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J-Resistance Curves of Aluminum Specimens Using Moire Interferometry

by

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J-Resistance Curves of Aluminum Specimens Using Moire Interferometry

B. S.-J. Kang^{*}, M.S. Dadkhah^{**} and A.S. Kobayashi^{***}

ABSTRACT

Errors involved in using the approximate J_I evaluation procedure are evaluated by comparing the resistance curves of large 2024-O and 5052-H32 aluminum, single edge cracked, cruciform specimens under uniaxial and biaxial loadings with those obtained by an exact procedure. This comparative study shows that under uniaxial loading, the J_I resistance curves obtained by the approximate procedure are within six percent of those obtained by the exact procedure. For the biaxial loading, however, the difference is about eighteen percent. The specimen size and geometry dependence of the J-resistance curves of 2024-O and 5052-H32 aluminum specimens are also discussed. *Aluminum. Suppl.*

INTRODUCTION

At present, most elastic-plastic fracture mechanics (EPFM) methodologies are based on the J-integral or the crack opening displacement (COD) approach. The J-resistance curve (J_R curve) approach in particular has been popular for evaluating elastic-plastic stable crack growth and ductile fracture of high toughness materials, such as A533B steel [1], and 2219-T87 aluminum [2]. Questions have been raised, however, regarding the specimen size and geometry dependence of the J-resistance curve [3,4,5], i.e. the use of J-resistance curve obtained by small laboratory specimens for predicting elastic-plastic crack growth resistance in large engineering structures.

Several experimental methods have been proposed for determining the $J-\Delta a$ (J_R) curve. Generally the J values are determined from the measured far-field load versus load-line displacement curve and the amount of crack

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growth, Δa , is determined by such methods as the unloading compliance method [6], the electric potential method [7], the key curve method [8] and the ultrasonic method [9]. In contrast to these far-field methods, the authors have presented an approximate [10,11] and an exact [12] procedures for determining the J-integral values based on the displacement fields obtained by moire interferometry. These two procedures are based on the original J-integral definition for evaluating the J values along a contour either the near, middle or far crack-tip fields, such as those shown in Figs. 1 and 2. The purpose of this paper is to assess the accuracy of the J values evaluated by the simple and convenient approximate procedure through a comparative study with those values obtained by the exact procedure. We then extend the analysis to the discussion of the size and specimen dependence of the J-based resistance curves of 2024-O and 5052-H32 aluminum specimens under uniaxial and biaxial loadings.

ASSESSMENT OF THE APPROXIMATE J-EVALUATION PROCEDURE

The approximate J-evaluation procedure [10] is based on the assumption that two-dimensional states of stress and strain in a fracture specimen can be approximated by the uniaxial states of stress and strains. The uniaxial state can be determined by using only the u_y -displacement field obtained by the moire interferometry. This simplification is theoretically correct when the integration contour is taken along a far field location, i.e. the edges, of a single-edge-notched (SEN) specimen shown in Fig. 1. As for J-evaluation along a near crack tip contour (also shown in Fig. 1), a sensitivity study [10] showed that the approximate J-evaluation procedure incurred a fourteen percent error in the elastic crack-tip stress field and decreased to less than one percent in the HRR field [13,14].

In this paper, we present further application of the approximate J-evaluation procedure in large 2024-O and 5052-H32 aluminum single-edge cracked, cruciform specimens which were subjected to uniaxial and biaxial loadings. The moire interferometry tests were conducted by the second author who developed an exact J-evaluation procedure [12,15] which utilize both u_x and u_y moire displacement fields. Here, we apply the approximate J-evaluation procedure to the same u_y moire fringe patterns and compare these results to those obtained by the exact J-evaluation procedure. Material properties of the specimens are shown in Table 1.

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RESULTS

Accuracy Assessment

Near- and far-field J values were evaluated by both procedures. Figures 3 and 4 show typical moire interferometry patterns corresponding to the u_y displacement field in an uniaxially loaded 5052-H32 and an biaxially loaded 2024-0 aluminum cruciform specimens. The J values evaluated by the approximate and the exact J -evaluation procedures are listed in Tables 2, 3 and 4. These results show that the J values, which were obtained by the approximate procedure, are within six percent of those obtained by the exact procedure for uniaxially loaded cruciform specimens. However, the difference is about twenty percent for those under biaxial loading. This discrepancy is due to the region of large biaxial state of stress which invalidates the assumption of a dominant uniaxial state for the simplified approximation procedure.

Geometry Dependence of J - Δa Resistance Curve

Having proved the accuracy of the approximate J -evaluation procedure, previous J_R curves generated for small single edge notched (SEN) specimens using the approximate procedure can thus be used in a comparative study with those generated by the large cruciform specimens. Figure 5 shows superposed plots of the J - Δa curves for small 2024-0 aluminum SEN specimens and large single-edge cracked cruciform specimens [11,15]. For the limited amount of crack growth considered in this study, the results indicate that the J_R curve is specimen size and geometry independent. This conclusion is reinforced by similar superposed plots of the COD and the CTOD resistance curves shown in Figs. 6 and 7. Figure 8 shows superposed plots of the J - Δa curves for small SEN and large 5052-H32 aluminum cruciform specimens. As shown in Fig. 8, the J_R curves start to deviate after about 0.6 mm of crack extension. Figure 9 shows superposed plots of the corresponding COD resistance curves. Similar deviation in the two curves after crack extension of 0.6 mm is observed.

DISCUSSION

The advantages of the approximate J -estimation procedure, which utilize a simplified contour integration based solely on the the dominant u_y

displacement field, are; i) simpler optics in the moire interferometry setup, and ii) the associated reduction in the data evaluation effort. Results of the comparative study of the J values obtained by the approximate and exact J -evaluation procedures indicate, however, that the approximate procedure can be used without incurring large errors only under uniaxial loading.

In the following, the specimen size and geometry dependence of the J -based resistance curves of 2024-O and 5052-H32 aluminum specimens are discussed.

J-Controlled Crack Growth

The base for the J -resistance curve approach for stable crack growth is the condition of J -controlled crack growth. Under such condition, nearly proportional loading must exist at the crack tip region and the amount of crack growth must be small compared to the region dominated by the HRR fields [13,14]. Within the condition of J -controlled crack growth, the J -integral and the related dJ/da are meaningful parameters for characterizing the crack growth [16,17]. Also, within the range of J -controlled crack growth, the J -resistance curve is unique and independent of the specimen size and geometry. Uncertainties arise as how to define the maximum range of crack extension for J -controlled crack growth [3]. Shih et.al [1] proposed that crack growth be limited to six percent of the ligament to ensure J -controlled crack growth. Recent studies [18] of J_R curves calculated using ASTM E1152, however, showed no specimen size dependence under large crack extension far in excess of the ASTM standard. In our previous studies based on the moire interferometry data [10,11,19], a J -dominated region was found in 2024-O aluminum specimens (a strain hardening material, see Table 1) and did not exist in 5052-H32 aluminum specimens (a nonhardening material, see Table 1). Figure 5 shows that for strain hardening material such as 2024-O aluminum of the same specimen thickness, the J_R curve is independent of the specimen size and geometry for crack extension at least up to 1 mm. For low strain hardening material, such as 5052-H32 aluminum, Figure 8 shows that the J_R curves deviate after 0.6 mm crack extension in this nonhardening material where the J -dominated zone shrinks to zero [20,21]. Thus some amount of strain hardening is essential for a valid J_R curve, which can be used to characterize ductile stable crack growth, to exist.

CONCLUSIONS

1. The errors involved in using the approximate J-evaluation procedure in large 2024-O and 5052-H32 aluminum, single-edge cracked, cruciform specimens under uniaxial and biaxial loadings are evaluated by comparing these results with those obtained by an exact procedure. This comparative study shows that under uniaxial loading, the J-integral values obtained by the approximate procedure are within six percent of those obtained by the exact procedure. For the biaxial loading, however, the difference is about eighteen percent.
2. Specimen size and geometry dependence of the J_R curves of 2024-O and 5052-H32 aluminum specimens are discussed. For 2024-O aluminum specimens of the same thickness, the J_R curve is independent of the specimen size and geometry for crack growth at least up to 1 mm. For 5052-H32 aluminum, however, the J_R curves deviate after 0.6 mm crack growth. These results suggest that some amount of strain hardening is necessary to ensure a specimen size and geometry independent J_R curve for characterizing ductile stable crack growth.

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Table 1 Test Material Properties

Aluminum	Yield Stress MPa (ksi)	Young's Modulus MPa (ksi)	α	n
2024-O	67 (9.7)	74200 (10760)	1.0	4
5052-H32	190 (27.6)	70000 (10150)	1.0	16

$$\frac{\epsilon}{\epsilon_y} = \frac{\sigma}{\sigma_y} + \alpha \left(\frac{\sigma}{\sigma_y} \right)^n$$

(Ramberg-Osgood Relation)

Table 2 Measured J-integral Values for Different Contours in a Uniaxially Loaded 5052-H32 Aluminum Single-edge Cracked, Cruciform Specimen

Applied Load (N)	Crack Extension (mm)	J* (kPa-m)		J** (kPa-m)		% Difference	
		Contour		Contour		Contour	
		# 1	# 2	# 1	# 2	# 1	# 2
2371	0.0	4.80	5.20	4.22	4.35	12%	16%
3812	0.2	8.00	7.30	6.76	6.32	15%	13%
4404	0.36	12.10	11.60	12.50	12.30	3%	6%
5253	0.50	18.45	17.10	18.40	19.20	0.3%	12%
5760	0.75	23.81	25.29	23.40	23.62	2%	6%
6779	1.35	42.80	40.40	42.20	41.60	1%	3%
7455	1.95	66.70	64.70	66.60	61.20	0.2%	5%

* : Measured J values based on the exact J-evaluation procedure

** : Measured J values based on the approximate J-evaluation procedure

Table 3 Measured J-integral Values for Different Contours in a Uniaxially Loaded 2024-O Aluminum Single-edge Cracked, Cruciform Specimen

Applied Load (N)	Crack Extension (mm)	J* (kPa-m)		J** (kPa-m)		% Difference	
		Contour		Contour		Contour	
		# 1	# 2	# 1	# 2	# 1	# 2
1019	0.0	0.25	0.26	0.21	0.22	16%	15%
1490	0.1	1.90	1.76	1.88	1.81	1%	3%
2576	0.33	6.30	6.70	6.20	6.30	2%	6%
3283	0.96	19.70	20.30	18.80	18.90	5%	7%
3763	1.34	31.00	28.50	31.70	30.10	2%	6%

* : Measured J values based on the exact J-evaluation procedure

** : Measured J values based on the approximate J-evaluation procedure

Table 4 Measured J-integral Values for Different Contours in a Biaxially Loaded 2024-O Aluminum Single-edge Cracked, Cruciform Specimen

Applied Load(Y) (N)	Applied Load(X) (N)	Crack Extension (mm)	J* (kPa-m)		J** (kPa-m)		% Difference	
			Contour		Contour		Contour	
			# 1	# 2	# 1	# 2	# 1	# 2
4066	2086	0.04	4.00	3.80	3.26	3.08	19%	19%
5489	2896	0.50	11.00	10.50	9.25	9.11	16%	13%
5591	3305	0.85	18.10	18.40	14.30	14.70	21%	20%
5845	3888	1.34	31.00	29.00	25.70	24.36	17%	16%
6076	3914	1.40	32.00	29.20	26.00	25.10	19%	14%
6720	4524	1.68	34.00	31.00	28.50	28.00	16%	10%
6810	4626	2.20	50.00	47.00	40.50	39.80	19%	15%

* : Measured J values based on the exact J-evaluation procedure

** : Measured J values based on the approximate J-evaluation procedure

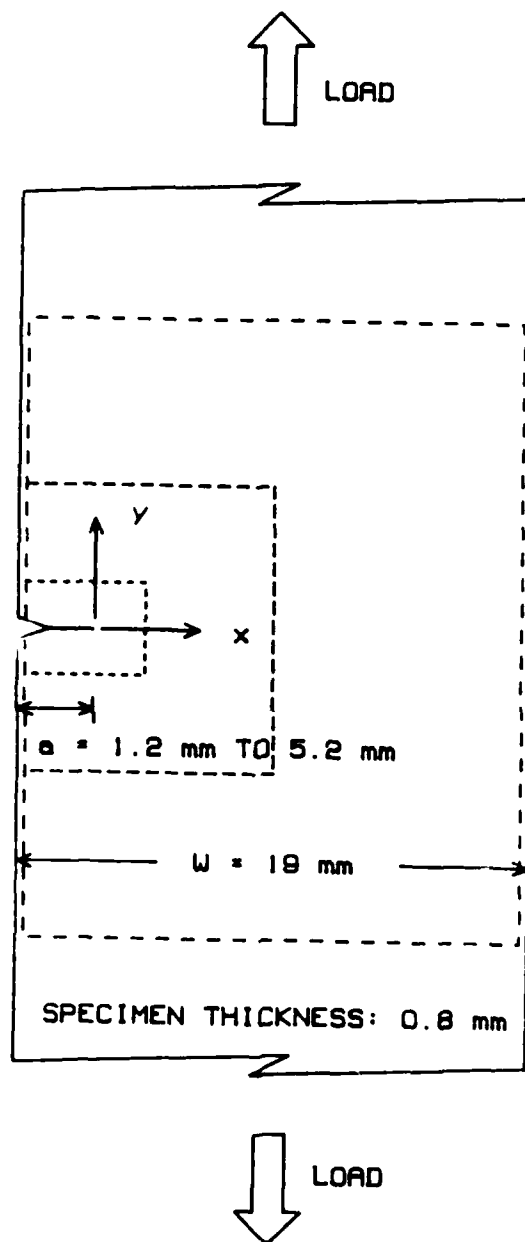


Fig. 1 Single Edge Notched (SEN) Specimen and Contours for J Evaluation.

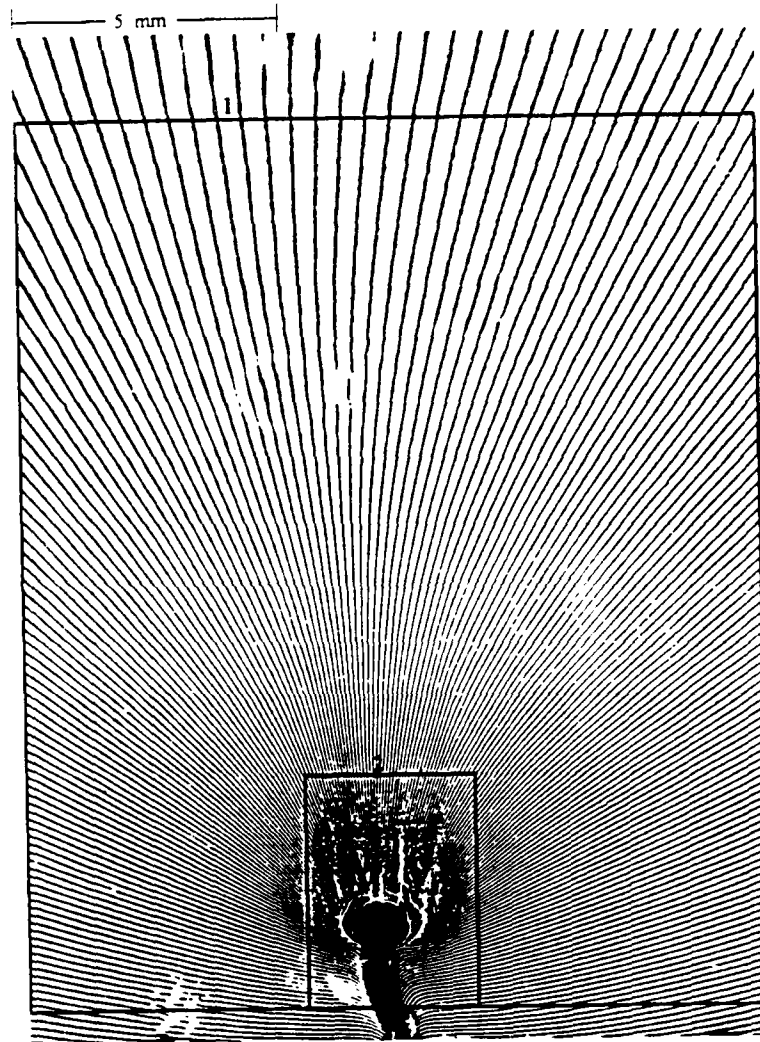


Fig. 3 u_y -Displacement in a Uniaxially Loaded 5052-H32 Aluminum Single Edge Cracked, Cruciform Specimen; Applied Load 5760 (N).

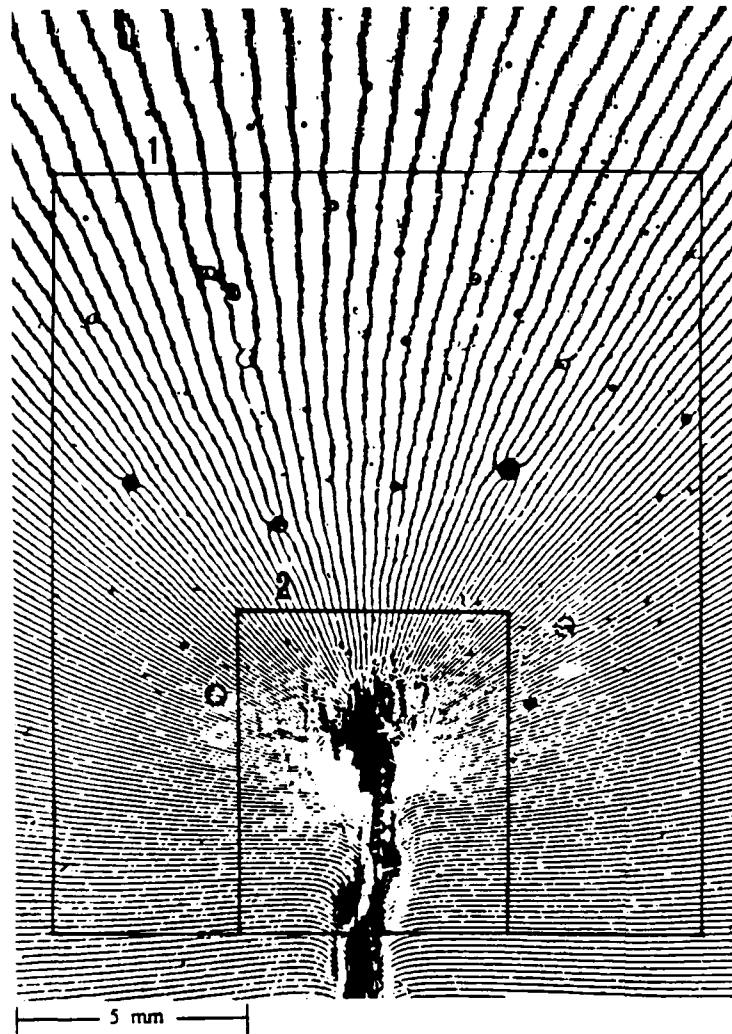


Fig. 4 u_y -Displacement in a Biaxially Loaded 2024-O Aluminum Single Edge Cracked, Cruciform Specimen; Applied Load $F_x = 5489$ (N), $F_y = 2896$ (N).

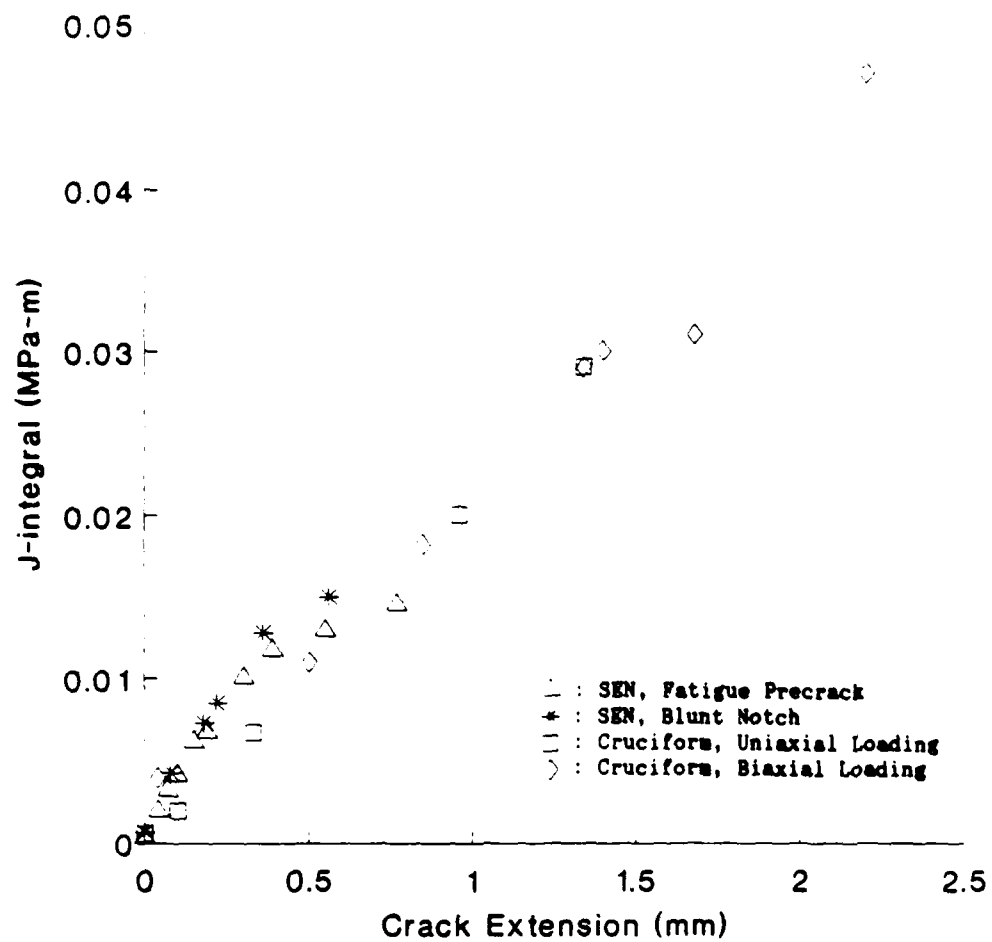


Fig. 5 J_R Curves of 2024-O Aluminum Small SEN and Large Single Edge Cracked, Cruciform Specimens.

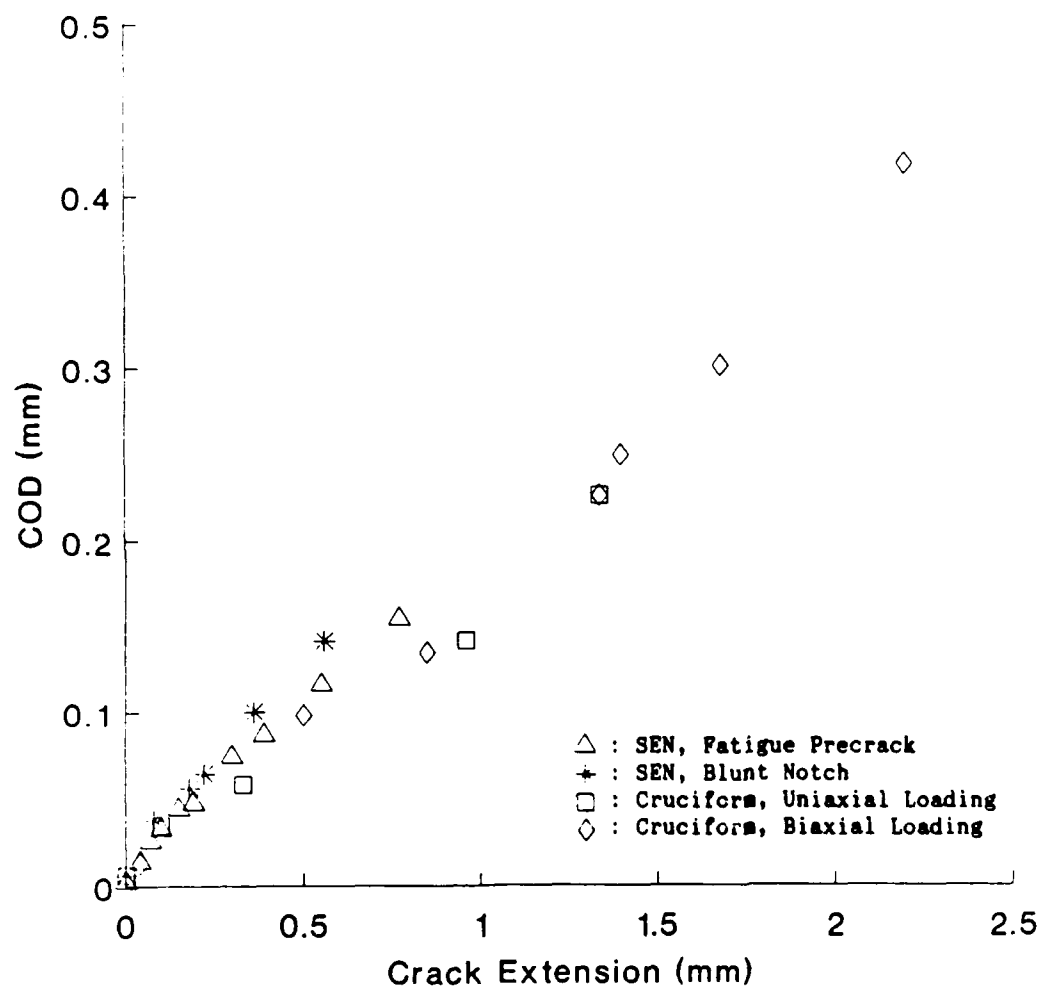


Fig. 6 COD Resistance Curves of 2024-O Aluminum Small SEN and Large Single Edge Cracked, Cruciform Specimens.

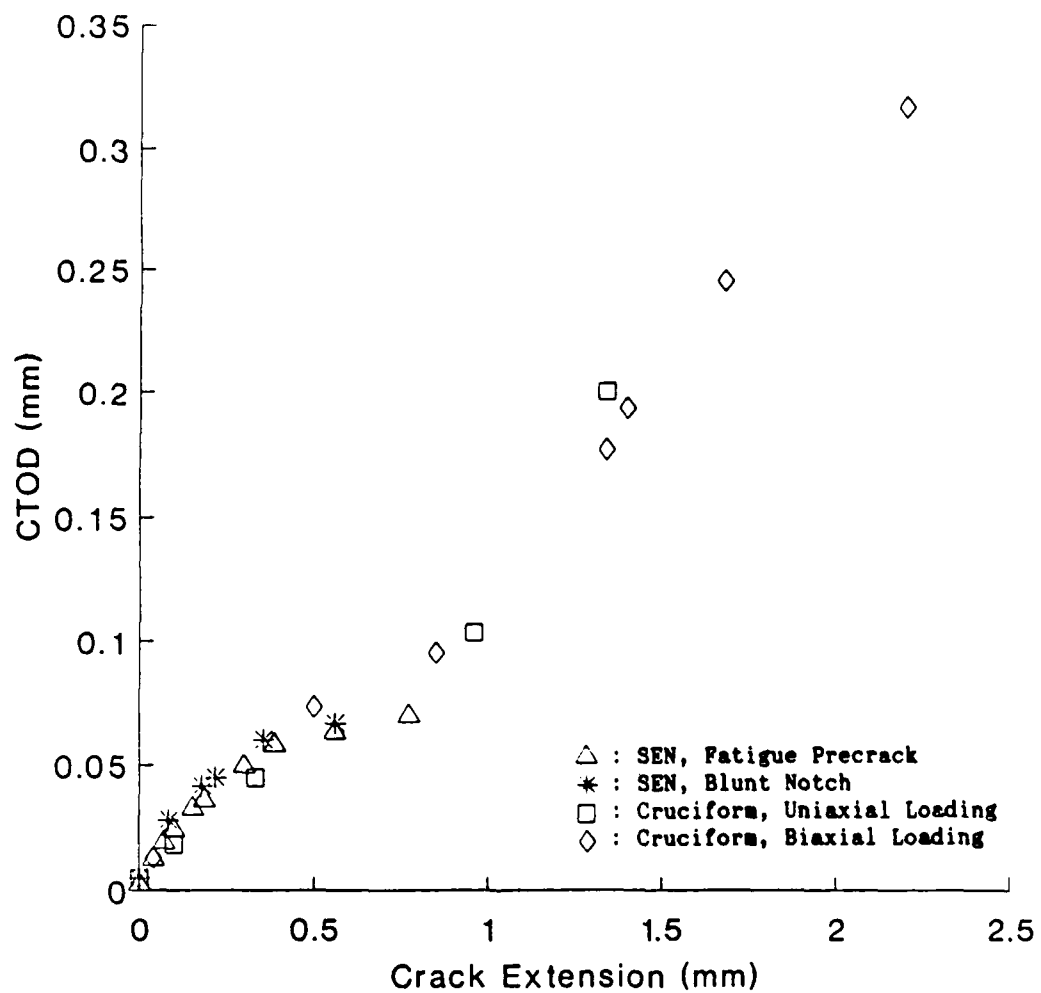


Fig. 7 CTOD Resistance Curves of 2024-0 Aluminum Small SEN and Large Single Edge Cracked, Cruciform Specimens.

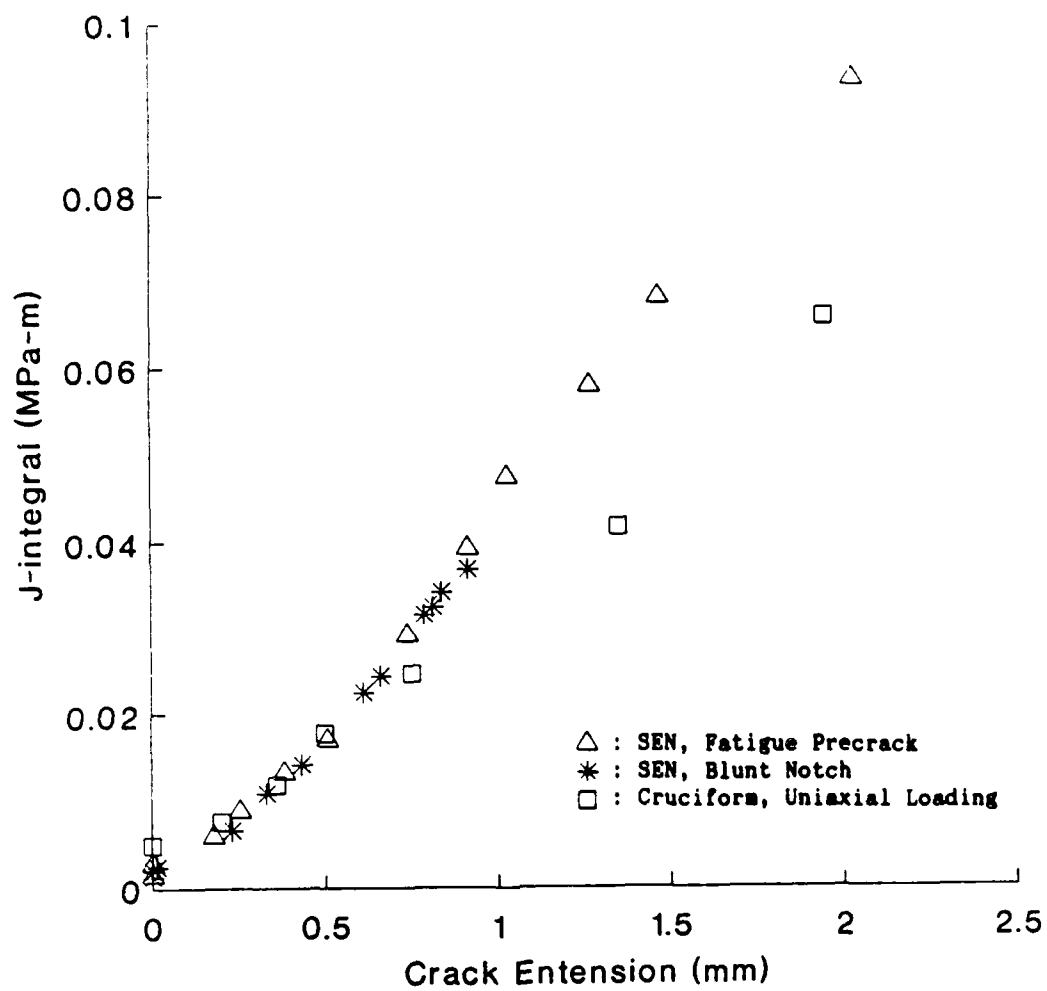


Fig. 8 J_R Curves of 5052-H32 Aluminum Small SEN and Large Single Edge Cracked, Cruciform Specimens.

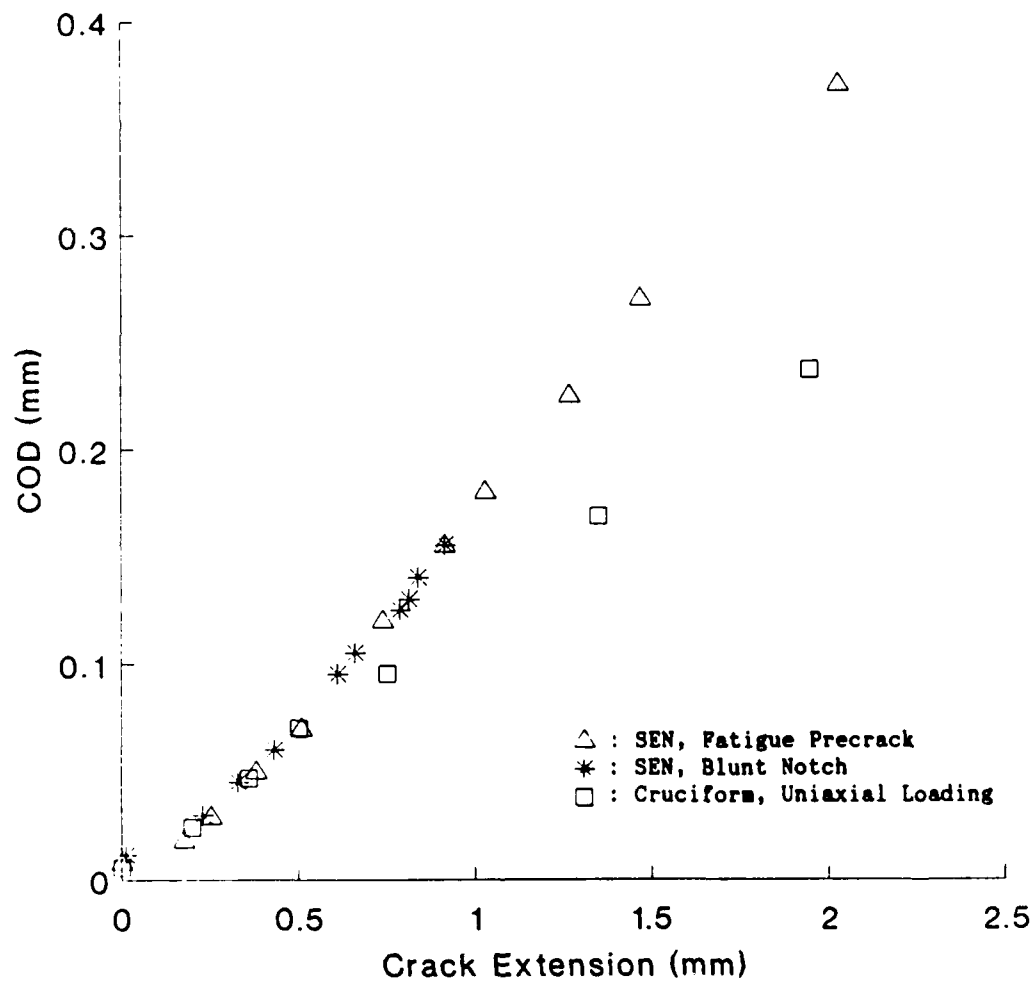


Fig. 9 COD Resistance Curves of 5052-H32 Aluminum Small SEN and Large Single Edge Cracked, Cruciform Specimens.

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18. SUPPLEMENTARY NOTES		
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Errors involved in using the approximate J-evaluation procedure are evaluated by comparing the resistance curves of large 2024-0 and 5052-H32 aluminum, single-edge cracked, cruciform specimens under uniaxial and biaxial loadings with those obtained by an exact procedure. This comparative study shows that under uniaxial loading, the J-resistance curves obtained by the approximate procedure are within six percent of those obtained by the exact procedure. For the biaxial loading, however, the difference is about eighteen percent. (over)		

20. Abstract (continued).

The specimen size and geometry dependence of the J-resistance curves of 2024-0 and 5052-H32 aluminum specimens are also discussed.