficients. These experimentally determined coefficients for three different gage lengths on the inner surface of radially-cracked ring segments verified those determined analytically by a boundary collocation method.

INTRODUCTION

Where K_{Ic} fracture toughness testing of tubular products is required, the C-shaped specimen configuration (fig. 1) provides an attractive alternative to the compact and three-point bend specimen configurations currently specified in ASTM Standard Method of Test E-399-74 for Plane Strain Fracture Toughness of Metallic Materials (ref. 1). The C-shaped form provides the most efficient use of the available stock, and incorporates a more representative cross-section of the original stock into the test. Also, assuming a reasonable degree of concentricity and circularity of the cylindrical sections, specimens can be prepared by simply slicing cross-sections, surface grinding, halving, and machining the loading holes and the fatigue crack starter notches.

Two C-shaped specimen configurations (fig. 1) are being considered by ASTM Committee E-24 on Fracture Testing for inclusion in ASTM Method E-399. Tests conducted by eight laboratories in a cooperative program organized by ASTM Task Group E-24.01.12 have provided data for evaluation of this specimen type. The authors were responsible for the NASA Lewis Research Center's contribution to the cooperative program.

All required test results will be documented in a report which summarizes the total cooperative test effort. Those from NASA LeRC are given in Table I. In addition to this laboratory's contribution of that required test data, it was evident that the techniques used here in the preparation, dimensional measurements, and testing of this unique specimen configuration should also be documented. Equally important, the specimens of this program provided an opportunity to verify experimentally some C-shaped specimen displacement coefficients recently determined analytically by Gross (ref. 2).

SPECIMEN PREPARATION AND PRELIMINARY EXAMINATION

Specimen blanks

The specimen material supplied by the round robin coordinators* was a Ni-Cr-Mo steel having a 0.2% offset yield strength of 191 Ksi (1317 MN/m^2) and a Rockwell C hardness of 43. The material was initially forged tube. Specimen blanks were prepared at the coordinator's facility by lathe turning the tube to an outside diameter of 4.06 inch (103.12 mm), slicing the tube into rings, and surface grinding the sliced surfaces. The rings were then sectioned into C-shaped halves prior to distribution to the cooperating laboratories. The inner radial surfaces of the C-shaped segments, as received by the cooperating labs, were as forged and heat treated. A scale coating, having a depth as great as 0.003 inch (0.076 mm) was observed on the inner surface. This scale was removed by vapor blasting at this laboratory. In the initial dimensional check of the specimen blanks, it was noted that the ground surfaces were not perpendicular to the curved surfaces. The maximum deviation from perpendicularity was 2.1 degrees at the notch zone of one of the specimen blanks.

Measurements showed that the cylindrical surfaces were not concentric. Measured specimen width, W (fig. 1), varied as much as 0.10 inch (2.54 mm) from the nominal value of 2.01 inch (51.05 mm) reported by the coordinators.

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*J. H. Underwood and D. P. Kendall
Benet Weapons Laboratory
Watervliet Arsenal
Watervliet, New York

The specimen geometry makes very difficult any improvement of the previously noted dimensional variations after the rings have been sectioned into halves. It should be emphasized that preliminary dimensioning on the ring segments is advisable prior to sectioning, so that, dimensional deviations can be corrected at this point.

Specimen machining

The as-received blanks were machined to the geometry and dimensions illustrated in fig. 1. Loading holes, fatigue crack starter notches, and crack mouth displacement gage knife edges were machined perpendicular to the major flat surfaces. Notch depths and hole locations were referenced from mid-thickness, B, to compensate for the non-perpendicularity of the circumferential surfaces to the flat surfaces. Five specimens were machined to a nominal ratio X/W of zero, and four to a nominal ratio X/W of 0.5, where X is the offset of the loading hole center line from the smaller radius surface, and W is the specimen width.

Dimensional measurements

The dimensional measurements required before testing the C-shaped specimens are as shown in fig. 1. Because of the shape of the specimens some of the measurements required special methods. Such measurements were made more complex by the previously described eccentricities and obliquities common to the specimens of this study. The methods used to obtain these measurements are described in the following paragraphs.

The thickness, B, of each specimen was fairly consistent. The greatest variation observed on a single specimen was 0.002 inch (0.051 mm).

The width, W, of the specimen at the notch location was obtained by use of a micrometer fitted with a ball attachment. Because the notch mouth contains no material upon which to rest a micrometer, width values were determined by averaging the four radial distances across the specimen taken at each knife edge, and on both sides of the specimen.

Measurement of the load-line offset, X (fig. 1), was obtained with the aid of snug fitting pins inserted in the loading pin holes. The pins extended from the holes to serve as stops for a straight edge butted to them as shown in fig. 2(a). The maximum distance from the outer straight edge surface to the outer edge of the specimen was measured with a micrometer. This process was repeated for the reverse side of the specimen, and the results were averaged. Care was taken to ensure that the micrometer referenced the outer edge of each specimen. Measurement to the non-perpendicular outer curved surface could result in a false indication of the "A" distance during this measurement. The X dimension was calculated by subtracting the specimen width, W, the width of the straight-edge, S, and the loading hole radius, D/2, from the micrometer reading "A". The maximum variation in "A" measurements for any specimen was 0.025 inch (0.635 mm).

The radial dimensions were measured prior to the machining of the C-shaped blanks into specimens so that the uniformity of these dimensions among specimens could be cataloged prior to the removal of end and notch material during specimen fabrication. These measurements were repeated after specimen machining because slight variations in radii on the order of a few thousandths of an inch were observed in individual blanks. These variations possibly occurred where residual stresses were relieved when the ring sections were halved. Comparison of both sets of measurements indicated that the pre-machining measurements were in agreement with those taken after the fatigue crack starter notch was milled. Although such verification of the radii may appear redundant, it is a procedure to consier in specimens whose ring sections may have large residual stresses.

Since the specimen blanks were received as half-ring segments, rather than full cylindrical sections, conventional micrometers or calipers could not be used in determining the radial dimensions. Measurement by optical comparator was deemed impractical due to the specimen size and alignment difficulties resulting from the obliquity of the curved surfaces relative to the flat surfaces. As a result, a method was developed to measure the radii of this type of cylindrical segment.

This method utilizes a conventional micrometer (or dial type) depth gage with a ball-end rod. The depth gage sits atop an additional rigid base plate of known length, "L", as shown in fig. 3, with the rod extending thru a centrally located clearance hole in the plate. The edges of the additional base plate rest upon the inside wall of the cylinder, and in effect the length of this base plate (L) becomes a chord of the circle whose radius is that of the inside radius of the cylinder. The edges of the plate, being parallel, are readily aligned with the longitudinal axis of the cylinder segment.

The depth gage is used in the conventional manner to measure the distance between the base plate and the cylinder wall. The thickness of the additional base plate must be subtracted from the micrometer reading to obtain the true distance of the chord (bottom of the additional base plate) from the wall. This distance is represented as "h" in the sketch. Measurements may be made in several locations, if desired, to obtain an average "h" value.

The inside radius of the cylinder (r_1) is given by:

$$r_1 = \frac{L^2 + 4h^2}{8h} \qquad (1)$$

The outside radius also could have been measured using this method by adding vertical side plates to the additional base plate and spanning the outer surface of the cylinder. For this study, however, it was felt that a more appropriate value for outer radius at the notch zone of the specimens could be obtained by adding the width of the specimen at the notch to the inside radius dimension. The nominal values of inside and outside radius (r_1 and r_2, respectively) are presented in fig. 1(a).

The depth of the machined notch was determined by use of a toolmaker's microscope. The distance from the knife edges to the notch root was measured along the longitudinal centerline of the notch, as indicated in fig. 2(b). This value was greater than the center line distance, however, due to the curvature of the specimen. Therefore, a correction factor was calculated which compensated for this error, as shown in the figure. Both sides of the specimen were measured in this manner, and the results were averaged. This correction procedure was also applied to the post test determination of the fatigue crack length, a (fig. 1). The actual crack measurements were made from the knife edges as prescribed in ASTM test method E-399-74.

TEST EQUIPMENT AND PROCEDURES

In order to obtain test data for use in establishing displacement coefficients for C-shaped specimens, load-displacement slopes were determined for each of the four specimens with $X/W \cong 0.5$, first in the machined notch condition, and finally after the specimens had been fatigue cracked in preparation for the K_{Ic} tests. Displacements were determined simultaneously at three locations (fig. 1(b)): across the crack mouth (H_1), at the load line (H_3), and across a distance intermediate to these (H_2). A load line displacement measurement was also made for one of the specimens with $X/W \cong 0$, in the machined notch configuration. This displacement was measured at the crack mouth (fig. 1(a)). For determination of K_{Ic} values only notch mouth displacement data need be obtained, but in the case of the 0.5 X/W ratio specimens, load line displacement was also determined.

Displacement gages

Displacement measurements in both the slope determinations and the K_{Ic} tests were made using either the standard double-cantilever clip-in gage described in ASTM Test Method E-399 or an adapation of it. Measurements of crack mouth displacement were made using the standard clip gage mounted on the machined knife edges of the specimens. For the measurements of load-line and intermediate point displacements the gages were modified so they could register and engage in indentations made with a tool steel center punch.

The modified gages and a standard gage all mounted in a specimen are pictured in fig. 4. The spacer blocks of the modified gages were machined to lengths approximating the gage mark spacing. The lengths were not critical since additional adjustment could be made at the points of the gage. The points were made from 6-32 machine screws with the ends ground to a conical tip to engage the center punch gage marks.

The screws were locked in place by nuts which also permitted adjustment of the original distance between the points. Interchanging of points or spacer blocks permits adaption of a single set of strain-gaged beams for use over an extensive range of gage distances.

The points of the gage were held in place by the outward spring force of the compressed gage beams. The gages were free to pivot laterally. This feature permitted the multiple installation of the three gages at H_1, H_2 and H_3 as illustrated in fig. 4 and allowed the simultaneous measurement of displacement over three gage lengths.

In applications where this gage modification can be used, two machining cost savings are incorporated over knife edge mounting. The gage beam ends need no machined V slot for knife edge engagement and the specimen knife edges are eliminated, being replaced by center punch indentations.

The gages were calibrated using the device shown in fig. 5. This calibrator incorporates a precision micrometer head graduated to a least division of 0.0001 inch (0.0025 mm). Calibrations of the point gage modification were well within the limits specified in ASTM Test Method E-399-74. The test method required a maximum deviation of 0.0001 inch (0.0025 mm) from a least-squares-best-fit straight line through the data. The maximum deviation determined in the point-gage calibrations was 0.00003 inch (0.00076 mm) over a 0.050 inch (1.27 mm) range. Preparatory to the determinations of the load-displacement slopes, the amplified output of each gage was calibrated directly to an XYY' recorder chart axis. In these calibrations no displacement measurements deviated from linearity more than +0.7 or -0.5 percent.

DATA RECORDING AND SLOPE DETERMINATIONS

Two XYY' recorders were used for the slope determinations for comparison with the analytically determined displacement coefficients. Load was recorded on the X axis of each recorder and the crack mouth displacement on the Y axis of each. This permitted correlation of the two recorder records. The load-line and intermediate displacements were each recorded on a Y' axis of the two recorders. The maximum loads used for slope determinations were kept below those used in fatigue cracking the specimens. Loads were measured with a 10,000 lb (44,500 N) capacity load cell rated linear within $\pm$0.1 percent of capacity. Three replicate load-displacement slopes were determined for each specimen, first with a machined notch, and then again after fatigue cracking. The average of each of the three replicate values was used in the calculations of the displacement coefficients. Since each crack mouth slope was recorded on both recorders, there were six values to be averaged for that gage location.

For the specimens with $X/W \cong 0.5$, recorder gains were chosen to give chart slopes within the range of 0.4 to 1.1 with a minimum trace length of 4 inch (102 mm). The slope of the single record obtained from a specimen with $X/W \cong 0$ was 0.1 with the trace length exceeding 10 inch (254 mm).

DISCUSSION OF TEST RESULTS

In addition to the cooperative program test results and the previously described techniques developed and used in obtaining these results, the C-shaped specimen round robin program provided an opportunity to determine experimentally the displacement coefficients for this specimen configuration. These experimentally determined values were compared with the results of Gross (ref. 2), who determined the displacement coefficients along the inner radii of ring segments by the boundary collocation method.

A comparison was made of K_{Ic} results obtained from test records where displacements were recorded simultaneously at two gage locations: across the crack mouth and the load line.

Comparison of experimentally and analytically determined displacement coefficients

The experimentally determined displacement coefficients, Δ, were calculated using the relationship (ref. 2, eq. (8)):

$$\Delta = \frac{EBf}{P} \cdot \frac{(W - a)^2}{2a(3X + 2W + a)} \tag{2}$$

The symbols used in the relationship are defined in fig. 6. A nominal Young's modulus value of $30\text{x}10^6$ was used in the calculations.

The experimental values of the displacement coefficients are tabulated in Table II together with analytical values obtained by interpolation from the chart (fig. 6) which provides the displacement coefficients as a function of crack to width ratio, a/W, with the gage length to width ratio, H/W, as a parameter. A linear interpolation was used for values of H/W falling between the curve values. The values of displacement coefficients used in plotting the curves of fig. 6 were obtained from Gross' data (ref. 2) using a summation method.

Agreement between experimental and analytical values is within ±3% for the crack mouth and intermediate gage point locations. The greater disagreement (0 to -7%) in the load-line results can be attributed partly to the failure of the analytical model to accurately approximate the experimental loading conditions, and partly to the lower accuracy of displacement measurement expected at this location.

The good agreement of the experimental and analytical results might be considered fortuitous when the previously described dimensional discrepancies in the test specimen are recalled. It is more likely that the influence of these discrepancies on the load-displacement slopes and on the subsequently determined displacement coefficients were minimal for the following reasons. Where specimen inner and outer radii were eccentric, an increase in stiffness of the section on one side of the crack plane would be counteracted by a decrease in stiffness on the opposite side. The load-displacment slope would reflect this balancing effect and approach that of a concentric radii specimen having the same crack plane cross-section. The previously described measurement methods used in determining the X, a, and W specimen dimensions provided values that would relate properly to the analytical model and thus reduce any differences in the experimental and analytical displacement coefficients which might be due to specimen obliquity.

K_{Ic} variation with displacement measurement location

The actual K_{Ic} tests of the nine C-shaped specimens were performed in accordance with ASTM Test Method E-399-74, as prescribed for the compact specimen. The expression necessary for computation of K_{Ic} is provided in ref. 3. The K_{Ic} values are also given in Table 1(a). In addition to measuring load displacements at the knife edges in the $X/W \cong 0.5$ specimens load displacement was also recorded simultaneously at the load-line gage points using the modified point gage previously described. The K_{Ic} results were then determined from both records. The two K_{Ic} values from each specimen were averaged. In any single specimen, the maximum deviation from this average was 0.6%; the minimum; 0.05%. In two specimens the load-line displacement test curve gave the higher result, in the other two, the crack mouth displacement curve did.

CONCLUDING REMARKS

This report documents the contribution of the Lewis Research Center as a participant in a cooperative program for evaluation of C-shaped specimens for inclusion in ASTM Standard Method of Test E-399 for Plane Strain Fracture Toughness of Metallic Materials. The information reported here includes a description of methods by which the C-shaped specimens were prepared and tested.

The following suggestions are offered, based on the experience gained from this endeavor:

1. Machining of the radial surfaces of C-shaped specimen blanks, and measurement of the blanks, should be completed prior to cutting the blanks into C-shaped segments, as corrective machining and diametrical measurements beyond this point are difficult.

2. Perpendicularity of the flat surfaces to the curved surfaces of the specimen blanks should be maintained during the surface machining operations: lathe turning at least one of the flat surfaces of each ring prior to halving it may be one method of accomplishing this.

3. In addition to the initial diametral measurements of the ring segments, measurement of the radial dimensions of the finished specimens should also be made to determine possible dimensional variations which may result from relief of residual stresses in the ring segments during the halving and notch machining operations. A depth-gage type of device, developed for obtaining the radius dimensions of tubular segments, is described in this report.

4. Specimen dimensions which allude to the notch plane in C-shaped specimens, but are in practice measured using the notch mouth knife-edge as a reference, should incorporate a correction for specimen curvature. A method of determining this correction, described herein, was used in this study to determine the distance from the inside radius of the specimen at the notch plane to the loading axis ("X" distance), and in determining the fatigue crack length (a) after fracturing the specimen.

5. Load-line displacement measurements may be obtained using a modification of the double-cantilever clip-in displacement gage described in ASTM Standard Method for Test E-399-74. This modification, described herein, incorporates a spacer block having a length commensurate with the specimen's gage mark spacing, and adjustable points at the free ends of the cantilever beams which engage in punch-mark indentations in the specimen. This design permits "nesting" of the gages, so that several gage lengths on a C-shaped specimen may be monitored simultaneously during a single test run.

K_{Ic} results were obtained using both the notch mouth knife edge and center punch indentations located on the inside radial surface of the specimen at the loading axis as displacement measurement reference locations. Both sets of K_{Ic} results compared favorably.

In addition to providing fracture toughness results for the cooperative program, the specimens were used to establish load-displacement slopes for the determination of displacement coefficients. These experimentally determined coefficients verified analytically determined displacement coefficients for three different gage lengths on the inner surface of radially-cracked ring segments.

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TABLE I. - VALUES ASSOCIATED WITH K_I CALCULATIONS FOR C-SHAPED SPECIMENS

(a) Table of values for specimens having nominal X/W ratio of 0.5

Specimen number	W (a)	B	X (a)	a (a)	r_1	r_2	P_Q	P_{max}/P_Q	K_Q	K_{Ic}	Displacement measurement location
9-1	1.963 in. 49.94 mm	0.996 in. 25.34 mm	0.985 in. 25.06 mm	1.031 in. 26.23 mm	2.057 in. 52.33 mm	4.021 in. 102.29 mm	7.83 k-lb 34.83 MN	1.02	93.27 ksi - in$^{1/2}$ 103.72 MPa - m$^{1/2}$	93.27 ksi - in$^{1/2}$ 103.72 MPa - m$^{1/2}$	Crack mouth
							7.79 k-lb 34.65 MN	1.02	92.80 ksi - in$^{1/2}$ 103.19 MPa - m$^{1/2}$	92.80 ksi - in$^{1/2}$ 103.19 MPa - m$^{1/2}$	Load line
10-2	2.033 in. 51.72 mm	0.995 in. 25.31 mm	1.015 in. 25.82 mm	1.042 in. 26.51 mm	2.060 in. 52.41 mm	4.094 in. 104.15 mm	8.06 k-lb 35.85 MN	1.06	90.51 ksi - in$^{1/2}$ 100.65 MPa - m$^{1/2}$	90.51 ksi - in$^{1/2}$ 100.65 MPa - m$^{1/2}$	Crack mouth
							8.16 k-lb 36.30 MN	1.05	91.63 ksi - in$^{1/2}$ 101.89 MPa - m$^{1/2}$	91.63 ksi - in$^{1/2}$ 101.89 MPa - m$^{1/2}$	Load line
13-1	1.957 in. 49.79 mm	0.995 in. 25.31 mm	0.975 in. 24.80 mm	1.048 in. 26.66 mm	2.059 in. 52.38 mm	4.017 in. 102.19 mm	7.40 k-lb 32.92 MN	1.05	91.37 ksi - in$^{1/2}$ 101.60 MPa - m$^{1/2}$	91.37 ksi - in$^{1/2}$ 101.60 MPa - m$^{1/2}$	Crack mouth
							7.41 k-lb 32.96 MN	1.05	91.49 ksi - in$^{1/2}$ 101.74 MPa - m$^{1/2}$	91.49 ksi - in$^{1/2}$ 101.74 MPa - m$^{1/2}$	Load line
14-1	1.958 in. 49.81 mm	0.996 in. 25.34 mm	0.977 in. 24.85 mm	1.064 in. 27.07 mm	2.062 in. 52.46 mm	4.019 in. 102.24 mm	7.27 k-lb 32.34 MN	1.03	92.30 ksi - in$^{1/2}$ 102.64 MPa - m$^{1/2}$	92.30 ksi - in$^{1/2}$ 102.64 MPa - m$^{1/2}$	Crack mouth
							7.32 k-lb 32.56 MN	1.03	92.94 ksi - in$^{1/2}$ 103.35 MPa - m$^{1/2}$	92.94 ksi - in$^{1/2}$ 103.35 MPa - m$^{1/2}$	Load line

(b) Table of values for specimens having nominal X/W ratio of zero

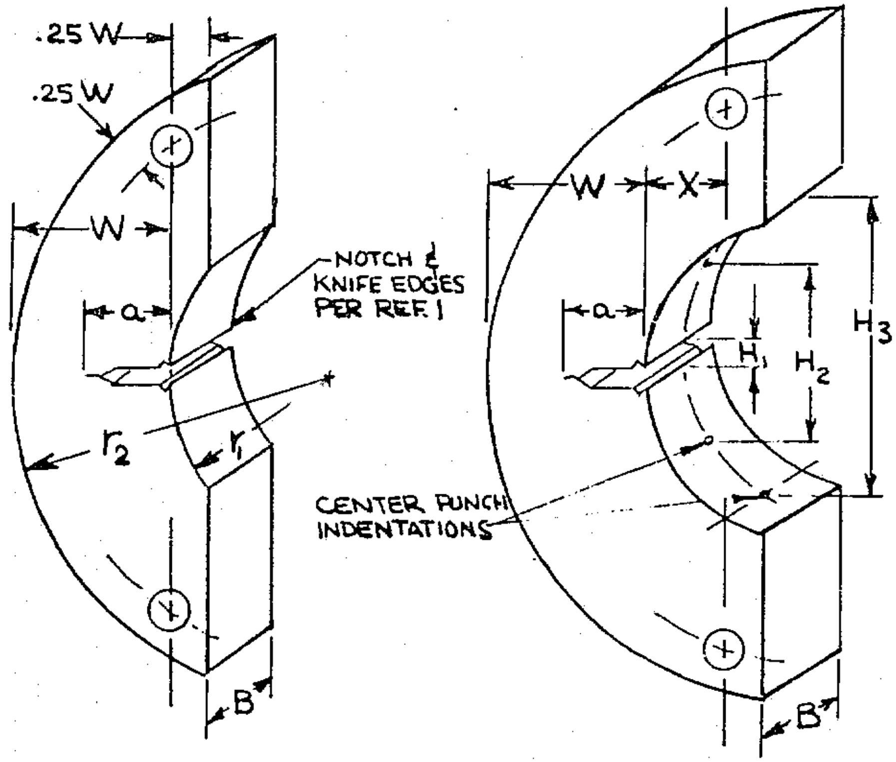
16-2	2.049 in. 52.13 mm	0.999 in. 25.41 mm	-0.004 in. -0.102 mm	1.064 in. 27.07 mm	2.067 in. 52.58 mm	4.115 in. 104.69 mm	13.62 k-lb 60.58 MN	1.06	95.96 ksi - in$^{1/2}$ 106.71 MPa - m$^{1/2}$	95.96 ksi - in$^{1/2}$ 106.71 MPa - m$^{1/2}$	
17-2	2.047 in. 52.08 mm	0.999 in. 25.41 mm	-0.003 in. -0.076 mm	1.117 in. 28.42 mm	2.068 in. 52.61 mm	4.115 in. 104.69 mm	12.44 k-lb 55.33 MN	1.06	97.12 ksi - in$^{1/2}$ 108.00 MPa - m$^{1/2}$	97.12 ksi - in$^{1/2}$ 108.00 MPa - m$^{1/2}$	
23-1	1.953 in. 49.68 mm	1.001 in. 25.47 mm	+0.001 in. +0.025 mm	1.137 in. 28.93 mm	2.067 in. 52.58 mm	4.020 in. 102.27 mm	10.16 k-lb 45.19 MN	1.07	92.85 ksi - in$^{1/2}$ 103.25 MPa - m$^{1/2}$	(b)	
23-2	2.041 in. 51.92 mm	1.001 in. 25.47 mm	-0.009 in. -0.229	1.188 in. 30.22	2.065 in. 52.53 mm	4.106 in. 104.46 mm	10.46 k-lb 46.53 MN	1.06	93.13 ksi - in$^{1/2}$ 103.56 MPa - m$^{1/2}$	(b)	
27-1	1.964 in. 49.96 mm	1.001 in. 25.47 mm	-0.001 in. -0.025 mm	1.061 in. 26.99 mm	2.067 in. 52.58 mm	4.031 in. 102.55 mm	11.42 k-lb 50.80 MN	1.08	88.90 ksi - in$^{1/2}$ 98.86 MPa - m$^{1/2}$	88.90 ksi - in$^{1/2}$ 98.86 MPa - m$^{1/2}$	

[a]Average values (see section on Dimensional measurements).
[b]K_{Ic} values not valid, as the difference between two of the crack length (a) measurements exceeded 5% of the average. (See ref. 1, Section 8.2.3.)

TABLE II. - COMPARISON OF ANALYTICALLY AND EXPERIMENTALLY DETERMINED DIMENSIONLESS DISPLACEMENT COEFFICIENTS FOR C-SHAPED SPECIMENS

[See fig. 6 for symbol identification.]

Specimen number	X/W	r_1/r_2	Displacement measurement location	H/W	Machined notch			Fatigue crack		
					a/W	Displacement coefficient, Δ		a/W	Displacement coefficient, Δ	
						Experimental	Analytical		Experimental	Analytical
9-1	0.502	0.512	Crack mouth	0.100	0.478	3.36	3.26	0.525	3.20	3.17
	.502	.512	Intermediate	1.050	.478	4.26	4.22	.525	4.06	4.01
	.502	.512	Load line	1.792	.478	6.53	6.87	.525	6.08	6.32
10-2	.499	.503	Crack mouth	.106	.456	3.28	3.31	.512	3.17	3.19
	.499	.503	Intermediate	1.022	.456	4.20	4.24	.512	3.99	3.99
	.499	.503	Load line	1.759	.456	6.78	6.93	.512	6.28	6.29
13-1	.498	.513	Crack mouth	.088	.478	3.30	3.26	.536	3.07	3.15
	.498	.513	Intermediate	1.061	.478	4.26	4.22	.536	3.90	3.98
	.498	.513	Load line	1.796	.478	6.50	6.87	.536	5.86	6.26
14-1	.499	.513	Crack mouth	.099	.478	3.38	3.26	.543	3.09	3.14
	.499	.513	Intermediate	1.060	.478	4.30	4.23	.543	3.85	3.95
	.499	.513	Load line	1.790	.478	6.49	6.85	.543	5.78	6.17
23-1	.0005	.514	Crack mouth	.104	.474	3.16	3.11			

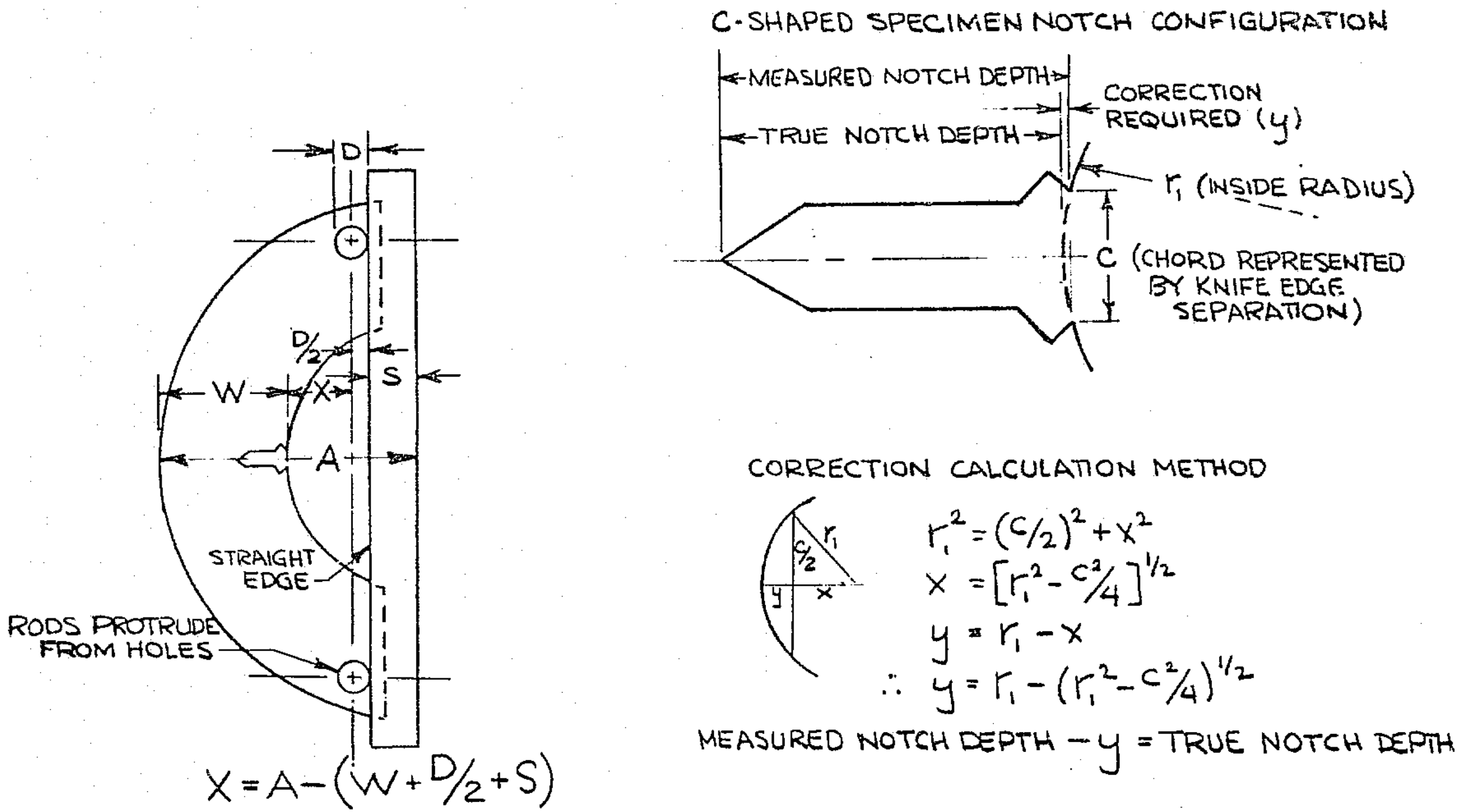


(a) X/W ≅ 0 (b) X/W ≅ 0.5

NOMINAL SPECIMEN DIMENSIONS

DESIGNATION	IN.	MM.
W	2.01	51.05
B	1.00	25.4
r_1	2.05	52.07
r_2	4.06	103.12
a	1.00	25.4
HOLE DIA.	0.25	6.35
H_1 (KNIFE EDGE OPENING)	0.20	5.08
H_2 (INTERMED. GAGE LENGTH)	2.080	52.83
H_3 (LOAD LINE GAGE LENGTH)	3.538	89.87
NOTCH ROOT RADIUS	0.003	0.076

Figure 1. - C-shaped specimen configurations and measurement designations.



(a) X Determination.

(b) Determination of true notch depth by applying correction to measured value.

Figure 2. - Methods used for measuring offset of loading axis (X) and notch depth for C-shaped specimens.

$$r_1 = \frac{L^2 + 4h^2}{8h}$$

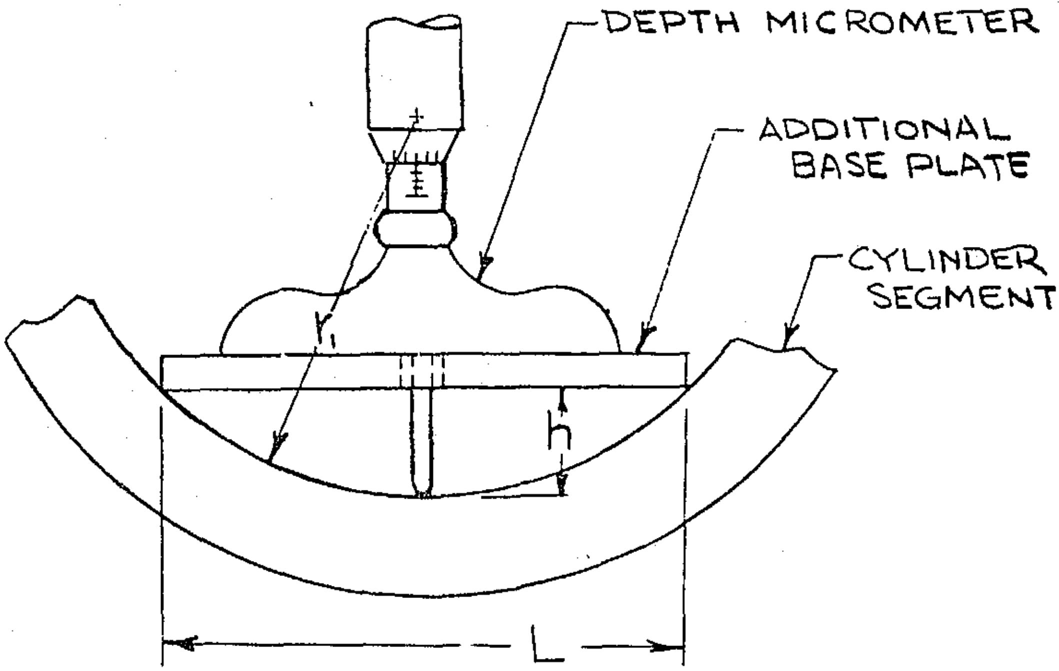


Figure 3. - Method used for determining inside radius dimension of tubular segment.

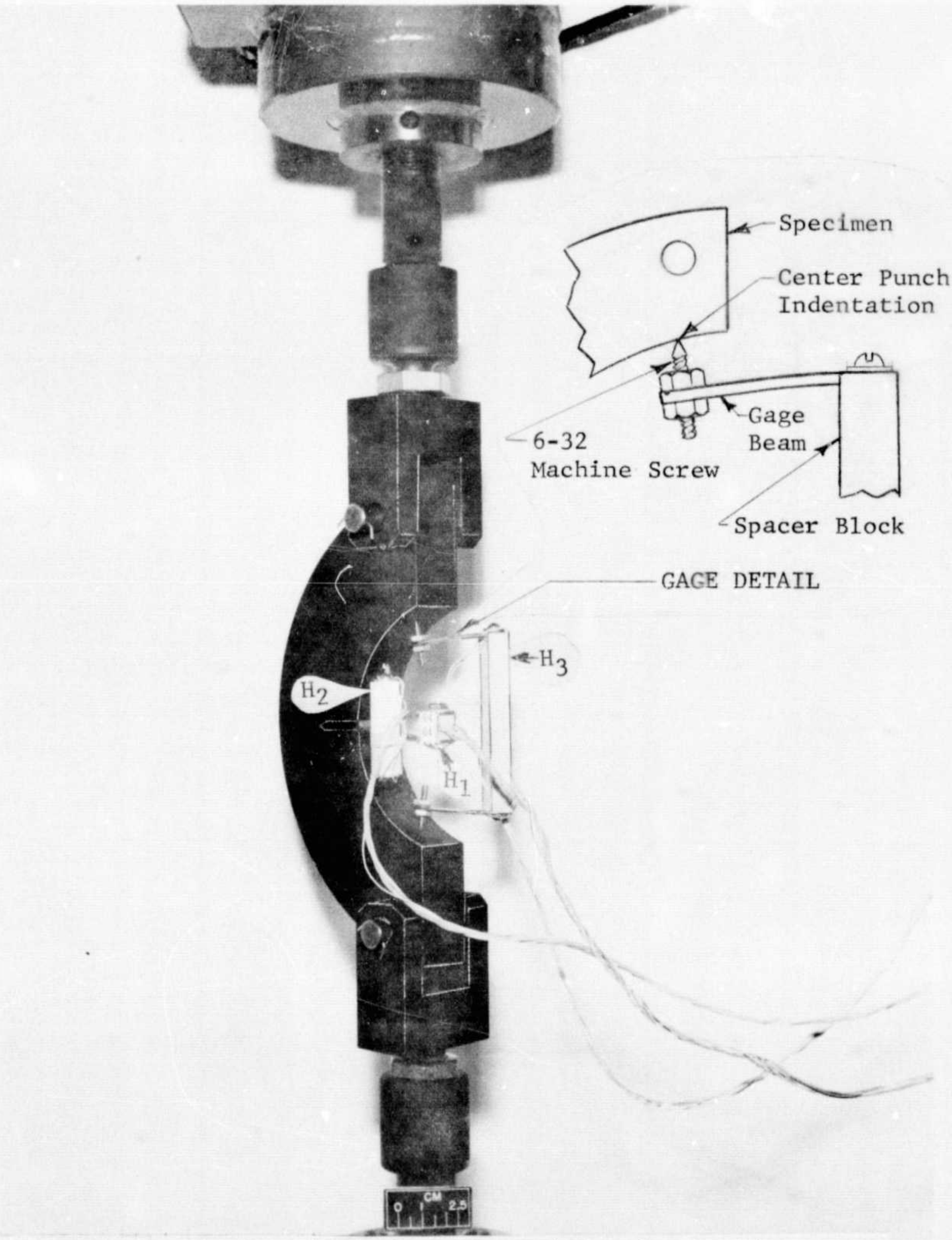


Figure 4. - C-shaped specimen in position for testing. Displacement gages referenced to notch mouth (H_1), an intermediate location (H_2), and the load line (H_3).

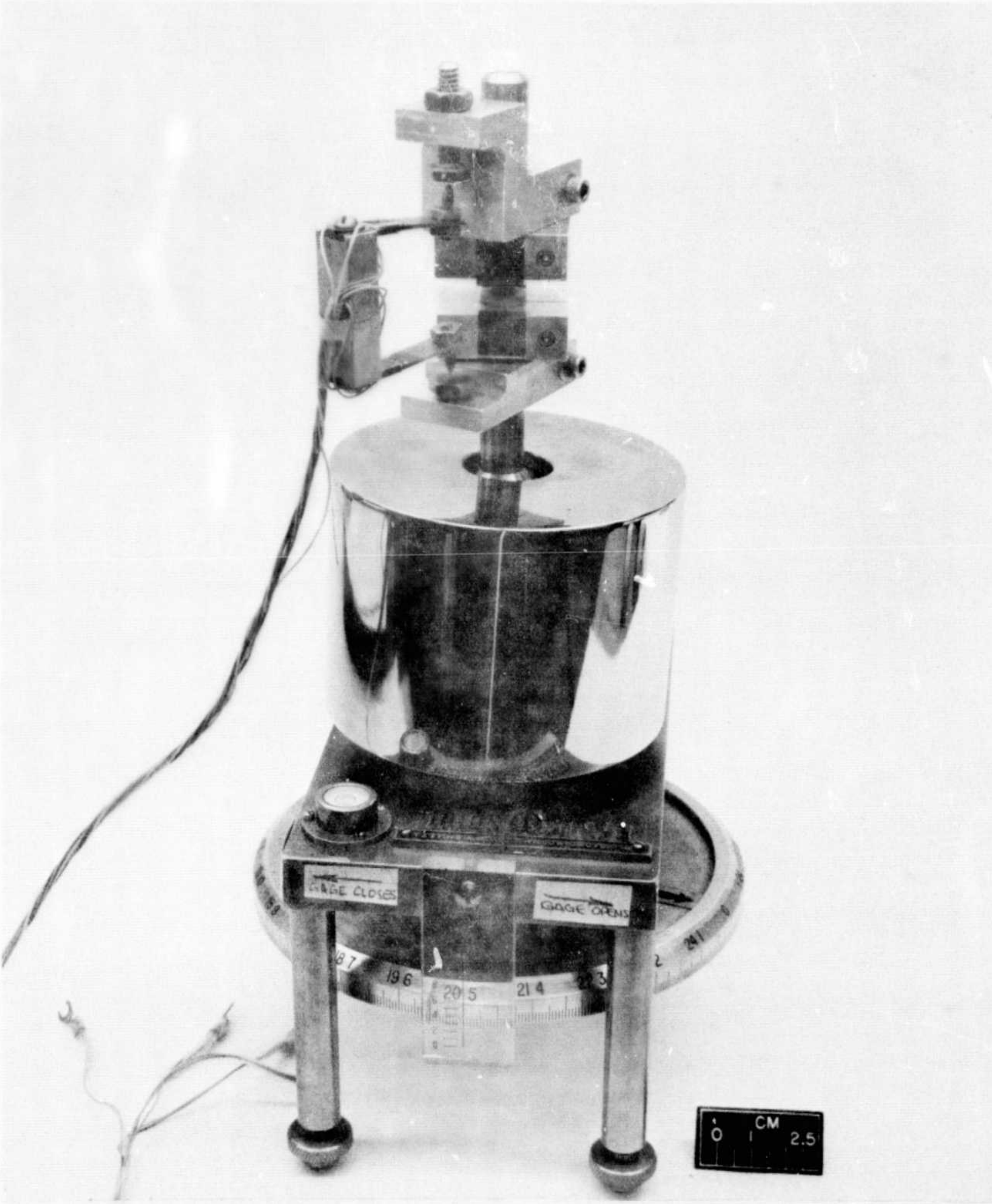


Figure 5. - Point engagement displacement gage modification in position for calibration. Also shown are knife edges used in calibration of standard ASTM E399 displacement gages.

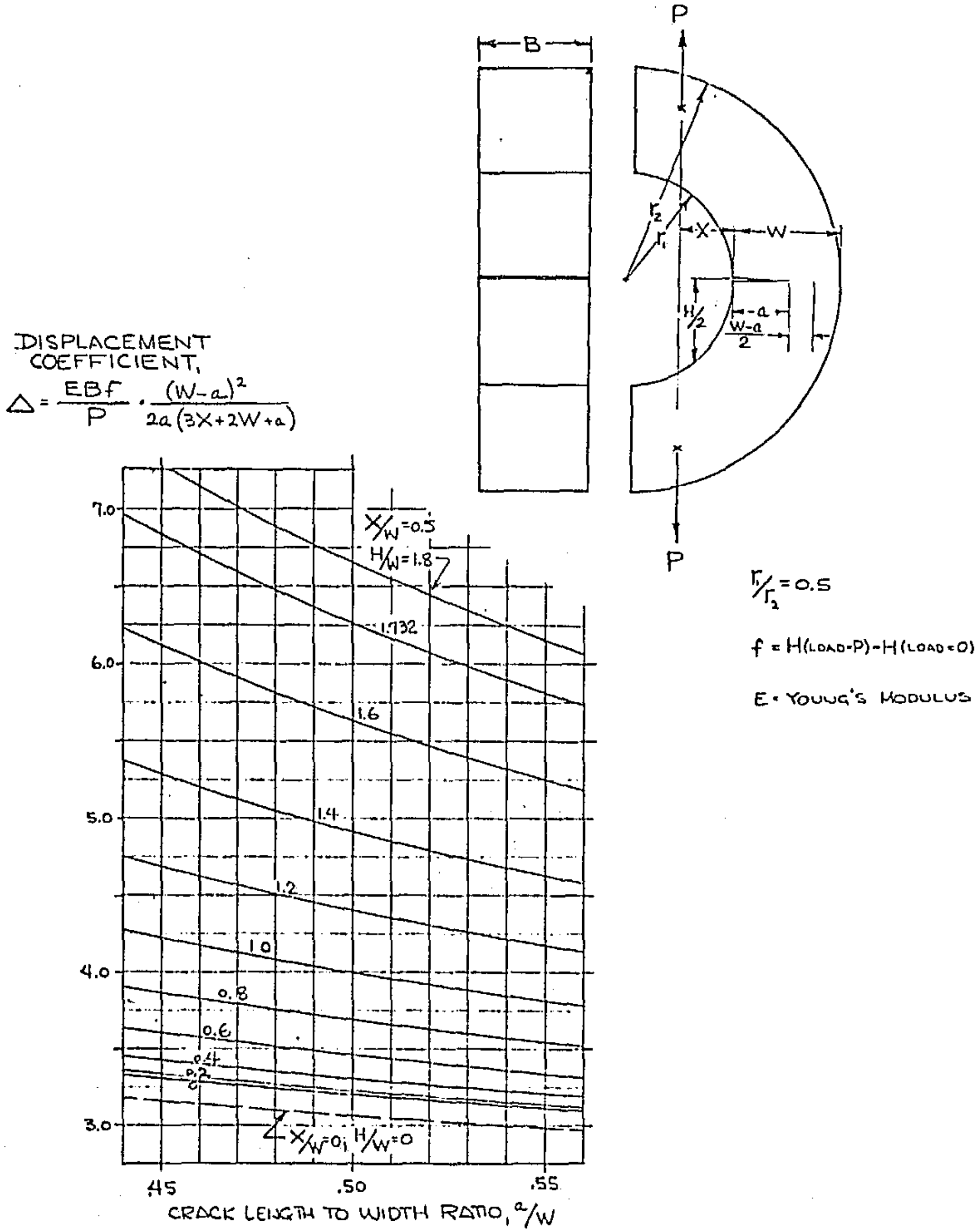


Figure 6. - Plane stress dimensionless displacement coefficient as a function of crack length to width ratios for varying gage length to width ratios.