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**SHERATON PLAZA HOTEL
ORLANDO, FLORIDA**

PROCEEDINGS

A Fracture Mechanics Based Approach for Quantifying Corrosion Damage

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A fracture mechanics based approach to quantify the influence of initial corrosion damage on structural integrity is described. This approach assumes that corrosion can be approximated by a geometric structural change consisting of a general thickness reduction combined with a localized stress concentration. These two parameters enable quantification of the damage and the application of fracture mechanics principles to corrosion. Several numerical examples of this concept are discussed and a test program, combined with inspection capabilities, is introduced.

Introduction

The ever increasing age of the nation's transport fleet has caused escalated maintenance concerns due to the damage caused by fatigue and corrosion. Material degradation resulting from environmental attack poses a serious threat to the airworthiness of older aircraft, and as a larger number of aircraft operate beyond their original design lives, corrosion becomes more of an issue. Historically, corrosion damage assessment has been almost exclusively qualitative [1,2]. If the safety of so called "aging aircraft" is to be ensured, however, quantitative definitions of corrosion are required. One possible solution to this problem is to apply the principles of fracture mechanics to evaluate the effects of corrosion on subsequent life. By modeling environmental degradation much like damage caused by fatigue cracking, a protocol for quantitative structural evaluation can be applied to corrosion in aging aircraft.

Model of Corrosion Damage

In order to apply fracture mechanics to evaluate corrosion, an initial damage assumption is required. As a first approximation, corrosion damage can be modeled as a combination of the following two geometric changes [3].

1. *Uniform damage*: a general thickness reduction that increases the stress experienced by the remaining structure.
2. *Local damage*: a stress concentration that can be considered to be an equivalent crack.

These two corrosion damage assumptions are presented schematically in Fig. 1. Corrosion in a structure can be modeled either by one of the parameters (exfoliation as a thickness reduction and pitting as local damage, for example) or by a combination of the two.

Once the corrosion parameters are obtained (by non-destructive measurement, for example), fracture mechanics can be applied by using the thickness loss and equivalent flaw size to compute the potential loss in residual strength due to subsequent loading (Fig. 2). More importantly, these geometric parameters can be used to quantify the existing corrosion state with respect to various remaining life criteria. This latter point could enable results to be placed in handbook-type form and therefore used as a structural evaluation tool. Parametric variations on damage, geometry, and loading could be incorporated into such a handbook for use by those responsible for airframe air-

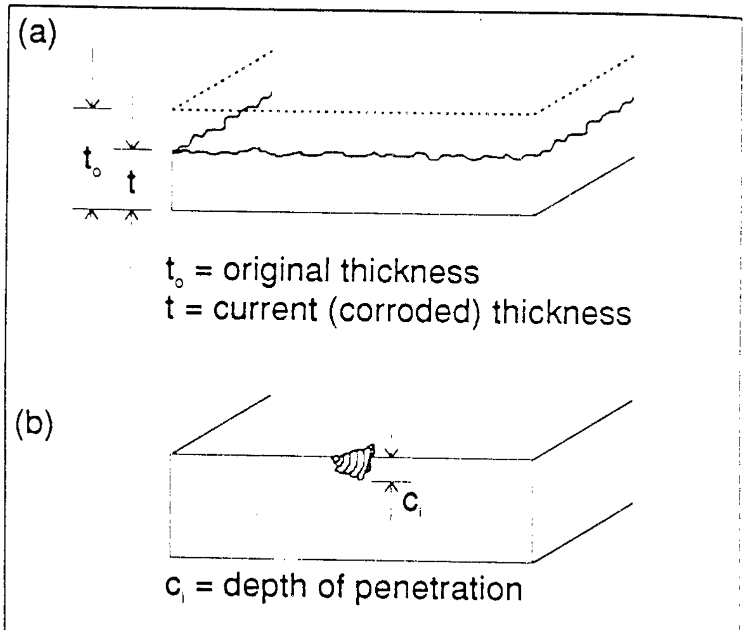


Figure 1. Geometric model of corrosion damage (a) thickness loss (b) local stress concentration

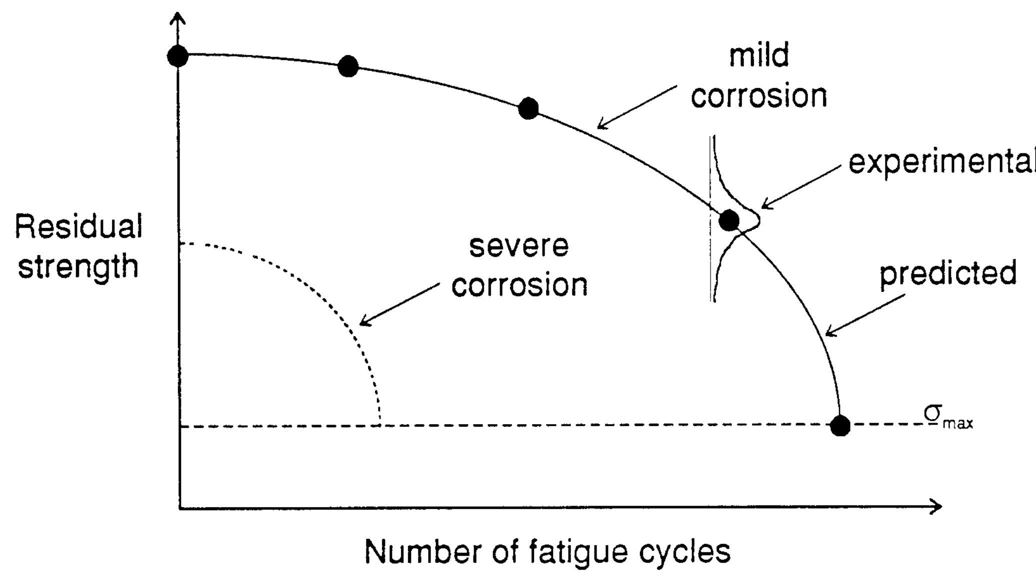


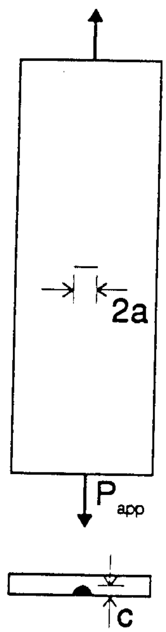
Figure 2. Effect of corrosion on residual strength after fatigue [3]

worthiness. One possible format for this evaluation tool could be a "constant-life diagram," where combinations of thickness reduction and effective flaw penetration are plotted for specific values of life-to-failure under given loading conditions. Several numerical examples are discussed to demonstrate this constant-life concept.

Examples of Corrosion Evaluation Protocol

Example 1. Simple plate specimen

For an initial example of the application of fracture mechanics to quantify corrosion damage, consider the small Al 2024-T3 plate in Fig. 3. Environmental attack on the plate would likely result in a thinning of the original 0.1 inch thickness, and this would correspond to an increase in the stress experienced by the remaining uncorroded thickness (assuming a constant applied cyclic load range). In addition, stress concentrations might result from pitting or some other local damage mechanism. The deepest one of these flaws (weakest link concept) is modeled as an "equivalent" initial crack. Cyclic loading upon this plate (after the environmental attack) would cause fatigue crack growth, and the initial flaw would propagate to failure. For this example, an iterative crack growth algorithm was employed to calculate combinations of thickness reduction and initial flaw depth that correspond to various life-to-failure values for the specimen loaded under a constant applied cyclic load. The results,



Aluminum 2024-T3 plate
height = 6.0 in
width = 2.0 in
original thickness (t_o) = 0.1 in
maximum load (P)= 4,000 lbs
stress ratio (R) = 0.1
initial semi-circular crack
Forman law [3]:

$$\frac{da}{dN} = \frac{C_f(\Delta K)^m}{(1-R)K_f - \Delta K}$$

$C_f = 3.295*10^{-7}$
m = 2.70
$K_f = 64.886$

$$\left(\Delta K : ksi\sqrt{in}, \frac{da}{dN} : \frac{in}{cycle}\right)$$

Figure 3. Surface-cracked plate geometry for the first constant-life example

plotted in Fig. 4 as a constant-life diagram, reveal the relationship of the damage parameters to one another as well as to the expected life of the specimen. The y-axis of the graph corresponds to the initial depth of an assumed semi-circular initial flaw. The knee in the plot of 20,000 cycles-to-failure results from the ability of the plate to withstand a through-the-thickness crack with a thickness loss of 15% or less.

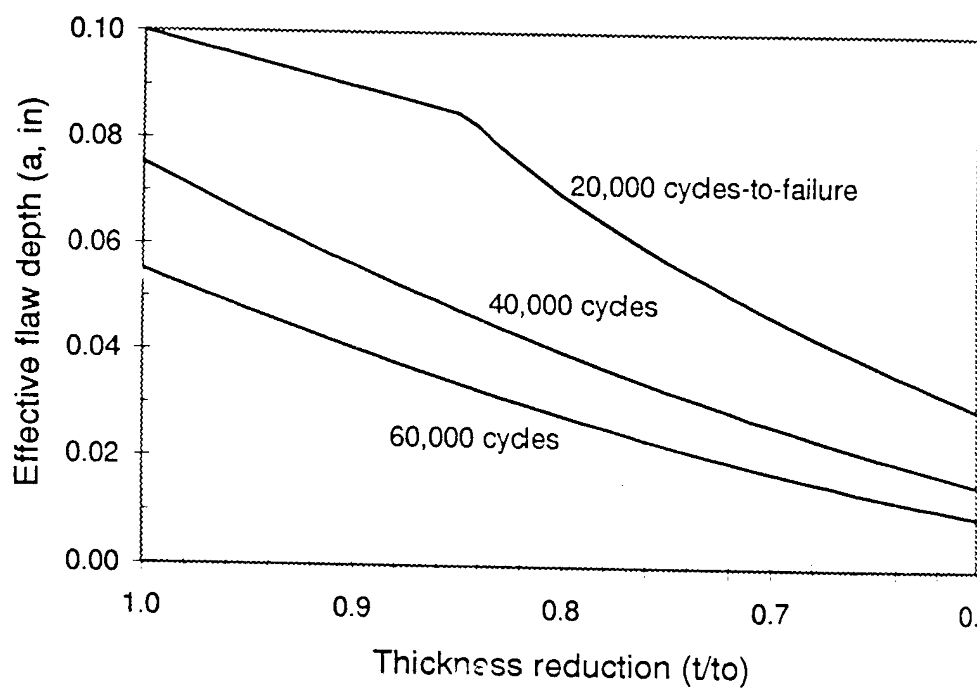
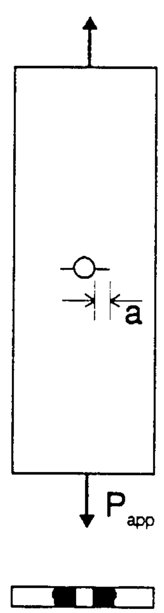


Figure 4. Constant-life diagram for the surface-cracked plate example

Results like those presented in Fig. 4 could be used as a structural evaluation tool by conducting parametric variations in loading conditions and component dimensions so as to include all combinations of interest. The results could be placed in handbook form and looked up according to the dimensions and loading experienced by a particular in-service structure. The corrosion damage to the structure would be measured as a combination of thickness loss and flaw penetration, allowing the corrosion to be quantified by the numerically generated constant-life plot. That is, one could predict the remaining life that a plate would be expected to survive under the specific loading conditions. The parametric variations would similarly allow assessment of damage under other loading conditions as well.

Example 2. Simple hole specimen

Analysis similar to example 1 can be conducted for other geometries as well, and this second example considers a single hole in a plate with symmetric through-cracks. Application of a crack growth algorithm to the Al 2024-T3 specimen presented in Fig. 5 allows one to generate constant-life diagrams similar to those for the simple plate geometry discussed above. Note that for this example, the equivalent flaw is defined by the surface length rather than the depth of penetration as it was in the initial example. The results of the analysis (Fig. 6) could similarly be used as a structural evaluation tool that would be able to quantify corrosion damage in other like specimens. Parametric variations on the loading and specimen dimensions would additionally allow application of the corrosion definitions to any similar hole specimen with different loading.



Aluminum 2024-T3 plate
height = 6.0 in
width = 2.0 in
original thickness (t_o) = 0.1 in
hole radius = 0.075 in
maximum load (P) = 2,000 lbs
stress ratio (R) = 0.1
through-the-thickness crack
Forman law [3]:

$$\frac{da}{dN}=\frac{C_f(\Delta K)^m}{(1-R)K_f-\Delta K}$$

$C_f = 3.295 * 10^{-7}$
m = 2.70
K_f = 64.886

$$\left(\Delta K: ksi\sqrt{in}, \frac{da}{dN}: \frac{in}{cycle}\right)$$

Figure 5. Through-cracked hole in plate specimen for the second constant-life example

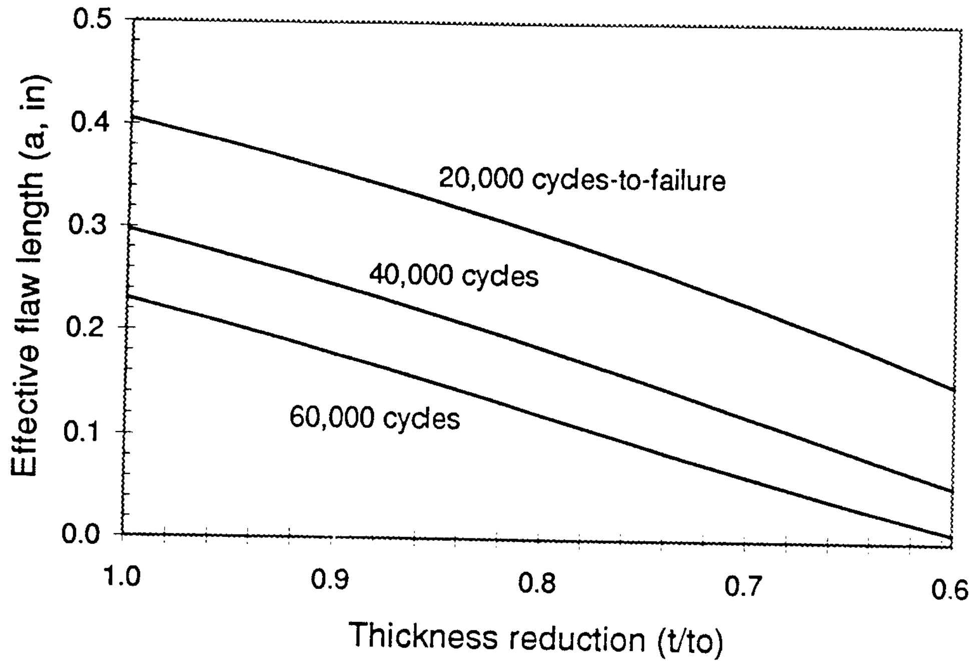


Figure 6. Constant-life diagram for thru-cracked hole-in-plate example

Example 3. Multiple site damage specimen

A more complex geometry is provided as a third example of the corrosion assessment technique. The multiple site damage (MSD) panel presented in Fig. 7 is a simple model of a row of fastener holes in an aircraft structure. A computer algorithm developed to accurately predict the growth of multiple cracks emanating from a row of holes [4] was modified here to compute a constant-life plot for an Al 2024-T3 MSD panel with 8 holes. The panel dimensions and loading conditions are presented in Fig. 7. For this simple example, it was assumed that each hole would have symmetric through-the-thickness cracks and that all cracks were of equal length. The results, presented in Fig. 8, provide insight to the relationship between the corrosion parameters of uniform thickness loss and local damage at all fastener holes. Once again, such plots could be used to evaluate damage in other similar MSD panels. This example shows that the corrosion evaluation protocol is not only applicable to simple geometries, but can be applied to complex geometries as well.

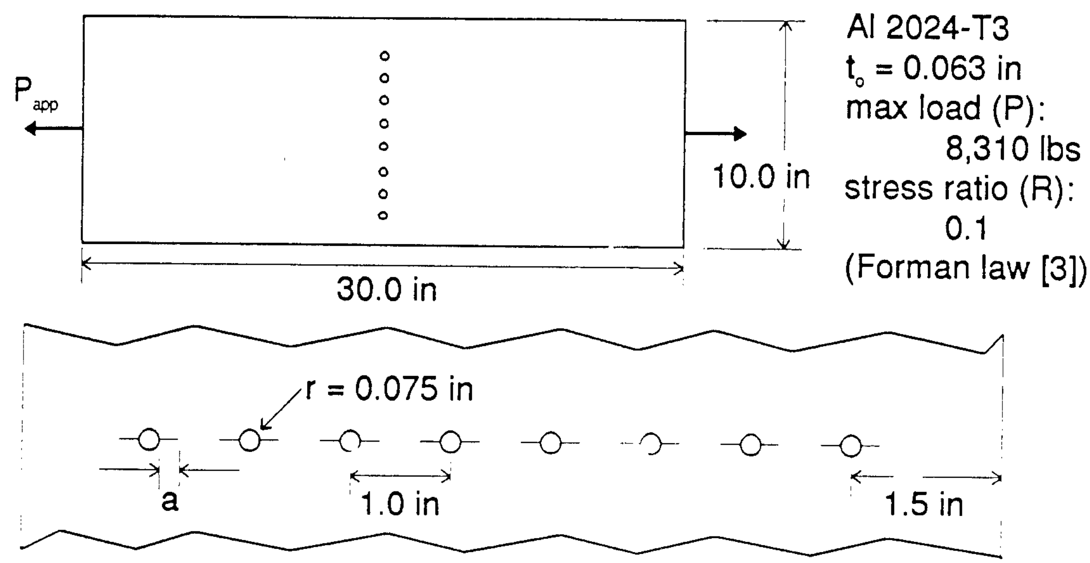


Figure 7. MSD specimen for the third constant-life example

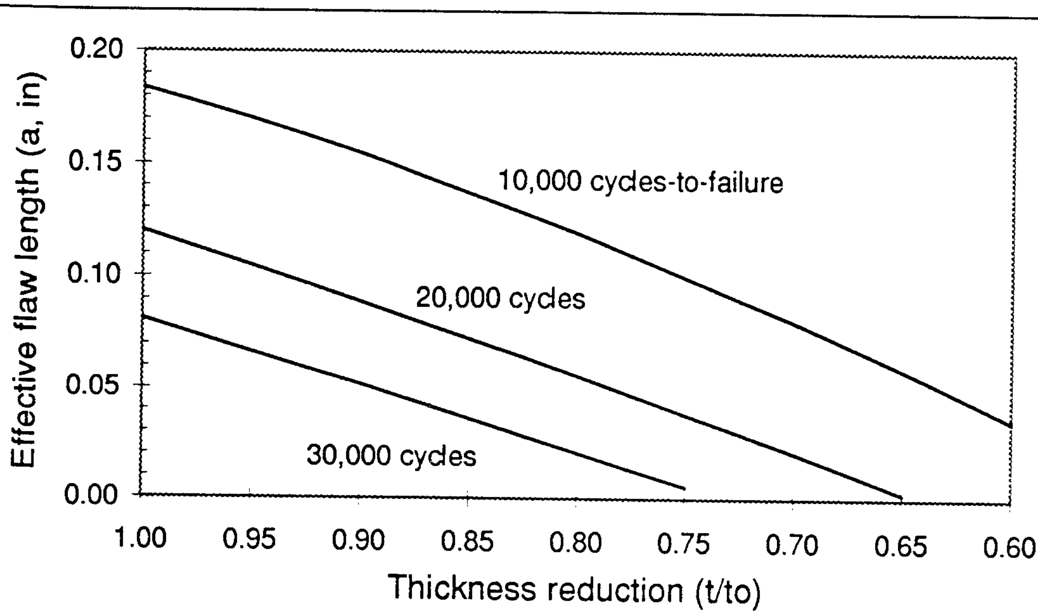


Figure 8. Constant-life diagram for the MSD example

Example 4. Variation of applied loading for surface-cracked geometry

As discussed during the surface-cracked plate example, the corrosion evaluation protocol can be used as a structural evaluation tool by conducting analysis of similar geometries under various loading conditions. It is important to consider the effects of differing applied load because fracture mechanics concepts should be able to account for varying stress levels in the assessment of corrosion damage. Here, in order to demonstrate the effect of load on the relationship between general thickness reduction and local initial flaw size, the surface-cracked plate geometry (Fig. 3) has been analyzed for three values of maximum applied cyclic load (3,000 lbs, 4,000 lbs, and 5,000 lbs). The results, presented in Fig. 9, compare the same geometry with a required life-to-failure of 40,000 cycles. As expected, the specimen is able to tolerate the smallest amount of damage at the largest applied load if it is to survive the desired number of cycles. The least severe load permits more environmental damage, and even allows for a through-the-thickness initial flaw with a thickness reduction of up to 23%.

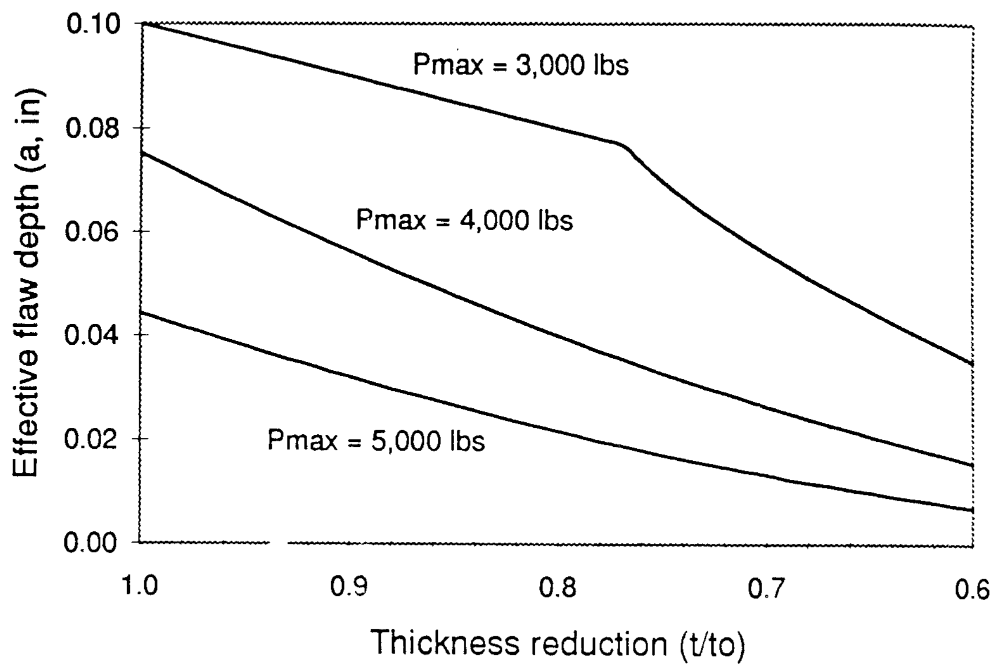


Figure 9. Results of varying the applied load on corrosion assessment of the surface-cracked plate with an assumed initial semi-circular local flaw

Example 5. Comparison of geometries

Not only can fracture mechanics prin:iples be applied to the assessment of damage for the case of varying loading conditions on a single geometry, but to the case of different geometries under similar loading conditions. For this analysis, the effect of corrosion damage on three similar through-cracked geometries was considered. Figure 10 presents a combined constant-life diagram for a center-cracked panel, a panel with symmetric cracks emanating from a single hole, and a multiple site damage panel with symmetric cracks at every hole. The overall dimensions of each Al 2024-T3 panel were equivalent (30.0 in x 10.0 in x 0.063 in, hole radii: 0.075 in), and the applied loading was such that the net-section stress for each undamaged panel (i.e. no thickness reduction or initial equivalent crack) was equal tc 15.0 ksi. The applied stress ratio was the same as in previous examples (R=0.1), as was the crack growth rate curve [3]. The life-to-failure for each geometry was 20,000 cycles.

The results, as expected, reveal that the center-cracked panel can tolerate much larger initial equivalent cracks for a given value of thickness reduction, and that the presence of MSD significantly reduces the damage tolerance capabilities of the panel. It should be noted that the crack lengths plotted in Fig. 10 are the lengths that would need to be resolved in an inspection (by nondestructive testing, for example), and are not the tip-to-tip values for all crack types. The lengths presented for the MSD and single-hole geometries are those on one side of the hole, from the edge of the hole to the tip of the crack ("a" in Figures 5 and 7). The values given

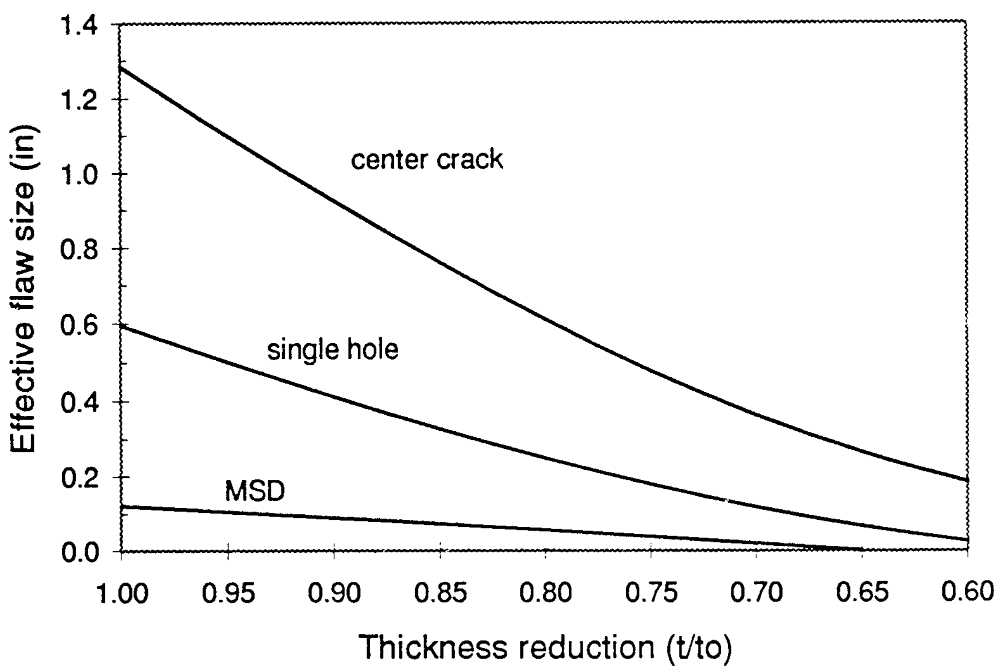


Figure 10. Comparison of constant-life curves for three similar geometries under equivalent loading conditions

for the center-cracked panel are the tip-to-tip values ("2a" in Fig. 3). The important result of this demonstration is that the application of fracture mechanics principles to corrosion assessment enables the comparison of the effect of environmental damage on different geometries.

Test Program

An experimental program is being developed to verify the concepts of the proposed corrosion quantification method. Simple specimens manufactured from an aircraft alloy will be artificially corroded [5-7], with the duration of exposure being varied in order to produce different degrees of corrosion damage. After the environmental attack, the specimens will be mechanically tested by two separate methods. One group of specimens will first be fatigue tested to a predetermined number of cycles. Following this, each specimen will undergo a residual strength test [8]. The second group will be fatigue tested to failure under constant amplitude loading.

The residual strength tests will be conducted in order to determine if fracture mechanics concepts can be used to predict the results of damage due to corrosion. Post-test measurements of specimen thickness and deepest flaw depth will provide a quantitative assessment of the degree of corrosion damage for one specimen geometry and duration of environmental exposure. These parameters will be used to predict the residual strengths of the original specimens as well as the residual strengths of the other specimen geometries (with equivalent durations of environmental exposure). This point is of great importance because in order to verify the validity of the concept, it must be proven that fracture mechanics can predict results for one geometry by using data obtained from different geometry. Results would be in a form like that of Fig. 2. At least five specimens will be tested at each desired life interval in order to provide an estimate of the statistical nature of the results. It is planned to test several degrees of corrosion damage (i.e. exposure duration) and at least 5 intervals of applied fatigue cycles.

The group of specimens to undergo constant amplitude fatigue tests will have the damage characterized in a number of ways. One method will be to measure the final flaw size and specimen thickness after failure of the specimen. An equivalent initial flaw size will be calculated from these values using fracture mechanics concepts, and the results (to be compared with the residual strength results) will define the corrosion damage for the degree of exposure. This corrosion assessment will then be applied to the other specimen geometry. A second method will be to predict the life-to-failure for the constant amplitude specimens using the corrosion assessment determined from the residual strength tests. And third, nondestructive inspection (NDI) methods will be applied as an attempt to measure the values of thickness loss and flaw size. These measured values will be used to predict the life-to-failure of each specimen. This latter method is understood to be of importance because in order for the concept of corrosion damage quantification to be of practical use, one must be able to assess environmental damage in an aircraft structure during a routine maintenance inspection. Although studies of present NDI techniques reveal that accurate and reliable measurement is often difficult [9,10], the knowledge of what specific parameters inspectors must measure could help to improve current NDI technologies.

Summary

A fracture mechanics based approach to the quantification of corrosion damage has been introduced and several examples of how this protocol might be applied were discussed. The concept relies on a geometric model of corrosion that assumes damage can be treated as a combination of a general thickness reduction and a local stress concentration. A test program that will make use of artificially corroded specimens and fracture mechanics principles has been suggested as a way to verify the concept of corrosion assessment for simple geometries. Once the applicability of the technique had been determined, corrosion in more complex geometries can be quantitatively defined, and constant-life diagrams can be used as structural evaluation tools for in-service use.

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