REVIEW OF PITTING CORROSION FATIGUE MODELS

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The combined effect of corrosion and cyclic loading have been shown to produce cracks from corrosion pits and pits have frequently been the source of cracks on aircraft components operating in fleets. Once the pit or group of pits form, the rate of pit growth is dependent mainly on the material, environmental conditions, and type and state of stress. Therefore, to estimate the total corrosion fatigue life of a component, it is of great importance to develop realistic models to establish the component life in these situations and to formulate methods by which designers and operators know likely sources of pitting early in the design and fleet operation. Therefore, to understand this phenomena, some models based on **pitting corrosion fatigue (PCF) mechanisms** and understanding have been proposed in the past and new ones are emerging.

It is important to note that both pitting theory and crack growth theory have been used in pitting corrosion fatigue model development. The first known conceptual (notional) model was presented in 1971 and subsequently the pit growth rate theory proposed by Godard was combined with fatigue crack growth concepts. Following this basic idea, a few models have been proposed.

This paper presents some examples of critical pitting corrosion fatigue situations in aircraft, discusses the framework of the PCF models to date, presents some applications of the models, and discusses current work underway. Additionally, some recommendations are made related to future work needed to enhance structural integrity and degradation of aircraft from this failure mechanism.

INTRODUCTION

The phases of life of a structure may be classified as follows (1):

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- Nucleation or formation of damage by a specific, physical or corrosion damage process interacting with the fatigue process if appropriate. Corrosion and other processes may act alone to create the damage. a transition from the nucleation stage to the next phase must occur. *Phase* L_1.
- Microstructurally dominated crack linkup and propagation (“short” or “small” crack regime). *Phase* L_2.
- Crack propagation in the regime where either LEFM, EPFM, or FPFM may be applied both for analysis and material characterization (the “long” crack regime). *Phase* L_3.
- Final instability. *Phase* L_4.

Thus, the total life ($\mathbf{L_T}$) of a structure is $\mathbf{L_T = L_1+L_2+L_3+L_4}$. Figure 1 presents a depiction of the degradation process. The regions shown, e.g. 1, 2, 3, and 4, illustrate the portion of life, on the abscissa, and the corresponding growth in discontinuity size plotted schematically on the ordinate. This paper concentrates on the phases L_1 and L_2. That is, the corrosion process that results in the generation of a specific form of corrosion generating a specific form of discontinuity that is not necessarily a crack like discontinuity, and the development of short cracks and their propagation. The requirement of the community to come up with design methods to deal with corrosion or other degradation, fatigue, creep, and wear, is essential and some of the elements are depicted in Figure 2. This figure illustrates that most of the quantitative methods that have been developed used the concepts of mechanics of materials with an incorporation of fracture mechanics (2).

EFFECTS OF CORROSION ON STRUCTURAL INTEGRITY OF AIRCRAFT

The issue of the effects of corrosion on structural integrity of aircraft has been a question of concern for some time (3-38). The potential effects are many and they can be categorized as follows. In the discussion below the use of the terms global and local refers to the likely extent of the corrosion on the surface of a component. Global means the corrosion would be found on much of the component whereas local means the corrosion may be localized to only small, local areas.

1) Reduce the section with a concomitant increase in stress. Global or local.
2) Produce a stress concentration. Local.
3) Nucleate cracks. Local, possibly global. Source of Multiple-site cracking.
4) Produce corrosion debris. This may result in surface pillowing by various means, which may significantly change the stress state and structural behavior. Local and global.
5) Create a situation that causes the surfaces to malfunction. Local and global.
6) Cause environmentally assisted crack growth (EACG) under cyclic (Corrosion fatigue) or sustained loading (SCC) conditions. Local.
7) Create a damage state that is missed in inspection when the inspection plan was not developed for corrosion or when corrosion is missed. Local and global.
8) Change the structurally significant item due to the creation of a damage state not envisioned in the structural damage analysis or fatigue and strength analysis. If

the SSI is specified, for example, by location of maximum stress or strain, then the corrosion may cause another area(s) to become significant. Local or global.

9) Create an embrittlement condition in the material that subsequently affects behavior. Local or Global.

10) Create a general aesthetic change from corrosion that creates maintenance to be done and does damage to the structure. Local or global.

11) Corrosion maintenance does not eliminate all the corrosion damage and cracking or the repair is specified improperly or executed improperly thus creating a damage state not accounted for in the design. Local or global.

12) Generate a damage state that alters either the durability phase of life or the damage tolerant assessment of the structure or both.

13) Create a widespread corrosion damage (WCD) state or a state of corrosion that impacts the occurrence of widespread fatigue damage (WFD) and its concomitant effects. (See references 3, 5, 6, 15, 17, 28, 29, 30, 34, 35, 36, 37, 38 for more information).

The question of whether corrosion, corrosion fatigue and stress corrosion cracking are safety concerns or just maintenance/economic concerns has been a point of discussion related to aircraft structural integrity for over 30 years. Nonetheless, a great deal of the aircraft structural integrity community believes that corrosion related degradation is just an economic concern. It was with this situation in mind that Campbell and Lehay (14) and Wallace, Hoeppner and Kandachar (15) pursued the presentation of technical facts and knowledge to illustrate the potential for a safety issue as well as a maintenance/economic issue. Finally, Hoeppner et al (30) at the 1995 ICAF meeting in Melbourne, Australia reviewed failure data obtained from the USAF, USN, US Army, FAA, and the NTSB related to aircraft incidents and accidents in the USA between 1975-1994 to evaluate further the potential for corrosion and fretting related degradation to be significant safety issues. Recently, several instances of pitting corrosion in aircraft and helicopter components have been identified as critical safety issues as discussed in the following section.

EXAMPLES OF PITTING CORROSION INCIDENTS

A survey was performed of incidents and accidents of aircraft and helicopters caused by pitting corrosion, where an incident is any damage to the aircraft and/or injuries to passengers and crew and an accident is loss of the aircraft and/or fatal injuries to passengers and crew. Data were taken from the NTSB and FAA web-sites, which include their databases of all aircraft incidents and accidents since 1983. It was determined that of the 91 incidents and accidents found under corrosion, seven of those gave the cause of failure as pitting corrosion.

Unfortunately, it has been found that there are problems in reporting the causes of the incidents and accidents in the NTSB and FAA in that the real cause of an incident or accident is not reported properly and, therefore, does not show up in the database. For example, in reading through some of the incidents and accidents caused by corrosion, it was found in the text that the real cause of failure was, more specifically, due to pitting corrosion or exfoliation. But those words were not highlighted so that incident or accident did not show up in a search of pitting corrosion or exfoliation. This makes the validity of numbers of incidents and accidents caused by pitting corrosion questionable due to the fact that additional incidents and accidents may be listed under different causes and/or more general causes. Also included in the survey were the three Embraer 120 incidents involving propeller blades, the Aero Commander 680 lower spar cap, and the F-18 trailing edge flap failure. These civilian and military incidents and accidents were all due to pitting corrosion as shown in Table 1. When these examples are taken with the general information cited in the previous references they clearly show that corrosion related degradation is a significant safety issue in the assurance of structural integrity of aircraft.

Therefore, the potential regrettable occurrence of accidents from corrosion related crack nucleation is a constant threat to aircraft safety. The following quote from the recent NATO RTO conference on fatigue in the presence of corrosion adds some understanding to the need for greater effort to understand the potential role of effects of corrosion on structural integrity.

> *"Some of the workshop papers discussed the significance of corrosion-fatigue as a safety issue or an economic issue. There is ample data to support the contention that it is definitely an economic issue. There is also ample data to support the contention that it has not been a significant safety problem. However, the problem is certainly a potential safety concern if maintenance does not perform their task diligently. In addition, management must continuously update established maintenance and inspection practices to address additional real-time degradation threats for aircraft operated well beyond their initial design certification life. The economic issue alone is sufficient to motivate the support of research and development that can reduce the maintenance burden. This research will also reduce the threat of catastrophic failure from the corrosion damage." (Lincoln, J., Simpson, D., Introduction to Reference 38).*

Another quote from a different reference also sheds further light on this issue (36-page 1-1).

> *"At the present time, structural life assessments, inspection requirements, and inspection intervals, are determined by Durability and Damage Tolerance Assessments (DADTAs) using fracture mechanics crack growth techniques in accordance with the Aircraft Structural Integrity Program (ASIP). These techniques do not normally consider the effects of corrosion damage on crack initiation or crack growth rate behavior. Also, these techniques do not account for multiple fatigue cracks in the DADTAs of the structural components susceptible to WFD. For aircraft that are not expected to have significant fatigue damage for many years, such as the C/KC-135, this approach has severe limitations since it does not account for corrosion damage or WFD. The impact of corrosion damage and WFD on stress, fatigue life, and residual strength must be understood to ensure maintenance inspections and repair actions are developed and initiated before serious degradation of aircrew/aircraft safety occurs."*

Thus, the community clearly now recognizes the potential impact of corrosion related degradation on structural integrity of aircraft. The need to understand the potential for the occurrence of corrosion on aircraft components is critical. Thus, to even begin the assessment of this potential the community needs to know the following:

- the chemical environment likely to be encountered on the structure of interest at the location of interest,
- the material from which the component is manufactured,
- the orientation of the critical forces (loads) applied externally and internally with respect to the critical directions in the material,
- the susceptibility of the material to a given type of corrosion,
- the temperature of exposure of the component,
- the type of forces applied i.e. sustained force or cyclic force (constant force amplitude or variable force amplitude),
- the type of exposure to the chemical environment i.e. constant, intermittent, concomitant with the forces (corrosion fatigue or stress corrosion cracking) or sequentially with force (corrosion/fatigue or corrosion-fatigue),
- the rates of corrosion attack,
- the potential influence of the effects of corrosion on fatigue crack nucleation and propagation,
- the impact of any related corrosion degradation to residual strength,
- the potential for widespread corrosion damage to occur (WCD), and
- the potential impact of corrosion on the occurrence of widespread fatigue damage (WFD) and its impact on structural integrity.

In corrosion fatigue conditions, several studies showed greater increase in fatigue crack growth rates compared to “baseline” fatigue conditions. Although major efforts were expended to understand the crack propagation behavior of materials, a few studies have focused on the crack nucleation stage in the overall fatigue process [39-41]. McAdam first suggested that corrosion induced pits might act as stress concentrators from which cracks could form [42]. A large number of chemical or electrochemical factors such as potential, passive film, pH, and composition of environment are found to affect the pitting corrosion fatigue process. As well, mechanical factors such as stress range, frequency, stress ratio (R), and load waveform and metallurgical factors such as material composition, microstructure, heat treatment, and orientation can influence pitting corrosion fatigue process. Nucleation of cracks from corrosion pits were observed by many researchers including the works of Hoeppner [37-39], Goto [43] in heat-treated carbon steel, and Muller [44] in several steels. As well, in NaCl environment, lowering of the fatigue life due to the generation of pits in carbon steel [45] and 7075-T6 aluminum alloy [46] was observed under corrosion fatigue conditions.

Once the pit forms, the rate of pit growth is dependent mainly on the material, local solution conditions and the state of stress. Cracks have been observed to form from pits under cyclic loading conditions. Therefore, to estimate the total corrosion fatigue life of an alloy, it is of great importance to develop some realistic models to establish the relationship between pit propagation rate and the state of stress. Furthermore, pitting corrosion in conjunction with externally applied mechanical stresses, for example, cyclic stresses, has been shown to severely affect the integrity of the oxide film as well as the fatigue life of a metal or an alloy. Therefore, to understand this phenomena, some models based on pitting corrosion fatigue mechanisms have been proposed as discussed below.

PITTING CORROSION FATIGUE MODELS

Linear Elastic Fracture Mechanics (LEFM) concepts are widely used to characterize the crack growth behavior of materials under cyclic stresses in different environmental conditions. It is important to note that both pitting theory and crack growth theory have been used in the model development as follows. Pit growth rate theory proposed by Godard is combined with the fatigue crack growth concepts. The time (or cycles or both) to nucleate a Mode I crack from a pit (under cyclic loading) could be modeled using LEFM concepts. Based on this idea, a few models [41, 47-49] were proposed. All of the models assume hemispherical geometry for the pit shape and the corresponding stress intensity relation is used to determine the critical pit depth using the crack growth threshold (ΔK_{th}) that is found empirically. For a hemispherical pit geometry, these models provide "a reasonable estimate" for the total corrosion fatigue life. Details of these models are presented in Table 2. The applicability of the proposed pitting corrosion fatigue models in practical cases is discussed in the next section.

THE VALIDITY OF PITTING CORROSION FATIGUE (PCF) MODELS

In this section, two of the PCF models proposed in the past viz. Hoeppner (41), and Kawai & Kasai (48) are examined to illustrate the applicability of these models in practice. Hoeppner in 1979 proposed the first model to estimate the time or cycles for a pit to reach the critical pit depth to nucleate a Mode I crack under pitting corrosion fatigue conditions based on the conceptual framework presented in 1971. It was proposed that with the pit growth rate theory as well as data from fatigue crack growth experiments in a corrosive environment, the cycles needed to develop a critical pit size that will form a Mode I fatigue crack can be estimated. Using this model, the pit-to-crack transition length and cycles to failure for various stresses can be determined. However, currently, there are many unknowns for the analysis of an aircraft component to estimate accurately the fatigue life under PCF conditions. For example, for any material, no attempt has been made to date to determine the rate of pitting growth and the size of pits at various times. This is necessary to determine the *Phase 1* life (L_1, time or cycles to nucleate pits) of a component under PCF conditions. Once the pits are formed, it is necessary to estimate the time or cycles for the pits to reach a critical condition or critical depth to nucleate fatigue cracks from those pits (L_2). First, the transition of pits to "short" cracks occur and then cracks will grow to "long" cracks (50). Therefore, the time or cycles to form "short" cracks from fatigue nucleated pits and propagation to mode I crack need to be determined to estimate the *Phase 2* life (L_2) of a component. To accurately estimate the PCF life of a component using the model proposed by Hoeppner, the following information is necessary to estimate the Phase 1 and the Phase 2 of the total fatigue life:

- The material,

- The geometry,
- The predicted maximum stress on the part,
- The realistic chemical environment around the part,
- The loading spectra,
- A reasonable value for maximum stress on the part,
- The time or cycles to nucleate pits (L_1) - can be estimated from pit growth rate experimental data at different stress levels including the predicted maximum stress on the part,
- Quantified depth of pits from either damage tracking or failure analysis or both,
- "Short" crack behavior of the material, such as fatigue crack growth rate data in the "short" crack regime and the "short" crack threshold stress intensity value,
- The Mode I fatigue crack growth rate data in a realistic corrosive environment including empirical parameters, C and n,
- Certain material parameters, such as the Mode I threshold stress intensity value as a function of frequency, environment, waveform, and R value, and
- Fatigue crack propagation data for evaluating the effect of prior corrosion on the fatigue crack propagation behavior of the component.

As mentioned in Table 2, Kawai and Kasai proposed a model to estimate allowable stresses based on the allowable stress intensity threshold. They recognized that large safety factors are often used in determining allowable stresses because considerations like corrosion are often neglected in S-N curves. Knowing the allowable stress intensity threshold (K_{all}) determined from corrosion fatigue experiments and the maximum pit depth (h_{max}) measured from corrosion pit growth rate experiments for a given "machine-material-environment system", the allowable stress at which the particular component can be operated is determined using the following relation:

$$\Delta\sigma_{all} = \frac{\Delta K_{all}}{F\sqrt{\pi h_{max}}} \text{ -------------------- (1)}$$

where, ΔK_{all} can be determined from a da/dN vs. ΔK plot for a material, h_{max} is the maximum pit depth, and F is a geometric factor.

Combining these two models, two approaches are suggested to estimate the total fatigue life of a component under PCF conditions as discussed below.

The first approach needs data from either failure analysis or extensive experimentation on the design problem of interest. Both approaches are vital. Assuming that the failure analysis of a component revealed that the fatigue crack originated from a pit and because of it fracture occurred, then, the depth of the pit (a) could be measured. The quantified pit depth can be correlated to the pit growth rate curve for the material and the time or cycles to nucleate the size of the pit measured from failure analysis can be determined (Phase 1, L_1). From this, an estimate of the stress value for pit-to-crack transition corresponding to the measured pit depth (from fracture analysis) can be made.

The critical crack size for instability (a_c) can be calculated for the given value of K_{IC} for the material as well as the maximum applied stress for the component. Then, 'a' can be used in the calculation as the initial crack size and knowing the stress intensity threshold value, as well as a_c, the total number of cycles to failure can be estimated using the Paris relation as explained in the later part of this section.

The second approach involves determining the pit-to-crack transition length under various stresses using the stress intensity threshold value from fatigue crack growth experiment as explained in the following steps:

1) Pit-to-crack transition:

This is performed to determine the critical size of pit in terms of pit depth that would transition to a crack (not necessarily a Mode I crack) for different stresses. The stress values that could be used in the calculation are: (a) the estimated maximum applied stress that the component would be subjected to and (b) the ultimate stress for the material in question. From Hoeppner’s pitting corrosion fatigue model, the following equation can be used to determine the critical pit depth:

$$K_{sf} = 1.1\sigma \sqrt{\pi (a/Q)} \text{ --------------------------- } (2)$$

where,

K_{sf} = Stress intensity factor for a surface discontinuity (MPa $\sqrt{m}$),

σ = Applied stress (MPa),

a = Size of the pit in terms of pit depth (μm or m),

Q = f[(a/2c, tensile yield stress (σ_{ty}))] (dimensionless).

In this calculation, it can be assumed that K_{sf} is equal to "short" crack stress intensity threshold (ΔK_{scth}) for the material. It is recommended value of ΔK_{scth} be used because the pit-to-crack transition first would result in a non-Mode I crack, that is in the "short" crack region. It is important to note that there is no standard value for the ΔK_{scth} in the "short" crack region for a particular material as there is no standard test method to measure the fatigue crack growth rates in this regime. Therefore, this value can either be determined from conducting "short" fatigue crack growth experiments or determined from literature for a specific material. The shape parameter, Q, for a surface crack can be assumed depending on the pit morphology. For different stress levels, ranging from the estimated applied stress for the component to the ultimate stress of the material, the critical pit depth 'a' that would enable the transition of the pit to a "short" crack can be determined. The resultant value of 'a' can be compared with the measured depth of the pit from the failure analysis of a similar component, if there is any. Moreover, the calculated value of 'a' can be correlated to the experimentally generated pit growth rate curve to estimate the phase 1 life (L_1). Then, equation (1) can be used to determine the critical crack size for instability (a_c) given the value of K_{IC} for the material as well as the maximum applied stress for the component.

After this, the total cycles to failure under corrosion fatigue conditions can be estimated as discussed below:

2) Estimation of fatigue cycles to failure:

The total fatigue cycles to failure under corrosion fatigue conditions can be estimated using the well known Paris relation as given below:

$$da/dN = C\,\Delta K^{n} \text{ ----------------------- } (3)$$

where,
da/dN = The rate of crack growth per cycle (m/cycle),
'C' and 'n' are empirical parameters, and
ΔK is the stress intensity range (MPa $\sqrt{m}$)

The fatigue crack growth data per ASTM 647 standard is needed for the component. From this, a plot of da/dN vs. ΔK can be made. Also, to estimate the fatigue life, the initial discontinuity size, in this case, the initial pit depth is needed. This is in fact the size of the pit-to-crack-transition as determined from step 1. This can be calculated for various stress values as discussed in step 1. Starting with the initial size of the pit-to-crack-transition that is considered as the initial crack size, first, K_{sf} (that is assumed to be equal to ΔK) can be calculated for equal change or increment of crack size (Δa) at a particular stress level using equation (2). Then, the plot of da/dN vs. ΔK for the component can be used to find the corresponding crack growth rate per cycle (da/dN) for each calculated ΔK. Knowing the value of da/dN, ΔN can be calculated from [Δa/(da/dN)]. This iterative process will be continued until the critical crack length (a_c) is reached. The critical crack size (a_c) can be calculated for different applied stresses for the given K_{IC} for the material using equation (2) as discussed in step 1. Then, the total number of fatigue cycles is added over all of the increments of Δa up to the critical crack size at a particular stress level. This procedure can be repeated for various stress levels and the total fatigue cycles to failure can be compared.

The accuracy of the estimation can be improved if fatigue crack growth rate data under realistic corrosive environments are used in calculating the total cycles to failure. As well, the data on the effect of prior corrosion on the fatigue crack propagation also can help in getting more accurate estimation. The following case study is provided to illustrate the applicability of the PCF models described above in estimating the fatigue life of a component.

CASE STUDY

Background information (51):

A landing gear shock-strut cylinder was subjected to fatigue tests with an applied internal pressure of 41.4 MPa (6 ksi) and an R-value of zero in the laboratory air environment. The cylinder (wall thickness 't' = 5.59 mm or 0.22 in. and inner radius = 44.5 mm or 1.75 in.) was made from the die forging of 7075-T73 aluminum alloy material. The K_{Ic} value for 7075-T73 is about 32.6 MPa$\sqrt{m}$. After 30,000 cycles, fracture occurred along the parting plane as shown in Figure 3. Subsequent failure analysis revealed numerous pits on the internal surface of the cylinder. Figure 4 shows a transverse section through one of those pits. The depth of the pit was quantified at about 6 mils or 0.15 mm. Also, as shown in Figure 5 the fracture surface revealed a semi-circular fatigue crack that originated from a pit on the internal surface of the cylinder.

The crack depth (a) and crack width (2c) were found to be 4.32 mm (0.17 in.) and 9.65 mm (0.38 in.) respectively (52). Nominal hoop stress at the fracture location was calculated at about 331.2 MPa (48 ksi). The calculated hoop stress was about 68% of the parent material ultimate strength and 80% of the nominal design stress (414 MPa or 60 ksi) for the component.

As there is no data available with regard to the pit growth rate for 7075-T73, the *Phase 1* life, that is, the time or cycles to nucleate the pit, from which the crack formed resulting in fracture of the cylinder, can not be estimated. In addition, fatigue crack growth rate data for 7075-T73 in a realistic environment is not available to estimate the number of fatigue cycles for fracture of the cylinder. However, fatigue crack growth rate data for 7075-T73 in a laboratory environment will be used in the estimation. Therefore, with the available information from the failure analysis, the applicability of the PCF models proposed by Hoeppner (41) and Kawai & Kasai (48) to the shock-strut cylinder is demonstrated below.

Calculation of critical stress intensity factor at fracture:

From equation (2), the critical stress intensity factor at fracture can be calculated. Considering the measured crack depth value from the failure analysis as 'a', the calculated σ_{hoop} as σ and Q is assumed as 2.48, the critical stress intensity factor at fracture is found to be 26.95 MPa√m. However, as mentioned before, the K_{Ic} value for 7075-T73 was about 32 MPa√m. The lower K_{Ic} value at fracture could be attributed to numerous pits that were found on the surfaces of the cylinder.

Estimation of pit to crack-transition length:

Using equation (2) from Hoeppner's PCF model, the pit-to-crack transition can be estimated. For $\sigma = \sigma_{hoop} = 331.2$ MPa, Ksf = $\Delta K_{scth} = 0.75$ MPa√m (for 7075-T6 from ref. 50), the pit-to-crack-transition length is determined to be 0.0035 mm.

Estimation of fatigue cycles to failure:

Considering the pit-to-crack-transition length (0.0035 mm) as the initial crack size and the measured crack depth from the failure analysis (4.32 mm) as the critical crack size, the number of fatigue cycles to failure once the pit is transitioned to a crack is determined as shown in Table 3. The procedure outlined in the previous section is used in estimating the number of cycles to failure. The fatigue crack growth rate data for 7075-T73 is used in determining da/dN for each calculated ΔK. As determined from Table 3, the estimated number of cycles to failure is 20,793. When it is compared to the actual cycles to fracture from testing, that is, 30,000 cycles, it is a reasonable estimate.

Estimation of the allowable stress:

Using the model proposed by Kawai and Kasai, the allowable stress at which the shock-strut cylinder can be operated is determined using equation (1). In this equation, ΔK_{all} (allowable stress intensity threshold value) is considered equal to the "long" crack threshold stress intensity value for 7075-T73, that is, 5 MPa√m (from ref. 51). The geometric factor 'F' is assumed as 1. The quantified depth of pit (6 mils or 1.5e-04 m) on the inner surface of the cylinder from failure analysis is considered as h_{max}, that is, the maximum pit depth. Substituting these values in equation (1), the estimated allowable stress at which the shock-strut cylinder can be operated is determined to be 230.3 MPa. It is about 30% lower when compared to the calculated hoop stress (331.2 MPa) at the fracture location of the shock-strut cylinder.

SUMMARY AND CONCLUSIONS

This paper reviewed some PCF models and discussed their usefulness and limitations in estimating the total fatigue life of a component. The applicability of PCF models was demonstrated with a realistic case study involving the fatigue failure of a landing gear shock-strut cylinder. Some examples of critical pitting corrosion fatigue incidents in aircraft and helicopter components were provided to illustrate the significance of developing more realistic models to address this particular failure mechanism. To accomplish this, fatigue growth rate data in a realistic environment need to be generated. Also, the materials response to nucleation of pits and their growth rate under various stresses and environments should be studied.

ACKNOWLEDGMENTS

The research reported herein was performed as a part of the research program "Modeling corrosion growth on aircraft structure" for NCI Information Systems, Fairborn, OH, under contract NCI USAF 9138-003 with Mr. Garth Cooke as the program manager. The support of NCI Information Systems in conducting this research is gratefully acknowledged. The authors also would like to thank the University of Utah for use of facilities and encouragement.

REFERENCES

1) Hoeppner, D.W., "Parameters that Input to Application of Damage Tolerance Concepts to Critical Engine Components," AGARD Conference Proceedings No. 393, Damage Tolerance Concepts for Critical Engine Components, 1986, pp. 4-1 - 4-16.

2) Hoeppner, D.W., and Chandrasekaran, V., "Corrosion and Corrosion Fatigue Predictive Modeling - State of the Art Review," FASIDE report to NCI Information Systems, Fairborn, OH, 1998.

3) Stress Corrosion Cracking in Aircraft Structural Materials, AGARD Conference Proceedings Series 18, Report of a two day Symposium held by the Structures and Materials Panel of AGARD in Turin, Italy, 18,19 April, 1967, NATO-AGARD, 64 Rue De Varenne, Paris, France, 1967.

4) Fundamental Aspects of Stress Corrosion Cracking, Editors: Staehle, R. W, Forty, A.J., van Rooyen, D., Proceedings of a conference held at the Ohio State University, 11-15Sept. 1967, NACE-1, National Association of Corrosion Engineers, Houston, TX, 1969.

5) Effects of Environment and Complex Load History on Fatigue Life, ASTM STP 462, Proceedings of the Symposium on Effects of Environment and Complex Load History on Fatigue Life held in Atlanta, GA, 29Sept. -4Oct., 1968, Edited by M. Rosenfeld, D.W. Hoeppner, and R. I. Stephens, ASTM, Philadelphia, PA., 1970.

6) Corrosion Fatigue: Chemistry, Mechanics, and Microstructure, Editors:, Devereux, O., McEvily, A.J., Staehle, R. W., Proceedings of the Conference held at the University of Connecticut, 14-18June1971, NACE-2, National Association of Corrosion Engineers, Houston, TX, 1973.

7) Brown, B.F., Stress-Corrosion Cracking in High Strength Steels and in Titanium and Aluminum Alloys,, Naval Research Laboratory, Washington, D.C., 1972.

8) Hall, L.R., Finger, R.W., Spurr, W.F., “Corrosion Fatigue Crack Growth in Aircraft Structural Materials”, AFML-TR-73-204, Boeing Company, September, 1973.

9) Pettit, D., Ryder, J., Krupp, W., Hoeppner, D., “Investigation of the Effects of Stresss and Chemical Environments on the Prediction of Fracture in Aircraft Structural Materials”, AFML-TR-74-183, Lockheed California Company, December, 1974.

10) Corrosion-Fatigue Technology, ASTM STP 642, Proceedings of a Symposium held in Denver, CO, 14-19 Nov.1976, Edited by H.L.Craig, Jr., T.W. Crooker, and D. W. Hoeppner, ASTM, Philadelphia, PA, 1978.

11) Aircraft Corrosion, AGARD Conference Proceedings No. 315, Papers presented at the 52nd Meeting of the AGARD Structures and Materials Panel Meeting held in Cesme, Turkey, 5-10 April 1981, , NATO-AGARD, 64 Rue De Varenne, Paris, France, 1981.

12) Corrosion Fatigue, AGARD Conference Proceedings No. 316, Papers Papers presented at the 52nd Meeting of the AGARD Structures and Materials Panel Meeting held in Cesme, Turkey, 5-10 April 1981, , NATO-AGARD, 64 Rue De Varenne, Paris, France, 1981.

13) Corrosion Fatigue, ASTM STP 801, Proceedings of the Symposium on Corrosion Fatigue: Mechanics, Metallurgy, Electrochemistry, and Engineering held in St. Louis, MO21-22 OCT. 1981, Edited by T.W. Crooker, B.N.Leis, ASTM, Philadelphia, PA., 1983.

14) Campbell, G. S., Lahey, R., Int. J. Fatigue, Vol. 6, No. 1, 1984, pp. 25-30. Metals Handbook, 9th ed., Vol. 13, *Corrosion*, American Society for Metals, Metals Park, Ohio, 1985, pp. 584-609

15) Wallace, W., Hoeppner, D., Kandachar, P. V., "Aircraft Corrosion: Causes and Case Histories", AGARD Corrosion Handbook, Vol. 1, , AGARD-AG-278-Vol. 1, 1985.

16) ASM Handbook, Vol. 13, Corrosion, ASM International, Metals Park, Ohio, 1987.

17) The Boeing Company, Corrosion Prevention and Control, Manual for Training Operators of Boeing Commercial. Aircraft, Seattle, WA, 1988.

18) NTSB Metallurgist's Report, "Aloha Airlines Flight 243," Materials Laboratory Report 88-85, 1988.

19) Environment Induced Cracking of Metals, Editors: Gangloff, R.P., Ives, M.B., Proceedings of the conference held in Kohler, WI, 2-7Oct. 1988, NACE-10, National Association of Corrosion Engineers, Houston, TX, 1990

20) ASM Handbook, Volume 18, Friction, Lubrication, and Wear Technology, ASM International, Metals Park, Ohio,, 1992

21) Naval Aviation Safety Program, US Navy, OPNAVINST 3750.6Q CH-1, OP-05F, March 1991.

22) Federal Aviation Administration, Aircraft Accident and Incident Synopses Related to Corrosion, Fretting, and Fatigue for the Period 1976-1993, obtained July 1994.

23) National Transportation Safety Board, Aircraft Accident and Incident Synopses Related to Corrosion, Fretting, and Fatigue for the Period 1975-1993, obtained July 1994.

24) Federal Aviation Administration, Aircraft Accident and Incident Synopses Related to Corrosion, Fretting, and Fatigue for the Period 1976-1993, obtained July 1994.

25) Karpala, F., Hageniers, O.L., "Characterization of Corrosion and Development of a Broadboard Model of a D sight Aircraft Inspection System", Phase 1, Diffracto Ltd., Report to DOT, August, 1994.

26) United States Air Force, Navy, and Army, Aircraft Accident and Incident Synopses Related to Corrosion, Fretting, and Fatigue, obtained June-August 1994.

27) Cooke, G. Vore, P.J., Gumienny, C., Cooke, G. Jr., "A Study to Determine the Annual Direct Cost of Corrosion Maintenance for Weapon Systems and Equipment in the United States Air Force", Final Report, Contract Number F09603-89-C-3016, SEPT., 1990.

28) Schutz, W., "Corrosion Fatigue-The Forgotten Factor in Assessing Durability", ICAF 95, Estimation, Enhancement and Control of Aircraft Fatigue Performance, Vol. 1, Edited by J.M. Grandage, G.S. Jost, Proceedings of the 18th Symposium on the International Committee of Aeronautical Fatigue, 3-5 May, 1995, Melbourne, Australia, EMAS, Warley, West Midlands, U.K., 1995, pp 1-52.

29) Swift,S.J., "The Aero Commander Chronicle", ICAF 95, Estimation, Enhancement and Control of Aircraft Fatigue Performance, Vol. 1, Edited by J.M. Grandage, G.S. Jost, Proceedings of the 18th Symposium on the International Committee of Aeronautical Fatigue, 3-5 May, 1995, Melbourne, Australia, EMAS, Warley, West Midlands, U.K., 1995, pp 507-530.

30) Hoeppner, D.W., Grimes, L., Hoeppner, A., Ledesma, J., Mills, T., Shah, A., " Corrosion and Fretting as Critical Aviation Safety Issues", ICAF 95, Estimation, Enhancement and Control of Aircraft Fatigue Performance, Vol. 1, Edited by J.M. Grandage, G.S. Jost, Proceedings of the 18th Symposium on the International Committee of Aeronautical Fatigue, 3-5 May, 1995, Melbourne, Australia, EMAS, Warley, West Midlands, U.K., 1995, pp 87-106.

31) Brooks, C.L., Liu, K., Eastin, R.G., "Understanding Fatigue Failure Analyses Under Random Loading Using a C-17 Test Article", ICAF 95, Estimation,

Enhancement and Control of Aircraft Fatigue Performance, Vol. 1, Edited by J.M. Grandage, G.S. Jost, Proceedings of the 18th Symposium on the International Committee of Aeronautical Fatigue, 3-5 May, 1995, Melbourne, Australia, EMAS, Warley, West Midlands, U.K., 1995, pp 449-468.

32) ASM Handbook, Vol. 19, Fatigue and Fracture, ASM International, Metals Park, Ohio,, 1996.

33) Schmidt, C.G., Crocker, J.E., Giovanola, J.H., Kanazawa, C.H., Schockey, "Characterization of Early Stages of Corrosion Fatigue in Aircraft Skin", Final Report, Contract No. 93-G-065, SRI International Final Report to DOT, Menlo Park, CA, Report No. DOT/FAA/AR-95/108, February, 1996.

34) Cole, G.K., Clark, G., Sharp, P.K., Implications of Corrosion With Respect to Aircraft Structural Integrity, DSTO –RR-0102, AMRL, Melbourne, Australia, March, 1997.

35) Aging of U.S. Air Force Aircraft, Report of the Committee on Aging of U.S. Air Force Aircraft, NMAB (National Materials Advisory Board), Commission on Engineering and Technical Systems, National Research Council, Publication NMAB-488-2, 1997.

36) Boeing, Corrosion Damage Assessment Framework, Corrosion/Fatigue Effects on Structural Integrity, Report D500-13008-1, USAF Contract No. F9603-97-C-0349. 1998.

37) Paul, C., Mills, T., "Corrosion/Fatigue", Presentation made at AeroMat, "A Study to Determine the Cost of Corrosion Maintenance for Weapon Systems and Equipment in the United States Air Force", Final Report, Contract Number F09603-95-D-0053, February 1998.

38) Fatigue in the Presence of Corrosion, RTO Proceedings 18, Papers Presented at the Workshop of the RTO Applied Technology (AVT) Panel, held in Corfu, Greece, 7-9 October, 1998, AC/323(AVT) TP/8, NATO, Research and Technology Orgranization, BP 25, 7 Rue Ancelle, F-92201, Neully-Sur-Seine, Cedix, France, 1999.

39) Hoeppner, D.W., Mann, and Weekes, "Fracture Mechanics Based Modelling of Corrosion Fatigue Process," in Corrosion Fatigue: Proceedings of the 52nd meeting of the AGARD Structural and Materials Panel held in Turkey, 5-10 April, 1981.

40) Hoeppner, D.W., Corrosion Fatigue Considerations in Materials Selections and Engineering Design", Corrosion Fatigue: Chemistry, Mechanics, and Microstructure, NACE, 1972, pp. 3-11.

41) Hoeppner, D.W., "Model for Prediction of Fatigue Lives Based Upon a Pitting Corrosion Fatigue Process," Fatigue Mechanisms, Proceedings of an ASTM-NBS-NSF Symposium, J.T. Fong, Ed., ASTM STP 675, American Society for Testing and Materials, 1979 pp. 841-870.

42) McAdam, D.J., and Gell, G.W., "Pitting and Its Effect on the Fatigue Limit of Steels Corroded Under Various Conditions", *Journal of the Proceedings of the American Society for Testing Materials,* Vol. 41, 1928, pp. 696-732.

43) Goto, M., and Nisitani, H., "Crack Initiation and Propagation Behavior of a Heat treated Carbon Steel in Corrosion Fatigue", *Fatigue Fracture Engineering Material Structure,* Vol. 15, No. 4, 1992, pp. 353-363.

44) Muller, M., "Theoretical Considerations on Corrosion Fatigue Crack Initiation", *Metallurgical Transactions*, Vol. 13A, 1982, pp. 649-655.

45) Mehdizadeh, P., et al., "Corrosion Fatigue Performance of a Carbon Steel in Brine Containing Air, H2S, CO2", *Corrosion*, Vol. 22, 1966, pp. 325-335.

46) Corsetti, L.V., and Duquette, D.J., "The Effect of Mean Stress and Environment on Corrosion Fatigue Behavior of 7075-T6 Aluminum", *Metallurgical Transactions,* Vol. 5, 1974, pp. 1087-1093.

47) Lindley, T. C., McIntyre, P., and Trant, P. J., "Fatigue Crack Initiation at Corrosion Pits," *Metals Technology*, **Vol. 9**, 1982, pp. 135-142.

48) Kawai, S. and Kasai, K., "Considerations of Allowable Stress of Corrosion Fatigue (Focused on the Influence of Pitting)," *Fatigue Fracture of Engineering Materials Structure,* Vol. 8, No. 2, 1985, pp. 115-127.

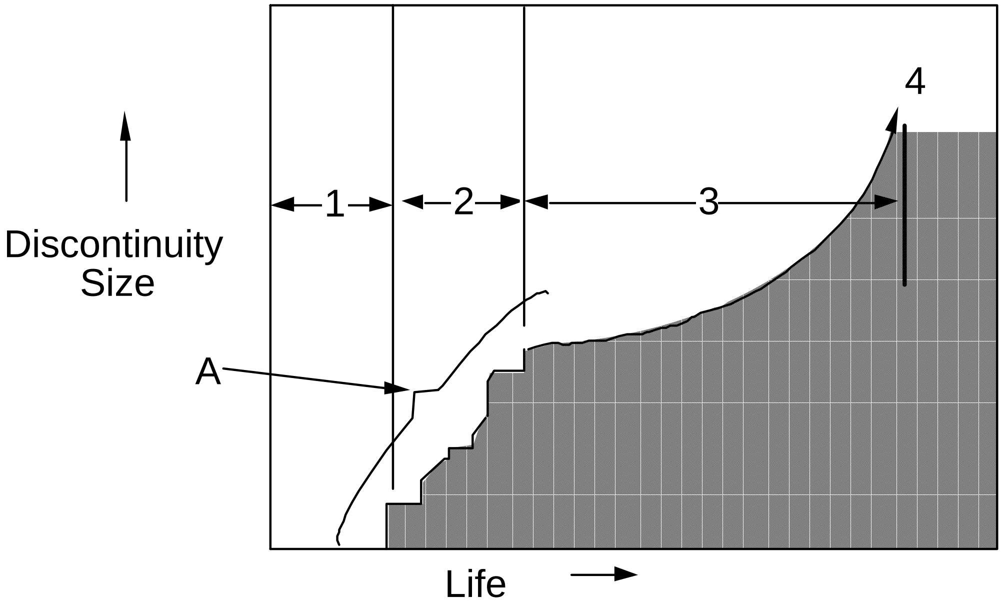
49) Kondo, Y., "Prediction of Fatigue Crack Initiation Life Based on Pit Growth," *Corrosion Science*, Vol. 45, No. 1, 1989, pp. 7-11.

50) Newman Jr., J.C., Phillips, E.P., and Swain, M.H., "Fatigue-Life Prediction Methodology Using Small-Crack Theory," *International Journal of Fatigue,* 21, 1999, pp. 109-119.

51) Bowie, G.E., Van Orden, J.M., Besari, M.S., Pettit, D.E., Weber, K.E., Krupp, W.E., Fairchild, J., and Meyer, D.R., Correlation of Failure Analysis Data: Pitting Corrosion, LR 27399, Lockheed-California Company Report, 1975.

52) Hoeppner, D.W., Prevention of Fracture in Materials, Lockheed Continuing Education Course, 1970.

The degradation process



A= "FIRST" detectable crack

1. Nucleation phase, "NO CRACK"
2. "SMALL CRACK" phase-steps related to local structure (Anisotropy)
3. Stress dominated crack growth, LEFM, EPFM
4. Crack at length to produce instability

Figure 1 -- A depiction of the degradation process (after Hoeppner-1971, 1986).

METHODS FOR EACH LIFE PHASE

NUCLEATION	**"SMALL CRACK"** GROWTH	STRESS DOMINATED CRACK GROWTH	FAILURE (FRACTURE)
Material failure mechanism with appropriate stress/strain life data	Crack Prop. threshold related to structure (micro)	Fracture mechanics •similitude •boundary cond. LEFM EPFM ?	K_{Ic} etc. C.O.D. Tensile/ compressive buckling
Nucleated discontinuity (not inherent) type, size, location	Structure dominated crack growth	Data base**	
Presence of malignant D*, H*	Mechanisms, rate	Appropriate stress intensity factor Initial D*, H* size, location, type	
Possibility of extraneous effects •Corrosion •Fretting •Creep •Mechanical Damage	Onset of stress dominated crack growth	Effects of •R ratio •Stress state •Environment •Spectrum -waveform t chem T	
	Effects of •R ratio •Stress state •Environment •Spectrum -waveform t chem T		

Figure 2 -- Methods for each life phase (after Hoeppner-1971, 1986).

NOTE: Initiation as frequently used by the technical community is usually part of the nucleation (or formation), short crack growth, and stress dominated crack growth phase of life. One is never sure however how much of the life is taken up by the traditional use of the “initiation” concept. To avoid this we have used the term initiation herein only to refer to the beginning of a specific degradation process such as corrosion, fatigue, or initiation of crack propagation. As depicted in Figure 1 what often is referred to as “initiation” is life to a certain detectable crack size or damage size. This is a critical distinction in that use of “first” crack detection concepts, or related on condition evaluation terms, forces the designer to think about inspectability and detectability of specific forms of degradation. As well, it is imperative that the technical community develop an understanding of the nucleation and growth phases of degradation processes.

Table 1 -- Pitting corrosion incidents of aircraft and helicopters

Aircraft	**Location of Failure**	**Cause**	**Incident Severity**	**Place**	**Year**	**From**
Bell Helicopter	Fuselage, longeron	Fatigue, corrosion and pitting present	Serious	AR, USA.	1997	NTSB
DC-6	Engine, master connecting rod	Corrosion pitting	Fatal	AK, USA.	1996	NTSB
Piper PA-23	Engine, cylinder	Corrosion pitting	Fatal	AL, USA.	1996	NTSB
Boeing 75	Rudder Control	Corrosion pitting	Substantial damage to plane	WI, USA.	1996	NTSB
Embraer 120	Propeller Blade	Corrosion pitting	Fatal and serious, loss of plane	GA, USA.	1995	NTSB
Gulfstream GA-681	Hydraulic Line	Corrosion pitting	Loss of plane, no injuries	AZ, USA.	1994	NTSB
L-1011	Engine, compressor assembly disk	Corrosion pitting	Loss of plane, no injuries	AK, USA.	1994	NTSB
Embraer 120	Propeller Blade	Corrosion pitting	Damage to plane, no injuries	Canada	1994	NTSB
Embraer 120	Propeller Blade	Corrosion pitting	Damage to plane, no injuries	Brazil	1994	NTSB
F/A-18	Trailing-edge Flap (TEF) Outboard Hinge Lug	Corrosion pitting, fatigue	Loss of TEF	Australia	1993	AMRL
Mooney Mooney 20	Engine, interior	Corrosion pitting, improper approach	Minor injuries	TX, USA.	1993	NTSB
Aero Commander 680	Lower Spar Cap	Corrosion pitting	Fatal	Sweden	1990	Swedish CAA

Table 2 -- Pitting corrosion fatigue models

	Proposed by	**Summary**	**Description**	**Advantages/ Limitations**
1	Hoeppner (1971 - current)	• Proposed a model to determine critical pit depth to nucleate a Mode I crack under pitting corrosion fatigue conditions. • combined with the pit growth rate theory as well as the fatigue crack growth curve fit in a corrosive environment, the cycles needed to develop a critical pit size that will form a Mode I fatigue crack can be estimated.	• Using a four parameter Weibull fit, fatigue crack growth threshold (ΔK_{th}) was found from corrosion fatigue experiments for the particular environment, material, frequency, and load spectrum. • The stress intensity relation for surface discontinuity (half penny shaped crack) was used to simulate hemispherical pit. i.e.) $K = 1.1\,\sigma\sqrt{\pi\left(\frac{a}{Q}\right)}$ where, σ is the applied stress, a is the pit length, and Q is the function of a/2c, S_{ty}. • Using the threshold determined empirically, critical pit depth was found from the stress intensity relation mentioned above. • Then, the time to attain the pit depth for the corresponding threshold value was found using $t = \left(\frac{d}{c}\right)^3$ where, t is the time, d is the pit depth, and c is a material/environment parameter.	• This model provides a reasonable estimate for hemispherical geometry of the pits. • This model is useful to estimate the total corrosion fatigue life with knowledge of the kinetics of pitting corrosion and fatigue crack growth. • This model did not attempt to propose mechanisms of crack nucleation from corrosion pits. • This model is valid only for the conditions in which LEFM concepts are applicable. • Material dependent.

	Proposed by	**Summary**	**Description**	**Advantages/ Limitations**
2	Lindley et al. (1982)	• Similar to Hoeppner's model, a method for determining the threshold at which fatigue cracks would grow from the pits was proposed.	• Pits were considered as semi-elliptical shaped sharp cracks • Used Irwin's stress intensity solution for an elliptical crack in an infinite plate and came up with the relationship to estimate threshold stress intensity values related to fatigue crack nucleation at corrosion pits. i.e.) $\Delta K_{th} = \dfrac{\Delta\sigma\sqrt{(\pi a)\left[1.13-0.07\left(a/c\right)^{1/2}\right]}}{\left[1+1.47\left(a/c\right)^{1.64}\right]^{1/2}}$ where, $\Delta\sigma$ is the stress range, a is the minor axis, and c is the major axis of a semi-elliptical crack. • From the observed pit geometry i.e. for a/c ratio, threshold stress intensity can be calculated. • For the corresponding a/c ratio, critical pit depth can be estimated.	• The proposed stress intensity relation can be used in tension - tension loading situations where stress intensity for pits and cracks are similar. • Critical pit depths for cracked specimens can be estimated using the existing threshold stress intensity values. • This model is valid only for the conditions in which LEFM concepts are applicable. • Material dependent.

	Proposed by	**Summary**	**Description**	**Advantages/ Limitations**
3	Kawai and Kasai (1985)	• Proposed a model based on estimation of allowable stresses under corrosion fatigue conditions with emphasis on pitting. • As corrosion is not usually considered in developing S-N fatigue curves, a model for allowable stress intensity threshold involving corrosion fatigue conditions was proposed.	• Considered corrosion pit as an elliptical crack. • Based on experimental data generated on stainless steel, new allowable stresses based on allowable stress intensity threshold was proposed. i.e.) $\Delta\sigma_{all} = \frac{\Delta k_{all}}{F\sqrt{\pi h_{max}}}$ where, ΔK_{all} can be determined from a da/dN vs. ΔK plot for a material, h_{max} is the maximum pit depth, and F is a geometric factor.	• Using this model, allowable stress in relation to corrosion fatigue threshold as a function of time can be estimated. • Material dependent. • This model is valid only for the conditions in which LEFM concepts are applicable.

	Proposed by	**Summary**	**Description**	**Advantages/ Limitations**
4	Kondo (1989)	• Corrosion fatigue life of a material could be determined by estimating the critical pit condition using stress intensity factor relation as well as the pit growth rate relation.	• Pit diameter was measured intermittently during corrosion fatigue tests. • From test results, corrosion pit growth law was expressed as $2c \ \alpha \ C_p \ t^{1/3}$ where, 2c is the pit diameter, t is the time, and C_p is an environment/material parameter. Then, critical pit condition (ΔK_p) in terms of stress intensity factor was proposed by assuming pit as a crack. $\Delta K_p = 2.24\sigma_a \sqrt{\pi c \alpha / Q}$ where, σ_a is the stress amplitude, a is the aspect ratio, and Q is the shape factor. • Critical pit condition was determined by the relationship between the pit growth rate theory and fatigue crack growth rates. $c = c_p \ (N/f)^{1/3}$ where, N is the number of stress cycles, f is the frequency, and 2c is the pit diameter. • The pit growth rate dc/dN was developed using ΔK relation as given below. $dc/dN = \left(\frac{1}{3}\right) C_p^{\ 3} f^{-1} \alpha^2 \pi^2 Q^{-2} (2.24\sigma_a)^4 \Delta K^{-4}$ dc/dN was determined using experimental parameter C_p. • Finally, the critical pit size $2C_{cr}$ was calculated from the stress intensity factor relation. i.e.) $2C_{cr} = (2Q/\pi\alpha)(\Delta K_p/2.24\sigma_a)^2$	• The aspect ratio was assumed as constant. • Material and environment dependent.

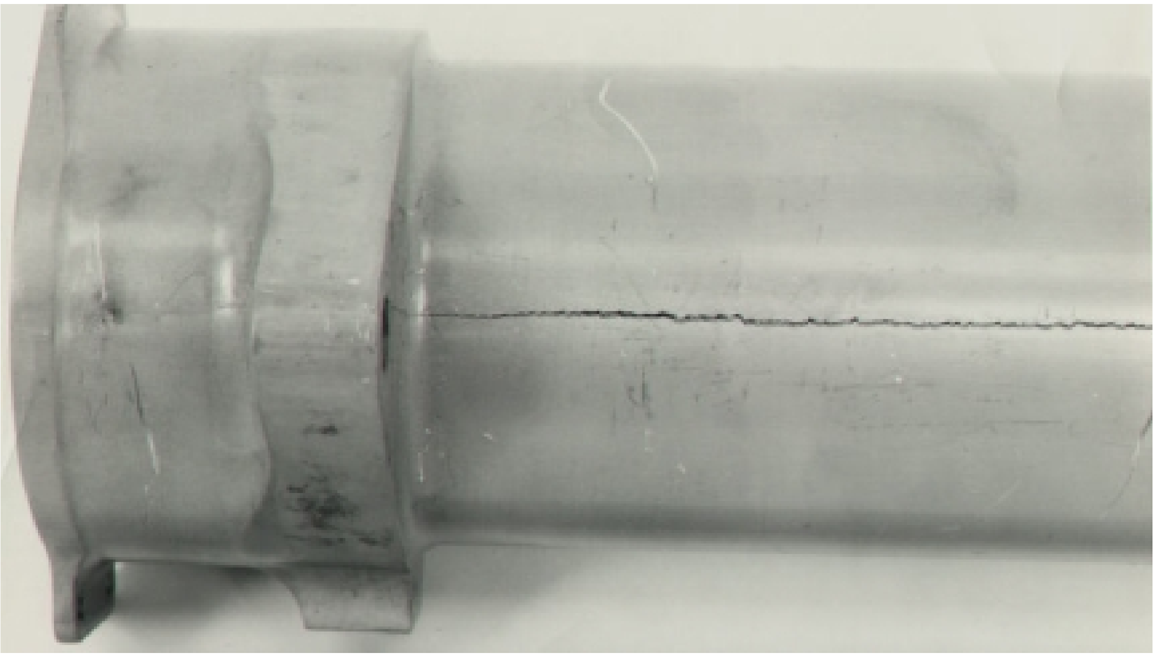


Figure 3 -- Fracture along the parting plane of 7075-T73 shock-strut cylinder.

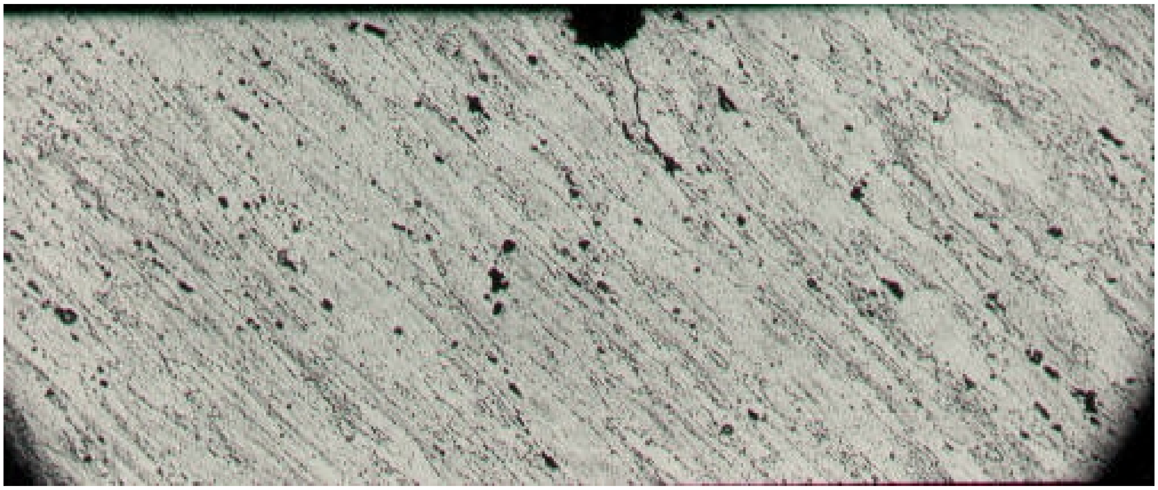


Figure 4 -- A transverse section of a pit on the inner surface of the shock-strut cylinder. Note a fatigue crack nucleated from the pit.

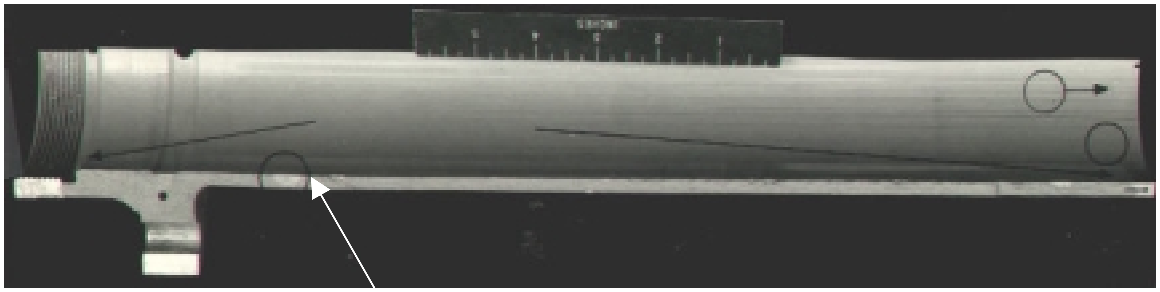


Figure 5 -- A semi-circular crack originated from a pit that was found on the inner surface of the shock-strut cylinder (shown by an arrow pointing a circle).

Table 3 -- Fatigue life estimation for the shock-strut cylinder

a	K = ΔK	Δa	da/dN***	Avg. da/dN	ΔN	N_{total}
m	MPa*m$^{1/2}$	m	m/cycle	m/cycle	cycles	cycles
3.35E-06*	0.75075**		2.54E-12			
5.03E-04	9.1996	0.0005	5.08E-08	2.5401E-08	19684	19684
1.00E-03	12.9885	0.0005	2.03E-06	1.0414E-06	480	20164
1.50E-03	15.8987	0.0005	5.08E-07	0.00000127	394	20558
2.00E-03	18.3532	0.0005	2.03E-05	1.0414E-05	48	20606
2.50E-03	20.5160	0.0005	1.65E-05	1.8415E-05	27	20633
3.00E-03	22.4717	0.0005	1.27E-05	1.4605E-05	34	20667
3.50E-03	24.2702	0.0005	1.02E-05	0.00001143	44	20711
4.00E-03	25.9444	0.0005	2.54E-06	0.00000635	79	20790
4.32E-03****	26.9614	0.00032	0.000216	0.00010922	3	20793

* The calculated pit-to-crack transition length based on Hoeppner's PCF model (considered as the initial crack length).

** The "short" crack stress intensity threshold (ΔKscth) for 7075-T6 from reference (50).

*** Determined from the plot of da/dN vs. ΔK for 7075-T73.

**** The measured crack depth from the fracture surface of the shock-strut cylinder (considered as the critical crack length).