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Experimental Compliance Calibration of the Compact Fracture Toughness Specimen

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EXPERIMENTAL COMPLIANCE CALIBRATION OF THE COMPACT FRACTURE TOUGHNESS SPECIMEN

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SUMMARY

An experimental calibration of the compact fracture toughness specimen was performed to provide compliance and stress intensity coefficient values over a crack length to specimen width ratio range ($^a/W$) of 0.1 to 0.8. Displacements were measured at the load points, on the load line near the crack surface, and at the crack mouth. Load point displacements were obtained on the specimen loading hole surface central in the load application region. This measurement was accomplished by use of loading tubes and point gages which registered on the specimen through holes in the tube walls.

Compliance and stress intensity results were generally in agreement with the results of boundary collocation analyses now used for the specimen. Results emphasize the need to use load point displacements rather than load line displacements for the determination of stress intensity coefficients at the lower values of $^a/W$. Use of load line displacement rather than load point for energy determination in ductile fracture toughness measurement techniques would result in understatement of the energy over the entire range of crack length ratios investigated.

INTRODUCTION

The compact specimen is well established for the determination of plane strain fracture toughness (1). The specimen, with some slight dimensional variations from those detailed in reference 1, is now also used for a variety of other tests including fatigue crack propagation rate determination as a function of the stress intensity factor K (2), and elasto-plastic fracture analysis by J integral techniques (3).

The wide range stress intensity (K) calibration for the specimen by Srawley (4), which is included in the standard test method, was based on the analytical work of Newman (5). Newman's treatment was an improvement over the prior collocation work of Srawley and Gross (6) in that load distributions at the loading holes were modeled whereas in the prior analysis they were not. The two analyses give essentially the same results for the crack length to width ratio ($^a/W$) of 0.45 to 0.55 specified in the ASTM E-399 fracture toughness test method. For this range of crack length ratios, the crack tip stress fields are far enough from the load that they are not affected significantly by variations in loading.

The displacements at the points of load application are those critical for the derivation of a specimen's stress intensity (K) calibration or for the determination of the energy applied to a specimen in J integral fracture toughness methods. Experimental verification of the Newman work was limited to a comparison of crack mouth displacements with the unpublished experimental results of R. T. Bubsey and M. H. Jones of NASA Lewis. Because of the increased variety of usage of the compact specimen over wider ranges of crack length to specimen width ratios, a more extensive calibration of

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the specimen was warranted. This calibration was primarily based on load point displacements but also included those of the load line and crack mouth for comparison. This study was carried out in conjunction with the truncated round specimen (7).

STRESS INTENSITY CALIBRATION BY THE COMPLIANCE METHOD

The compliance method of determining the fracture toughness related crack-extension force ($\mathcal{G}$) calibration of a crack specimen type was established by Irwin and Kies (8). A complete discussion of the principle and method is found in reference 9. The compliance method is based on the relationship:

$$\frac{dC}{d(^a/W)} = \frac{2B\,\mathcal{G}_I W}{P^2}$$

where C is compliance, that is, load point displacement (f) per applied force (P); a is crack length; W specimen width; and B specimen thickness. For convenience the compliance is often described in a non-dimensional form, EfB/P, where E is the material's elastic modulus in tension. In practice a series of compliance values is obtained for increasing crack lengths with the crack approximated by a saw cut. A fitting function relating compliance with the ratio of crack length to width is then determined. Differentiation of this function provides the relationship of crack extension force to load and specific dimensions for any specimen of similar planar geometry.

The calibration reported here can be considered as being obtained from conditions approaching plane stress since a very small volume of the specimen approximates a plane strain state. A discussion of the relation of $\mathcal{G}$ and K_I in regard to the stress state attained in a calibration specimen as compared with that treated in an analytical solution is provided in reference 9.

COMPLIANCE MEASUREMENT PROCEDURE

Specimen

The compliance specimen of this investigation is shown in figure 1. It has the planar dimensional proportions specified in ANSI/ASTM test method E-399. Specimen material was 7075-T651 aluminum alloy with an elastic modulus (E) in tension of 7.19×10^4 MPa. The crack simulating saw cut was 0.61 mm in width.

Displacement Measurement

Displacements were measured at three locations: between (a) the load points (load point), (b) the notch surfaces at the loading center line (load line), and (c) the crack mouth knife edges (crack mouth). These points of displacement measurement are identified in figure 1. Separate displacement gages were used for each measurement. The crack mouth displacement was measured with a standard clip gage as detailed in the E-399 test method. The load line displacements were measured with a variation of the standard clip gage which had sharp conical points at the beam ends for registry at the middle of the specimen thickness.

In order to minimize any extraneous displacement component in the measurement of the load point displacements, a special method was developed for the determination of the displacement on the specimen itself in the middle of the load application area. This method is illustrated in figure 2 and is identical to that used on the truncated round specimen (7). Load was applied to the specimen with tubes rather than solid pins. The clip gage used for these measurements had extra-long arms with conical-point set screws at the beam ends. For the load point displacement measurements, the set screws protruded through 4.8 mm diameter holes in the loading tube walls and registered centrally on the load contact area at the mid thickness of the specimen.

The loading tubes were aged 300 grade maraging steel with wall thicknesses of 5.4 mm. Outside diameters of the loading tubes were 36.57 mm which complied with the pin diameter requirements of the E-399 test method. The clevis loading holes had flat loading surfaces to minimize frictional effects.

Loading Tubes

In preliminary use of hollow loading cylinders, it was observed that sufficient wall thickness was necessary so that the load versus load line displacement slope obtained using the loading tubes would be the same as the slope obtained using solid loading pins of equal diameter to the outside diameter of the tubes. It was assumed that if the load line and crack mouth displacement slopes obtained using loading tubes were equal to those using solid cylinders, the tubular wall was adequate to ensure that the load point displacement determined accurately described that which would occur using the solid pins.

The load versus displacement slopes for the four shortest slot lengths in the calibration were determined with both solid loading pins and the loading tubes previously described. The slopes agreed within +0.6 to -0.3 percent (avg + 0.3) at the load line and within +1.0 to -0.4 (avg +0.1) at the crack mouth. Because of this agreement, subsequent slope determinations for longer slot lengths were made using the loading tubes only.

Procedure

Each of the three displacement gages was calibrated prior to and following a compliance run. Each gage was calibrated over the specific range of gage opening it encountered at a particular slot length slope determination. Calibrations were made using an extensometer calibrator reading to a least division of 0.00127 mm. The gages were calibrated to the XYY' recorder channel on which the test displacement was registered.

Least squares linear regressions were made on all calibrations and the observed load-displacement slopes corrected accordingly. This procedure eliminated the need for exact adjustment of displacement gage excitation voltages with changes in recorder scales or amplifier gains. It also reduced any error which might have occurred due to slight non-linearities in the recorder calibrations.

A single 44.5 kN load cell was used for all compliance determinations. Slight modifications in excitation voltage were made based on the applicable load range. These adjustments were based on calibration of the load cell using a proving ring for loads exceeding 4.45 kN and using a dead weight system incorporating a 10:1 lever arm 1.016 m in length for loads of 4.45 kN or less. Load calibrating resistor checks were made prior to every compliance series.

Load versus displacement slopes were recorded on XYY' pen recorders. Four slope determinations were made for each crack length and the last three averaged for record. The first loading slope was disregarded in case it included irregularities due to load train alignment. A slight residual load was kept on the specimen between the four runs.

RESULTS

Compliance

Experimental compliance values for the three displacement locations are tabulated in table IA. The dimensionless form of compliance (EfB/P) is used where E is the elastic modulus in tension; f is the displacement at the load, P; and B is the specimen thickness. Polynomials were fitted to the experimental values by Dr. Bernard Gross, NASA Lewis Research Center, and the corresponding values obtained from these polynomials are listed with their percent variation from the experimental values. The polynomials are detailed in table IB.

Compliance values determined from the polynomials are compared in table II with those of Newman (10). These comparisons cover a range of $^a/_W$ from 0.10 to 0.80. This range extends beyond the recommended lower limit of the polynomials so that the full range of the experimental values could be examined.

Stress Intensity

Stress intensity coefficients, $KB\sqrt{W}/P$, derived from the polynomial for the load point compliances are compared in table III with those of the E-399 test method wide range polynomial. As in the comparison of the compliances, the lower recommended limit of $^a/_W$ for the analytical polynomial was extended to match the larger range of the experimental values.

Table IV provides a comparison of stress intensity coefficients derived from the polynomials fitted to the experimental compliance values for the load point and load line data. The agreement is good in the $^a/_W$ range of 0.35 - 0.80, but in the range 0.1 - 0.3 the displacement at the load line exceeds that at the load point by an amount which increases as $^a/_W$ decreases, reaching 45.9 percent at $^a/_W = 0.1$.

DISCUSSION AND CONCLUSIONS

The experimental work of this report in general corroborates the analytical work of Newman (5, 10) for both compliance and stress intensity values. Experimentally derived stress intensity coefficients agree with the analytic within +0.2 to -2.7 percent over the 0.2 - 0.8 $^a/_W$ range designated for the analytic solution. Extension of the analytical soution range to an $^a/_W$ of 0.1 so that the full range of experimental work could be considered gave stress intensity results differing by under 4 percent.

A divergence in the experimental and analytic compliance values appears at approximately an $^a/_W$ of 0.30 and increases with decreasing $^a/_W$. The particular hole modeling analysis used by Newman predicts greater compliances over this range than those obtained experimentally. Apparently

Newman recognized this possibility and established a lower a/W limit of 0.2 on his work.

The comparison in table IV of stress intensity coefficients obtained from experimental load point and load line displacements emphasizes further Newman's (10) precaution that load point displacements should be used for stress intensity derivations particularly when the crack tip is in the proximity of the loading holes; that is, at an a/W under 0.30 in the case of the E-399 test method specimen configuration.

It is also emphasized that considerable error in the determination of energy input to the specimen can result frpm the use of the load line displacement rather than load point. This is illustrated in table II by the differences in compliances measured at the load line and the load point for any given a/W. Use of the load line displacement will result in an understatement of energy over the entire range of a/W examined. The error in energy input is of particular note in the determination of ductile fracture toughness by J integral methods. The polynomials detailed in table IB provide a means for converting load line displacements to load point.

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DIMENSIONLESS COMPLIANCE, EfB/P

CRACK LENGTH TO WIDTH RATIO (a/W)	LOAD LINE DISPLACEMENT			LOAD POINT DISPLACEMENT			CRACK MOUTH DISPLACEMENT			CRACK LENGTH TO WIDTH RATIO, (a/W)
	EXPERIMENTAL	POLYNOMIAL	% DIFF.	EXPERIMENTAL	POLYNOMIAL	% DIFF.	EXPERIMENTAL	POLYNOMIAL	% DIFF.	
.078	3.68	3.68	0	11.23	11.30	+0.6	12.59	12.59	0	.078
.111	4.84	4.85	+0.2	11.94	11.83	-0.9	13.81	13.82	+0.1	.111
.150	6.46	6.43	-0.5	12.84	12.72	-0.9	15.59	15.51	-0.5	.150
.201	8.79	8.78	-0.1	14.08	14.35	+1.9	18.07	18.19	+0.7	.201
.225	9.97	10.02	+0.5	15.19	15.33	+0.9	19.57	19.68	+0.6	.225
.250	11.40	11.41	+0.1	16.76	16.51	-1.5	21.58	21.41	-0.8	.250
.274	12.88	12.87	-0.1	17.72	17.81	+0.5	23.16	23.27	+0.5	.274
.299	14.51	14.52	+0.1	19.45	19.36	-0.5	25.52	25.42	-0.4	.299
.327	16.56	16.57	+0.1	21.44	21.35	-0.4	28.37	28.14	-0.8	.327
.349	18.43	18.37	-0.3	23.18	23.14	-0.2	30.52	30.54	+0.1	.349
.400	23.24	23.27	+0.1	28.03	28.12	+0.3	36.90	37.10	+0.5	.400
.450	29.48	29.45	-0.1	34.41	34.44	+0.1	45.05	45.29	+0.5	.450
.500	37.57	37.55	-0.1	42.85	42.71	-0.3	55.69	55.89	+0.4	.500
.549	48.19	48.24	+0.1	53.17	53.54	+0.7	70.90	69.71	-1.7	.549
.599	63.53	63.51	- 0	69.09	68.93	-0.2	88.45	89.31	+1.0	.599
.650	86.40	86.64	+0.3	92.24	92.24	0	119.5	119.0	-0.4	.650
.700	122.6	122.7	+0.1	128.9	128.8	-0.1	163.7	165.3	+1.0	.700
.749	184.9	183.5	-0.8	191.4	190.7	-0.4	245.8	243.4	-1.0	.749
.800	303.5	305.4	+0.6	313.5	315.2	+0.5	397.4	399.0	+0.4	.800
.850	571.3	570.4	-0.2	585.5	584.5	-0.2	731.3	730.8	-0.1	.850

TABLE IA. - EXPERIMENTALLY DETERMINED COMPLIANCE VALUES WITH THE COMPARABLE VALUES FROM FITTED POLYNOMIALS (TABLE IB)

$$\ln\left[EfB/P\right] = A + B(a/W) + C(a/W)^2 + D(a/W)^3 + \cdots$$

DISPLACEMENT, f, LOCATION *	COEFFICIENT VALUES **					
	A	B	C	D	E	F
LOAD LINE	0.440	13.46	-35.97	73.22	-76.84	35.16
LOAD POINT	2.376	0.060	7.298	0.107	-15.21	14.75
CRACK MOUTH	2.326	2.580	0.382	8.143	-18.69	14.77

* SEE FIG. 1
* * SOURCE: Dr. B. Gross, NASA-LEWIS

TABLE IB. - COEFFICIENTS OF POLYNOMIALS FIT TO EXPERIMENTAL COMPLIANCE DETERMINATIONS

CRACK LENGTH TO WIDTH RATIO, a/W	DIMENSIONLESS COMPLIANCE, EfB/P					
	LOAD LINE		LOAD POINT		CRACK MOUTH	
	EXPERIMENTAL POLYNOMIAL	NEWMAN(10)	EXPERIMENTAL POLYNOMIAL	NEWMAN(10)	EXPERIMENTAL POLYNOMIAL	NEWMAN(10)
0.10	4.45	5.01 *	11.63	12.66 *	13.39	13.61 *
0.15	6.43	6.58 *	12.72	13.44 *	15.50	15.34 *
0.20	8.73	8.55	14.32	14.83	18.13	17.70
0.25	11.41	11.13	16.51	16.95	21.41	20.90
0.30	14.59	14.22	19.43	19.72	25.52	24.90
0.35	18.45	18.03	23.22	23.32	30.65	29.88
0.40	23.27	22.80	28.12	27.98	37.10	36.16
0.45	29.45	28.90	34.44	34.02	45.29	44.22
0.50	37.55	36.92	42.71	42.04	55.89	54.74
0.55	48.50	47.84	53.80	52.94	70.04	68.98
0.60	63.88	63.32	69.30	68.42	89.78	89.02
0.65	86.64	86.28	92.24	91.54	119.0	118.7
0.70	122.7	122.7	128.8	127.9	165.3	165.5
0.75	185.1	185.4	192.3	190.6	245.5	245.4
0.80	305.4	303.0	315.2	308.2	399.0	395.0

* VALUES BEYOND SUGGESTED a/W LIMIT FOR ANALYTIC SOLUTION

TABLE II. – A COMPARISON OF COMPACT SPECIMEN DIMENSIONLESS COMPLIANCES FROM POLYNOMIALS OF EXPERIMENTAL RESULTS (TABLE IB) AND FROM ANALYTIC SOLUTIONS WHERE PIN LOADING WAS MODELED

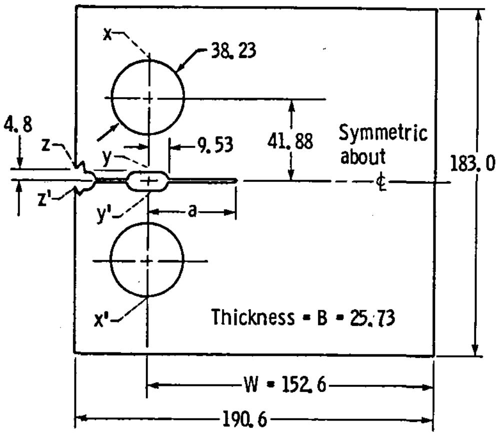
CRACK LENGTH TO WIDTH RATIO, a/W	STRESS INTENSITY COEFFICIENT, $KB\sqrt{W}/P$		
	FROM LOAD POINT EXPERIMENTAL POLYNOMIAL	SRAWLEY (4)	PER CENT DIFFERENCE
0.10	2.92	3.03 *	3.6
0.15	3.65	3.65 *	0
0.20	4.33	4.27	−1.4
0.25	5.03	4.92	−2.2
0.30	5.77	5.62	−2.7
0.35	6.56	6.39	−2.7
0.40	7.45	7.28	−2.3
0.45	8.48	8.34	−1.7
0.50	9.74	9.66	−0.8
0.55	11.38	11.36	−0.2
0.60	13.62	13.65	0.2
0.65	16.83	16.86	0.2
0.70	21.64	21.55	−0.4
0.75	29.18	28.86	−1.1
0.80	41.64	41.20	−1.1

* VALUES BEYOND SUGGESTED a/W LIMIT FOR ANALYTIC SOLUTION

TABLE III. – COMPARISON OF COMPACT SPECIMEN DIMENSIONLESS STRESS INTENSITY COEFFICIENTS DERIVED FROM EXPERIMENTAL RESULTS WITH THOSE OF THE WIDE RANGE EXPRESSION OF THE ASTM E 399 TEST METHOD

CRACK LENGTH TO WIDTH RATIO, a/W	STRESS INTENSITY COEFFICIENT, $KB\sqrt{W}/P$, FROM EXPERIMENTAL DATA		
	LOAD POINT	LOAD LINE	PER CENT DIFFERENCE
0.10	2.92	4.26	+45.9
0.15	3.65	4.63	+26.8
0.20	4.33	4.98	+15.0
0.25	5.03	5.39	+ 7.2
0.30	5.77	5.90	+ 2.3
0.35	6.56	6.55	− 0.2
0.40	7.45	7.36	− 1.2
0.45	8.48	8.38	− 1.2
0.50	9.74	9.66	−0.8
0.55	11.38	11.32	− 0.5
0.60	13.62	13.57	− 0.4
0.65	16.83	16.75	−0.5
0.70	21.64	21.48	− 0.7
0.75	29.18	28.89	− 1.0
0.80	41.64	41.21	− 1.0

TABLE IV.- COMPARISON OF LOAD POINT STRESS INTENSITY COEFFICIENTS WITH THOSE DERIVED FROM LOAD LINE COMPLIANCES



Displacement points:
xx' - load point
yy' - load line
zz' - crack mouth

Dimensions in mm

Figure 1. - Compact compliance specimen.

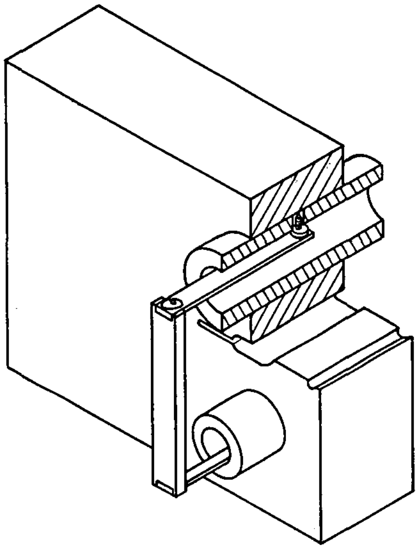


Figure 2. - Schematic of load displacement measurement.

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16. Abstract

Compliances and stress intensity coefficients were determined over crack length to width ratios from 0.1 to 0.8. Displacements were measured at the load points, load line, and crack mouth. Special fixturing was devised to permit accurate measurement of load point displacement. The results were generally in agreement with the currently used results of boundary collocation analyses. Results emphasize the errors which occur in stress intensity coefficients or specimen energy input determinations made from load line displacement measurements rather than from load point measurements.

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