# AN EMPIRICAL APPROACH TO DETERMINING K FOR SURFACE CRACKS

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## ABSTRACT

Fatigue crack growth data has been obtained and used in combination with newly developed marking techniques, using high stress ratios to delineate the crack progression for corner cracks at holes and surface cracks in tension loaded rods. Experimental stress intensity factors (K's) were developed using 9Ni steel plate and fatigue marking for the following parameters: hole diameter to plate thickness ratios of 0.5 and 1.0, crack depth to length ratio of 1.0 to 1.3 for both single corner cracks and double corner cracks on diagonally opposite faces of open holes. Normalized stress intensities have also been developed for the more complex case of a corner crack at the base of a countersink. Comparison of the experimental K's with current analytical values indicate the necessity for including a variable crack aspect ratio in any analytical scheme. The trend in normalized stress intensity (β) for surface cracks in tension loaded rods developed by fatigue crack growth, are shown to agree quite well with those obtained from compliance. However, the shape of the natural crack front resulted in β factors more representative of the problem with values 40% lower than those obtained from simulated cracks.

## KEYWORDS

Fracture mechanics analysis; fatigue crack growth; stress intensity factors; three dimensional cracks; experimental techniques.

## INTRODUCTION

In the tear-down and subsequent inspection of aircraft structure, cracks are predominately found in the fastener holes. The majority of these cracks start as part-through, corner cracks. Due to increased thickness of some areas, the crack can become critical prior to reaching a through-crack condition. Until recently, the only applicable stress intensity (K) solution was that of Bowie (1961) which has been used successfully by several investigators (Broek & co-workers, 1971; Grandt, 1974; Liu, 1972; and Shah, 1974) to analyze both fracture and crack growth from holes. The through-crack solution has been modified to analyze the part-through symmetrical crack (crack depth equals crack length) with varying degrees of success (Newman, 1976; Brussat, 1977; Hsu, 1978; Wilhem, 1979). One difficulty in obtaining a viable stress intensity solution is the three dimensional nature of the part-through crack problem coupled with a changing K with crack growth along the crack front. Recent studies by Raju and Newman (1978) and McGowan & Smith (1974), using three dimensional finite element analysis and the photoelastic results of Smith and co-workers (1979) have confirmed the changing stress intensity for this problem. This variability has also been demonstrated experimentally in metals by the results of Brussat (1977) and Wilhem (1979). One way to determine the stress intensity factors for complex three dimensional crack problems is by the James-Anderson (1969) approach. They showed that basic fatigue crack growth data obtained from known stress intensity specimens could be used in combination with unknown stress intensities (the complex problem), through a fatigue crack growth matching technique. This approach has been used with good success in this study for corner crack growth at countersunk and non-countersunk holes, as well as surface cracks in tension loaded round bar or bolt.

## CORNER CRACK(S) AT HOLES

Three (3) distinct flaw geometries were examined for the corner crack at an open hole; single corner crack at a straight hole, single corner crack at the base of a countersink and diagonally opposite corner cracks at a straight hole. The configuration of coupon and preflaw are shown in fig. 1. HP-9Ni-4Co-.2C steel, 1.41GPa ultimate strength, 0.0064m thick were studied for the straight hole problem. As noted in fig. 1, two (2) hole diameters were examined, 0.0064m and 0.013m.

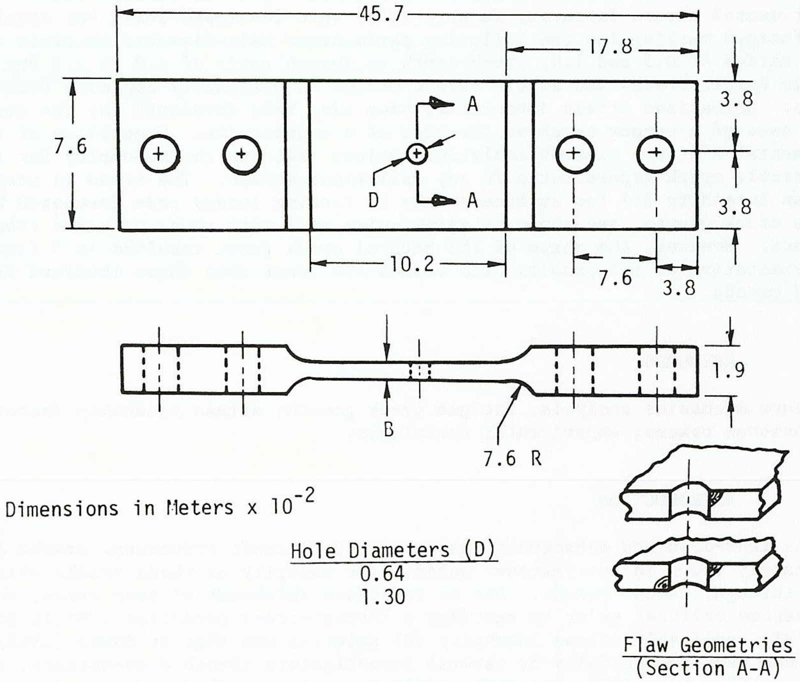

Fig. 1. Specimen and Part-Through Crack Configuration

Thus, the basic variables examined were crack geometry, hole diameter, and ratio of diameter (D) to thickness (B). In all cases, the preflaw consisted of a jeweler's saw cut (>2.5 x $10^{-4}$m) at the corner(s) of the final reamed hole. Subsequent constant amplitude sharpening of the pre-crack and fatigue cracking were accomplished at a stress ratio ($R = \sigma_{min}/\sigma_{max}$) of 0.1. Surface crack length was recorded with the aid of a traveling microscope at periodic intervals. The key ingredient to the success of the James-Anderson (1969) approach for stress intensity determination is valid constant amplitude fatigue crack growth data obtained from fracture mechanics type specimens. The data used in this study were obtained from ASTM E399 type compact specimens of the same thickness and material heat treatment.

A marking technique, to be described next, was used to outline the fatigue crack front with crack progression.

## FATIGUE MARKING PROCEDURE

A short description of the fatigue marking procedure will be given here since the detailed procedure will be presented in a subsequent publication. With the aid of a basic fatigue crack growth/stress intensity relationship such as given by Paris (1963) and modifications to treat maximum stress intensity ($K_{max}$) and stress ratio, e.g. FitzGerald (1977), one can solve for the appropriate stress ratio to produce a given crack growth rate. This implies apriori knowledge of $K_{max}$ for the flaw condition. In the case of surface cracks at holes, the $K_{max}$ value is unknown and is approximated by converting the elliptically shaped corner crack to an equivalent through-the-thickness crack. The resulting value of $K_{max}$ can then be determined by solving the basic fatigue crack growth equation, iteratively. To avoid retardation effects, the maximum (peak) load is kept constant throughout the test. In this fashion, the value of $K_{max}$ remains constant during both the marking and non-marking periods.

In this study the marking process used a stress ratio, R, which varied from 0.6 to 0.9, depending on crack length, and produced a typical marker band width of 5.1 x $10^{-5}$m. With this size marker band, the basic crack growth equation could be solved for the number of cycles required to produce that width of mark. Visual measurement can assure that marking is occurring as predicted. Subsequent to marking, the R ratio is reduced to the level employed prior to the marking cycle, i.e. R = 0.1, and additional fatigue crack growth data is obtained for the crack. Thus, periods of growth rate data are obtained periodically between marker bands, which outline the macroscopic crack front behavior. Figure 2 shows the typical marking pattern obtained from the double corner flaws in this 9 Ni steel material.

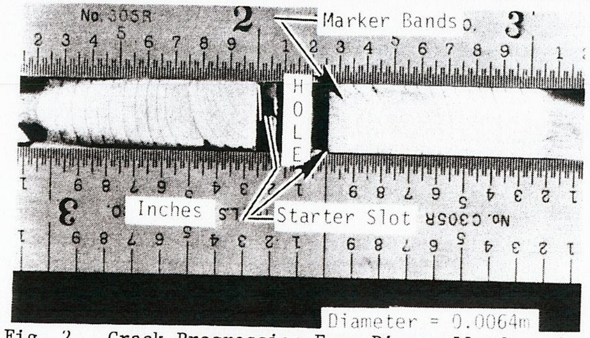

Fig. 2. Crack Progression From Diagonally Opposite Cracks at Hole

It should be noted that the crack progression is faster down the bore of the hole, an observation which has been correlated with the analytical work of Raju and Newman (1978) and by Wilhem (1979) for single corner cracks at holes.

## STRESS INTENSITIES

To illustrate the procedure utilized in experimental stress intensity factor determination, refer to fig. 3.

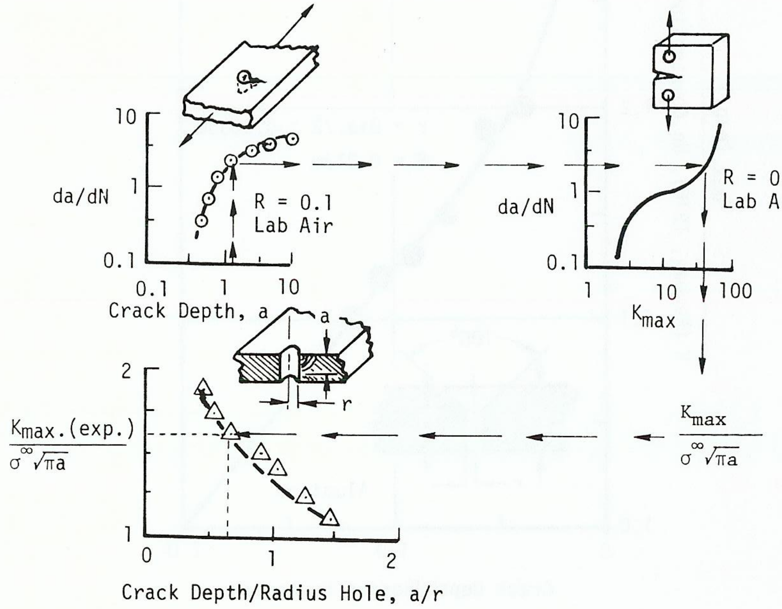

Fig. 3. Schematic Representation of the Development of Experimental Stress Intensities

Fatigue crack growth rates are obtained from the crack configuration with unknown stress intensities (upper left). At a given crack length (hence, growth rate or da/dN), a known $K_{max}$ can be found for the same material from data for a fracture mechanics type specimen, tested under identical conditions (upper right). This value of maximum stress intensity represents the value for the corner crack at hole, since fatigue crack growth has been shown to be uniquely related to stress intensity, K (Paris, 1963; Paris and Erdogan, 1963). It is of interest to find the normalized value of stress intensity β, at a given crack length, where:

$$\beta = \frac{K_{max}\ \text{(Hole)}}{\sigma^{\infty}\sqrt{\pi a}} . \qquad (1)$$

The beta term represents that value of correction factor necessary to permit the classic K, i.e. $\sigma^{\infty}\sqrt{\pi a}$, to be modified to treat the corner crack at hole problem. This correction is shown in fig. 3 lower left, as a function of normalized crack length. A rotational axis is indicated in the lower right to complete the progression of experimental determination.

Basic fatigue crack growth data are generally obtained from specimens which contain through-the-thickness cracks in the L-T or T-L orientation. In the case of the hole, the part-through-corner crack surface growth, c, will be in the L-T or T-L direction, but the crack in the bore, a, will be in either the L-S or T-S direction. Basic crack growth data in these directions are generally not available. From first principles of fracture mechanics, self similar crack extension must occur for both situations to obtain equality in crack tip stress intensity. However, for this 9Ni steel in the thickness studied, insignificant differences in crack growth would be expected between the L-T and L-S direction. Therefore, even though self similar growth in "a" is violated, reasonable data will be obtained for a homogenous material such as used in this study. Estimates of this error would be 1 to 2% based on differences between L-T and L-S crack growth data.

Figure 4 is a composite of all fatigue crack growth rates determined for the double (diagonally opposite) and single corner crack(s) at a hole.

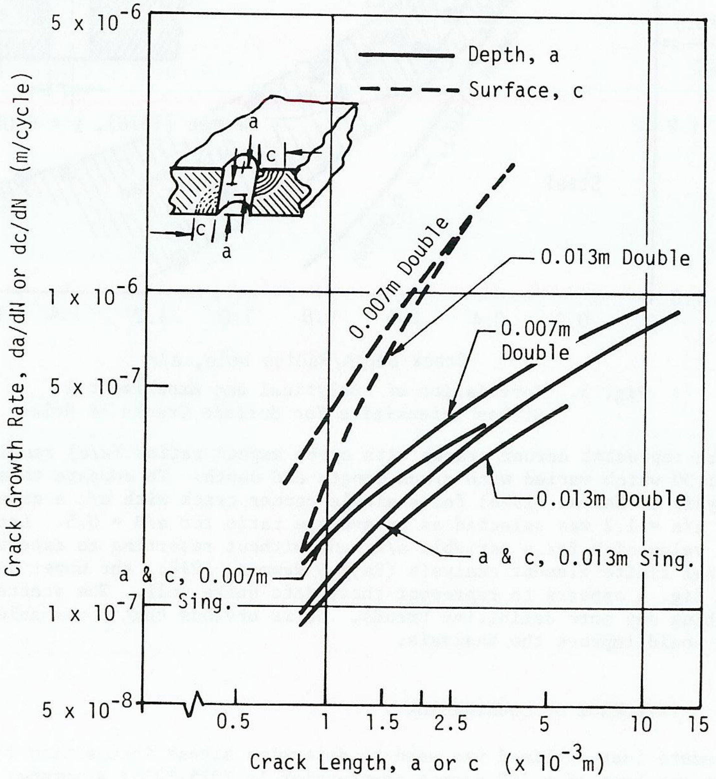

Fig. 4. Summary of Crack Growth Rates for Corner Cracks at Holes

There is some indication by change in rate for the surface crack, of the interaction effect for the double flaw condition. The rates (slopes) are similar for the same diameter hole for crack growth down the bore of the hole. The single flaw has higher growth rates for the smaller hole, indicating an influence of hole diameter.

Experimental values of beta for all flaw conditions are shown in fig. 5.

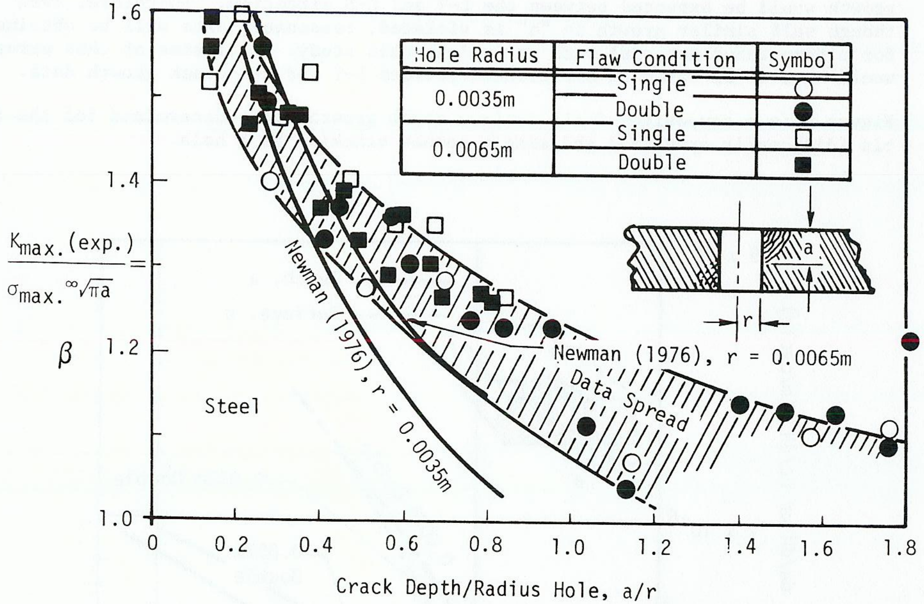

Fig. 5. Correlation of Analytical and Experimental Stress Intensities for Surface Cracks at Holes

These data represent corner cracks with crack aspect ratios (a/c) ranging from 1.03 to 1.30 which varied with crack length and depth. To compare these data with the analysis of Newman (1976) for a single corner crack with a/c a constant, a value of a/c = 1.2 was selected as an average ratio for a/B = 0.5. Lacking a definitive value of K for a variable a/c, and without resorting to expensive three dimensional finite element analysis (Raju & Newman, 1978), the upper data scatter curve of fig. 5 appears to represent these data quite well. The scatter precludes establishing any more definitive trends. It is obvious that a variable beta (K) with a/c would improve the analysis.

### INFLUENCE OF COUNTERSINK

The procedure just outlined was used to determine stress intensities for surface cracks at the base of a 100 degree countersink in 7075-T7351 aluminum. This flaw geometry has no known stress intensity solution and readily lends itself to the experimental K approach. The experimental beta factors are shown in fig. 6, normalized by the non-countersunk open hole solution of Newman (1976).

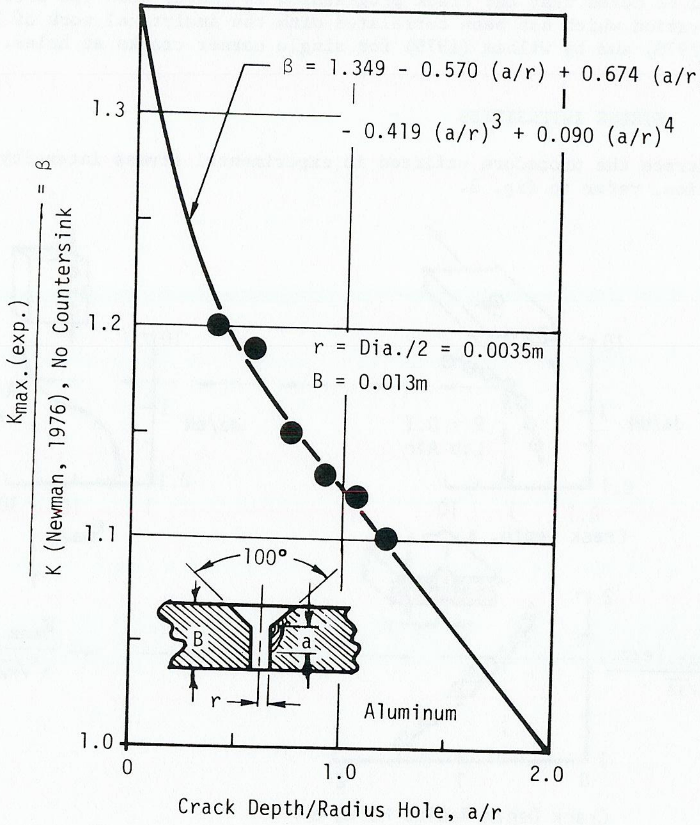

Fig. 6. Normalized Stress Intensities for a 100° Countersunk, 0.007m Diameter Hole

Obviously, the countersink must be accounted for in the analysis.

To develop the proper function, limits were placed on the beta factor. These are 1.35 (Cheng, 1978) for no crack, and 1.0 for a crack length equal to the hole Dia. Values are normalized by the Newman (1976) open hole solution. The resulting least squares polynomial fit to the data should only be used for this flaw/hole geometry due to the limits placed on the data fit. These beta corrections have been used to predict spectrum fatigue crack growth for this flaw condition. Predictive capability was within 7 percent of the experimental compared to a 14 percent longer life using a non-countersunk hole solution.

### SURFACE CRACK IN TENSION ROD

The surface flaw in a rod has many practical applications in engineering. Situations such as bolts, pins, reinforcements, etc., employ rod shaped material. In many cases, the loading situations can be quite complex, particularly in preloaded bolts, shear pins, etc. As with the corner crack at a hole, the evaluation of the stress intensity is both complex and three dimensional which, therefore, lends itself to experimental stress intensity determination. Experimental compliance measurements by Bush (1976) have been used for determining K for surface flawed rods loaded in bending. Modifications or compounding of stress intensities have also been attempted by several investigators in unpublished works, with mixed results.

## Test Procedures and Data

Fatigue crack growth data from surface cracks in rods has been obtained by Swift (1979). These data included fatigue marking to delineate the crack progression during tension-tension fatigue. In the investigation, heat treated steel rod material (ultimate strength = 1.52 GPa), in two diameters, 0.016m and 0.025m, were tested using the fatigue marking procedure already discussed. The preflaw was produced by electrical discharge machining (EDM). A fatigue crack was produced at the EDM notch by constant amplitude cycling in bending. Subsequent testing was accomplished in tension-tension loading. The thicker material was tested at two (2) stress ratios, 0.1 and 0.5; the 0.016m diameter rod was tested at R = 0.1 only. Figure 7 shows a comparison of the crack growth rate data used in the experimental K evaluation.

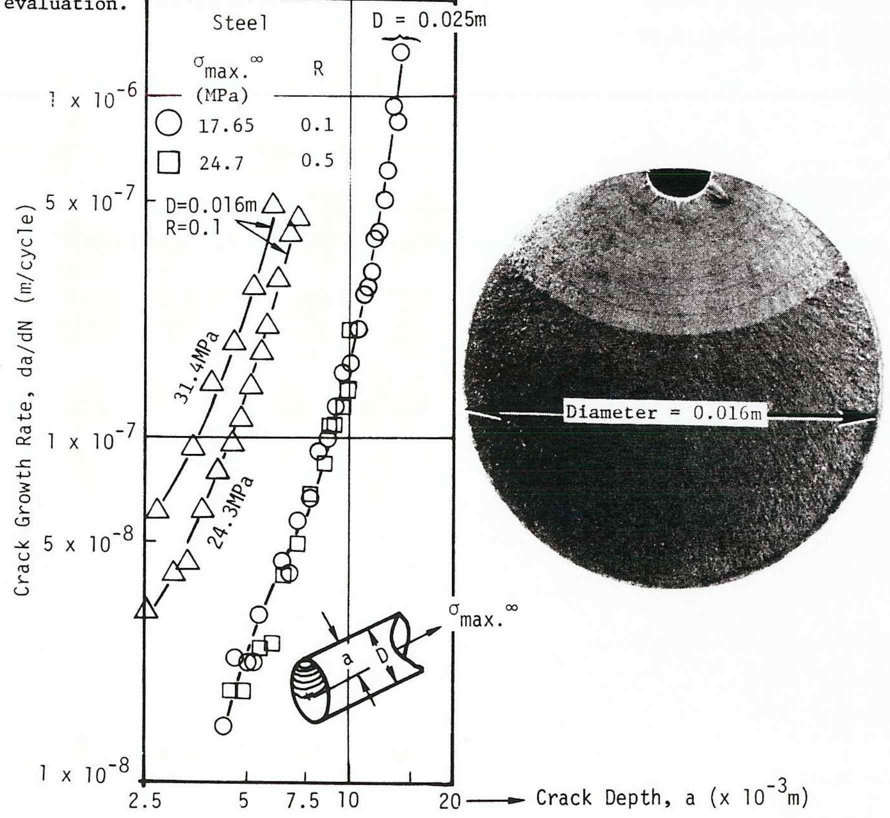

Fig. 7. Summary of Crack Growth for Surface Cracks in Rods in Tension

Note the symmetrical crack progression in the cross section of the fracture face of the rod shown in the insert. Several conclusions can be drawn from these data; first, there is little influence of stress ratio; second, the influence of the 30 percent increase in maximum stress at the same stress ratio results in a significant increase in fatigue crack growth rate; and third, higher growth rates occur for smaller diameter rods at similar R ratios.

## STRESS INTENSITY SOLUTION

The experimental results on cracked rods were examined using the James-Anderson (1979) approach and compact specimen da/dN data from our evaluation of this material. The resulting normalized K's are shown in fig. 8.

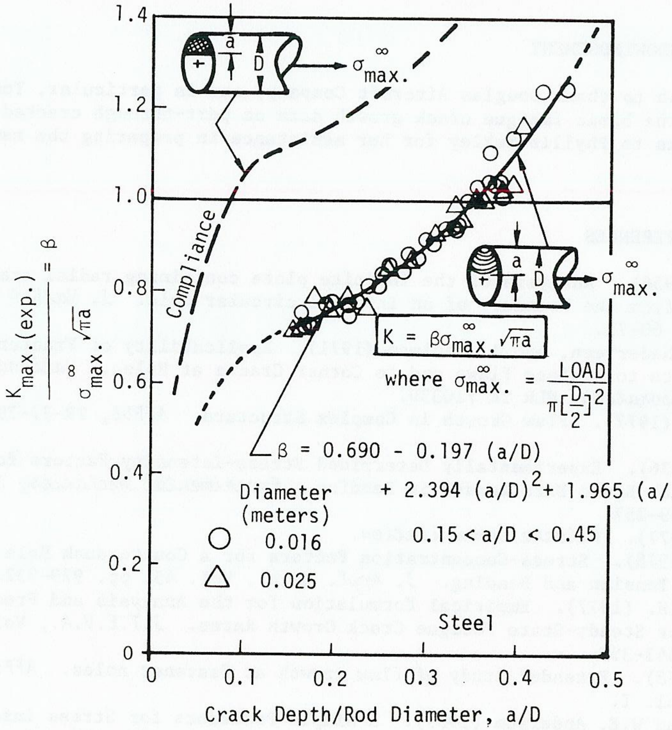

Fig. 8. Normalized Stress Intensities for Surface Crack in Tension Loaded Rod

A third degree polynomial fits the data quite well. Within the range of crack length/diameter values investigated, the change in rate of increase in correction factor Beta, appears to increase, decrease, then increase again. This behavior can be explained by the changing nature of the combined bending and tension caused by the crack progression through the rod.

Bush's (1977) unpublished compliance data is also shown in fig. 8 in which a saw cut was used to produce a simulated flat crack front. A natural crack will be constrained at the free surfaces due to the semi-circular shape of the crack front. It is obvious that a straight front of equal depth will be larger in area, and thus, produce higher betas, due to larger compliance. It's encouraging to note the similarity in shape between the compliance and fatigue crack growth beta curves of fig. 8.

## CONCLUSIONS

Several conclusions can be made as the result of these investigations. The fatigue marking procedure, previously a guessing proposition, has been refined and can be used to delineate the crack progression of part-through-cracks. The experimental approach for determining stress intensity factors can be a powerful tool in providing an analysis for common crack geometries, which would normally require a three dimensional solution.

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