APPLICATION OF THE EQUIVALENT INITIAL DAMAGE METHOD TO FRETTING FATIGUE

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ABSTRACT

The equivalent initial damage method consists in determining the size of a hypothetical crack or flaw which, if presumed to have existed at the beginning of a fatigue history, would have grown under the actual loading to the observed final crack size. Subsequently, this equivalent initial flaw (EIF) size can serve as the starting point for crack growth calculations used in analysis and design. Because there is a great deal of uncertainty concerning the initiation and early growth of cracks under conditions of fretting, the equivalent initial damage method is of potentially great use in placing fretting fatigue life calculations on a sound and rational basis.

EIF sizes have been determined for a series of fretting fatigue test coupons of 7075-T7351 aluminum alloy under a variety of loading conditions. These included three stress ratios, at constant load amplitudes as well as with periodic high tensile or compressive loads. Computer-based crack growth calculations were performed to find the EIF sizes, which averaged 0.365 mm. This is large compared to many other sources of fatigue damage -- e.g., in aircraft structures -- and symptomatic of the severe consequences of fretting. EIF sizes did not appear significantly dependent upon stress levels, stress ratio, or the presence of periodic high tensile or compressive loads. It thus seems possible to incorporate equivalent initial damage concepts into methodologies for fretting-initiated cracking, which could then be based entirely upon crack growth -- a particularly appropriate tactic because rapid crack formation is characteristic of fretting fatigue.

KEYWORDS

Fretting fatigue; equivalent initial damage; equivalent initial flaw size; equivalent initial quality; design life; crack propagation; damage tolerance; spectrum loading.

INTRODUCTION

Fretting occurs when two bodies in contact under normal load slide back-and-forth with respect to one another. Often the sliding -- or "slip" -- is caused by deformations in one or both of the bodies as a result of varying loads.

Fretting can take place in many types of machines and structures. Common examples are bolted or riveted connections in aircraft, where conditions leading to fretting may exist within fastener holes as well as at the faying surfaces of the joint.

Under such circumstances, the localized stresses caused by the Hertzian contact and by slip cause rapid surface damage, principally abrasion and plastic flow (Alic, Hawley, and Urey, 1979). Surface oxidation or corrosion may also occur. The surface and near-surface damage caused by fretting can lead to early formation of propagating cracks when cyclic stresses exist -- hence fretting fatigue.

PHENOMENOLOGY OF FRETTING FATIGUE

It now seems clear that the mechanical contribution to the formation of fretting fatigue cracks is paramount -- overshadowing, for example, the effects of corrosion or oxidation. It is also becoming apparent that a considerable diversity in patterns of surface damage and microcracking is possible, depending upon the materials involved and other circumstances (Alic, Hawley, and Urey, 1979; Duquette, 1979). Furthermore, the high localized stresses in the contact region not only cause rapid crack formation, they also greatly accelerate the propagation rates of cracks so long as these remain within the local stress field of the fretting contact (Endo and Goto, 1976; Alic and Hawley, 1979). As a result, propagating cracks of macroscopic size may appear after only a few percent of the total fatigue lifetime (Edwards and Ryman, 1975).

DESIGN METHODOLOGIES

Although fretting damage and the early stages of microcrack propagation are becoming better understood, design methods remain primitive, typically based on S-N curves determined for simple laboratory specimens or simulated components and structural details. Such tests are often used to evaluate ameliorative measures such as surface hardening or coatings, or compressive residual stresses, but cannot easily discriminate between crack initiation life and crack propagation life.

A fundamental problem is that the fretted region cannot be easily observed or otherwise probed for evidence of crack formation. Thus it has not been practical to treat fretting fatigue as a pair of more-or-less independent processes -- crack initiation and crack propagation -- which might be handled separately for design purposes. In contrast, for conventional fatigue analysis, the initiation stage can often be analyzed as a strain-controlled process, with fracture mechanics procedures applied to the propagation stage.

While the inaccessibility of the fretted interface has made it difficult to measure initiation life and to develop models for the initiation process, many indirect results -- e.g., from two-stage tests -- indicate that the crack initiation period is often very short. This is particularly so for other than constant amplitude loading (Edwards and Ryman, 1975). Such findings suggest that the fretting fatigue process be treated, for purposes of design and analysis, as if consisting entirely of crack propagation, with the initiation period being ignored (Alic and Kantimathi, 1979). The starting point for the crack propagation calculation would be a hypothetical, pre-existing crack or flaw. A procedure of this kind requires knowledge of the appropriate size for such an assumed pre-existing crack, given the particular material(s), loading conditions, and other circumstances. This can be found by applying the equivalent initial damage method (Rudd and Gray, 1976) to give the proper starting point for a fracture

mechanics-based crack growth calculation, thus permitting design analyses based purely on crack growth and obviating the need for a model of the early stages in the development of fretting fatigue cracks.

EQUIVALENT INITIAL DAMAGE METHOD

The essence of the equivalent initial damage method (Rudd and Gray, 1976) is the determination of the size of the hypothetical crack or flaw, which, if presumed to have existed at the beginning of the fatigue history, would have grown under the particular loading to the observed final crack size. The latter must be found from actual service experience or testing. Such a "final" crack size might be that existing at some intermediate stage in the fatigue lifetime when a readily measured macrocrack can be located, or it might be found after failure. The latter approach has been used in our work, as illustrated by the fracture surface diagram of Fig. 1 (the assumption of a quarter-circular corner crack is discussed later).

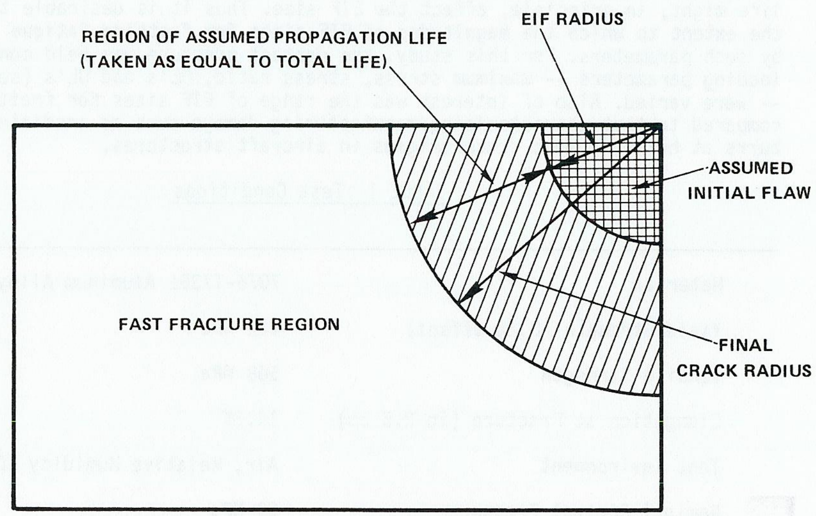

Figure 1 Schematic Diagram of Fracture Surface Showing Hypothetical Equivalent Initial Flaw (EIF) Size.

EXPERIMENTAL BACKGROUND

For the work reported here, final crack sizes were found for a series of fretting fatigue test coupons broken under a variety of axial loading conditions. These included both constant amplitude stresses (Alic and Kantimathi, 1979) and simple spectra including periodic high tensile or compressive loads -- overloads (OL's) or underloads (UL's) (Kantimathi and Alic, to appear).

The test apparatus, which employs a flat plate specimen in contact on one side only with a stationary fretting pad, has been described in detail by Alic and Kantimathi (1979). Both specimens and fretting pads were made of 7075-T7351 aluminum alloy. As indicated in Table 1, the nominal contact pressure between fretting pad and test coupon was held constant at 20 MPa, while the stress ratio (R = minimum stress/maximum stress) and maximum stress were varied. OL and UL stresses, when applied, were + 400 MPa or - 200 MPa.

Fatigue lifetimes for both constant amplitude and OL/UL tests have been previously reported (Alic and Kantimathi, 1979; Kantimathi and Alic, to appear). These lifetimes, plus the final crack sizes measured on the fracture surfaces, provide the basic data needed for determining equivalent initial flaw (EIF) sizes.

It should be noted that calculated EIF sizes might depend upon a variety of parameters -- e.g., stress level and stress ratio, spectrum characteristics for variable amplitude loading, contact pressure -- as well as the pair of materials in contact. Indeed, any parameter which has been shown to affect fretting fatigue life might, in principle, affect the EIF size. Thus it is desirable to determine the extent to which the magnitudes of EIF sizes for fretting fatigue are affected by such parameters. For this study, the contact pressure was held constant while loading parameters -- maximum stress, stress ratio, OL's and UL's (see Table 1) -- were varied. Also of interest was the range of EIF sizes for fretting as compared to that characterizing manufacturing damage such as anodizing pits or burrs at holes, common crack origins in aircraft structures.

TABLE 1 Test Conditions

Material	7075-T7351 Aluminum Alloy
Yield Strength (0.2% offset)	422 MPa
Tensile Strength	508 MPa
Elongation at Fracture (in 2.5 cm)	14.3%
Test Environment	Air, Relative Humidity 10% - 60%
Nominal Contact Pressure	20 MPa
Stress Ratios	+0.2, +0.5, -0.2
Maximum Stresses (Constant Amplitude)	150 MPa - 450 MPa
Tensile Overload (OL) Stress	+400 MPa
Compressive Underload (UL) Stress	- 200 MPa
Cyclic Frequencies	20 Hz (positive R) ~2 Hz (negative R) ~0.1 Hz (OL's and UL's)
OL or UL Occurences	1 per 1000 cycles

FLAW SIZE CALCULATIONS

The general procedure used in determining the EIF size was as follows. Referring to Fig. 1, the dimensions of the crack at fracture were first measured on the fracture surface. Crack growth calculations were then performed to find the initial flaw size which would have grown to the measured final crack size after the number of load cycles which caused the actual failure. This was done by means of a computer program based on the conventional fracture mechanics assumption that crack growth rate, da/dN, depends upon stress intensity factor range, ΔK. No attempt was made to use actual ΔK expressions or crack growth rates for microcracks at or close to the site of fretting, as the intent of the equivalent initial damage method is to avoid the need for treating the early stages of the fatigue process in detail. This amounts to two fundamental simplifications: (1) disregarding the localized stresses set up by the fretting and assuming that the bulk fatigue stresses alone determine ΔK and hence crack growth rate; and (2) disregarding any small-crack effects on growth rate. In reality, both these factors influence the rate of propagation of small fretting fatigue cracks (Alic and Hawley, 1979); but the virtue of the equivalent initial damage method is precisely that they may be ignored.

Much of the rest of the basis for the crack growth calculations has been previously described (Alic and Hawley, 1979). Fractography showed that virtually all fatal fretting fatigue cracks originated at a corner of the test coupon and grew as quarter-circular corner cracks or quarter-elliptical cracks of small eccentricity. For purposes of calculation, quarter-circular cracks were assumed (Fig. 1), as small deviations towards a quarter-elliptical shape make little difference in values of K. Futhermore, although fretting cracks grow at oblique angles to the fretted surface when short, perpendicular cracks were assumed. This is again appropriate for an EIF size calculation.

Liu (1972) has computed the stress intensity factor for such a quarter-circular corner flaw. The value of K varies along the crack front, being greatest at the surfaces and least at the midpoint. It is not clear why growing cracks of this type remain quarter-circular, yet they do. Thus we take the average value for K along the crack front, or

$$\Delta K = 1.32 \Delta \sigma \sqrt{a}$$

where a = crack radius. Again, we point out that $\Delta \sigma$ is the bulk cyclic fatigue stress (tensile component only) and does not include any contribution from the contact stresses.

For some of the test coupons (i.e., at low stresses) the actual crack grew completely across the width before fracture. This occurred for only a minority of the specimens, which were dropped from the program to avoid the complication of a transitioning procedure to a full-width crack. There remained a total of 42 specimens for which EIF sizes were found.

For computational purposes, the dependence of da/dN on ΔK was assumed to have the form

$$\frac{da}{dn} = C\,(\Delta K - \Delta K_{th})^n$$

where C and n are empirical constants and ΔK_{th} is the threshold stress intensity factor range. It is important to include threshold effects since we are dealing primarily with small cracks and, often, low stresses -- hence low ΔK's. Because of this, the equation above is suitable even though it is not valid for da/dN values greater than about 1 μm/cycle. Growth rates this high do not occur for the conditions of our tests except very near the point of fracture, where errors in da/dN will have negligible effect on the calculated EIF size.

Crack growth data for 7075-T7351 aluminum alloy were gathered from a number of sources (see notes to Table 2) for use in the calculations, the constants C and n being fit to these data with results as given in the table.

TABLE 2 Constants Used for Calculating Equivalent Initial Flaw Sizes

Stress Ratio, R	C	n	ΔK_{th} MPa $\sqrt{m}$
+0.2	5.166×10^{-4}	2.44	2.20
+0.5	1.013×10^{-4}	3.25	1.35
-0.2	5.166×10^{-4}	2.44	2.75

Notes

1. Values given are for da/dN in μm/cycle and ΔK in MPa $\sqrt{m}$.
2. The R = -0.2 case is taken as equivalent to R = 0.
3. Sources of 7075-T7351 crack growth data used to determine C and n were as follows:

   Damage Tolerant Design Handbook (1970). MCIC-HB-01, Battelle, Columbus, OH, USA, 8.1-192.

   Sippel, K.O., and D. Weisgerber (1975). Crack Propagation in Flight-by-Flight Tests on Different Materials. Proc., 8th ICAF Sym., Lausanne, June 2-5, 1975, J. Branger and F. Berger, eds., 7.1/1 - 7.1/55.

   Smith, B.L. (1978). Boeing Wichita Co., personal communication.
4. The threshold data for all three R's is from:

   Beevers, C.J. (1977). Some Aspects of Fatigue Crack Growth in Metals and Alloys. Fracture 1977, Vol. 1, D.M.R. Taplin, ed., University of Waterloo Press, 239 - 260.
5. As no crack growth data for R ~ +0.5 could be found that extended to low crack growth rates, the R = +0.5 C and n values were estimated following a procedure suggested by McEvily (1973).

The computer program calculated the propagation of a quarter-circular corner crack from a pre-assigned initial size for either constant or variable amplitude loading. The EIF size was found by matching the predicted crack growth for various pre-assigned initial crack sizes to the fractographic data for the actual crack. Compressive UL's were ignored in the calculation as they did not affect fretting fatigue lifetimes; however tensile OL's caused crack growth retardation which in some cases greatly extended the life (Kantimathi and Alic, to appear). Wheeler's (1972) model was used to account for this retardation.

The Wheeler model includes an adjustable parameter -- the retardation shaping exponent, m -- which is normally found by comparing the model's predictions to actual crack growth data. This shaping exponent depends not only upon the material, but also upon the loading spectrum (Katcher, 1973). As pointed out above, fretting fatigue cracks are inaccessible to direct measurement of crack length; attempts to acquire crack growth data via scanning electron fractography were, unfortunately, not successful (Kantimathi and Alic, to appear). Therefore, a "best value" m for 7075-T73 aluminum alloy as determined by Broek and Smith (1979) was adopted. This value, m = 1.4, is, as pointed out above, expected to be spectrum-dependent. Thus EIF sizes for several OL specimens were also computed using values of m = 1.2 and m = 1.6. Because the results did not vary greatly, the EIF sizes calculated for m = 1.4 are believed to be reasonable.

RESULTS

For brevity, rather than giving all the individual EIF results, Table 3 presents averages by groups of specimens tested under similar conditions. The complete results for all 42 specimens covered a rather wide range (0.071 to >1.5 mm), Figure 2. This follows directly from the scatter in fatigue lifetimes, which is reflected in the EIF size calculations. However the average results are fairly consistent, with exceptions as discussed in the next section (the averages do not include the two cases for which EIF size was >1.5 mm).

Figure 2 is a histogram showing the distribution of EIF's from all the tests. Most of the results are clustered in the range of 0.1 - 0.6 mm. The skewed distribution in Fig. 2 is similar to distributions observed for fatigue lifetimes, which is again to be expected, given the direct relationship between lifetime and EIF size.

DISCUSSION

Equivalent Initial Flaw Sizes

From the results in Table 3 it appears that neither OL's nor UL's exert much effect on EIF size. The EIF's calculated for OL's and for UL's averaged slightly larger than for the constant amplitude tests. However, the difference in the case of the OL's could well be caused by the use of a shaping exponent of m = 1.4 in the Wheeler model rather than a value based on actual experimental results.

EIF sizes for R = +0.5 (especially for specimens with OL's) were significantly larger than for the other two stress ratios. There seems no physical reason for such behavior; mechanisms of crack formation (Alic, Hawley, and Urey, 1979) did not appear to depend upon stress ratio. Instead, it is likely that the cause of the large EIF sizes calculated for R = +0.5 lies in the crack growth rates used for this stress ratio (Table 2). No actual crack growth data for 7075-T7351 alloy could be located which included da/dN values of less than about 1 μm/cycle for stress ratios in the vicinity of +0.5. Therefore the constants in Table 2 for R =+0.5 were determined using a stress ratio correction to crack growth rates suggested by McEvily (1973). These seem to be underestimates of the actual growth rates, resulting in calculated EIF sizes that are too large.

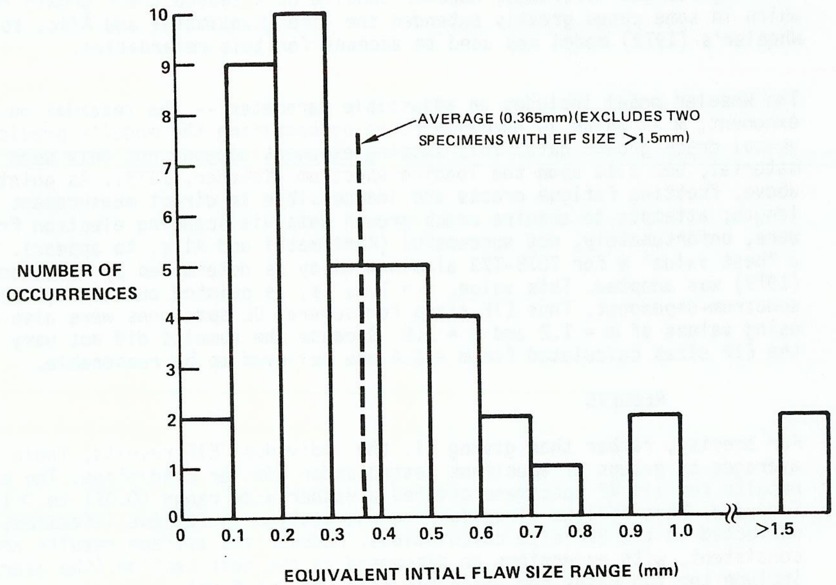

Figure 2 Distribution of Equivalent Initial Flaw Sizes.

If this is indeed the case, then EIF sizes for fretting fatigue can be taken as at least approximately independent of stress ratio, maximum stress, and OL's or UL's. Such a conclusion would only apply to this particular set of tests, and should be verified for other, more complex, load spectra. Nonetheless, this makes the equivalent initial damage method appear most promising for use as the starting point in crack growth calculations for fretting fatigue.

It is noteworthy that the average of all the EIF size calculations for fretting fatigue -- 0.365 mm -- is much larger than typically found for cracks which have formed in aircraft without fretting (Rudd and Gray, 1976). The latter -- attributable in general to manufacturing damage such as burrs or tears at holes and to corrosion pits left by anodizing -- tend to be an order of magnitude smaller. This graphically illustrates the severity of fretting damage. It would thus appear likely that, when present, fretting in an actual structure -- whether at a hole or between the faying surfaces -- would override other possible causes of eventual fatigue cracks except for the occasional "rogue" flaw.

While the large EIF sizes found for these tests do give dramatic illustration of the severity of fretting damage, it is also true that, to some extent, they are artifacts of the calculation procedure. This is because only the bulk cyclic fatigue stresses were assumed to cause crack growth, the contact stresses being unknown, though certainly important for determining initial crack growth rates. Likewise, the calculations are based on crack growth data and stress intensity factor expressions developed for long cracks, not the microcracks which exist in the early stages of fretting. Both these factors will lead to results which are underestimates of the actual crack growth rates, thus overestimates of the EIF size. (If crack growth is slower, a larger initial flaw is needed to give the same calculated life.) However, as has previously been pointed out, one of the advantages of the method is precisely that it circumvents the need for detailed knowledge of microcrack growth behavior.

TABLE 3 Average Equivalent Initial Flaw Sizes for Fretting Fatigue

Stress Ratio	Loading Spectrum	Number of Specimens	Average Equivalent Initial Flaw Radius (mm)
+0.2 +0.5 -0.2	Constant Amplitude	9 8 1	0.338 0.373 0.264
+0.2 +0.5 -0.2	Tensile Overload (OL)	7 4 3	0.265 0.536 0.439
+0.2 +0.5 -0.2	Compressive Underload (UL)	3 1 4	0.253 0.691 0.388
all	Constant Amplitude	18	0.349
all	Tensile Overload (OL)	14	0.380
all	Compressive Underload (UL)	8	0.375
+0.2	all	19	0.298
+0.5	all	13	0.448
-0.2	all	8	0.391
		GRAND AVERAGE	0.365

Crack Growth-Based Design and Analysis Procedures for Fretting Fatigue

By using appropriate initial flaw sizes, found as above, design procedures for fretting fatigue can be based on crack propagation alone. There is every reason to believe that such procedures could be successfully extended from the simple OL or UL spectra of the present study to more realistic service load spectra. This statement is reinforced by work showing that propagating cracks may be present after as little as 5% of the fatigue lifetime for fretting under random loading, a shorter crack initiation period than characteristic of constant amplitude fretting fatigue (Edwards and Ryman, 1975). Thus it should be more realistic to use an EIF size together with a fracture mechanics crack growth calculation for variable amplitude fretting fatigue than for constant amplitude conditions. Nonetheless, even for the latter case it appears that crack growth can justifiably be considered the dominant process.

To have maximum confidence in crack growth-based design and analysis methods for realistic loading spectra, knowledge of the following are required: (1) the appropriate equivalent initial flaw size; (2) effects of load interactions on short fretting fatigue cracks; and (3) desirable though perhaps not necessary, growth rates for microcracks propagating under the influence of the fretting contact stresses. As discussed above, the EIF sizes for our fretting fatigue tests did not appear to depend upon maximum stress or the presence of OL's or UL's. However there is clearly a wide range of possible EIF sizes, corresponding to the typical scatter for fatigue crack initiation phenomena, and statistical data on the characteristic distributions of EIF sizes would be needed for design purposes. It is important to gather such data for realistic load spectra and also to investigate the effect of changing the spectrum on calculated EIF sizes for fretting. Furthermore, EIF sizes might well depend on various factors which are known to affect fretting fatigue but which were held constant during the tests described in this report. Such factors include the pairs of materials in contact, the nominal contact pressure, and the environment, particularly as concerns lubricants or other surface treatments.

Load spectrum effects are also important for calculating crack growth from the assumed initial flaw. Load interactions -- specifically crack growth retardation following high tensile loads -- are of critical importance for the growth of long fatigue cracks. While it is clear that load interactions are equally important in fretting fatigue, the sizes of cracks for which retardation begins to have an effect are not known (Kantimathi and Alic, to appear).

In addition to quantitative data on load interaction effects for small fretting cracks, data on growth rates characteristic of such cracks for constant amplitude loading would be desirable. Although the EIF size calculations can mesh the microcrack propagation stages with macrocrack growth, if microcrack growth rates were known, it would not be necessary to rely entirely on the EIF sizes. This would lend confidence to calculations for new situations where no actual EIF size data were available -- see, for example, the work of Edwards, Ryman, and Cook (1977). The microcrack stage is particularly important because much of the life will be consumed in the slow growth of these short cracks.

CONCLUSION

Equivalent initial flaw sizes can be determined for fretting fatigue as for other sources of fatigue damage. The calculated EIF sizes appear to be at least approximately independent of maximum stress, stress ratio, and the presence of high tensile or compressive loads. For these tests, calculated EIF sizes averaged 0.365 mm. This is much larger than typical for other sources of fatigue damage such as manufacturing flaws. Values this large illustrate the severity of fretting when it does occur, and the need for including possible fretting-initiated cracking in life prediction methodologies. This can best be done by replacing the traditional S-N based fatigue lifetime approach with a fracture mechanics crack growth calculation using an equivalent initial flaw size appropriate for fretting damage as the starting point.

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