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$\partial C/\partial a$ Calibration of a Contoured Cantilevered Beam Specimen

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Materials Sciences Laboratory

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13 ABSTRACT

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FOREWORD

This report is published by The Aerospace Corporation, El Segundo, California, under Air Force Contract F04701-71-C-0172.

This report, which documents research carried out from January through April 1971, was submitted on 10 February 1972 to Captain Gary R. Edwards, SYAE, for review and approval.

Approved

W. C. Riley, Director
Materials Sciences Laboratory

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Gary R. Edwards, Capt, USAF
Project Officer

ABSTRACT

The contoured double cantilever beam specimen is reexamined to determine the effect of rigid extensions of the cantilever arms. The relationships between the apparent compliance, measured on the extension arm, and the true compliance, measured at the load points, are determined experimentally and compared with corrections estimated from beam theory and a "linear correction" method. It is shown that the correction factors required are large and can only be adequately determined by direct experiment.

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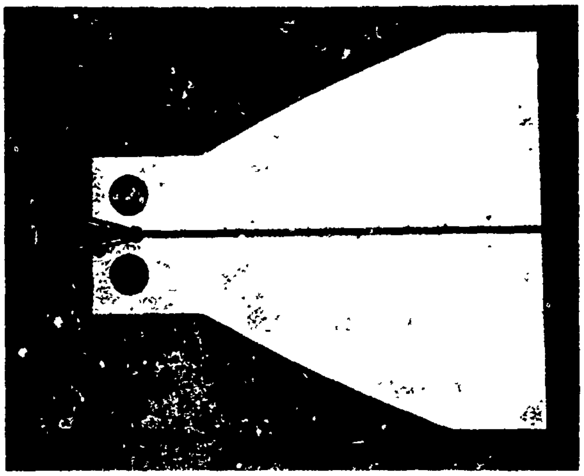
I. INTRODUCTION

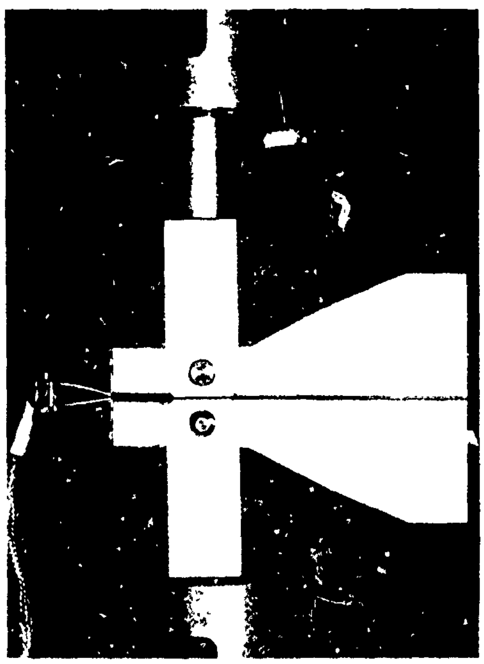
The contoured double cantilever beam (DCB) specimen is finding wide usage in fracture toughness testing, fatigue testing, and determination of material susceptibility to stress-corrosion cracking (SCC). Mostovoy (Ref. 1) presents the shape requirements for the DCB on the basis of a mathematical approach and suggests methods for its applications. Amateau (Refs. 2 and 3) has extensively used the contoured DCB specimen to characterize the fatigue properties and corrosion fatigue properties of Ladish D6AC and Ti-6Al-6V-2Sn alloy in various environments. Using a tapered DCB specimen, Van der Sluys (Ref. 4) has demonstrated its usefulness in stress-corrosion studies by measuring subcritical crack growth rates in AISI 4340 in an aqueous environment at various applied stress intensities.

Often, it is necessary to measure the compliance at positions not located directly in the line of loading. For example, in SCC studies, it is occasionally necessary to mount the opening displacement measuring device away from the specimen load line (Fig. 1) for protection from the environment. Another advantage is that the measured opening is somewhat increased because of a lever-like geometrical relationship (Fig. 2). At large extension distances D, it is possible to use various types of crack opening displacement measurement techniques.

However, when one attempts to determine the compliance C from crack opening displacements δ measured at points removed from the physical line of loading, certain correction factors must be applied. These factors, of



(a)



(b)

Fig. 1. Contoured DCB specimen with compliance gauge: (a) at line of loading and (b) at distance D = 2 in. from the line of loading, with recommended ASTM fixtures

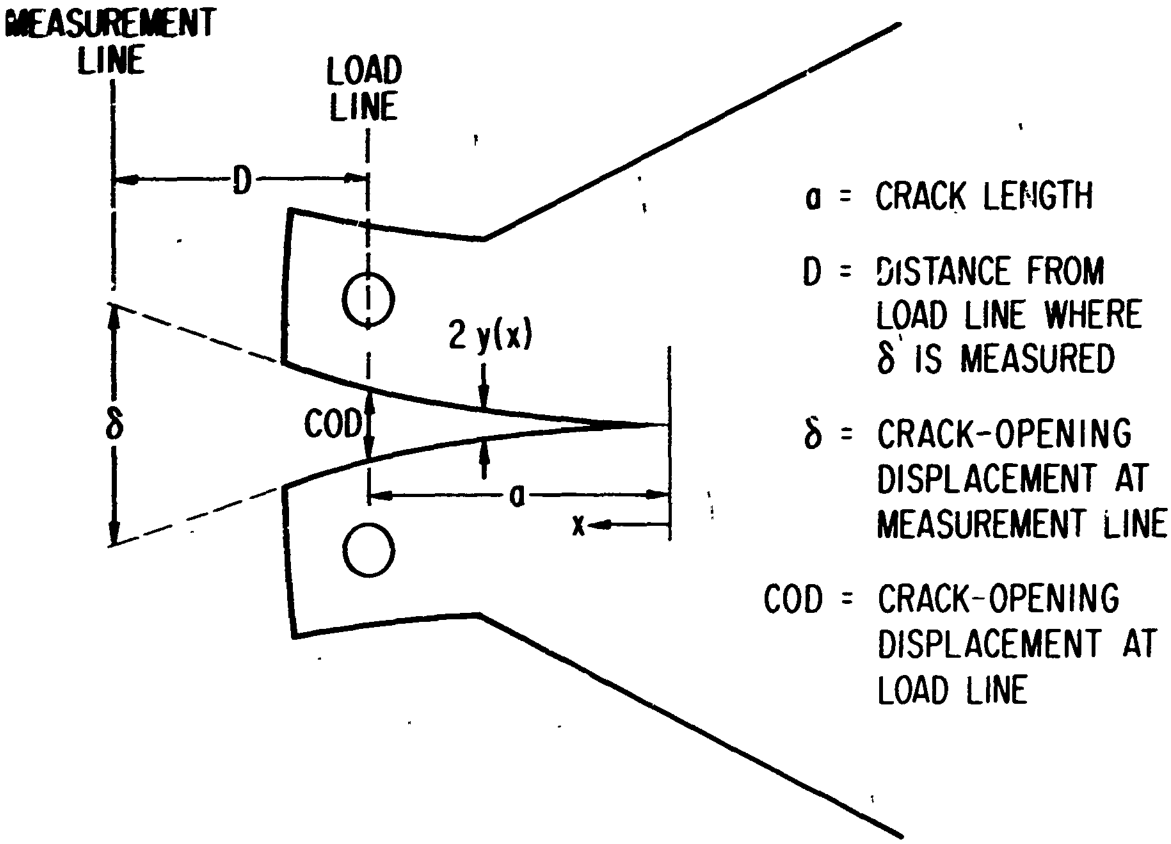


Fig. 2. Diagram showing the relationship of the defined variables

course, are related to the actual displacements and strains that occur in loading the entire system to a given load. Correction factors related to the effect of measurement extensions have not been openly reported in the literature. Gallagher (Ref. 5) has studied data reduction techniques for mea are-ments presumably taken on the load line but does not address the present problem of the effect of measurement location. The purpose of this study was to derive a relationship between the apparent rate of change of compliance measured at the device $[\partial(\delta/P)/\partial a]_D$ and the true rate of change of compliance measured at the load line $\partial C/\partial a$.

The latter factor is appropriate for determining stress intensity factors through the relationship:

$$K_{I(nominal)} = P\left(\frac{E(\partial C/\partial a)}{2b(1 - \nu^2)}\right)^{1/2} \tag{1}$$

where

$K_{I(nominal)}$ = nominal plane strain stress intensity

P = load

E = elastic modulus

ν = Poisson's ratio

b = specimen width

This relationship has been further refined by Freed and Krafft (Ref. 6) to account for side grooving by the following relationship:

$$K_I = K_{I(nominal)} (b/b_n)^m \tag{2}$$

where

K_I = plane strain stress intensity

b_n = crack front width

m = experimental parameter ($0.5 \le m \le 1.0$).

The m parameter essentially accounts for the combined effects of side grooving and anistropy of the material, which affect the crack front stress intensity parameter. In this study, the b/b_n ratio was maintained as a constant.

II. APPROACH

Two simplified postulates concerning the elastic deformation of the beam can be made as starting points for the estimation of the appropriate correction effects. The first approach is to assume that most of the deformation is due to a wedging effect at the crack tip. The material beyond the crack elastically deforms, resulting in a rotation and, hence, opening of the material on either side of the crack. In this extreme idealization, the beams are assumed rigid. In this case, the obvious correction is merely due to the length of the lever arms, and a linear correction technique (linear extrapolation of opening displacement from measuring point to load line) produces a linearly corrected compliance C_L:

$$C_L = \left(\frac{a}{a + D}\right)\left(\frac{\delta}{P}\right) \quad . \tag{3}$$

The second simplified approach is to assume that deflections in the specimen are simply those predictable by variable section cantilevered beam theory analysis, i.e., arm bending. This approach is somewhat attractive as Mostovoy indeed derived the appropriate specimen contour on such a basis.

By insertion of the actual specimen dimensions into the appropriate differential equation of beam theory, the openings under unit load at any point on the specimen crack line may be calculated. Of course, the opening per unit load at the crack line is, by definition, the compliance.

A typical plot of crack line opening per unit load vs the location on the crack plane is shown in Fig. 3 for a specimen with $E = 30 \times 10^6$ psi, $m = 4$ in.$^{-1}$,

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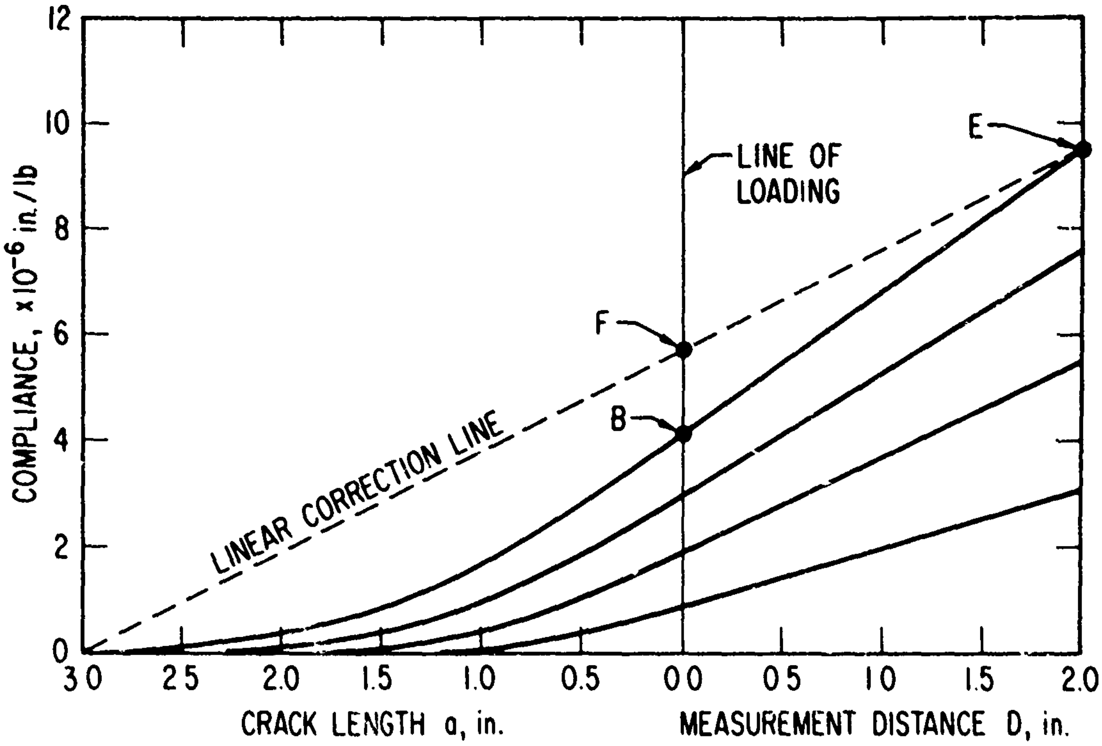


Fig. 3. Compliance based on beam theory analysis at various positions

and b = 0.5 in. for various crack sizes. It should be noted that the x coordinate of each case is shifted so that the line of loading occurs at a common point. Further, note that the simple linear correction shown as a dashed line for one case (a = 3.0 in., D = 2 in.) would fail to predict the true beam theory compliance at the line of loading; i.e., point E represents the measured compliance δ/P, point F represents the compliance C_L, and point B represents the true compliance C. The slopes $\partial y/\partial x$ are given in Fig. 4, which shows the stiffening effect of the square end. The stiffening effect clearly reduces the slope of the rigid extensions.

Because each of these corrections produces significantly different compliances when applied to the same measured compliance, it is of some importance to consider the selection of either. In actuality, the measured deflections will almost certainly consist of arm bending and wedge opening effects. Thus, direct experimental studies form the most clearly defined correction factor. In fact, the remainder of this report deals with the experimental determination of these correction factors and the comparison of this factor to those obtained from the above idealizations.

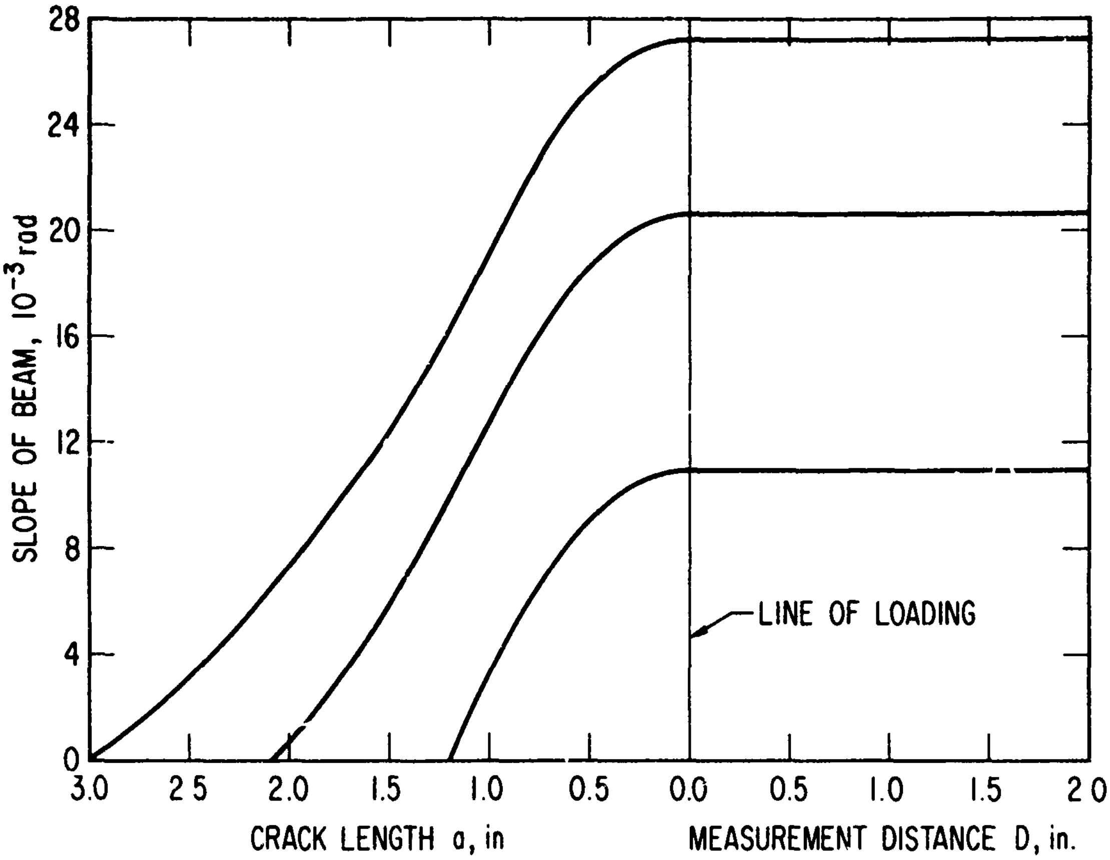


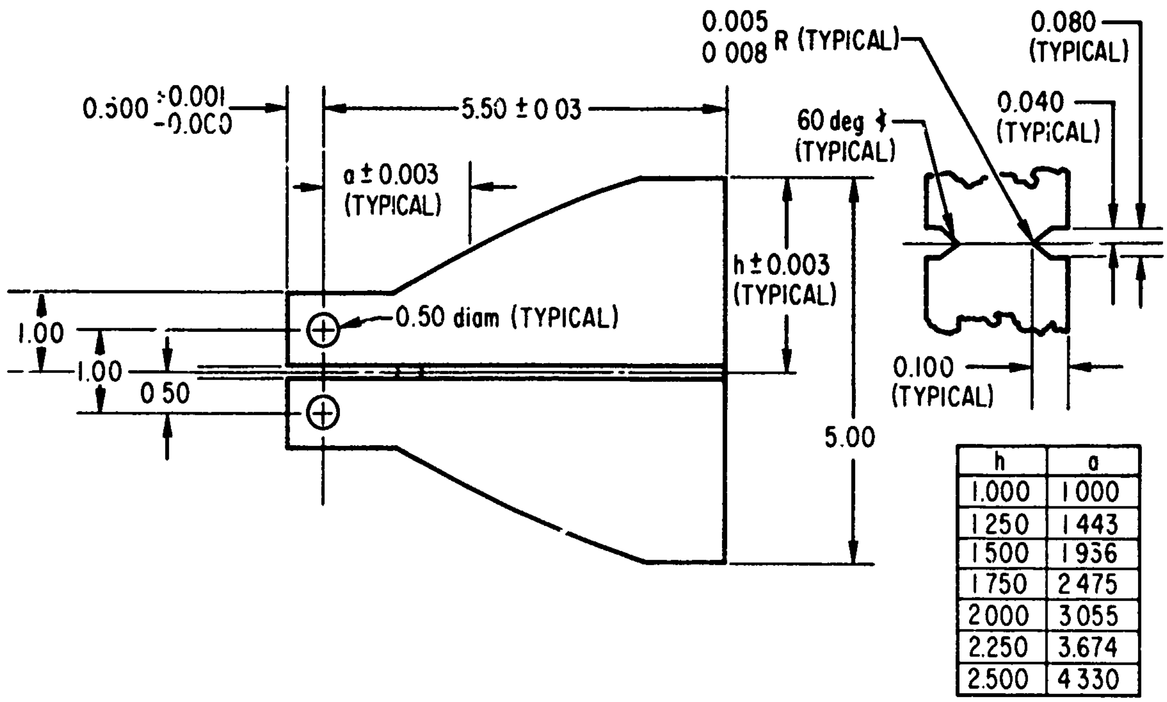
Fig. 4. Slope dy/dx based on beam theory analysis

III. EXPERIMENTAL PROCEDURE

Contoured DCB specimens were machined from E-4340 HR steel heat treated R_c-53 and annealed Ti-6Al-6V-2Sn alloy. Specimen dimensions are given in Fig. 5. A slot was made so that a clip-on compliance gauge could be used at the line of loading (Fig. 1a). The crack was extended as required by electrical discharge machining (EDM) with a 10-mil thick brass cutter. Since this study is directed only at the elastic behavior of the specimen, fatigue precracking was not required.

The compliance gauge follows the suggestions of ASTM Committee E-24 (Ref. 7). Calibration of the clip-on gauge was performed with a dial micrometer calibrator with a resolution of 0.0001 in. Binding and friction problems at the load pins were avoided through use of the recommended fixtures per ASTM Committee E-24 (Ref. 7). In addition, the pins were greased with MoS_2.

Compliance determination was conducted on a 20,000-lb Instron testing machine. The load and the COD were simultaneously recorded with the Instron recorder operating in the X-Y mode. Compliance was determined at several crack lengths ranging from 1.2 to 3.1 in. The different locations D, from the line of loading, were performed by inserting aluminum blocks between the knife edge blade and specimen edge (Fig. 1b). At each crack length a and position of measurement D, four runs were performed. The curve was examined for a hysteresis effect, which was found to be minimal. The maximum load applied was approximately 50% of the load to cause catastrophic failure.



h	a
1.000	1 000
1 250	1 443
1 500	1 936
1 750	2 475
2 000	3 055
2.250	3.674
2.500	4 330

Fig. 5. Contoured double cantilever beam specimen

IV. RESULTS

Figure 6 shows typical COD vs load of Ti-6Al-6V-2Sn at various measurement positions. A 200-lb preload was used for minimization of possible initial loading errors. The slope $(\partial\delta/\partial P)_D$ yields the compliance at that specific crack length where δ is the COD measured at $D > 0$. It can be seen that COD increases as the measurement extension D is increased. Figures 7 and 8 show the results obtained from testing of Ti-6Al-6V-2Sn and E-4340 HR. Note the increase in $\partial(\delta/P)/\partial a$ as D increases. A summary of these results is presented in Table 1. This table also includes linearly corrected data, $\partial C_L/\partial a$. All data are least squares fitted. Note that linearly correcting the compliance data still will not produce the desired $\partial C/\partial a$ as directly measured at the load line; i.e., $D = 0$.

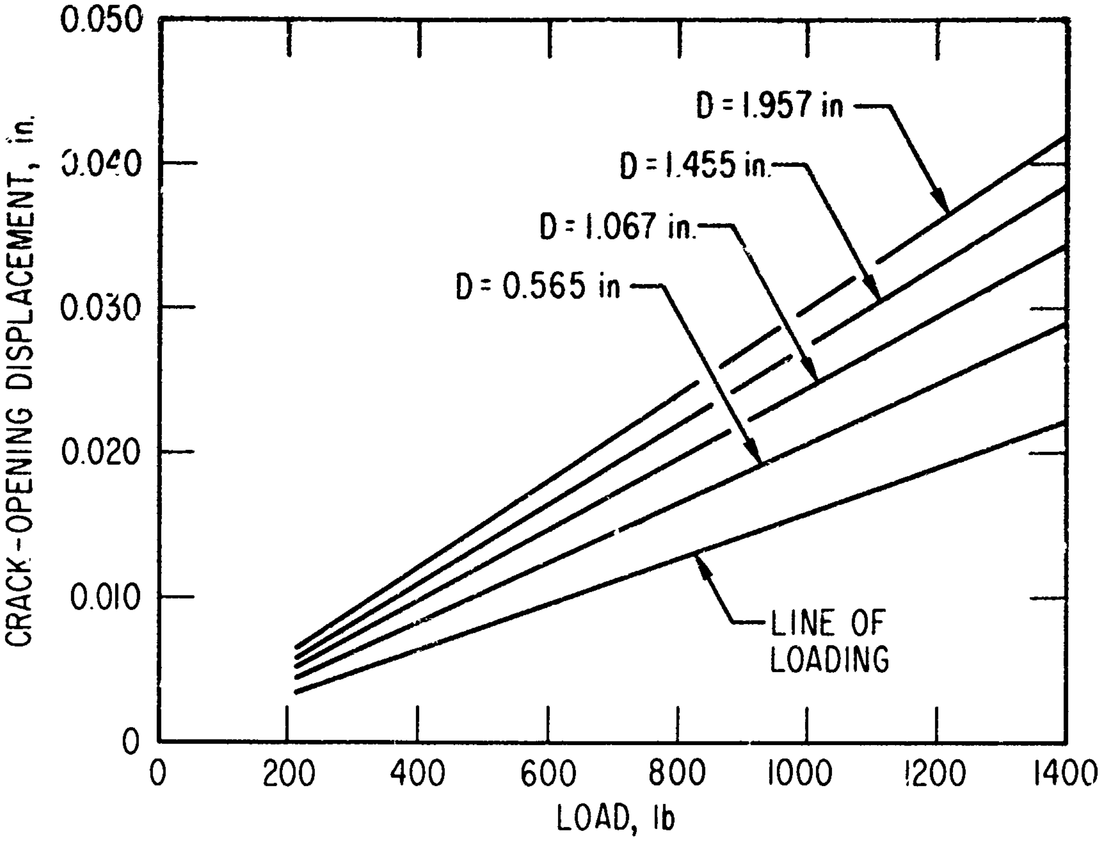


Fig. 6. Typical data of COD vs load of Ti-6Al-6V-2Sn at a crack length of 2.713 in.

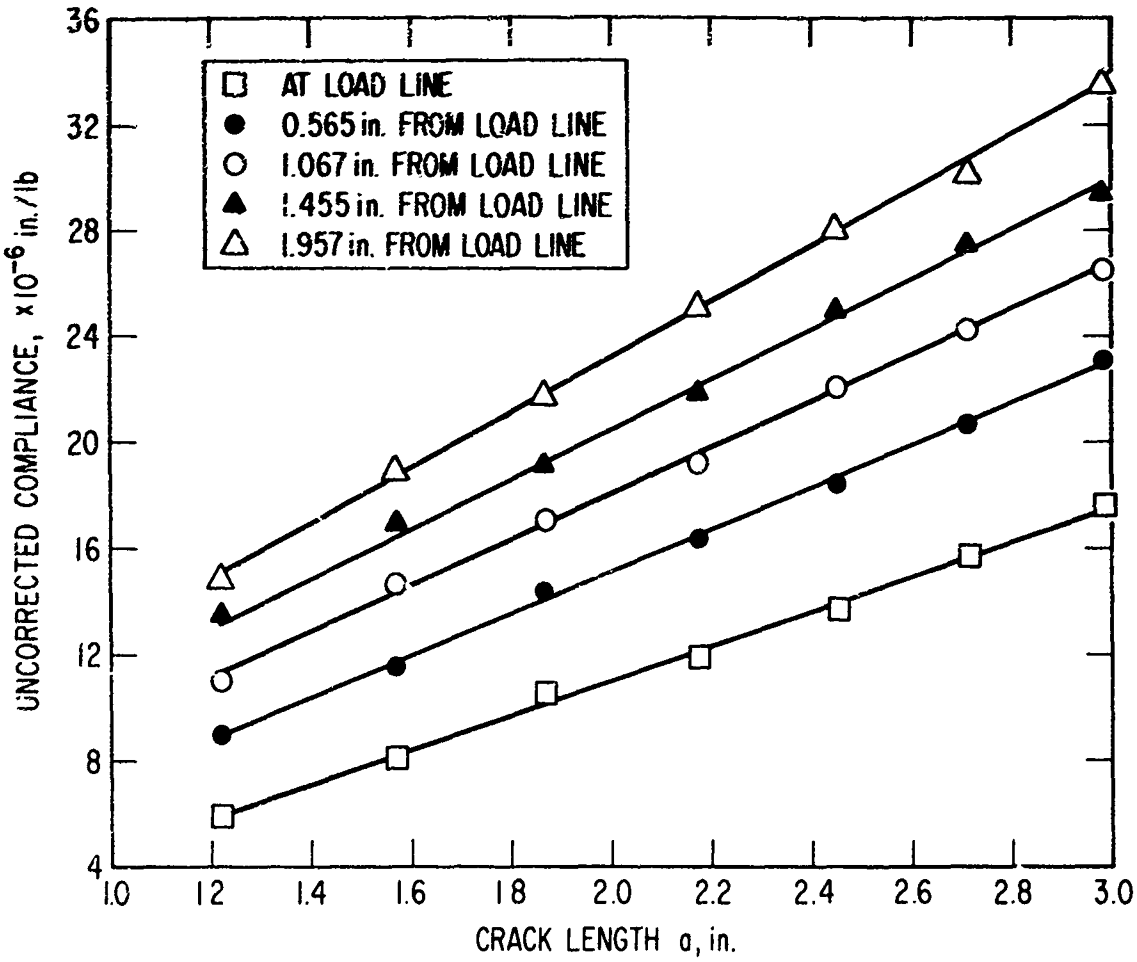


Fig. 7. Results of Ti-6Al-6V-2Sn material showing the compliance of various crack lengths measured at different positions

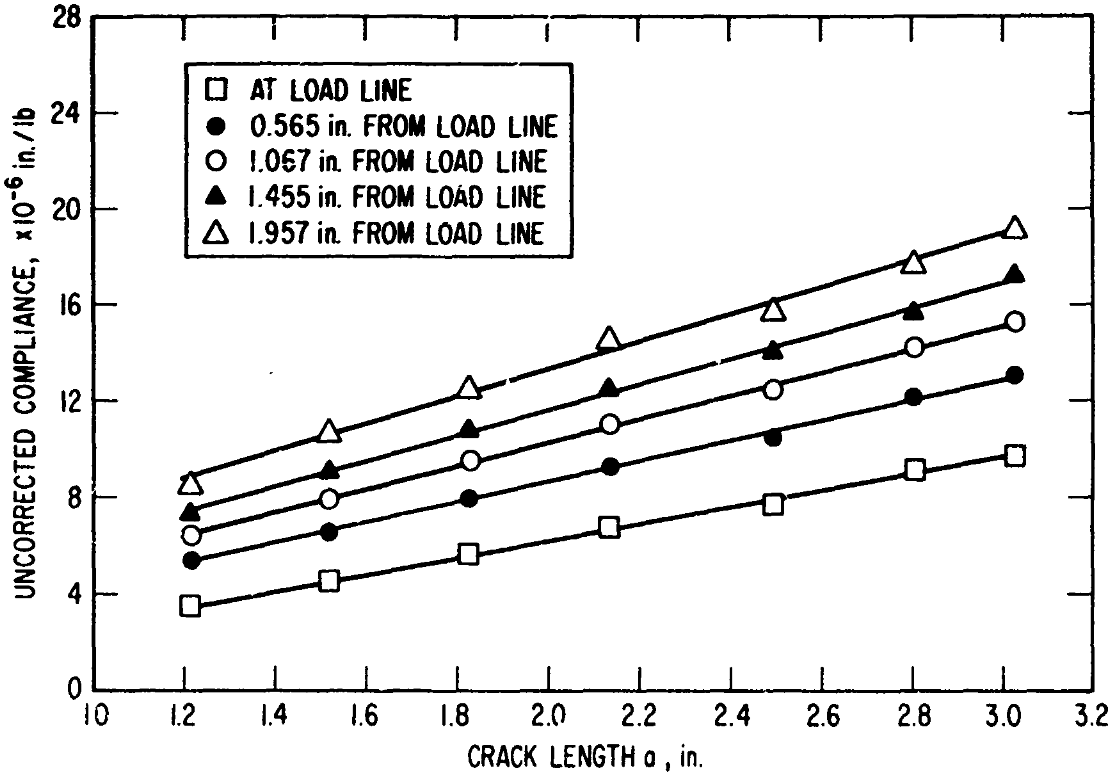


Fig. 8. Results of E-4340 HR steel material showing the compliance at various crack lengths measured at different positions

Table 1. Summary of Results

Material	Experimental, $[\partial(\delta/P)/\partial a]_D$ ($\times 10^{-6}$ lb^{-1})					Linear Corrected, $\partial C_L/\partial a$ ($\times 10^{-6}$ lb^{-1})			
	Measured Distance D					Measured Distance D			
	0.000	0.565	1.067	1.455	1.957	0.565	1.067	1.455	1.957
Ti-6Al-6V-2Sn	6.50[a]	7.89	8.65	9.38	10.42	7.45	7.68	7.93	8.18
E-4340 HR Steel	3.48[a]	4.23	4.85	5.28	5.68	4.04	4.34	4.16	4.22

[a] $\left(\frac{\partial(\delta/P)}{\partial a}\right)_{D=0} = \frac{\partial C}{\partial a}$

V. DISCUSSION

A comparison of the beam theory predicted crack opening displacements (Fig. 3) with the experimental E-4340 HR data (Fig. 3) reveals a large disparity. This disparity, exceeding a factor of two, carries with it the implication that any corrections derived from beam theory to account for the effect of the extension distance D are subject to considerable question. The bending of the specimen arms accounts for only a portion of the actual crack opening. This effect could have been anticipated by the fact that the beam theory predicted value for $\partial C/\partial a$ measured at the load points is lower than experimentally observed (Ref 1). Therefore, we dismiss beam theory corrections from further consideration.

The linear corrections for $\partial C/\partial a$, which essentially neglect the effect of arm bending, are summarized in Table 1. These are replotted as ratios of the $\partial C/\partial a$ values obtained at the load line in Fig. 9. If the compliance measured at the load line were indeed linear with crack size and if the linear correction were correct, all ratios would be unity instead of the approximate value of 1.2. The compliance at the load line obeys a good linear relationship, as is seen in Figs. 7 and 8, for both the titanium and steel specimens studied. From the beam theory results, it is known that appreciable arm bending does indeed occur, and, therefore, the conditions required for the validity of the linear approximation are violated. Consequently, the ratios in Fig. 9 are different from unity; and the linear correction results, in approximately 20% error for $\partial C/\partial a$.

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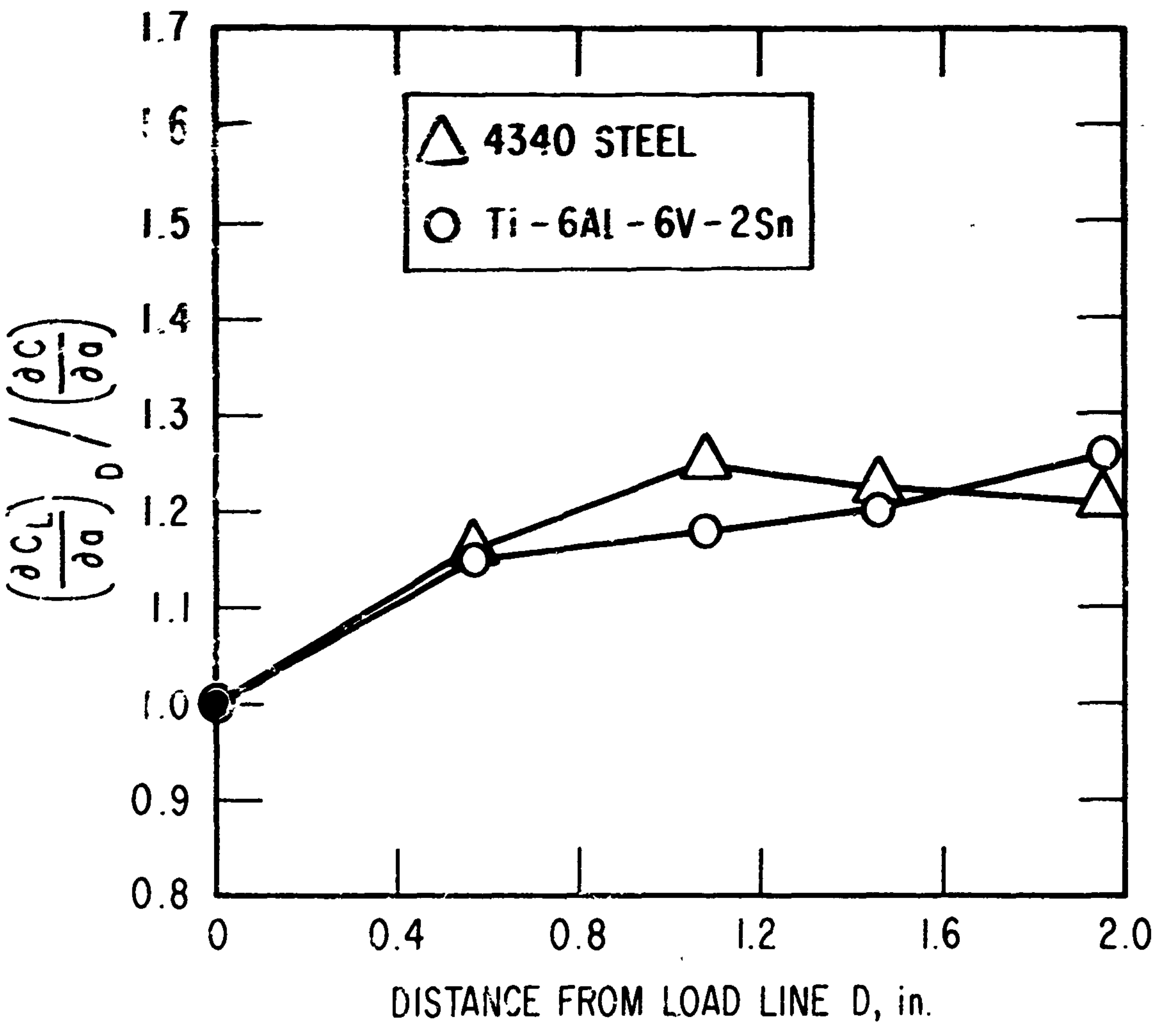

Fig. 9. Error in geometric linear approximations

Thus, direct experiment appears to be the only rational basis for correction, except for possibly a comprehensive complete finite element analysis of the specimen. The ratio of the measured openings per unit load evaluated at the measurement point D to those at the load line are given in Fig. 10 for various extensions D. These data points represent the experimentally determined factors that must be applied to the experimental data obtained at points other than the load line to correct to data obtained at the load line. We have included the single datum point available from McDonnell Douglas, St. Louis, which confirms the present results (Ref. 8).

Since the normalization or ratio procedure incorporates the modulus effect, these curves are valid for all sufficiently isotropic materials when used in this specimen geometry. It is implicitly assumed that plastic zone size effects were insignificant in the present experimental study.[1] The experimental data appear well fit by:

$$[\partial(\delta/P)/\partial a]_D = (\partial C/\partial a)(1.0 + 0.325\ D) \tag{3}$$

which was obtained by a least squares fit constrained to yield unity for zero extension. It, therefore, appears as if significant correction factors must be applied to experimental data obtained with extension arms. The above relationship expresses the interrelationship between the data so obtained and the results that would have been obtained at the load line.

[1] Plastic zone sizes r_p estimated from $r_p = (1/2\pi)(K_c/\sigma_{YS})^2$ are of the order of 0.01 in. or less.

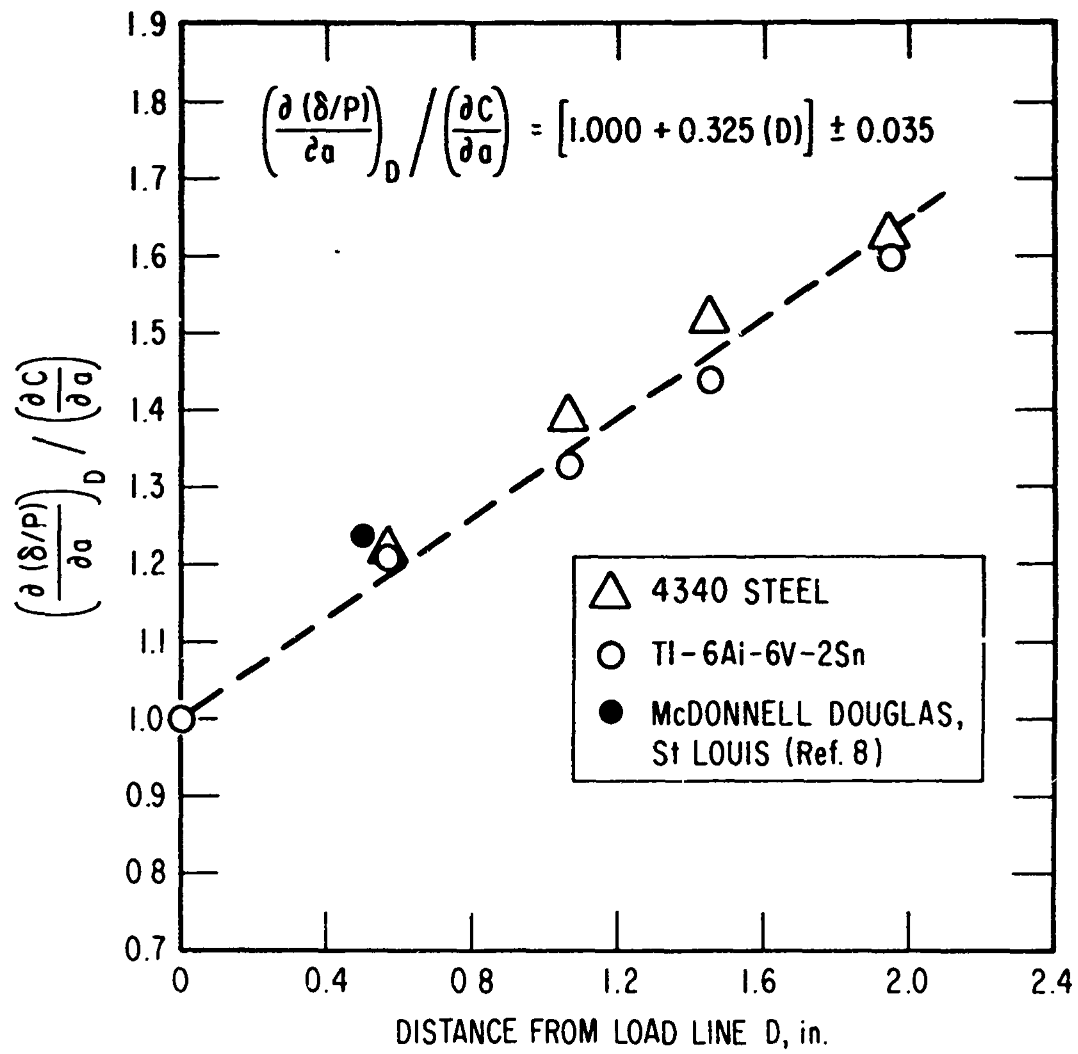

Fig. 10. Experimental correction factor

VI. CONCLUSIONS

The contoured DCB specimen is not well described by beam theory. While significant bending in the specimen arms does occur, the actual displacements at the load line significantly exceed those calculated from beam theory. However, the arm bending is not to be ignored, and a rigid wedge opening is also an invalid description of the crack opening. The net effect is to require that certain corrections must be applied to measurements that are to be made with specimens utilizing arm extensions. The corrections required for the raw $\partial C/\partial a$ data can exceed 60%. Data obtained through the use of a linear correction with no arm bending assumed is in error by approximately 20%. When extensions are used with any compliance measurement with any specimen, a direct experimental determination of the effect of extension is required.

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