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PROPOSED STANDARD ARC-BEND CHORD-SUPPORT FRACTURE TOUGHNESS SPECIMENS AND K EXPRESSIONS

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Collocation and finite element calculations and limit solutions were used to propose standard geometries and K expressions for measuring fracture toughness with arc-bend chord-support specimens. Polynomial expressions for K were determined for a wide range of crack length and for two span-to-depth ratios. Fracture toughness of steel and aluminum alloys was measured using the proposed methods and compared with results from existing standard methods.

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DEDICATION

This work is dedicated to the memory of the late John E. Srawley, Jr., a pioneer in the field of fracture mechanics testing and analysis.

INTRODUCTION

Recent work on arc-bend fracture specimens (refs 1-3) has included accurate stress intensity factor, K, calculations for a variety of chord-support geometries. Kapp's collocation analysis (ref 2), in particular, has provided the results required for accurate, wide range K expressions for arc-bend chord-support specimens. Figure 1 shows the basic geometry (ref 1) and some nomenclature. This arc-bend configuration approaches that of the rectangular bend specimen of ASTM Method E-399 (ref 4) as r_1/r_2 approaches unity. Thus, the results of Srawley and Gross (ref 3), on which the rectangular bend K expression was based, should be considered and used as a limiting solution for arc-bend chord-support specimens with r_1/r_2 near the value 1.0.

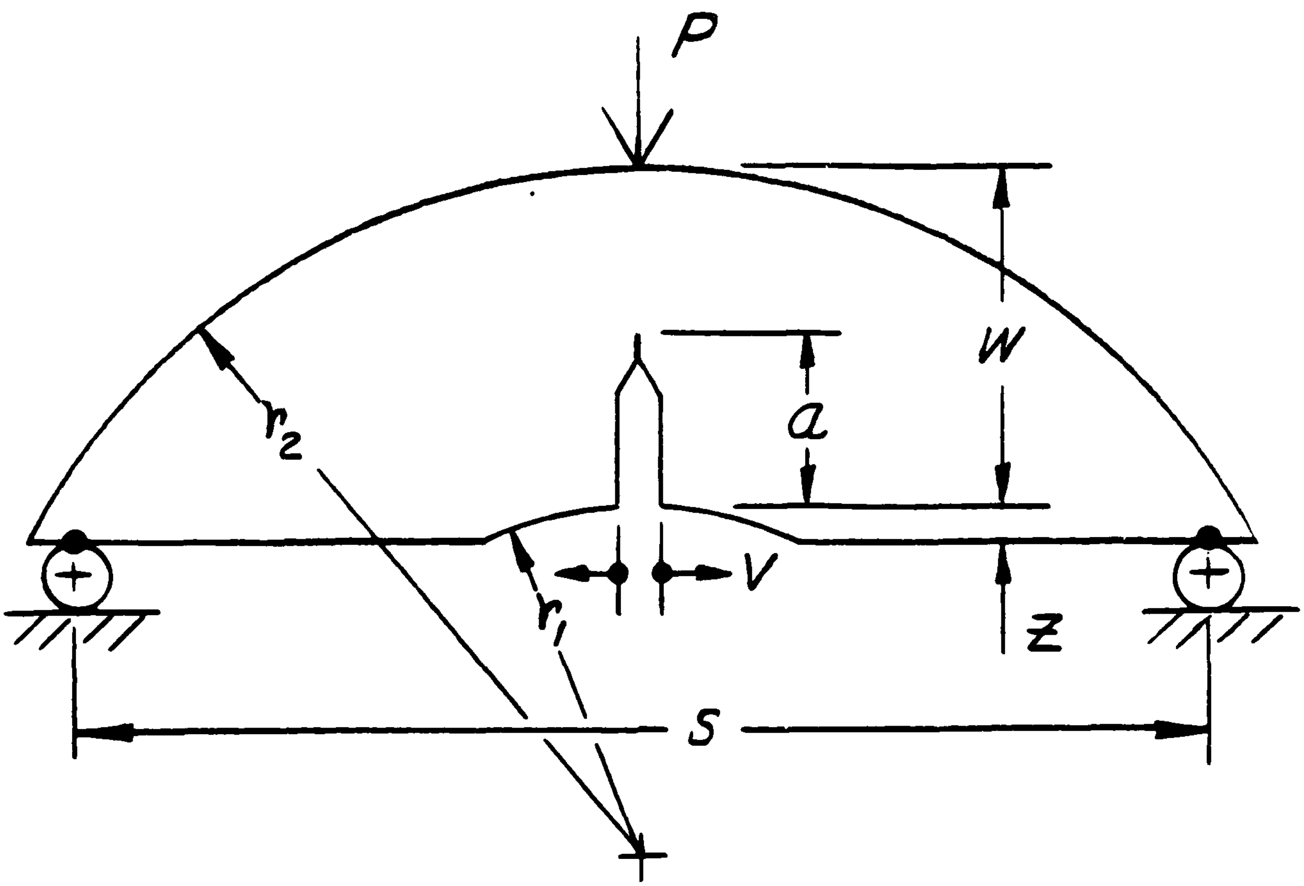

Figure 1. Arc-bend specimen geometry and nomenclature.

References are listed at the end of this report.

The objective here is to use the collocation and finite element calculations (refs 1,2), the rectangular bend calculations (ref 3), and a deep crack limit solution (ref 5) to obtain wide range K expressions and standard specimen geometries for use in fracture testing with arc-bend chord-support specimens. The range of crack depth relative to specimen depth considered is $0.2 < a/W < 1.0$, which would accommodate fatigue crack growth rate testing as well as fracture toughness testing. The range of arc-shaped geometries considered is $0.4 < r_1/r_2 < 1.0$ and two specimen span-to-width ratios, $S/W = 4$ and 3. A limited test program was also conducted as a physical check on the analytical work.

ANALYSIS AND RESULTS

The general approach for obtaining a wide range K expression is to choose a K parameter which, due to its mathematical form, approaches the shallow and deep crack limits, as discussed in prior work (refs 1-3). For arc-bend specimens with a wide range of r_1/r_2, it can be difficult to satisfy the shallow crack limit using a simple expression (ref 2). In this work the difficulty will be avoided by considering the range $0.2 < a/W < 1.0$, and only the deep crack limit will be considered. None of the standard fracture tests use $a/W < 0.2$, so avoiding this portion of the a/W range is no limitation for standard tests.

The deep crack limit solution of concern is (ref 5)

$$\{KBW^{3/2}/PS\}\{1 - a/W\}^{3/2} = 0.994 = Y$$

$$a/W = 1 \qquad (1)$$

where B is specimen thickness, P is applied load, and the other quantities are described in Figure 1. This form of Eq. (1) was used to obtain the K parameter, designated as Y, used for comparison of the various analytical results and for fitting of wide range expressions.

Figures 2 and 3 and Tables I and II compare K values from analysis for a range of geometries. For S/W = 4, the K results from two independent collocation analyses are compared in Table I and Figure 2. Also shown are the results from a wide range K expression which was fitted to the two sets of collocation results. The expression is

$$\{KBW^{3/2}/PS\}\{1 - a/W\}^{3/2} =$$

$$\{1 + [1 - r_1/r_2][0.29 - 0.66(a/W) + 0.37(a/W)^2]\} \times$$

$$\{0.677 + 1.078(a/W) - 1.430(a/W)^2 + 0.669(a/W)^3\}$$

$$S/W = 4 \quad , \quad 0.2 < a/W < 1.0 \quad , \quad 0.6 < r_1/r_2 < 1.0 \qquad (2)$$

Equation (2) fits the rectangular bend collocation results (ref 3) within 0.3 percent, the arc-bend collocation results (ref 2) within 0.5 percent, and the

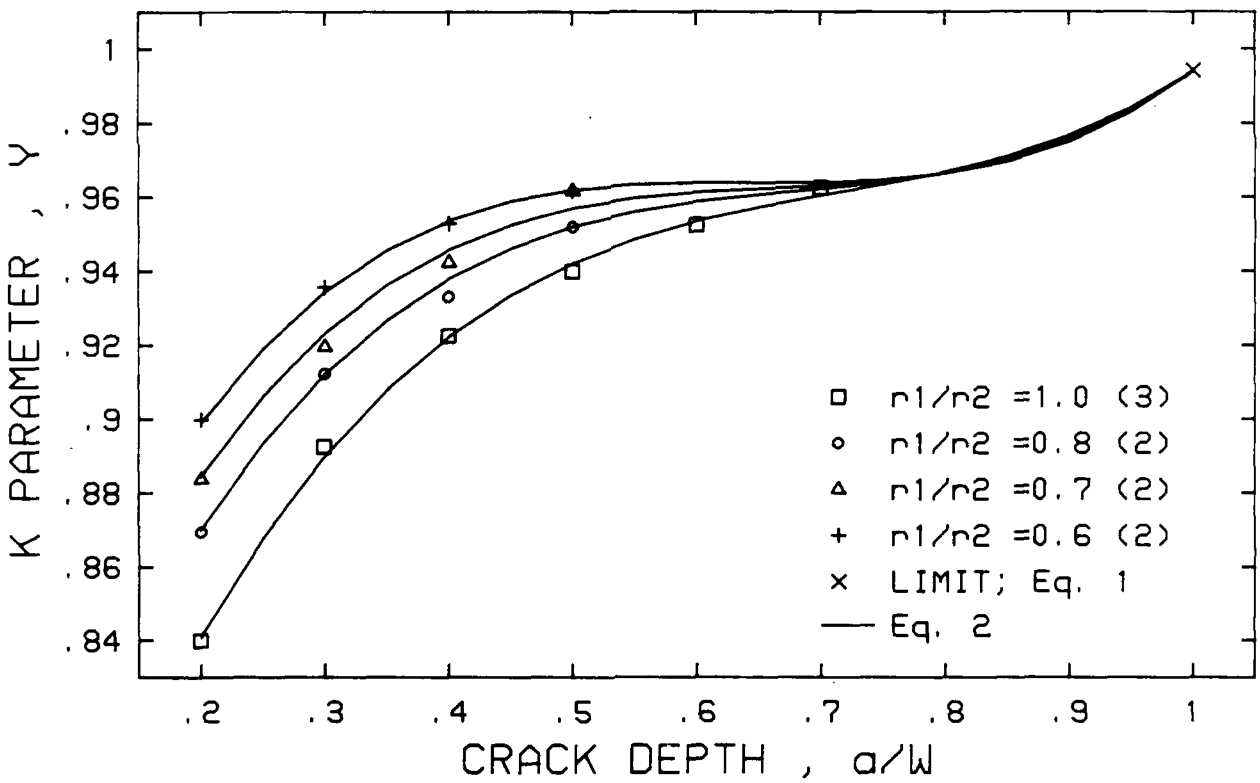

Figure 2. Comparison of stress intensity factor parameter, Y, from collocation and a wide range expression; S/W = 4.

limit solution (ref 5) within 0.1 percent. Note that for $r_1/r_2 = 1$, the term including r_1/r_2 equals unity, and Eq. (2) applies to the rectangular bend specimen.

TABLE I. COMPARISON OF K RESULTS AND EXPRESSIONS FOR S/W = 4

$$Y = (KBW^{3/2}/PS)(1 - a/W)^{3/2}$$

	$r_1/r_2 = 1.0$			$r_1/r_2 = 0.8$		$r_1/r_2 = 0.7$		$r_1/r_2 = 0.6$	
a/W	Ref 2	Ref 3	Eq. (2)	Ref 2	Eq. (2)	Ref 2	Eq. (2)	Ref 2	Eq. (2)
0.2	0.834	0.841	0.841	0.869	0.870	0.884	0.884	0.900	0.899
0.3	0.889	0.891	0.890	0.912	0.912	0.920	0.923	0.936	0.934
0.4	0.919	0.921	0.922	0.933	0.938	0.942	0.946	0.953	0.954
0.5	0.941	0.941	0.942	0.952	0.952	0.962	0.957	0.962	0.962
1.0	-	0.995	0.994	-	0.994	-	0.994	-	0.994

Another check on how well Eq. (2) fits numerical K results for arc-bend specimens can be made by comparison with finite element calculations from Reference 1. That prior work included results for S/W = 4, $r_1/r_2 = 0.667$, and a/W from 0.3 to 0.7. Equation (2) agrees with the finite element results within +1.0 and -2.1 percent for the two ends of the a/W range, respectively. Considering that the collocation and finite element methods are quite different and independent, this agreement is very good.

For S/W = 3 the comparison of results is shown in Table II and Figure 3, including the following wide range expression:

$$\{KBW^{3/2}/PS\}\{1 - a/W\}^{3/2} =$$
$$\{1 + [1 - r_1/r_2][0.20 - 0.32(a/W) + 0.12(a/W)^2]\} \times$$
$$\{0.644 + 1.110(a/W) - 1.490(a/W)^2 + 0.730(a/W)^3\}$$
$$S/W = 3 \quad , \quad 0.2 < a/W < 1.0 \quad , \quad 0.4 < r_1/r_2 < 1.0 \qquad (3)$$

Equation (3) fits the arc-bend collocation results (ref 2) within 0.6 percent except for one data point, and it fits the limit solution (ref 5) within 0.1 percent. The data point that is the exception is for r_1/r_2 = 0.4 and a/W = 0.3. Note in Table II that for this point the value of Y from collocation is 1.8 percent less than that from Eq. (3). Considering that the agreement between collocation results and the expression is much closer for all other points, this one collocation result is considered to be an outlier.

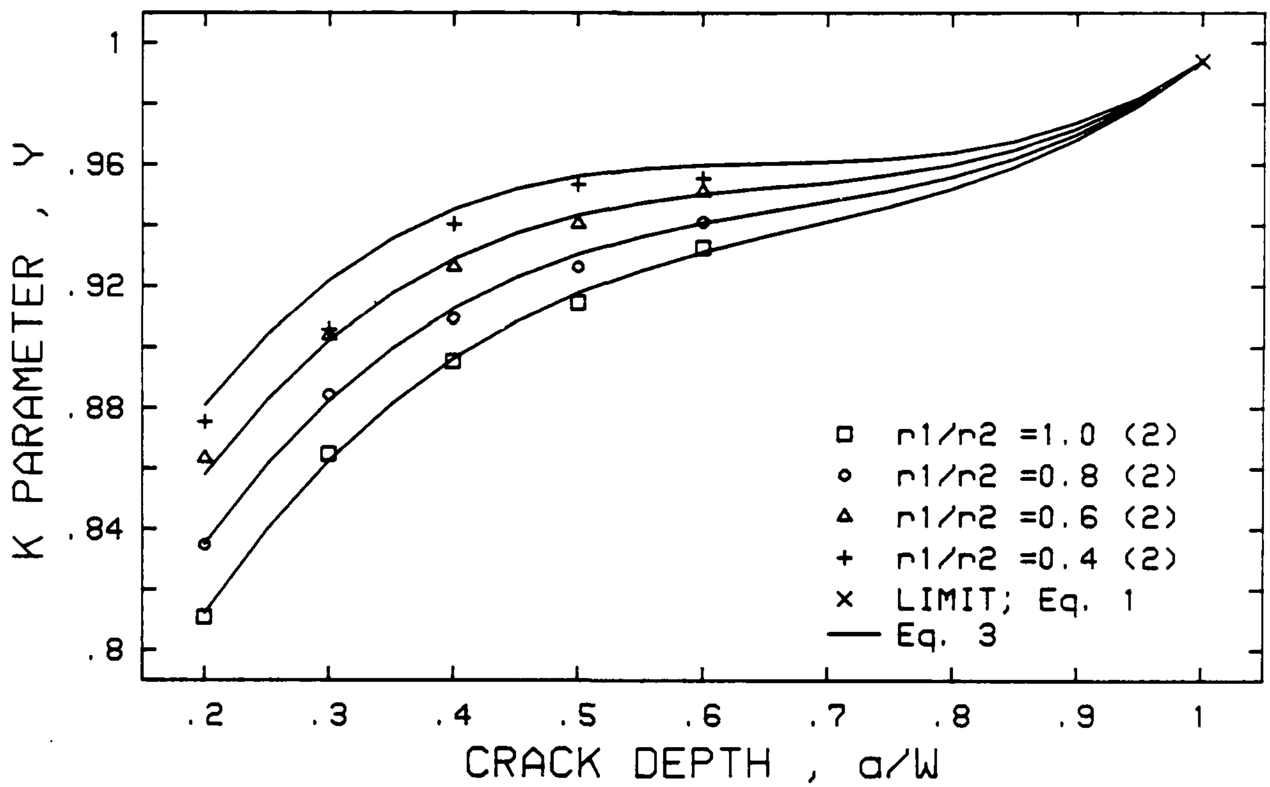

Figure 3. Comparison of stress intensity factor parameter, Y, from collocation and a wide range expression; S/W = 3.

TABLE II. COMPARISON OF K RESULTS AND EXPRESSIONS FOR S/W = 3

$$Y = (KBW^{3/2}/PS)(1 - a/W)^{3/2}$$

a/W	$r_1/r_2 = 1.0$		$r_1/r_2 = 0.8$		$r_1/r_2 = 0.6$		$r_1/r_2 = 0.4$	
	Ref 2	Eq. (3)	Ref 2	Eq. (3)	Ref 2	Eq. (3)	Ref 2	Eq. (3)
0.2	0.811	0.812	0.835	0.835	0.863	0.858	0.875	0.881
0.3	0.865	0.863	0.884	0.882	0.904	0.902	0.906	0.922
0.4	0.895	0.897	0.909	0.913	0.926	0.929	0.940	0.945
0.5	0.915	0.918	0.926	0.931	0.941	0.943	0.953	0.956
0.6	0.933	0.931	0.941	0.941	0.951	0.950	0.955	0.960
1.0	-	0.994	-	0.994	-	0.994	-	0.994

EXPERIMENTAL RESULTS

A limited cooperative test program was conducted which involved two test materials and three laboratories. A 7075-T6 aluminum and a 250 maraging steel were tested by each of the following:

Lab #1 - Armament Research, Development, and Engineering Center

Lab #2 - Unidentified*

Lab #3 - Idaho National Engineering Laboratory

The aluminum specimens had nominal B = 12.7 mm, W/B = 2, S/W = 4, $r_1/r_2 = 2/3$, and were cut so that the L-T orientation of the plate became the C-R orientation of the arc-bend specimen. See ASTM Method E-399 (ref 4) for a description of orientations. The steel specimens had nominal B = 13.0 mm, W/B = 2, S/W = 3, $r_1/r_2 = 1/2$, and had similar orientation.

*Note that Lab #2 has chosen to remain unidentified for proprietary reasons.

Additional tests of the same materials were performed by Lab #1 using ASTM E-399 test procedures and specimens (ref 4), that is, standard bend specimens with B = 12.7 mm from the aluminum and standard compact specimens with B = 12.7 mm from the steel. The 0.2 percent offset yield strength of the materials was also tested. Table III gives an outline of the tests as well as a summary of results. Both materials are quite high in strength and low in toughness, so results were expected which would meet the specimen size and other requirements for a plane-strain fracture toughness test. This proved to be true. The fracture toughness results in Table III met the critical specimen size and maximum load criteria of ASTM E-399. All of the individual fracture toughness results are plotted in Figure 4, which shows the generally good agreement between the arc-bend results from the three laboratories and the results from standard bend and compact specimens. Note that the one test was slightly outside the specified 0.45 to 0.55 range of a/W, having an a/W of 0.552.

TABLE III. FRACTURE TOUGHNESS TEST RESULTS

	7075-T6 Aluminum			250 Maraging Steel		
Yield Stress, MPa						
mean of 4 tests	508			1593		
standard deviation	4			9		
Standard Tests: K_{Ic}, MPa $m^{1/2}$	(bend)			(compact)		
mean of 5 tests	25.5			80.5		
standard deviation	0.5			3.2		
Arc-Bend Tests: K_Q, MPa $m^{1/2}$	Lab#1	Lab#2	Lab#3	Lab#1	Lab#2	Lab#3
mean of 3 tests	23.9	25.1	25.2	80.6	79.4	80.2
standard deviation	1.6	0.4	0.4	1.7	7.5	7.8

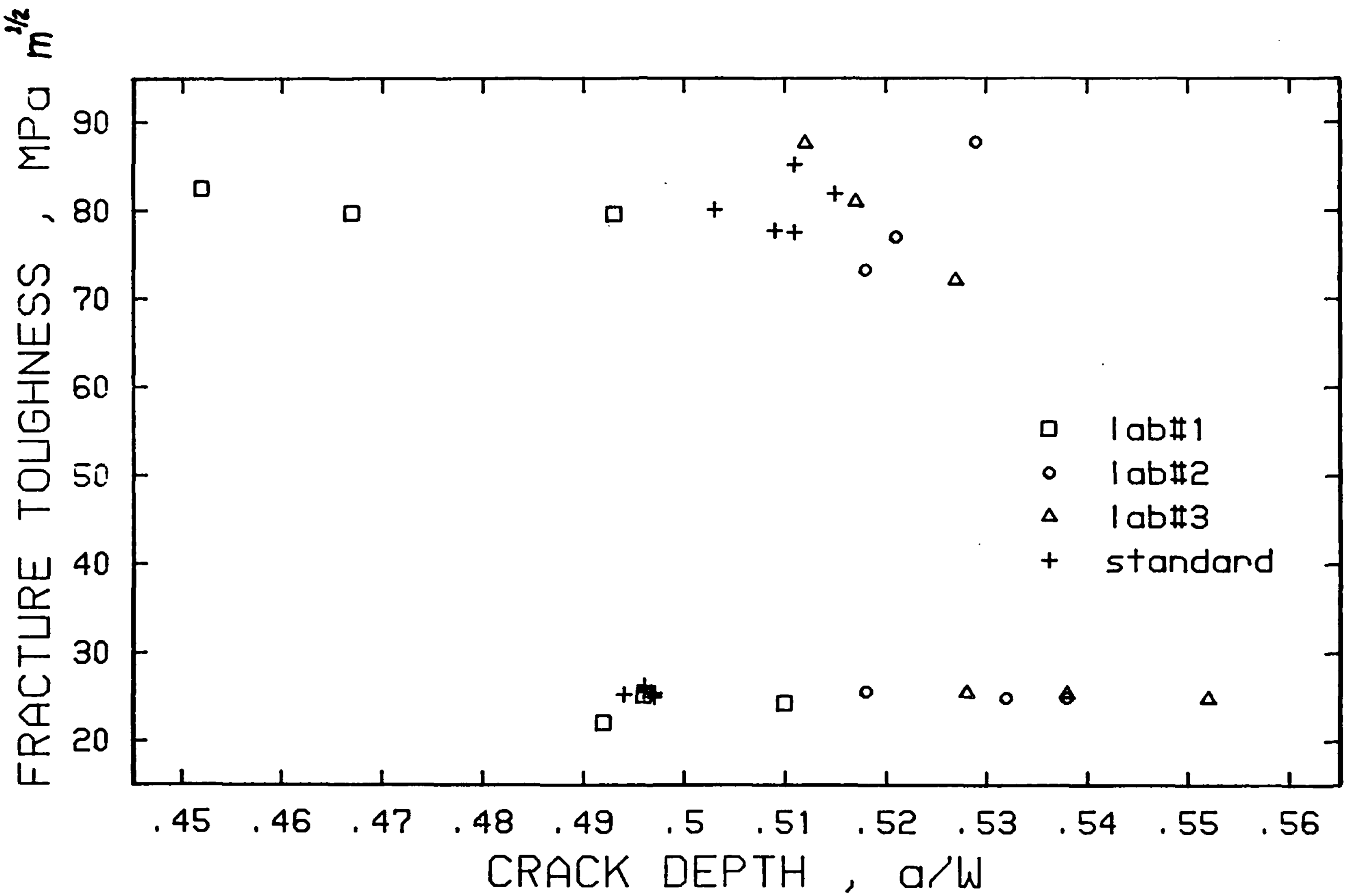

Figure 4. Comparison of arc-bend fracture toughness values with those from standard specimens.

The results of the cooperative test program show that the arc-bend test procedure gives a measurement of fracture toughness equivalent to that obtained using the existing standard E-399 procedures. For aluminum, the grand mean of the arc-bend tests is 3.0 percent below the mean of the standard rectangular bend tests. For steel, the grand mean is 0.5 below the mean of the standard compact tests.

The larger standard deviations for the steel fracture toughness tests compared with those for aluminum are believed to be due to the fact that the steel was heat treated as separate specimen blanks, albeit as one batch. The aluminum specimens were all cut from the same commercially processed plate.

SUMMARY AND CONCLUSIONS

The arc-bend chord-support specimens with $S/W = 4$ and 3 and the respective wide range expressions of Eqs. (2) and (3) are suitable for general fracture mechanics testing. The ranges of a/W and r_1/r_2 can accommodate a range of hollow cylindrical geometries for various fracture tests, including fracture toughness and fatigue crack growth tests.

The accuracy of the expressions, judged by how well they fit numerical and limit solutions, is believed to be the following:

for $S/W = 4$, $r_1/r_2 = 0.6 - 1.0$, $a/W = 0.2 - 1.0$; accurate within 1.0%

for $S/W = 3$, $r_1/r_2 = 0.4 - 1.0$, $a/W = 0.4 - 0.6$; accurate within 1.0%

$a/W = 0.2 - 1.0$; accurate within 1.5%

The cooperative test program provided a direct physical check on the results from analysis. No systematic differences were noted between the fracture toughness measurements from the proposed new specimens and K expressions and the measurements from the existing standard procedures.

The results of this report were used to propose a new annex for ASTM Method E-399 (ref 4). This new annex, "A7. Special Requirements for Testing Arc-Shaped Bend Specimens," is given as an Appendix to this report.

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APPENDIX

The following is a proposed annex to ASTM E-399-83, Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials for testing of arc-bend specimens.

A7. SPECIAL REQUIREMENTS FOR TESTING ARC-SHAPED BEND SPECIMENS

A7.1 <u>Specimen</u>

A7.1.1 The arc-shaped bend specimen is a single-edge notched and fatigue cracked ring segment loaded in bending. The general proportions of the standard specimen are shown in Figure A7.1. The value of the radius ratio r_1/r_2 is limited to the range of 0.6 to 1.0 when the specimen is loaded with a span-to-width ratio S/W of 4, and from 0.4 to 1.0 when the specimen is loaded with a span-to-width ratio S/W of 3. For cylinders with radius ratios of less than these limits, the arc-shaped tension-loaded specimen or the disk-shaped specimen should be used.

A7.1.2 The arc-shaped bend sample is intended to measure the fracture toughness in a crack plane normal to the circumferential direction and crack propagation in the radial direction. This is the C-R direction as defined in 5.1.3. For other orientations, a bend or a compact specimen should be used.

A7.1.3 Alternative specimens may have $2 \leq W/B \leq 4$, but with no change in other proportions. The use of the alternative specimen proportions for the arc-shaped bend specimen can be advantageous because in many cases it is possible to test ring specimens with no machining of the inner or outer radii, that is, with no change in W.

A7.2 Specimen Preparation

A7.2.1 For generally applicable specifications concerning specimen size and preparation, see Section 7.

A7.3 Apparatus

A7.3.1 Bend Test Fixture - The general principles of the bend test fixture are illustrated in Figure A7.2. This fixture is designed to minimize frictional effects by allowing the support rollers to rotate and move apart slightly as the specimen is loaded, therefore permitting rolling contact. Thus, the support rollers are allowed limited motion in a plane parallel to the flat surface on the notched side of the specimen, but are initially positively positioned against the stops that set the span length and are held in place by two low tension springs (such as rubber bands).

A7.3.2 Displacement Gage - For generally applicable details concerning the displacement gage, see 6.3.

A7.4 Procedure

A7.4.1 Measurement - Before testing an arc-shaped bend sample, measure (r_2-r_1) to the nearest 0.001 inch (0.025 mm) or to 0.1 percent, whichever is greater at mid-thickness positions on both sides of and immediately adjacent to the crack starter notch mouth. Record the average of these two readings as W. Also measure (r_2-r_1) at four positions, two as close as possible to the intersection of the inside radius and the machined flat surfaces, and two at approximately one-half the circumferential distance between the machined flat surfaces and the crack plane. If any of these four measurements differ from W by more than 10 percent, the specimen should be discarded or reworked. Next, measure to the nearest 0.001 inch (0.025 mm) or to the nearest 0.1 percent, whichever is greater, the distance in the crack plane between the chord that connects the two machined flat surfaces and the outer radius of the specimen. This measurement should be on both sides of the specimen referencing each flat machined surface. Subtract W from the average of these two measurements and record the result as Z. Measure within 5 percent the outer radius, r_2; if this is not possible, determine the average value of r_2 as follows (see Note A7.1): Measure within 5 percent the length, L, of the chord of the outer surface, which chord passes through the flat machined surfaces (see Figure A7.1). Using this measurement, calculate

$$r_2 = \frac{L^2}{8(W+Z)} + \frac{(W+Z)}{2}$$

Then $r_1/r_2 = 1 - W/r_2$.

<u>NOTE A7.1</u> - A 10 percent variation of the ratio r_1/r_2 will affect the value of the stress intensity factor by 1.2 percent or less providing that the relative crack length a/W is not less than 0.3. However, the stress analysis is based on the assumption that the specimens are to be cut from stock of a uniform, axisymmetric cross section. If inspection shows that the stock deviates from axisymmetry by more than 10 percent, it should be reworked to within this tolerance.

A7.4.1.1 After the fracture, measure the crack length in accordance with 8.2.2. An additional special procedure is necessary for the arc-shaped specimen due to its curvature. Thus, a length measurement, m, made from a reference point adjacent to the crack mouth to a point on the crack front will be greater than the corresponding distance from the virtual point of intersection between the crack plane and the inside circumference of the specimen (see Figure A5.3).

The error, e, may be computed from the following expression:

$$e = r_1 - [r_1^2 - g^2/4]^{1/2}$$

where g is the distance across the crack mouth at the reference points for the measurement of the crack length. It should be noted that g may be equal to N (Figure A7.3) or larger than N if machined knife edges are used to hold the clip gage. If the relative error $e/m < 0.01$, then record m as the crack length; otherwise e should be subtracted from m and the result recorded as the crack length.

A7.4.2 Arc-Shaped Bend Specimen Testing - Set up the test fixture such that the distance between the support roll centers, S, is equal to four times W if the ratio r_1/r_2 is greater than 0.6, or the distance S is equal to three times W if the ratio r_1/r_2 is greater than 0.4 and less than 0.6. Further adjust the fixture such that the line of action of the applied load shall pass midway between the support roll centers within 0.1 percent of the distance between these centers. Measure the span to within 0.5 percent of nominal length. Locate the specimen with the crack tip midway between the rolls to within 1 percent of the span and square to the roll axes within 2 percent. Seat the displacement gage on the knife edges to maintain registry between knife edges and gage grooves. In the case of attachable knife edges, seat the gage before the knife edge positioning screws are tightened.

A7.4.2.1 Load the specimen at a rate such that the rate of increase of the stress intensity factor is within the range 30 to 150 Ksi in.$^{1/2}$/min (0.55 to 2.75 MPa m$^{1/2}$/s). The corresponding loading rates for a standard (W/B = 2) 1-inch (25.4 mm) thick specimen are between 4500 and 32000 lbf/min (0.3 to 2.4 kN/s) for the S = 3W specimen, and between 3200 and 23000 lbf/min (0.2 to 1.7 kN/s) for the S = 4W specimen.

A7.4.3 For details concerning the recording of the test record, see 8.4.

A7.5 Calculations

A7.5.1 Interpretation of Test Record - For general requirements and procedures for interpretations of the test record, see 9.1.

A7.5.2 Validity Requirements - For a description of the validity requirements in terms of limitations on P_{max}/P_Q and the specimen size requirements, see 9.1.2 through 9.1.3.

A7.5.3 Calculation of K_Q - For the arc-shaped bend specimen, calculate K_Q in units of Ksi in.$^{1/2}$ (MPa m$^{1/2}$) as follows (Note A7.2):

For specimens with S = 4W:

$$K_Q = [P_Q S/BW^{3/2}][1 + (1-r_1/r_2)(0.29-0.66(a/W) + 0.37(a/W)^2)]f(a/W)$$

where

$$f(a/W) = \frac{0.677 + 1.078(a/W) - 1.43(a/W)^2 + 0.669(a/W)^3}{(1-a/W)^{3/2}}$$

For specimens with S = 3W:

$$K_Q = [P_Q S/BW^{3/2}][1 + (1-r_1/r_2)(0.20-0.32(a/W)+0.12(a/W)^2)]f(a/W)$$

where

$$f(a/W) = \frac{0.644 + 1.11(a/W) - 1.49(a/W)^2 + 0.73(a/W)^3}{(1-a/W)^{3/2}}$$

and where

P_Q = load as determined in 9.1.1 klbf (kN)

B = specimen thickness as determined in 8.2.1, in. (cm)

S = span as determined in A7.4.2, in. (cm)

W = specimen depth (width), in. (cm) as determined in A7.4.1

a = crack length as determined in 8.2.2, in. (cm)

r_1 = inner radius as determined in A7.4.1, in. (cm)

r_2 = outer radius as determined in A7.4.1, in. (cm)

To facilitate calculation of K_Q, values of f(a/W) are tabulated in the following tables for specific values of a/W:

S = 4W			
a/W	f(a/W)	a/W	f(a/W)
0.450	2.26	0.500	2.64
0.455	2.30	0.505	2.68
0.460	2.33	0.510	2.72
0.465	2.37	0.515	2.77
0.470	2.40	0.520	2.81
0.475	2.44	0.525	2.86
0.480	2.48	0.530	2.91
0.485	2.52	0.535	2.95
0.490	2.56	0.540	3.00
0.495	2.60	0.545	3.06
		0.550	3.11

S = 3W			
a/W	f(a/W)	a/W	f(a/W)
0.450	2.23	0.500	2.60
0.455	2.26	0.505	2.64
0.460	2.29	0.510	2.68
0.465	2.33	0.515	2.72
0.470	2.36	0.520	2.77
0.475	2.40	0.525	2.82
0.480	2.44	0.530	2.86
0.485	2.48	0.535	2.91
0.490	2.52	0.540	2.96
0.495	2.55	0.545	3.01
		0.550	3.06

NOTE A7.2 - The expressions given in A7.5.3 are considered to be accurate within ± 1.0 percent for $0.2 \leq a/W \leq 1.0$ and $0.6 \leq r_1/r_2 \leq 1.0$ for $S = 4.0W$; within ± 1.5 percent for $0.2 \leq a/W \leq 1.0$ and $0.4 \leq r_1/r_2 \leq 1.0$ for $S = 3.0W$; and within ± 1.0 percent for $0.4 \leq a/W \leq 0.6$ and $0.4 \leq r_1/r_2 \leq 1.0$ for $S = 3.0W$ [23].

A7.5.4 Calculation of R_{sb} - For the arc-shaped bend specimen, calculate the specimen strength ratio (which is dimensionless and has the same value in any consistent system of units):

$$R_{sb} = \frac{6P_{max}W}{B(W-a)^2\sigma_{ys}}$$

where

P_{max} = maximum load that the specimen was able to withstand

B = thickness of specimen as determined in 8.2.1

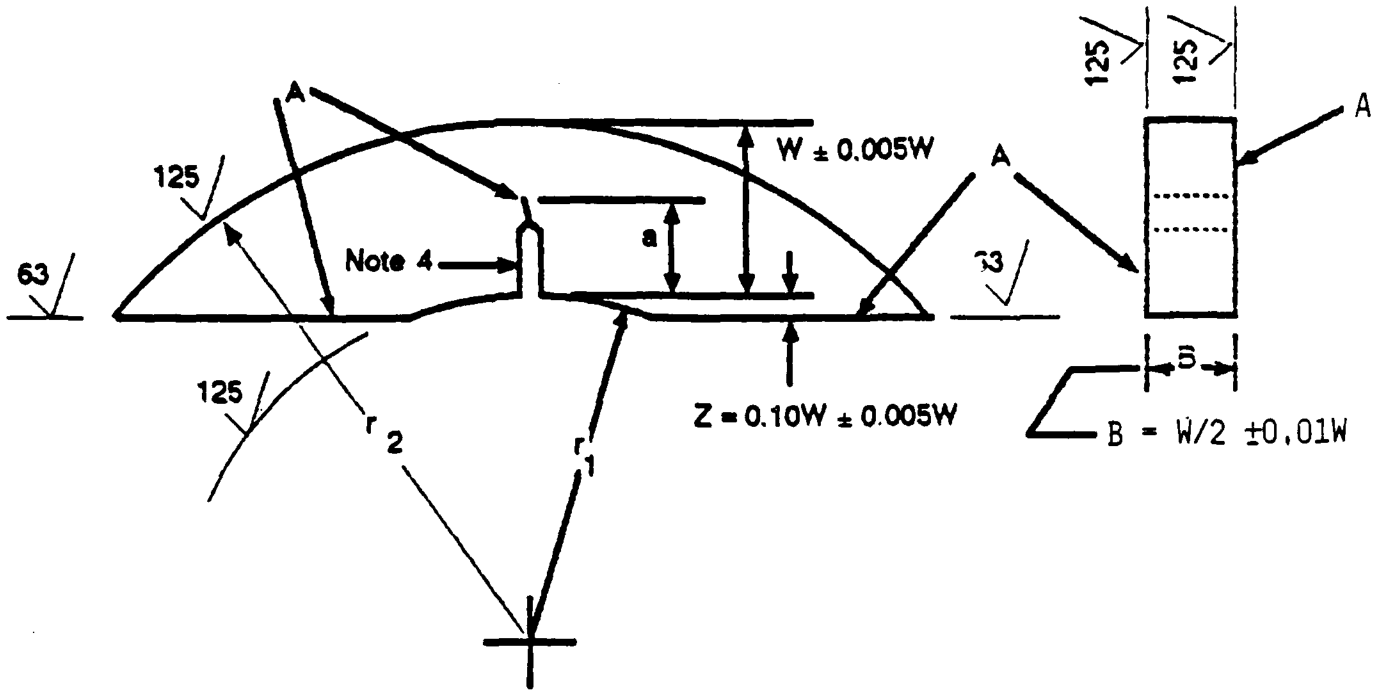
W = width (depth) of specimen as determined in A7.4.1

a = crack length as determined in 8.2.2

σ_{ys} = yield strength in tension (0.2 percent offset) (see Method E-8)

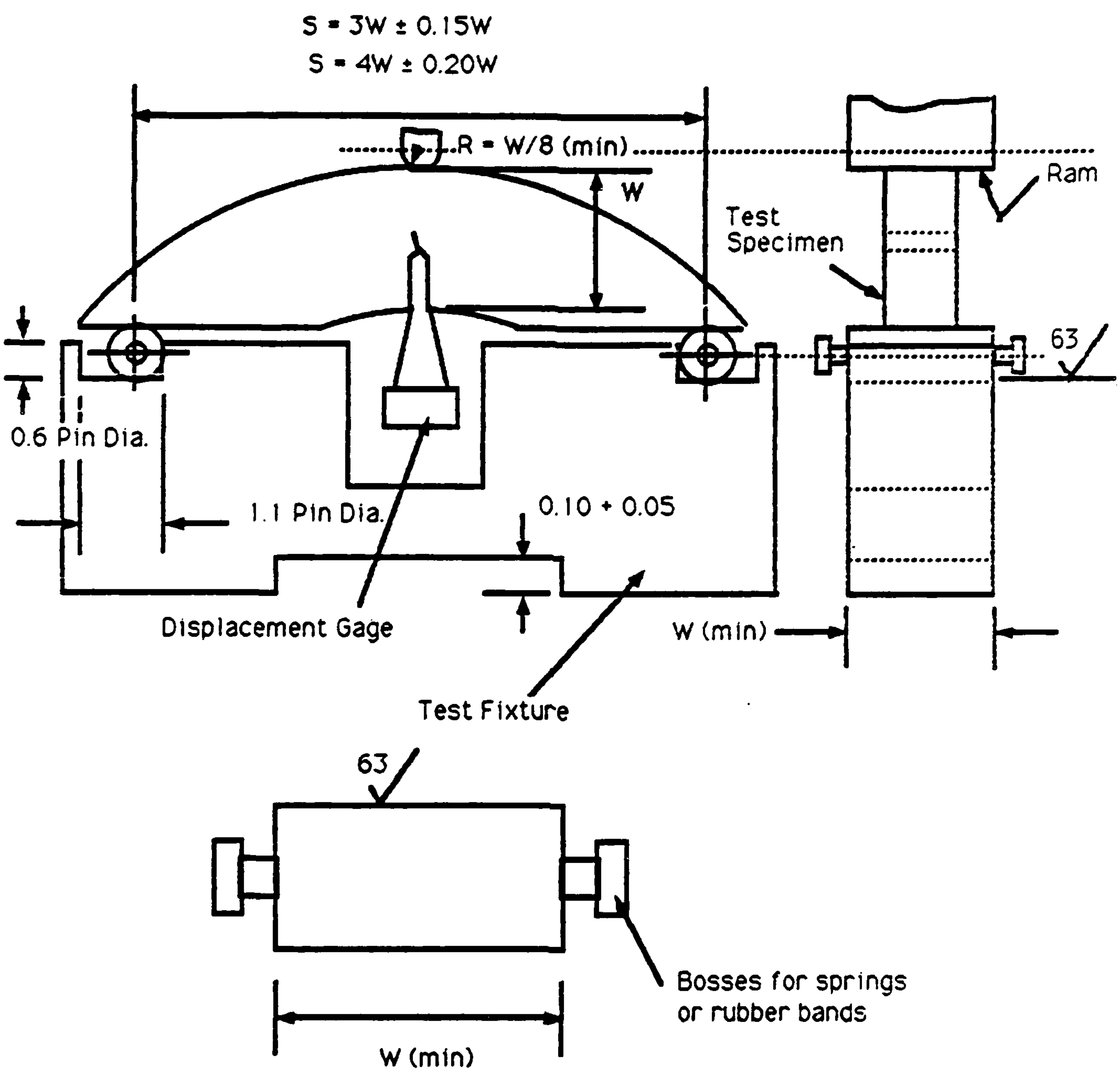
Reference [23] to be added to ASTM Method E-399:

23. Underwood, J. H., "Proposed Standard Arc-Bend Chord-Support Fracture Toughness Specimens and K Expressions," Journal of Testing and Evaluation, to be submitted.



Note 1 - A surfaces shall be perpendicular and parallel as applicable within 0.0001W TIR.
Note 2 - Crack starter notch shall be perpendicular to specimen surfaces to within ± 2 degrees.
Note 3 - Integral or attachable knife edges for clip gage attachment shall be used (see Figures 5 and 6).
Note 4 - For starter notch and fatigue crack configurations, see Figure 7.

Figure A7.1. Arc-bend specimen A (B) - standard proportions and tolerances.



Roller Pin Detail

Note 1 - Roller pins and specimen contact surface of loading ram must be parallel to each other within 0.002W.
Note 2 - 0.10 in. = 2.54 mm, 0.05 in. = 1.27 mm

Figure A7.2. Bend test fixture design.

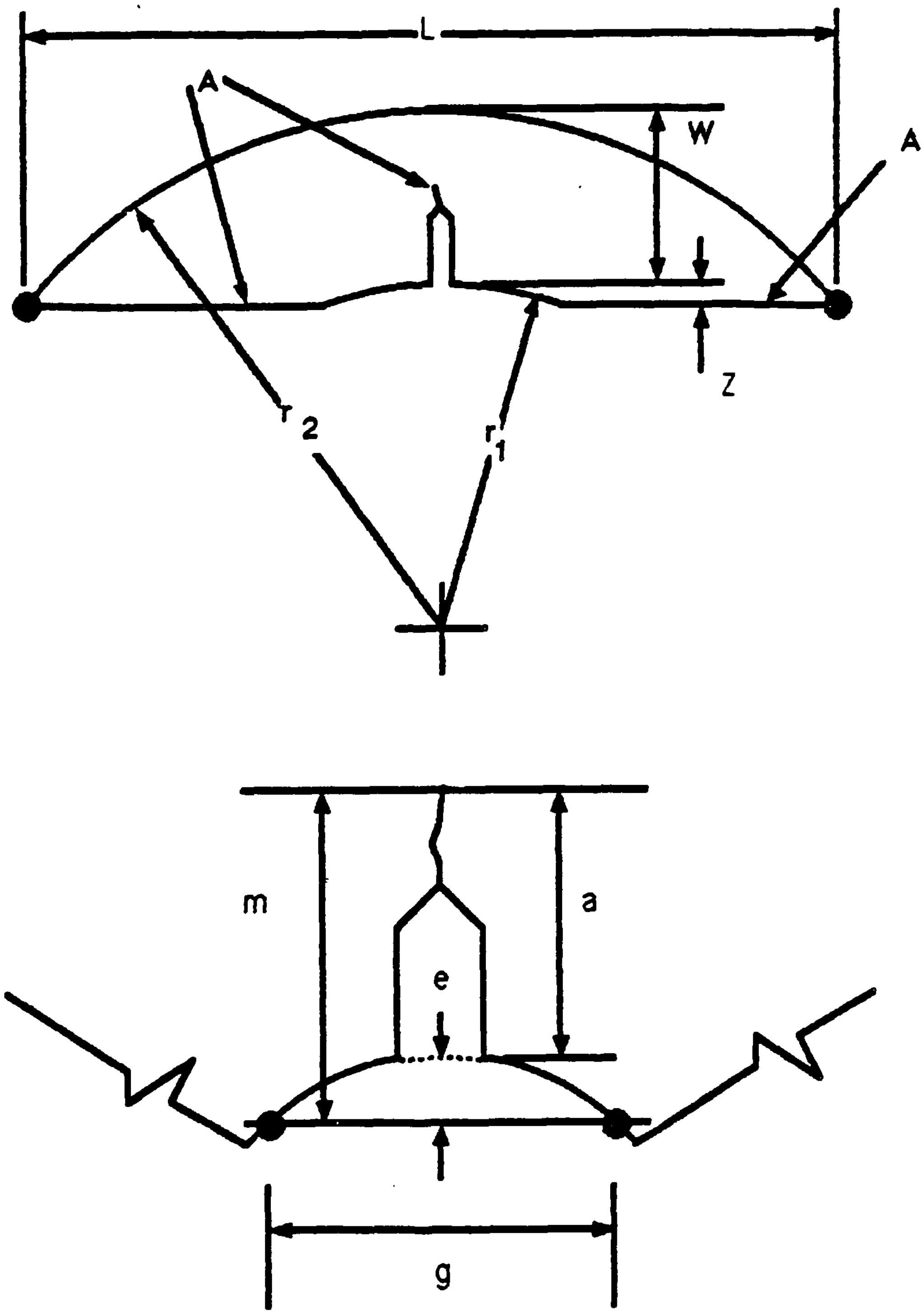


Figure A7.3. Measurement of outer radius (r_2) and crack length for arc-shaped specimens (see A7.4.1).

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