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TECHNICAL REPORT ARCCB-TR-90001

**WIDE RANGE STRESS INTENSITY
FACTOR AND CRACK-MOUTH-OPENING
DISPLACEMENT EXPRESSIONS SUITABLE
FOR SHORT CRACK FRACTURE TESTING
WITH ARC BEND-CHORD SUPPORT SAMPLES**

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**US ARMY ARMAMENT RESEARCH,
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expressions can be found elsewhere for crack lengths and specimen geometries more commonly used in fracture toughness determination or fatigue crack propagation.

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TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	1
ANALYSIS	1
CONCLUSIONS	5
REFERENCES	7

TABLES

I. COMPARISON OF NORMALIZED STRESS INTENSITY FACTORS FOR S/W = 4	8
II. COMPARISON OF NORMALIZED STRESS INTENSITY FACTORS FOR S/W = 3	9
III. COMPARISON OF NORMALIZED CRACK-MOUTH-OPENING DISPLACEMENTS FOR S/W = 4	10
IV. COMPARISON OF NORMALIZED CRACK-MOUTH-OPENING DISPLACEMENTS FOR S/W = 3	11

LIST OF ILLUSTRATIONS

1. Schematic of the arc bend-chord support specimen	12
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INTRODUCTION

The arc bend-chord support sample has been proposed for standardization with ASTM (ref 1). This specimen is an arc-shaped specimen loaded in three-point bending with the support loads resting on a chordal cut of a cylinder. Figure 1 is a schematic of the arc bend-chord support specimen. The stress intensity factor, crack-mouth-opening displacement, and load-line displacement have been developed for this specimen (ref 2). Wide range expressions for the stress intensity factor and crack-mouth-opening displacement have also been developed (ref 2). These expressions are valid in the range of $a/W \geq 0.2$, however, this restriction is not an inconvenience when performing fracture toughness or fatigue crack propagation tests.

A group within ASTM's committee E-24 has been formed to study the behavior of short cracks. One of the specimens being considered is the arc bend-chord support sample, since many of the components tested are tubular products. To use the arc bend-chord support sample for short crack testing, a new wide range expression is necessary that is applicable for short crack lengths for both the stress intensity factor and for the crack-mouth-opening displacement.

ANALYSIS

To develop the short crack limits for the stress intensity factor and the crack-mouth-opening displacement for any two-dimensional crack problem, the Wigglesworth stress intensity factor solution (ref 3) and the Paris application of Castigliano's theorem (ref 4) are used. For the stress intensity factor, the limit is

$$\lim_{a \rightarrow 0} K = 1.12 \sigma \sqrt{\pi a} \quad (1)$$

where K is the stress intensity factor, a is the crack length, and σ is the value of the normal stress at the surface. For crack-mouth-opening displacement, the limit is

$$\lim_{a \rightarrow 0} \Delta = 5.83 \frac{\sigma a}{E'} \quad (2)$$

where Δ is the crack-mouth-opening displacement, E' is the elastic modulus (E) for plane-stress or $E/(1-\nu^2)$ for plane-strain, and ν is Poisson's ratio. Similarly, the limits for the stress intensity factor and crack-mouth-opening displacement can also be determined for the case of the crack approaching a through-thickness crack. The limit for the stress intensity factor is from Wilson's solution (ref 5), and the crack-mouth-opening displacement can be determined using the Paris treatment (ref 4) once again.

The deep crack limit for the stress intensity factor is

$$\lim_{a \rightarrow W} K = 3.975 \frac{M}{(W-a)^{3/2}} \quad (3)$$

where M is the applied moment per unit thickness (B) and W is the specimen width. For the crack-mouth-opening displacement, the deep crack limit is

$$\lim_{a \rightarrow W} \Delta = 15.8 \frac{M}{E' (W-a)^2} \quad (4)$$

Using Eqs. (1), (2), (3), and (4) and some algebraic manipulation, we develop nondimensional forms of both the stress intensity factor and the crack-mouth-opening displacements that approach both the short crack and the deep crack limits correctly. The numerically determined stress intensity factor and crack-mouth-opening displacement can then be normalized using the proper forms developed and interpolating polynomials can be fitted to the numerical solutions as well as the limiting solutions.

For the arc bend specimen, there are two other variables that must be accounted for. These are the span (S) used and the effects of curvature as represented by the radius ratio (r_1/r_2). As shown in Reference 2, the effects of span cannot be accounted for simply with the limiting solutions. Therefore, two separate expressions were fit to the two proposed standard spans (span to width ratio (S/W) of 3 or 4) for either the stress intensity factor or the crack-mouth-opening displacement. The same expressions are also used in this report. The curvature effect is accounted for by the short crack limit solutions that involve the surface stress. At mid-span, the arc bend specimen is subjected to loading such that the surface stress is a pure bending stress. The shear stress at the surface is zero. Using the solutions for a curved beam subjected to pure bending, this surface stress can be determined as (ref 6)

$$\sigma = \frac{P(S/W)(1-r_1/r_2)^2(1-r_1^2/r_2^2-2\ln(r_2/r_1))}{BW((1-r_1/r_2)^2-4r_1^2/r_2^2\ln^2(r_2/r_1))} \quad (5)$$

Using Eqs. (1), (3), and (5), the normalized form of the stress intensity factor that has finite limits as the crack approaches both zero length and through-thickness is

$$\frac{KB\sqrt{W}(1-a/W)^{3/2}}{P(S/W)\sqrt{a/W}} = [1 + g(r_1/r_2)h(a/W)f(a/W)] \quad (6)$$

The numerical stress intensity factor results from Reference 2, the limit solutions outlined above, and the numerical results for the three-point bend specimen ($r_1/r_2 = 1$) (ref 7) are presented in Table I for S/W = 4. Table II gives the stress intensity factor results from Reference 2 and the above limit solutions for S/W = 3. The normalized solutions in the tables lead to the right-hand side of Eq. (6). The strongest effect of r_1/r_2 occurs when the cracks are very short. This curvature effect decays to zero when the cracks

approach through-thickness. Decreasing r_1/r_2 from the three-point bend case, ($r_1/r_2 = 1$), has a tendency to increase the stress intensity factor a relatively small amount that increases as the specimen becomes more curved. Therefore, the form of the interpolating polynomials (Eq. (6)) was chosen. With this form, $g(r_1/r_2)$ was fit to account for the maximum curvature effect ($a/W=0$), and $h(a/W)$ had a maximum value of one at $a/W = 0$ and a minimum value of zero at $a/W = 1$. Both of these polynomials can be obtained by least squares fitting to the data reported in the tables.

For $S/W = 4$, the three interpolating polynomials are

$$\begin{aligned} g(r_1/r_2) &= 0.832 - 1.376 r_1/r_2 + 0.544(r_1/r_2)^2 \\ h(a/W) &= 1.003 - 4.680 a/W + 9.953(a/W)^2 - 10.030(a/W)^3 + 3.754(a/W)^4 \\ f(a/W) &= 2.978 - 8.240 a/W + 17.157(a/W)^2 - 18.073(a/W)^3 + 7.174(a/W)^4 \end{aligned} \quad (7)$$

For $S/W = 3$, the interpolating polynomials are

$$\begin{aligned} g(r_1/r_2) &= 1.035 - 3.238 r_1/r_2 + 2.938(r_1/r_2)^2 - 1.005(r_1/r_2)^3 \\ h(a/W) &= 1.000 - 6.740 a/W + 22.224(a/W)^2 - 36.295(a/W)^3 \\ &\quad + 27.630(a/W)^4 - 7.820(a/W)^5 \\ f(a/W) &= 2.978 - 10.366 a/W + 32.196(a/W)^2 - 59.232(a/W)^3 \\ &\quad + 55.797(a/W)^4 - 20.378(a/W)^5 \end{aligned} \quad (8)$$

The accuracy of these polynomials is as follows: for $S/W = 4$, better than ± 0.1 percent at $a/W = 0$ and ± 0.9 percent for any a/W and $1 \leq r_1/r_2 \leq 0.6$; for $S/W = 3$, better than ± 0.1 percent at $a/W = 0$ and ± 3.2 percent for any a/W and $1 \leq r_1/r_2 \leq 0.4$, and ± 1.2 percent for any a/W and $1 \leq r_1/r_2 \leq 0.6$.

For crack-mouth-opening displacement, the normalized form that has finite limits as the crack approaches both zero length and through-thickness length is

$$\frac{E' B \Delta (1-a/W)^2}{P(S/W)(a/W)} = [1 + g(r_1/r_2)h(a/W)]f(a/W) \quad (9)$$

The numerical results from References 2 and 7 and the limits are normalized in accordance with Eq. (9) and are listed in Table III for $S/W = 4$, and the results from Reference 2 along with the limits for $S/W = 3$ are listed in Table IV. For the same reasons as presented above for the stress intensity factor solutions, the form of Eq. (9) was chosen. The interpolating polynomials for the crack-mouth-opening displacement were determined in the same manner as the stress intensity factor. They are

For $S/W = 4$:

$$\begin{aligned} g(r_1/r_2) &= 0.832 - 1.376 r_1/r_2 + 0.544(r_1/r_2)^2 \\ h(a/W) &= 1.007 - 3.249 a/W + 4.517(a/W)^2 - 2.275(a/W)^3 \\ f(a/W) &= 8.747 - 25.576 a/W + 66.722(a/W)^2 - 93.010(a/W)^3 \\ &\quad + 63.579(a/W)^4 - 16.509(a/W)^5 \end{aligned} \quad (10)$$

For $S/W = 3$:

$$\begin{aligned} g(r_1/r_2) &= 1.035 - 3.238 r_1/r_2 + 2.938(r_1/r_2)^2 - 1.005(r_1/r_2)^3 \\ h(a/W) &= 1.001 - 4.974 a/W + 10.425(a/W)^2 - 8.340(a/W)^3 + 1.885(a/W)^4 \\ f(a/W) &= 8.741 - 28.100 a/W + 75.198(a/W)^2 - 93.686(a/W)^3 + 41.800(a/W)^4 \end{aligned}$$

The accuracy of these polynomials is as follows: for $S/W = 4$, better than ± 0.1 percent at $a/W = 0$ and ± 1.5 percent for any a/W and $1 \leq r_1/r_2 \leq 0.6$; for $S/W = 3$, better than ± 0.1 percent at $a/W = 0$ and ± 3.8 percent for any a/W and $1 \leq r_1/r_2 \leq 0.4$.

CONCLUSIONS

The short crack limit solutions for the stress intensity factor and crack-mouth-opening displacement for the arc bend-chord support specimen have been derived. This limit, along with the deep crack limit and the numerically determined values of these same parameters, was used to develop interpolating

polynomials for a wide range of specimen configurations. These polynomials were specifically developed to ensure that the short crack limits were as accurate as possible. Interpolating polynomials for this specimen for crack lengths customarily used for fracture toughness testing and fatigue crack growth testing can be found elsewhere.

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TABLE I. COMPARISON OF NORMALIZED STRESS INTENSITY FACTORS FOR $S/W = 4$

$r_1 r_2$	a/W	0	0.2	0.3	0.4	0.5	0.6	0.7	1
1.0	K' (ref 7)	2.978	1.880	1.625	1.457	1.331	1.233	1.150	0.995
	K' (Eq. 7)	2.978	1.883	1.620	1.454	1.337	1.237	1.140	0.996
	Error	-0.0001	-0.0017	0.0031	0.0019	-0.0039	-0.0028	0.0084	-0.0010
0.8	K' (ref 2)	3.217	1.944	1.665	1.475	1.346			0.995
	K' (Eq. 7)	3.214	1.941	1.653	1.474	1.350			0.996
	Error	0.0009	0.0015	0.0077	0.0006	-0.0029			-0.0008
0.7	K' (ref 2)	3.378	1.976	1.679	1.490	1.360			0.995
	K' (Eq. 7)	3.381	1.981	1.675	1.488	1.360			0.996
	Error	-0.0009	-0.0026	0.0020	0.0010	0.0001			-0.0006
0.6	K' (ref 2)	3.582	2.012	1.708	1.506	1.360			0.995
	K' (Eq. 7)	3.580	2.031	1.703	1.505	1.371			0.995
	Error	0.0005	-0.0094	0.0032	0.0006	-0.0084			-0.0004

TABLE II. COMPARISON OF NORMALIZED STRESS INTENSITY FACTORS FOR $S/W = 3$

$r_1 r_2$	a/w	0	0.2	0.3	0.4	0.5	0.6	1
1.0	K' (ref 2)	2.978	1.813	1.579	1.416	1.293	1.204	0.995
	K' (Eq. 8)	2.978	1.802	1.569	1.412	1.291	1.202	0.995
	Error	-0.0001	0.0065	0.0063	0.0028	0.0022	0.0021	0.0000
0.8	K' (ref 2)	3.217	1.867	1.615	1.438	1.310	1.215	0.995
	K' (Eq. 8)	3.217	1.844	1.595	1.430	1.304	1.210	0.995
	Error	-0.0001	0.0122	0.0124	0.0051	0.0045	0.0039	0.0001
0.6	K' (ref 2)	3.582	1.931	1.650	1.465	1.330	1.228	0.995
	K' (Eq. 8)	3.582	1.908	1.634	1.459	1.325	1.223	0.995
	Error	0.0000	0.0116	0.0101	0.0041	0.0038	0.0038	0.0002
0.4	K' (ref 2)	4.216	1.957	1.654	1.487	1.348	1.233	0.995
	K' (Eq. 8)	4.216	2.020	1.701	1.508	1.361	1.246	0.995
	Error	0.0000	-0.0322	-0.0288	-0.0144	-0.0095	-0.0104	0.0004

$$K' = \frac{KB\sqrt{W}(1-a/W)^{3/2}}{P(S/W)\sqrt{a/W}}$$

$$\text{Error} = \frac{K'(\text{ref}) - K'(\text{Eq})}{K'(\text{ref})}$$

TABLE III. COMPARISON OF NORMALIZED CRACK-MOUTH-OPENING DISPLACEMENTS FOR $S/W = 4$

$r_1 r_2$ a/W		0	0.2	0.3	0.4	0.5	0.6	0.7	1
1.0	Δ' (ref 7)	8.745	5.656	5.047	4.687	4.459	4.268	4.136	3.950
	Δ' (Eq. 10)	8.747	5.653	5.043	4.698	4.447	4.287	4.126	3.953
	Error	-0.0002	0.0005	0.0008	-0.0024	0.0026	-0.0045	0.0023	-0.0008
0.8	Δ' (ref 2)	9.448	5.976	5.161	4.788	4.511			3.950
	Δ' (Eq. 10)	9.441	5.883	5.191	4.802	4.549			3.951
	Error	0.0007	0.0156	-0.0058	-0.0028	-0.0084			-0.0002
0.7	Δ' (ref 2)	9.921	6.032	5.263	4.880	4.598			3.950
	Δ' (Eq. 10)	9.931	6.045	5.296	4.875	4.604			3.949
	Error	-0.0010	-0.0022	-0.0061	0.0012	-0.0015			0.0002
0.6	Δ' (ref 2)	10.519	6.176	5.415	5.042	4.719			3.950
	Δ' (Eq. 10)	10.516	6.239	5.421	4.962	4.670			3.947
	Error	0.0003	-0.0102	-0.0011	0.0160	0.0103			0.0007

TABLE IV. COMPARISON OF NORMALIZED CRACK-MOUTH-OPENING DISPLACEMENTS FOR $S/W = 3$

$r_1 r_2$		a/w	0	0.2	0.3	0.4	0.5	0.6	1
1.0		Δ' (ref 2)	8.745	5.376	4.949	4.596	4.345	4.178	3.950
		Δ' (Eq. 11)	8.741	5.446	4.888	4.607	4.392	4.133	3.953
		Error	0.0005	-0.0131	0.0124	-0.0024	-0.0109	0.0106	-0.0008
0.8		Δ' (ref 2)	9.448	5.536	4.905	4.692	4.437	4.253	3.950
		Δ' (Eq. 11)	9.443	5.603	4.981	4.678	4.461	4.204	3.952
		Error	0.0005	-0.0121	-0.0153	0.0029	-0.0055	0.0117	-0.0004
0.6		Δ' (ref 2)	10.519	5.899	5.325	4.842	4.552	4.356	3.950
		Δ' (Eq. 11)	10.514	5.842	5.122	4.787	4.566	4.311	3.950
		Error	0.0006	0.0096	0.0381	0.0113	-0.0031	0.0105	0.0001
0.4		Δ' (Ref 2)	12.381	6.165	5.450	4.902	4.627	4.462	3.950
		Δ' (Eq. 11)	12.373	6.258	5.368	4.976	4.747	4.497	3.946
		Error	0.0006	-0.0150	0.0151	-0.0151	-0.0261	-0.0077	0.0009

$$\Delta' = \frac{E'BA(1-a/W)^2}{P(S/W)(a/W)}$$

$$\text{Error} = \frac{\Delta'(\text{ref}) - \Delta'(\text{Eq})}{\Delta'(\text{ref})}$$

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