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FRACTURE TESTING WITH ARC BEND SPECIMENS

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A limited review of existing stress, stress intensity factor, and displacement analyses is compared with new work in order to select arc bend geometries appropriate for fracture testing. Results from the literature for rectangular and arc bend specimens are compared with finite element and boundary collocation results from the present work.

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20. ABSTRACT (CONT'D)

Two series of comparative tests were performed, one with arc specimens cut from a steel forging with outer-to-inner radius ratio of 2.5, the other from an aluminum cylinder with outer-to-inner radius ratio of 1.3. Fracture toughness tests, K_{Ic} and J_{Ic}, when appropriate, were performed with standard arc tension specimens and with three-point arc bend specimens both arc and chord support.

Conclusions were drawn regarding the appropriate stress intensity factor, crack mouth displacement, and load-line displacement solutions for arc bend fracture specimens. Recommendations were offered for practical ranges of specimen geometry and for reliable test procedures.

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INTRODUCTION

The arc tension specimen, essentially a section of a hollow disk with tension loading, Figure 1a, is now used routinely. It has been part of ASTM Test for Plane-Strain Fracture Toughness of Metallic Materials, E-399-83, since 1978. For some applications the same type of section loaded in bending would be more convenient. The overall objectives of this report are to review the available analytical results related to arc bend specimens, perform additional analyses and tests, and propose some standardized procedures for fracture testing with arc bend specimens. Specific objectives are: (a) to review published analytical results of stress intensity factor, K, crack mouth opening displacement, v, and load-line displacement δ, for rectangular and arc bend specimens; (b) to perform additional analytical calculations of K, v, and δ, using boundary value collocation and finite element methods; (c) to perform fracture toughness tests of example geometries of arc bend specimens for experimental verification of K, v, and δ; (d) to propose arc bend test procedures, including a range of specimen geometries and associated K, v, and δ information suitable for accurate, wide-range expressions in a standard test method.

Some prior work has been done with arc bend geometries as fracture specimens. Most prior work included three-point bending in which the outer load points are a free rolling support on the inner radius, termed arc support here, Figure 1b. This type of testing has the advantage of loading directly on the existing inner and outer radius surfaces, if they are smooth and regular enough. Other prior work investigated arc bend specimens with support on a flat chordal surface, termed chord support here, Figure 1c. This specimens although requiring a machined surface, is similar to the rectangular bend specimen for which standard test procedures are already available. Jones (ref 1) investigated arc support geometries with outer-to-inner radius ratio, r_2/r_1, between 1.05 and 1.25 and various support angles, θ. Tracy (ref 2) analyzed arc support specimens with r_2/r_1 between 1.25 and 2.00 with one value of θ, 45 degrees. Ritter and Rea (ref 3) considered a chord support geometry with $r_2/r_1 = 1.31$ with various support spans, S. This prior work gave useful guidance for analysis and testing of arc bend specimens, but it did not provide the repeatability and accuracy of analytical and experimental results over a wide range of test conditions which are needed for a standard test method.

The recent boundary collocation results of Gross and Srawley (ref 4) gave additional guidance for arc bend testing as well as accurate analytical results for a wide range of arc support geometries. They provided tabular results of stress intensity factor, K, and crack mouth opening displacement, v, for r_2/r_1 between 1.10 and 2.50 and θ between 11.5 and 90 degrees. This includes much of the geometry range of interest in arc bend fracture testing.

The present work is described in two parts, analysis and testing. First, analysis results from the literature and the present investigation are

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[1]A. T. Jones, "Fracture Toughness Testing with Sections of Cylinders," Engineering Fracture Mechanics, Vol. 6, 1974, pp. 653-662.

[2]P. G. Tracy, "Analysis of a Radial Crack in a Circular Ring Segment," Engineering Fracture Mechanics, Vol. 7, 1975, pp. 253-260.

[3]J. C. Ritter and T. W. Rea, "A Curved Beam Fracture Toughness Specimen," International Journal of Pressure Vessels and Piping, Vol. 5, 1977, pp. 275-286.

[4]B. Gross and J. E. Srawley, "Stress Intensity and Displacement Coefficients for Radially Cracked Ring Segments Subject to Three-Point Bending," NASA Technical Memo 83059, March 1983.

specimen, although requiring a machined surface, is more similar to the compared on a common basis. By considering the basic geometry of arc specimens along with certain deep-crack limit solutions, K and v results from rectangular, arc bend-arc support and arc bend-chord support geometries can all be compared using the same, nearly constant-valued parameter. Literature results are compared with boundary collocation and finite element results from the present work for various geometries. The second part of this report describes two series of tests in which arc bend specimens were made from two hollow cylinders, one a high strength steel cylinder with outer-to-inner radius ratio, r_2/r_1 of about 2.5; the other a high strength aluminum alloy cylinder with r_2/r_1 about 1.3. K_{Ic} and some J_{Ic} test results from arc bend specimens with both arc and chord support were compared with results from arc tension tests of the same material.

ANALYSIS

Common Comparison

The prior K, v, and δ results for bend specimens can be compared with the current results using a parameter which takes account of most of the important mechanics of this type of specimen. By using such a common parameter, the prior and new results can be compared directly for the purpose of mutual verification. In addition, since the parameter has a nearly constant value for all rectangular and arc geometries, the results in this form lead directly to simple and accurate interpolation for whatever specimen geometries are of interest.

The basis for a common comparison of K results from rectangular and arc bend geometries is the combination of two deep-crack K limit solutions (ref 5):

$$K_{a/W \to 1} = \frac{3.975M}{B(W-a)^{3/2}} + \frac{1.4635P^*}{B(W-a)^{1/2}} \qquad (1)$$

where a is crack depth, B is specimen thickness, W is specimen depth, M is bending moment, and P* is the horizontal component of force exerted at the specimen support, see Figure 2. Equation (1) is an expression for the deep-crack limit K (as $a/W \to 1$) for an arc bend-arc support specimen. The first term in Eq. (1) is the K due to a pure bending moment, M, and the second term is the K due to the pure tension loading of force, P*, applied in line with the center of the uncracked ligament. Expressions for M, P*, and S can be obtained from plane geometry as

$$M = \frac{P}{2} \tan \theta \left(r_1 + \frac{W}{2} + \frac{a}{2}\right) \qquad (2)$$

$$P^* = \frac{P}{2} \tan \theta \qquad (3)$$

$$S = 2r_1 \sin \theta \qquad (4)$$

where P is the center load applied to the specimen and M is the moment about the center of the uncracked ligament.

Combining Eqs. (1) through (4) gives

[5] H. Tada, P. C. Paris, and G. P. Irwin, The Stress Analysis of Crack Handbook, Del Research Corp., Hellertown, PA, 1973.

$$\frac{KBW^{1/2}(1-a/W)^{3/2}}{P\left[\frac{S}{W\cos\theta} + \tan\theta(1+a/W)\right]\left[1 + \left[\frac{0.7366(1-a/W)}{\frac{S}{W\sin\theta} + (1+a/W)}\right]\right]} = \underset{a/W \to 1}{Y = 0.995} \qquad (5)$$

a dimensionless K parameter for use in comparing K results from rectangular and arc bend geometries. Important features of Eq. (5) are that it approaches the exact deep-crack limit solution and it includes both bending and normal force loading. For rectangular bend specimens and chord support-arc bend specimens, which have no normal force loading and $\theta = 0$, Eq. (5) reduces to:

$$\frac{KBW^{1/2}(1-a/W)^{3/2}}{PS/W} = \underset{a/W \to 1}{Y = 0.995} \qquad (6)$$

A similar common comparison of v results from various bend geometries can be made, based on the deep-crack v limit solution (ref 5):

$$\underset{a/W \to 1}{v} = \frac{15.8\ MW}{BE(W-a)^2} \qquad (7)$$

Using a similar approach to that described by Eqs. (1) through (6) and related discussion, gives

$$\frac{EBv\left[\frac{(1-a/W)^2}{(1+a/W)^2}\right]}{P\left[\frac{S}{W\cos\theta} + \tan\theta(1+a/W)\right]\left[1 + \frac{0.7366(1-a/W)}{\frac{S}{W\sin\theta} + (1+a/W)}\right]} = \underset{a/W \to 1}{Y_v = 0.9875} \qquad (8)$$

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[5]H. Tada, P. C. Paris, and G. P. Irwin, The Stress Analysis of Crack Handbook, Del Research Corp., Hellertown, PA, 1973.

a dimensionless K parameter for use in comparing v results from rectangular and arc bend geometries.

Comparison of load-line displacement, δ, for different types of bend specimens is expected to be less straightforward, because δ is more affected by uncracked specimen geometry than are K and v. The approach taken here is to use a δ parameter which approaches the proper deep-crack δ limit solution for load-line displacements due only to the presence of the crack, and further due only to bending. Normal stress effects and uncracked specimen effects are ignored in this δ parameter. The deep-crack δ limit solution used is (ref 5):

$$\delta_{a/W\to 1} = \frac{3.95\ MS}{BE(W-a)^2} \qquad (9)$$

so that the dimensionless δ parameter for use in comparing rectangular and arc bend geometries becomes:

$$\frac{EBW\delta(1-a/W)^2}{PS[\frac{S}{W}\cos\theta + \tan\theta(1+a/W)]} = Y_\delta = 0.9875_{a/W\to 1} \qquad (10)$$

Stress Analysis

Several arc bend geometries were modeled by boundary collocation and finite element methods. The K, v, and δ obtained were compared with results from the literature using the basis of comparison described previously. The boundary collocation method was similar to that developed by Hussain et al (ref 6) and used some of the modeling techniques of Gross and Srawley (refs

[5]H. Tada, P. C. Paris, and G. P. Irwin, The Stress Analysis of Crack Handbook, Del Research Corp., Hellertown, PA, 1973.

[6]M. A. Hussain, W. E. Lorenson, D. P. Kendall, and S. L. Pu, "A Modified Collocation Method for C-Shaped Specimens," Benet Weapons Laboratory Technical Report No. R-WV-T-X-6-73, Watervliet, NY, 1973.

4,7). The finite element method was based on that used by Kapp and Pu (ref 8) with important use of enriched finite elements (ref 9). The type of element array used for K determination of chord support geometries is shown in Figure 3. The necessary configurational changes were made to model the arc support and rectangular geometries. Changes in the element density were made to properly model displacements, as will be described in the following discussion of stress analyses results. Nine categories of results were obtained including K, v, and δ for rectangular, arc support and chord support geometries. Literature results extensive enough for comparison were available in five of these categories.

The comparison of collocation and finite element K results with appropriate data from the literature is shown in Figures 4a, b, and c using the parameter Y defined by Eq. (5). The solid line in each plot is for the standard rectangular bend specimen (ref 5). The dashed lines in Figure 4 are "eyeball" best fit lines considering all the data presented. In Figure 4a the Gross and Srawley (ref 4) arc support collocation K results are seen to be in

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[4]B. Gross and J. E. Srawley, "Stress Intensity and Displacement Coefficients for Radially Cracked Ring Segments Subject to Three-Point Bending," NASA Technical Memo 83059, March 1983.

[5]H. Tada, P. C. Paris, and G. P. Irwin, The Stress Analysis of Crack Handbook, Del Research Corp., Hellertown, PA, 1973.

[7]B. Gross and J. E. Srawley, "Analysis of Radially Cracked Ring Segments Subject to Forces and Couples," Developments in Fracture Mechanics Test Methods Standardization, STP 633, W. F. Brown, Jr. and J. G. Kaufman, Eds., American Society for Testing and Materials, 1977, pp. 39-56.

[8]J. A. Kapp and S. L. Pu, "Fatigue Design of Thick-Walled Cylinders Considering the OD as a Failure Initiation Site," Pressure Vessel Design, G. E. O. Widera, Ed., American Society of Mechanical Engineers, 1982, pp. 115-128.

[9]I. N. Gifford, Jr. and P. D. Hilton, "Stress Intensity Factors by Enriched Finite Elements," Engineering Fracture Mechanics, Vol. 10, 1978, pp. 485-496.

close agreement with the present results as well as with the rectangular bend results; that is, the arc support with $r_2/r_1 = 1.1$ compared well with the very similar rectangular bend geometry. In Figure 4b arc support finite element K results are close to the rectangular bend, particularly where expected, for $r_2/r_1 = 1.1$. In Figure 4c chord support collocation and finite element K results compare well with each other, as well as with the rectangular bend results. Note the direct comparison of rectangular geometries and the good agreement between finite element results with $r_2/r_1 = 1.0$ and the rectangular bend geometry.

The general trend of all the results in Figure 4 is that the K parameters for seven significantly different bend geometries agree within about four percent, and the K parameter tends to increase slightly with increasing r_2/r_1 or S/W. These results indicate that the Eqs. (1) through (4) input to the K parameter properly accounts for the important effects of arc-shaped geometry, method of support, and deep crack limit conditions of the arc bend specimen.

The comparison of v results is shown in Figure 5 using the parameter Y defined by Eq. (8). Again, the solid line in both plots is for the standard rectangular bend specimen (ref 5). The finite element v results here and the δ results in Figure 6 were obtained using an element array of the same type as in Figure 3 but denser. A total of 29 elements were used rather than the 13 shown in Figure 3. The denser array, particularly along the load-line, produces a more faithful simulation of the actual displacements in the

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[5]H. Tada, P. C. Paris, and G. P. Irwin, The Stress Analysis of Crack Handbook, Del Research Corp., Hellertown, PA, 1973.

specimen. In Figure 5a the finite element and collocation results are in reasonable agreement with each other and with the rectangular bend results. In Figure 5b the finite element results for the rectangular geometry, that is for $r_2/r_1 = 1.0$, agree well with the rectangular bend results from the literature. The general trend for all the v results is that separate calculations of Y_v for similar geometries agree within about two percent and Y_v tends to increase with increasing r_2/r_1 or S/W. The increases in Y_v with these variables are larger than those seen with Y, see Figure 4.

The comparison of δ results is shown in Figure 6 using the parameter Y_δ defined by Eq. (10). The solid line in each plot is obtained from the total load-line displacement, δ, for the standard rectangular bend specimen, determined in the following manner.

$$\delta = (\delta_{bend} + \delta_{shear})_{no\ crack} + \delta_{crack} \tag{11}$$

$$\delta_{bend} = \frac{MS^2}{BW^3E} \tag{12}$$

$$\delta_{shear} = \frac{3.12M}{BWE} \tag{13}$$

$$\delta_{crack} = \frac{6MS}{BW^2E} f_\delta \tag{14}$$

$$f_\delta = fn(a/W)$$

where δ_{bend} and δ_{shear} are the components of δ due to the pure bending and shear of the uncracked specimen, and δ_{crack} is the component due to presence of the crack. The expressions for δ_{bend} and δ_{shear} are from mechanics (ref 10)

[10] R. J. Roark and W. C. Young, Formulas for Stress and Strain, McGraw-Hill, 1975.

and (ref 11) and δ_{crack} is from Tada et al (ref 5).

A comparison of the results from the load-line displacement expression for a rectangular bend specimen, Eq. (11), can be made with data from ASTM Standard Test Method for J_{Ic}, A Measure of Fracture Toughness, E-813-81. A table of load-line displacements for the rectangular bend specimen is included in Method E-813 for use in checking the accuracy of some of the experimental measurements of the method. Three of these data are shown in Figure 6b in the form of Y_δ. The agreement with Eq. (11) is within about seven percent, but we believe the agreement should be closer. We suggest that the component of displacement due to shear of the uncracked specimen, as described by Eq. (13), has been omitted from the data in E-813. When this component is added to the three data points from E-813, the agreement with Eq. (11) is within 0.5 percent.

As indicated by Eqs. (11) through (14), there are three major contributions to δ, so separate calculations of δ might not be expected to agree as well with each other, as do K and v calculations. This is apparent in Figure 6. Separate calculations of δ for the same geometry agree within about one to six percent. The tendency toward increasing δ with increasing r_2/r_1 or S/W is more pronounced than with K and v.

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[5]H. Tada, P. C. Paris, and G. P. Irwin, The Stress Analysis of Crack Handbook, Del Research Corp., Hellertown, PA. 1973.

[11]F. M. Haggag and J. H. Underwood, "Compliance of a Three-Point Bend Specimen at Load Line," International Journal of Fracture, Vol. 126, 1984, pp. R36-R65.

EXPERIMENTS

Fracture toughness tests were performed both as a direct physical check on the analyses and as a means to identify unanticipated problems with arc bend testing. Table I outlines the test conditions. The arc tension tests of both aluminum and steel were the zero offset geometry of ASTM Test E-399, also shown sketched in Figure 1a. For this geometry the displacement measured at the crack mouth is also load-line displacement, $v = \delta$. Steel arc bend-chord support specimens were tested so that v and δ could be measured simultaneously. Aluminum arc bend specimens were tested by measuring v from four specimens for each type of support and measuring δ from three specimens each.

<u>Steel Tests</u>

Fourteen specimens were made with the C-R orientation from a steel hollow cylinder forging and tested so that both K_{Ic} and J_{Ic} could be determined. Table II shows the nominal specimen dimensions and the results. Actual specimen dimensions varied by up to about five percent from nominal and were taken into account in the K_{Ic} and J_{Ic} calculations. The results show that, as suspected before testing, the fracture toughness of the steel was very close to the value which separates a valid from an invalid K_{Ic} for the specimen size used. Only three of the seven arc tension specimens yielded a valid K_{Ic}. The arc bend results are listed as K_Q, because the arc bend is not a standard geometry. One of the arc bend results, #4, passed two critical ASTM Method E-399 requirements, that $K_{max}/K_Q \leq 1.1$ and $(K_Q/\sigma_y)^2/B \leq 0.4$. Putting aside the validity concern, it is clear that the arc tension and arc bend fracture toughness measurements were in close agreement.

A comparison of J_{Ic} measurements from arc tension and arc bend specimens is shown in Figure 7. Four of the seven combined K_{Ic} and J_{Ic} tests for each of the two groups were interrupted near maximum load, and the specimens were heat tinted. The resulting J versus heat tint Δa plots are shown. It must be emphasized that the calculation of J was approximate as best, since the ASTM Method E-813 procedures for the compact and rectangular bend specimens were used for the arc tension and arc bend specimens, respectively. So these J_{Ic} results should be considered only as some indication of how appropriate or inappropriate it is to use these existing procedures for the new arc specimen geometries. Comparing the results in Figure 7 with the K_{Ic} results of Table II, the compact procedure applied to the arc tension specimen gives a low measure of J_{Ic} and K_{Ic} and the rectangular bend procedure applied to the arc bend specimen gives a high measure of J_{Ic} and K_{Ic}. A possibly oversimplified analysis of these results is that the arc tension specimen is less compliant than the compact specimen and thus yields a low measure of J_{Ic} and K_{Ic}, and the arc bend specimen is more compliant that the rectangular bend specimen, and thus yields a high measure of J_{Ic} and K_{Ic}. Detailed analysis of J_{Ic} tests with arc tension specimens is described by Kapp and Bilinsky (ref 12), work related to this report.

Aluminum Tests

Twenty specimens were made with C-R orientation from an aluminum hollow cylinder extrusion and tested so that K_{Ic} and accurate crack mouth and load-

[12] J. A. Kapp and W. J. Billinsky, "J_{Ic} Testing With Arc Tension Specimens," submitted to The Seventeenth National Symposium on Fracture Mechanics.

line displacements could be determined. Roller bearings were used for the arc support tests with the intent that free rolling support on the inner radius was maintained during the test with no movement of the center of the rollers. Table III lists the results, which indicate that the fracture toughness measured by both the arc and chord support geometries was close to that from the arc tension tests. The three mean values differed by less than four percent. Also, unlike the steel tests, all the K_{Ic} and K_Q results were well within the maximum load and specimen size requirements of ASTM Method E-399.

The aluminum tests were planned to provide a comparison of measured and calculated displacements for arc bend specimens. The comparison is in Table IV. The measured parameters of v and δ were from the one specimen of each of the four groups which had S/W and a/W closest to the nominal dimensions; the calculations were based on values taken from Figures 5 and 6 for the nominal dimensions. The generally good agreement between measured and calculated displacements is an indication of the precision and accuracy of the analytical and experimental results in the work here and the literature cited. The apparent trend toward lower measured than calculated displacements for arc support could be explained by movement of the point of contact between roller and specimen so as to decrease θ and S/W and thus decrease the specimen compliance.

CONCLUSIONS

The arc support and chord support-arc bend specimens are suitable for fracture toughness testing, each in its own range of geometry. The arc support specimen is best suited for a constant value of relative span, S/W =

4, and for r_2/r_1 between 1.0 and 1.4, which corresponds to θ between 0 and 53 degrees. The chord support specimen is best suited to r_2/r_1 between 1.1 and 2.0, with the relative offset of the chordal surface at a constant value, $Z/W = 0.1$. This will allow a constant relative span, $S/W = 4$, for r_2/r_1 between 1.1 and 1.6, and a S/W gradually decreasing to 3.35 for r_2/r_1 between 1.6 and 2.0. The largest r_2/r_1 geometry of each of these specimen geometry ranges is shown in Figure 8.

The main reason for the upper limit on r_2/r_1 for each of the specimen types is the following. For arc support specimens with θ much above 50 degrees, the contact point between specimen and roller may move enough during the test to significantly change the K, v, and δ of the specimen. For chord support specimens with S/W much below 3.35, the amount of shear relative to bending is significant enough that some materials may not fracture in the pure opening mode which is intended in K_{Ic} and J_{Ic} tests.

We believe that K, v, and δ expressions can be determined from the results here with sufficient accuracy for K_{Ic} and J_{Ic} tests. The dashed lines in Figures 4, 5, and 6 are believed to be accurate within about one percent, two percent, and six percent, respectively, for K, v, and δ over the range of a/W from 0.3 to 0.7. For the range of specimen geometries described above and for a/W between 0.45 and 0.55, the K, v, and δ results here are believed to be accurate within one-half percent, one percent, and three percent, respectively.

Regarding J_{Ic} tests with arc bend geometries, the chord support specimen is most suitable, with $S/W = 4.0$ and $Z/W = 0.1$. As r_2/r_1 approaches 1.0, the testing and analysis of chord support J_{Ic} specimens will become identical to that of the rectangular bend specimen in ASTM Method E-813.

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12. J. A. Kapp and W. J. Bilinsky, "J_{Ic} Testing With Arc Tension Specimens," submitted to The Seventeenth National Symposium on Fracture Mechanics.

TABLE I. FRACTURE TOUGHNESS TEST CONDITIONS

Material			Geometry			
	Yield Strength MPa	Nominal Fracture Toughness $MPa \cdot m^{1/2}$	r_2/r_1	Number of specimens: Type of Displacement Measure		
				arc tension	arc bend; arc support	arc bend; chord support
A732 steel	1180	137	2.50	7:v, δ	-	7:v, δ
7075-T6 aluminum	540	28	1.29	5:v, δ	4:v 3:δ	4:v 3:δ

TABLE II. STEEL FRACTURE TOUGHNESS RESULTS: NOMINAL DIMENSIONS; r_1 = 47.4 mm, B = 35.6 mm, W = 71.1 mm

Arc Tension a/W = 0.51, X/W = 0					Arc Bend; Chord Support a/W = 0.51, S/W = 2.92, Z/W = 0.1			
Specimen Number	$\frac{2.5(K_Q/\sigma_y)^2}{B}$	K_{max} MPa·m$^{1/2}$	K_{Ic} MPa·m$^{1/2}$	K_Q MPa·m$^{1/2}$	Specimen Number	$\frac{2.5(K_Q/\sigma_y)^2}{B}$	K_{max} MPa·m$^{1/2}$	K_Q MPa·m$^{1/2}$
1	0.99	150.4	139.3	-	1	0.93	154.6	135.6
2	0.99	153.4	139.4	-	2	0.84	-	128.9
3	1.01	155.8	-	141.6	3	0.96	-	137.7
4	1.07	161.1	-	145.1	4	1.00	155.1	141.0
5	0.91	145.6	133.6	-	5	0.97	-	138.3
6	1.06	157.2	-	144.2	6	0.96	159.8	137.8
7	1.07	162.8	-	145.3	7	1.01	158.4	141.4
	mean:	155.2	137.4			mean:	157.0	137.3
	standard deviation:	6.0	3.3			standard deviation:	2.5	4.2

TABLE III. ALUMINUM FRACTURE TOUGHNESS RESULTS: NOMINAL DIMENSIONS; r_1 = 87.6 mm, B = 12.7 mm, W = 25.4 mm

Arc Tension X/W = 0			Arc Bend; Arc Support S/W = 4			Arc Bend; Chord Support S/W = 4; Z/W = 0.1		
Specimen Number	K_{max} $MPa \cdot m^{1/2}$	K_{Ic} $MPa \cdot m^{1/2}$	Specimen Number	K_{max} $MPa \cdot m^{1/2}$	K_Q $MPa \cdot m^{1/2}$	Specimen Number	K_{max} $MPa \cdot m^{1/2}$	K_Q $MPa \cdot m^{1/2}$
2	31.3	28.6	1	27.6	27.4	1	28.7	
3	29.0	28.0	2	28.2	28.1	2	27.4	26.6
4	29.0	29.0	3	28.7	27.9	3	28.5	
5	28.4	28.2	4	29.2	-	4	27.2	27.2
6	29.0	27.6	5	27.6	-	5	29.4	
			6	31.4	-	6	28.1	28.2
			7	26.2	25.7	7	27.8	26.7
mean:	29.3	28.3	mean:	28.4	27.3	mean:	28.2	27.2
standard deviation:	1.1	0.5	standard deviation:	1.6	1.1	standard deviation:	0.8	0.7

TABLE IV. COMPARISON OF MEASURED AND CALCULATED DISPLACEMENT, v and δ, FOR ALUMINUM ARC BEND SPECIMENS; $r_2/r_1 = 1.29$, $S/W = 4$, $a/W = 0.53$, $E = 68950$ MPa

	EBv/P		EBδ/P	
	Measured	Calculated	Measured	Calculated
chord support	43	43.2	70	66.0
arc support	55	66.4	86	93.4

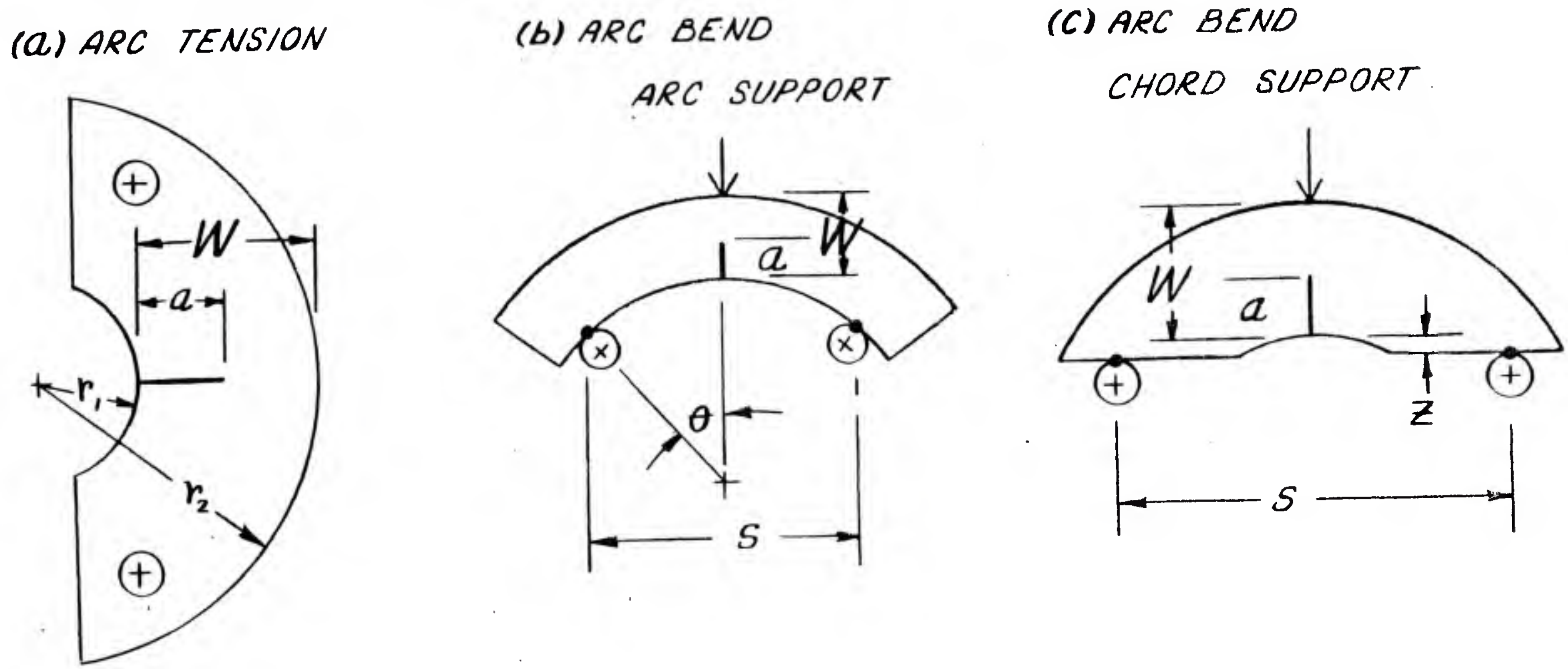


Figure 1. Arc shaped fracture specimen geometries.

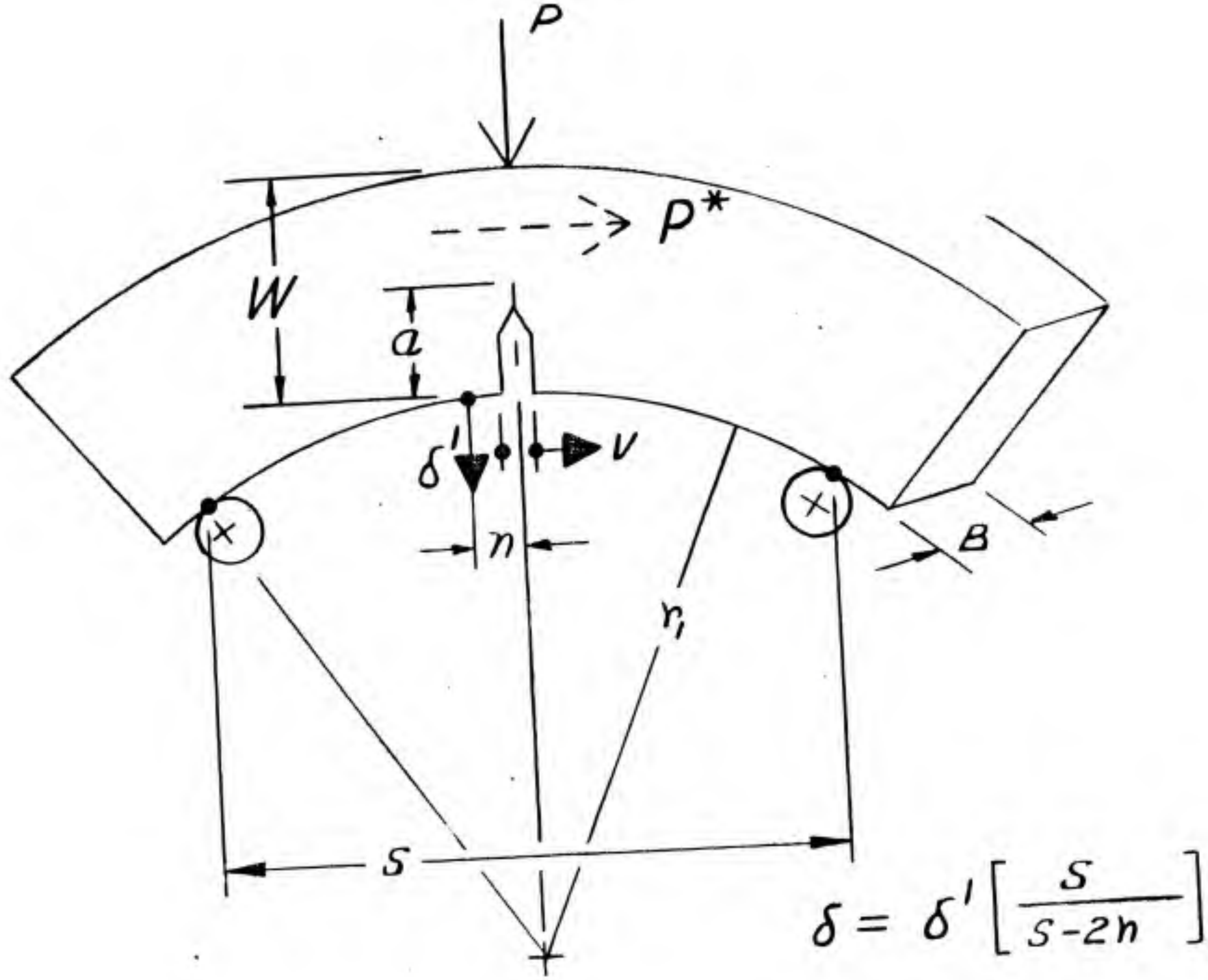


Figure 2. Arc bend-arc support specimen and nomenclature.

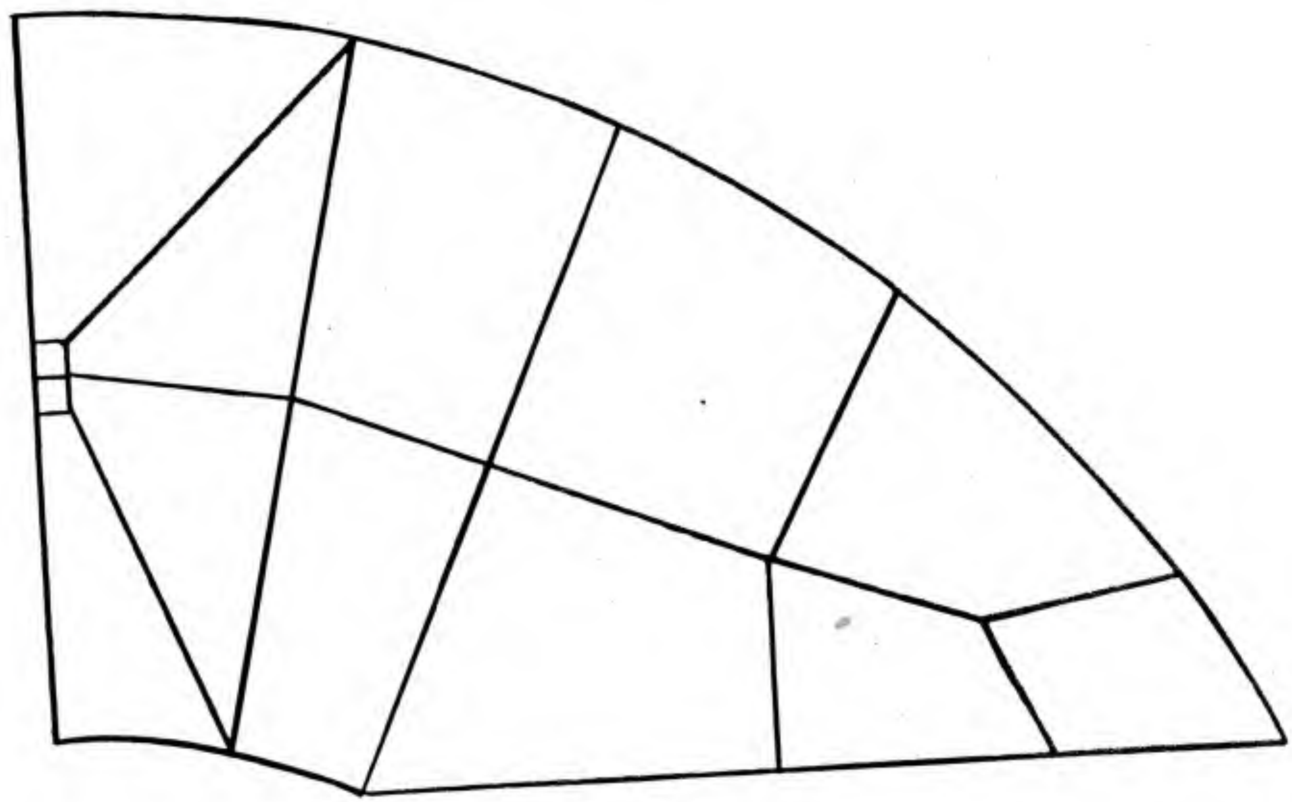


Figure 3. Finite element arrangement for arc bend-chord support specimen; $a/W = 0.5$, $r_2/r_1 = 2.0$, $S/W = 3.347$, $Z/W = 0.1$; crack tip element size = 0.05W.

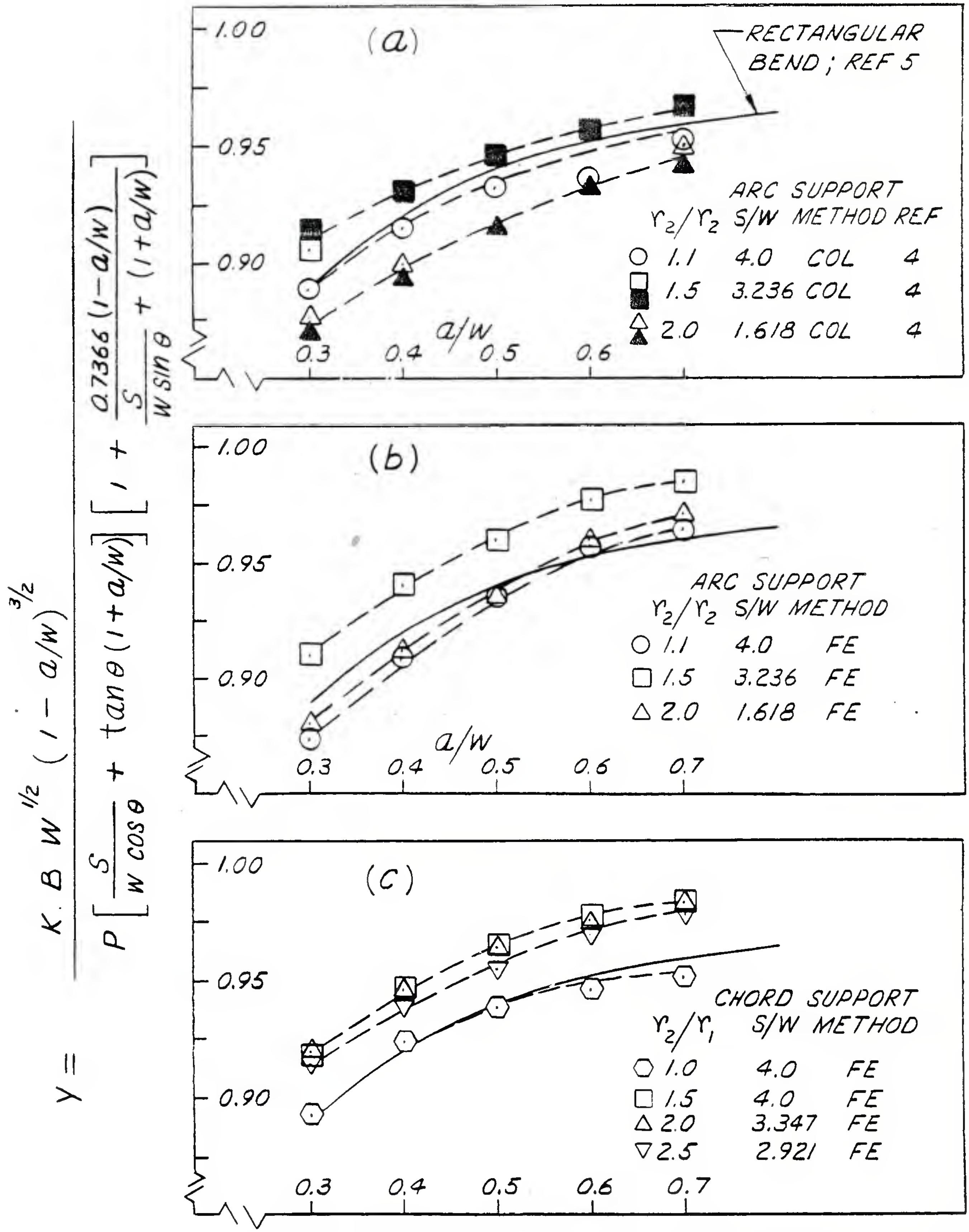


Figure 4. Stress intensity, K, versus a/W for bend specimens of various geometry.

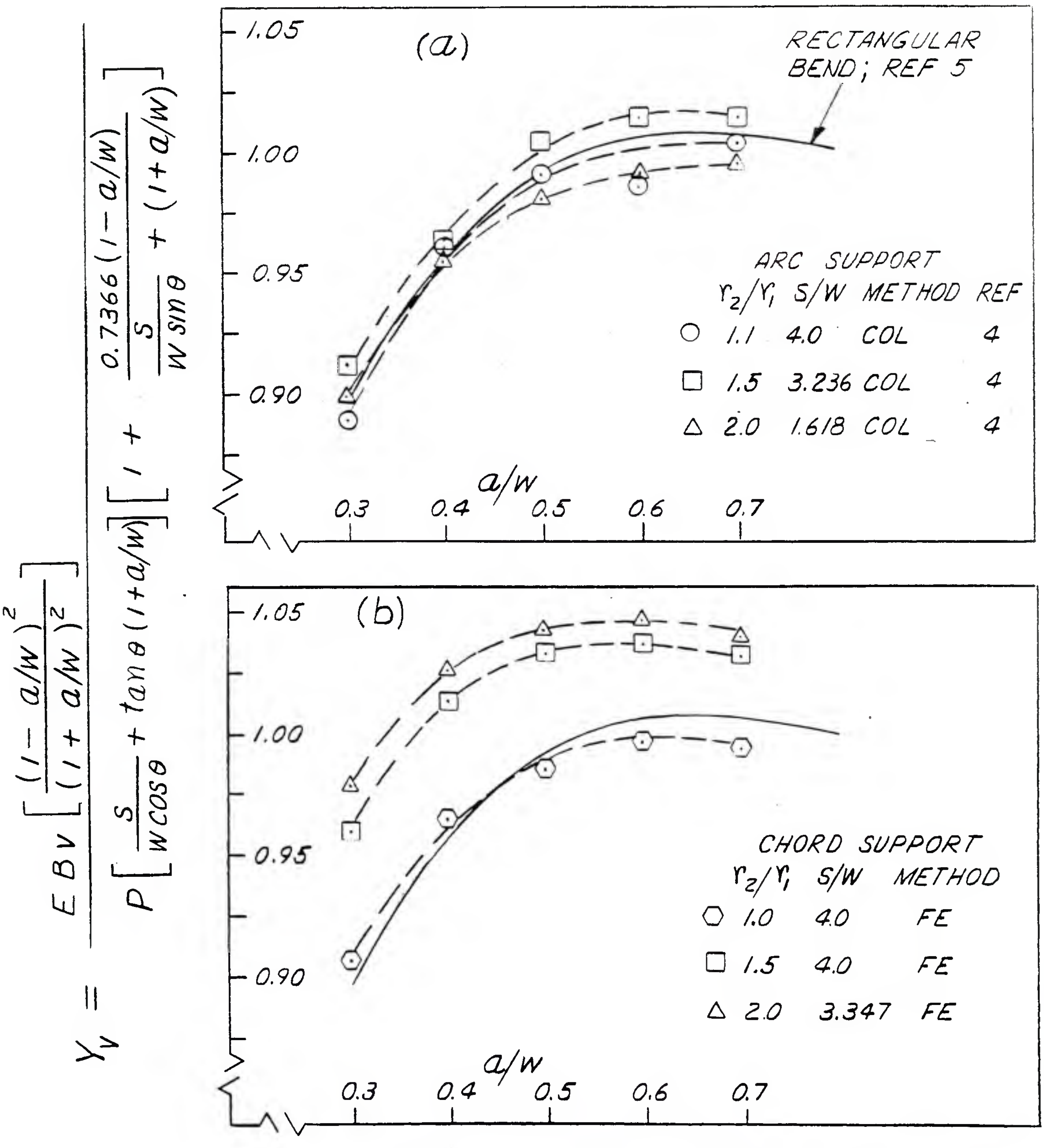


Figure 5. Crack mouth displacement, v, versus a/W for bend specimens of various geometry.

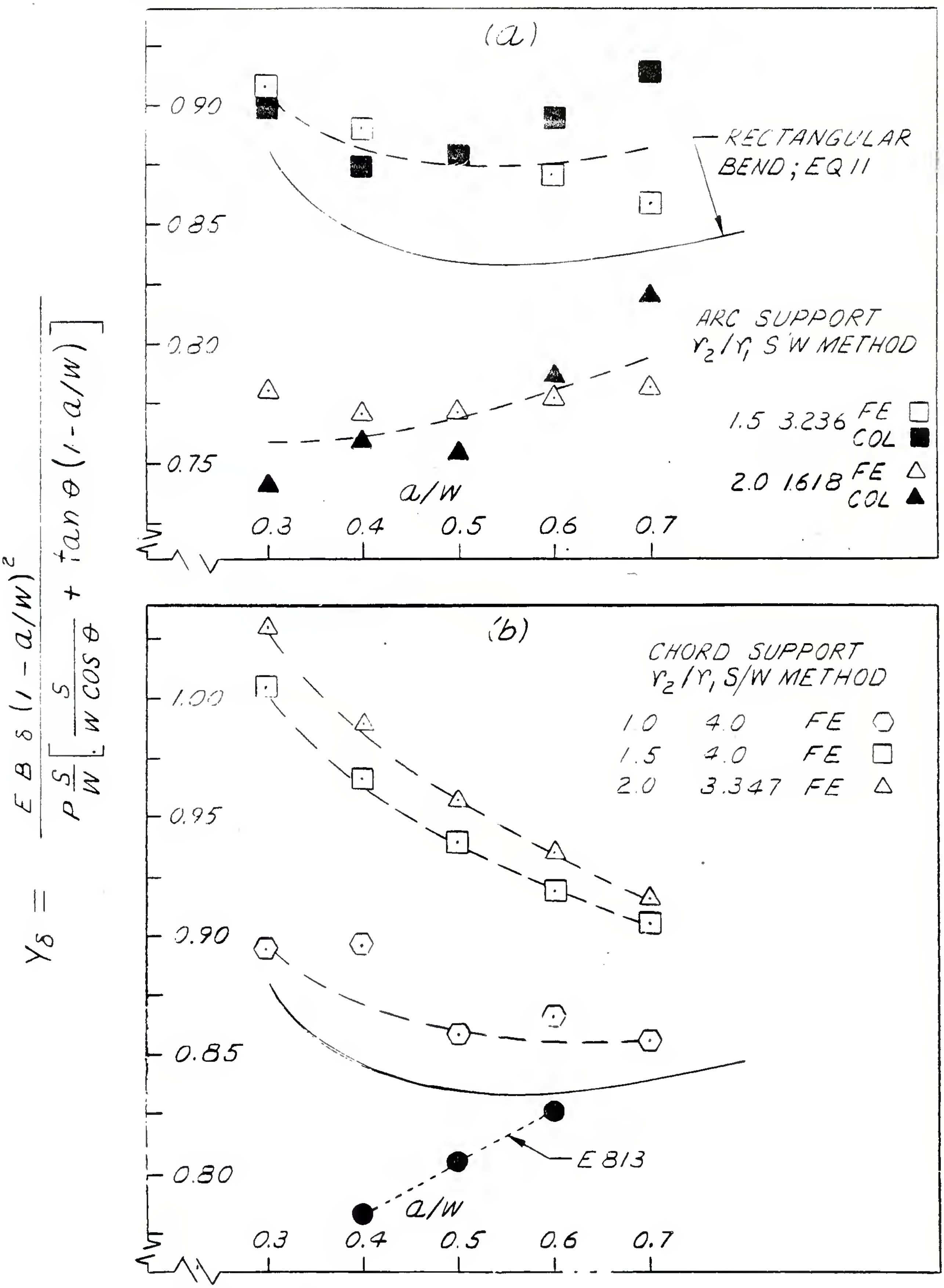


Figure 6. Load-Line displacement, δ, versus a/W for bend specimens of various geometry.

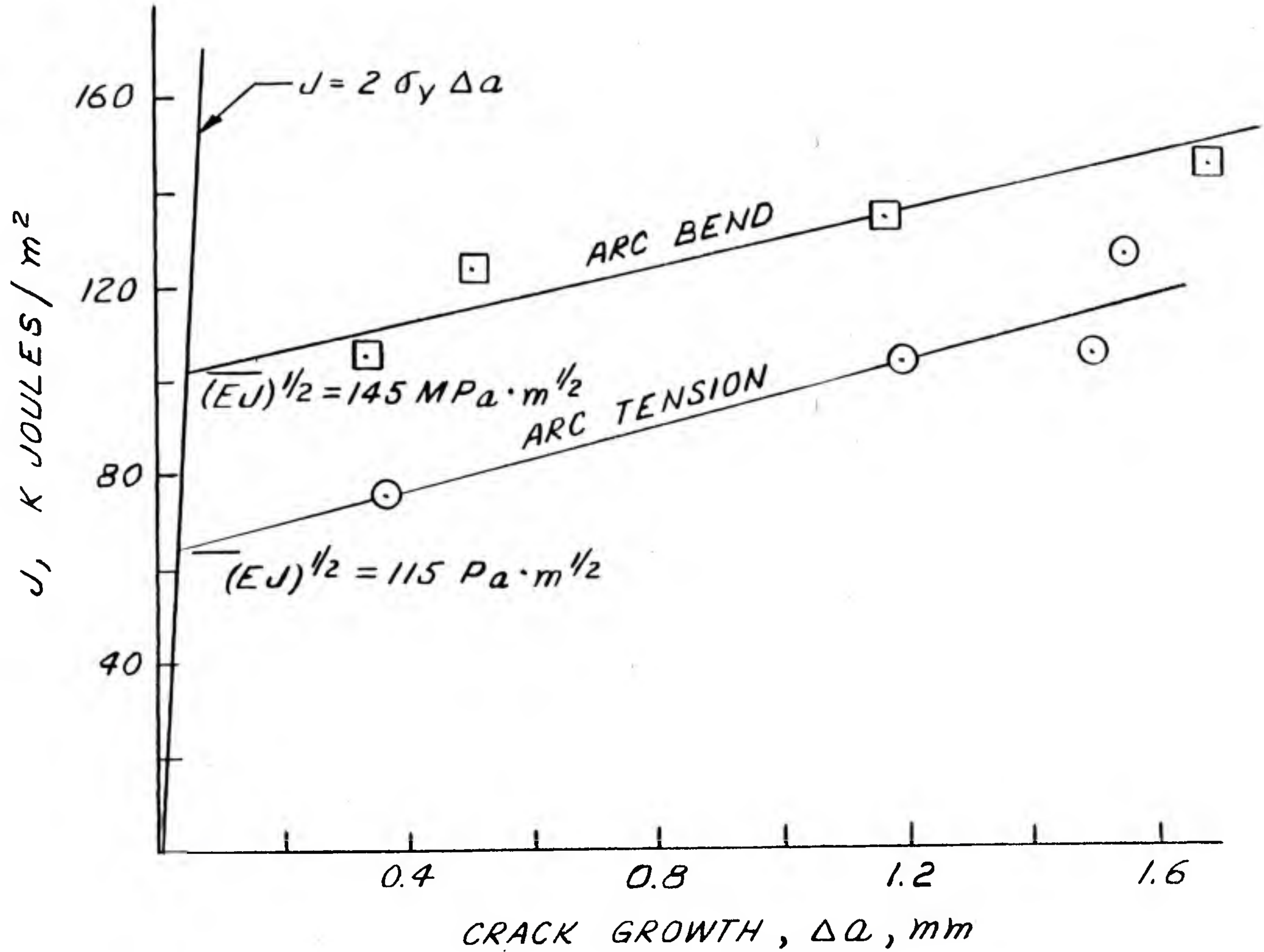
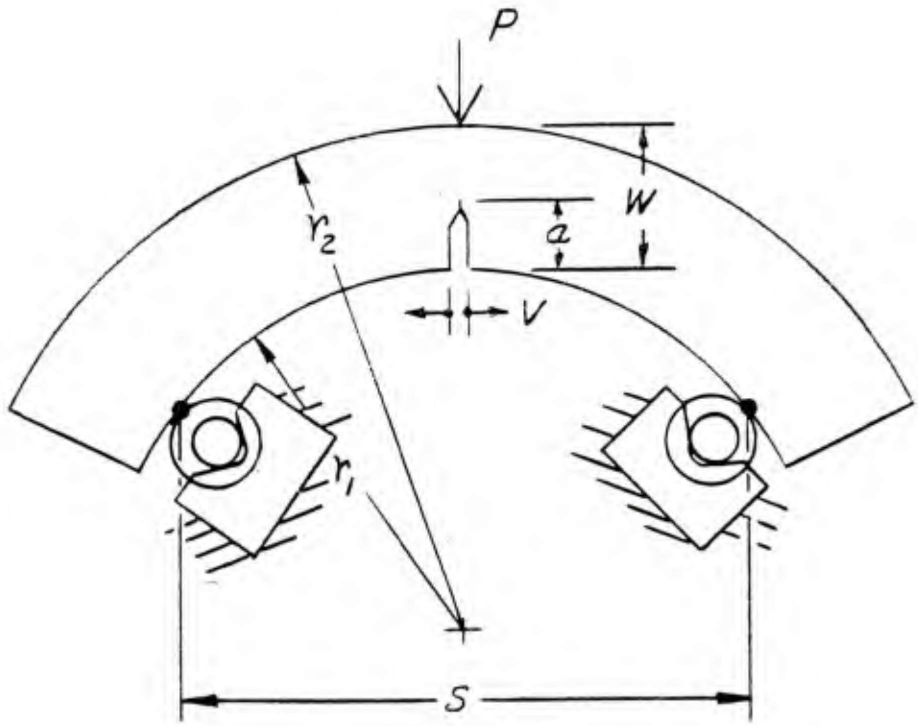


Figure 7. J versus Δa from arc tension and arc bend-chord support steel specimens described in Table II.

(a) ARC SUPPORT ; $1.0 \leq r_2/r_1 \leq 1.4$ WITH $S/W = 4.0$



(b) CHORD SUPPORT : $Z/W = 0.1$

$1.1 \leq r_2/r_1 \leq 1.6$ WITH $S/W = 4.0$

$1.6 \leq r_2/r_1 \leq 2.0$ WITH $3.347 \leq S/W \leq 4.0$

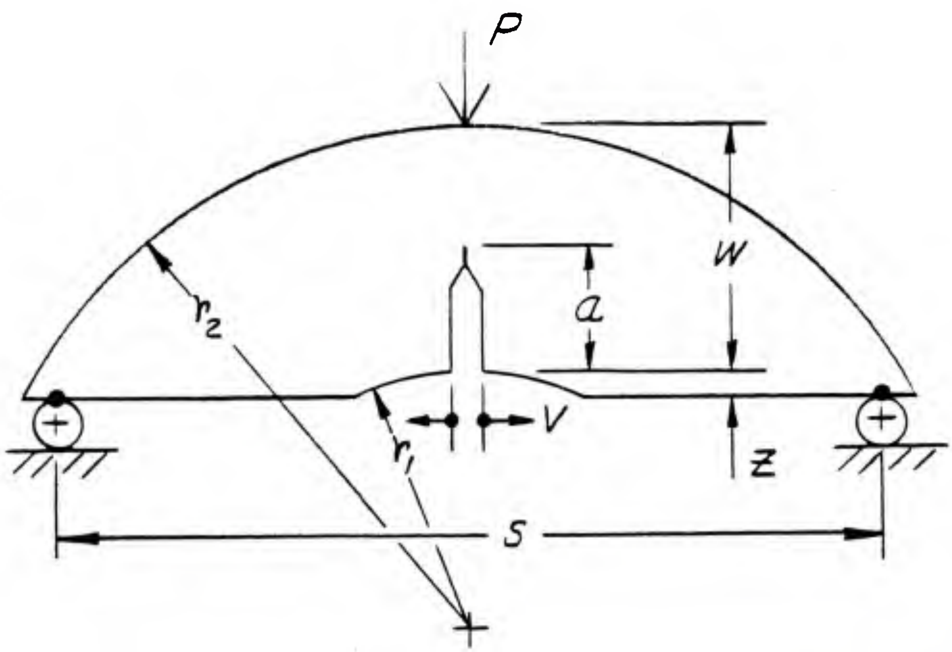


Figure 8. Recommended geometries for arc bend fracture testing; largest r_2/r_1 of recommended range is shown.

APPENDIX

An expression which is useful for analyzing arc bend-chord support specimens can be obtained from plane geometry, see Figure A1. Using

$$S = 2r_u \sin \phi$$

a nondimensional form can be written

$$S/W = 2[r_1/W + U/W] \sin[\cos^{-1} (\frac{r_1/W - Z/W}{r_1/W + U/W})] \quad (A1)$$

An example of the use of Eq. (A1) is, for $r_2/r_1 = 1.625$, $r_1/W = 1.6$, $U/W = 0.9$, $Z/W = 0.1$, S/W is calculated to be 4.0. This demonstrates that, for $U/W = 0.9$ and $Z/W = 0.1$, $r_2/r_1 = 1.625$ is the upper limit of arc bend geometries for chord support with $S/W = 4.0$.

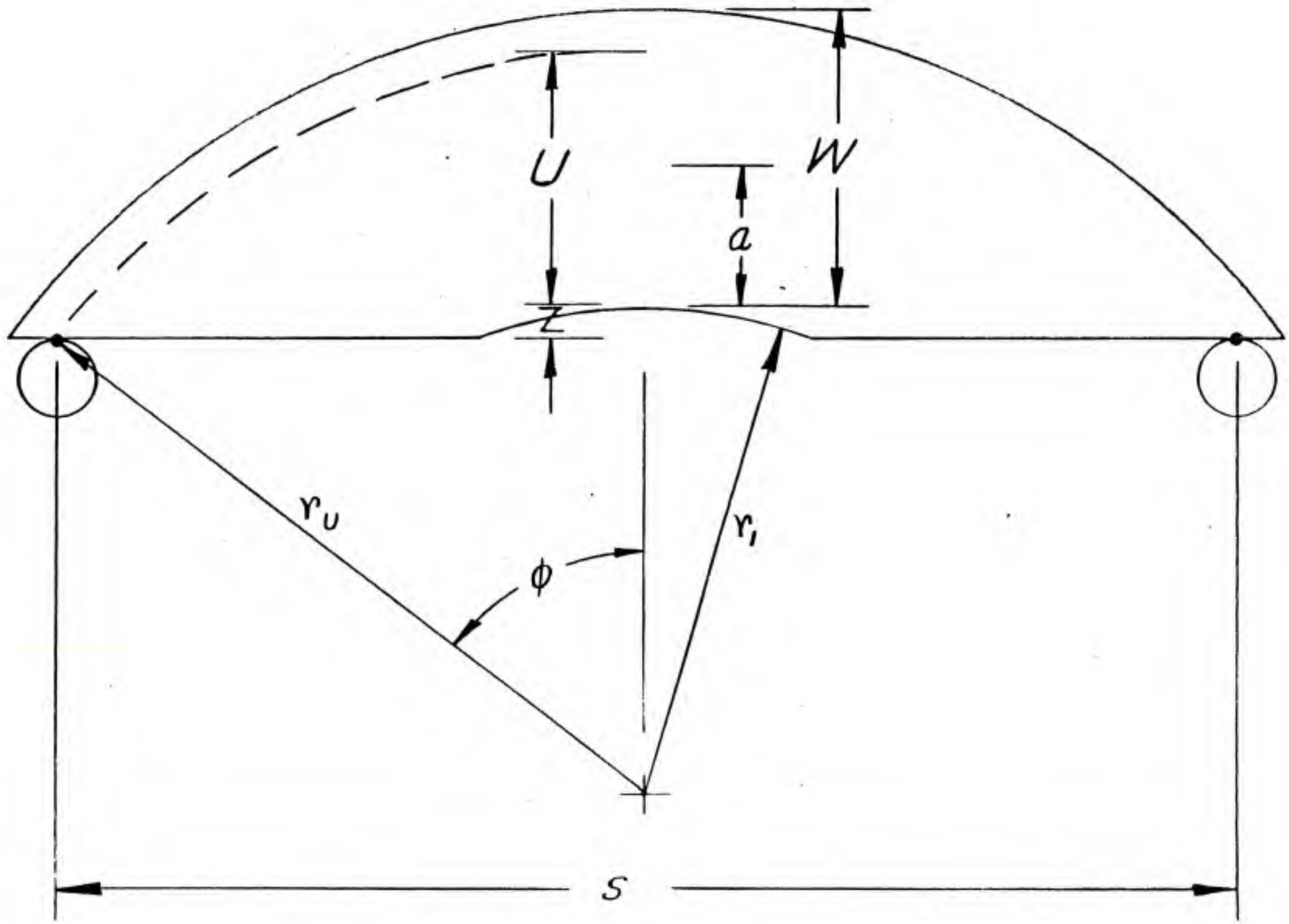


Figure A1. Arc bend-chord support specimen geometry.

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