Application of Fracture Mechanics Data to Aerospace Design

David. W. Hoeppner*
University of Missouri, Columbia, Mo.
and
W. Krupp† and D. Pettit‡
Lockheed California Company, Burbank, Calif.

This paper briefly reviews the concepts of fracture mechanics as they may be applied to subcritical and critical flaw growth analysis in engineering design and inspection. A simple presentation of the manner used to apply fracture mechanics is given in the paper. The principles of fracture mechanics applied to fatigue, stress corrosion cracking, and other subcritical flaw-growth problems as presented herein will serve as an introduction to many of these concepts for practicing engineers and students who have had only minimal exposure to fracture mechanics applications.

Nomenclature

a = crack size, cm (in.)
a_c = critical crack size for instability, cm (in.)
a_{cop} = critical crack size under a given operational stress, cm (in.)
a_i = initial crack size, cm (in.)
a_p = crack size after proof, cm (in.)
a_{th} = threshold crack size, cm (in.)
da/dN = fatigue-crack growth rate, cm/cycle (in./cycle)
da/dt = crack growth rate, cm/sec (in./sec)
K_{Ic} = critical plane strain stress intensity factor, mpa$\sqrt{m}$ (ksi$\sqrt{in.}$)
K_{Ii} = initial plane strain stress intensity factor, mpa$\sqrt{m}$ (ksi$\sqrt{in.}$)
K_{Iq} = plane strain stress intensity factor, noncritical value mpa$\sqrt{m}$ (ksi$\sqrt{in.}$)
K_{Iscc} = plane strain stress intensity factor for stress corrosion cracking, mpa$\sqrt{m}$ (ksi$\sqrt{in.}$)
K_{th} = threshold value of stress intensity factor below which a crack will not grow, mpa$\sqrt{m}$ (ksi$\sqrt{in.}$)
ΔK = change in stress intensity factor, mpa$\sqrt{m}$ (ksi$\sqrt{in.}$)
N = number of cycles
Q = correction factor for surface flaws, $[\phi^2 - 0.212 (\sigma/\sigma_y)^2]$
R = ratio of minimum stress to maximum stress in a cycle, (S_{min}/S_{max})
S_{op} = operating stress, mpa (ksi)
S_p = proof stress, mpa (ksi)
ΔS = change in stress, mpa (ksi)
t = time, sec
Δt = change in time, sec
σ = applied stress, mpa (lb/in.^{2})
σ_y = yield stress (or yield strength), mpa (lb/in.^{2})
ϕ = elliptic integral of the second kind

Introduction

THE design of safe and reliable structures using fracture mechanics principles involves the following areas of consideration: material selection (K_{Ic}, etc.); initial flaw size, shape, and probable location; subcritical flaw growth; periodic inspection; and the probability of high load applying stress in excess of the remaining strength. Where fail safety and/or integrity cannot be assured by using design concepts incorporating either redundancy or crack stoppers, including "safety" factors and/or scatter factors, fracture mechanics principles can be used by considering all the five areas listed above. There are many possible variations within the above framework. These variations will depend on the material, structural component, and application. Some of these variations are illustrated in the following paragraphs.

The remainder of the paper deals with conceptual applications of fracture mechanics to several cases frequently encountered in engineering design. Many of the concepts

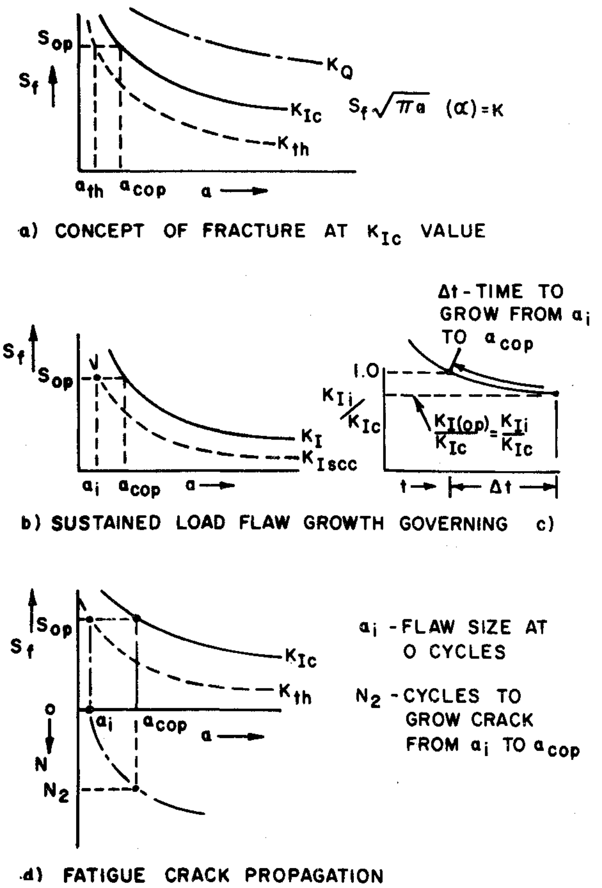

Fig. 1 Applications of fracture mechanics

Received May 10, 1976; revision received June 28, 1977.
Index categories: Aerospace Technology Utilization; Materials, Properties of; Structural Design.

*Professor of Engineering. Member AIAA.
†Group Engineer.
‡Research Engineer.

presented are not only applicable to preliminary design (or equivalent), but also can be utilized in formulating fix, maintenance, or retrofit practices when (if) field failures are encountered. The latter section of the paper deals with the importance of inspection, materials processing, and probabilistic assessment of all factors that can impact the life prediction to develop the most reliable structures permissible. It is to be emphasized that this paper is only meant as an introduction to many of these concepts for practicing engineers and students who have not had extensive exposure to applications of fracture mechanics

Fracture mechanics has been applied in various areas for fracture resistant design and prediction of material and structural integrity. It has been applied in the aerospace, nuclear, and power-generation industry to design rocket motor cases, pressure vessel tankage, and nuclear pressure vessels. In addition, it has been used in thick-gun-tube-design applications and rotating-machinery design. These applications are discussed in Refs. 1-6. Reference 7 discusses how fracture mechanics principles can be used in design for materials that possess extensive toughness, i.e., materials that up to now were considered low or medium strength. Fracture mechanics can be used to aid in the evaluation and selection of materials, the evaluation of performance and life prediction, the establishment of fracture toughness values in material and process specifications, as an aid in design for fracture resistance during service, and as a method for determining service inspection intervals. The question immediately arises, how do data generated in laboratory programs aid in the above considerations? The following subsections indicate how these data may be applied in practice in conceptual form.

Typical Use of Fracture and Flaw Growth Data

Figures 1-4 illustrate schematically the manner in which fracture- and flaw-growth data may be used.§ Figure 1a shows stress at failure (S_f) versus a flaw parameter (a on the figure, but for surface flaws a/Q). The three lines on Fig. 1a represent K_Q – the fracture toughness at a given transition condition, K_{Ic} – the critical plane-strain stress intensity (fracture toughness), and K_{th} – a threshold value of K below which crack growth of an initial flaw is not practically measurable. The fracture value indicated by K_Q in Fig. 1a is any conditional value of toughness determined from a fracture toughness test. When the value of K_Q determined in a test is found to satisfy the validity requirements for plane strain conditions (ASTM E399 test standard) then it is equivalent to K_{Ic}, i.e., $K_Q - K_{Ic}$. However, if the value of K_Q determined in a test does not satisfy the validity requirements, then it remains a conditional transition (K_Q) value. Transition as used here refers to values that lie between the critical plane strain stress intensity factor, K_{Ic}, and the critical plane stress intensity factor, K_c. This is the value of K for crack growth "initiation," which is equivalent to saying either that $da/dN > 0$ or $da/dt > 0$ in the fatigue-crack propagation or sustained load crack growth processes, respectively. If the operating stress (S_{op}) is at the value indicated in Fig. 1a, then a subcritical flaw of a size equal to or greater than a_{th} can grow to a critical size in a given lifetime ($a_{cop} - a_{th}$). The crack propagation rate must be large enough for this behavior to occur. However, suppose a flaw of critical size, a_{cop} is present. Then upon the first application of the operating stress, failure will occur. Because, as shown in the figure, the critical stress intensity resulting from the presence of the flaw (a_{cop}) was equaled or exceeded. The critical flaw size at the operating stress can be computed by

$$a_{cop} = (1/\pi\alpha^2)(K_{Ic}/S_{op})^2 \tag{1}$$

§The generation of these data is a matter of concern of numerous technical organizations. If the reader is interested in generation of fracture mechanics data, it is suggested that the appropriate test practices be consulted.

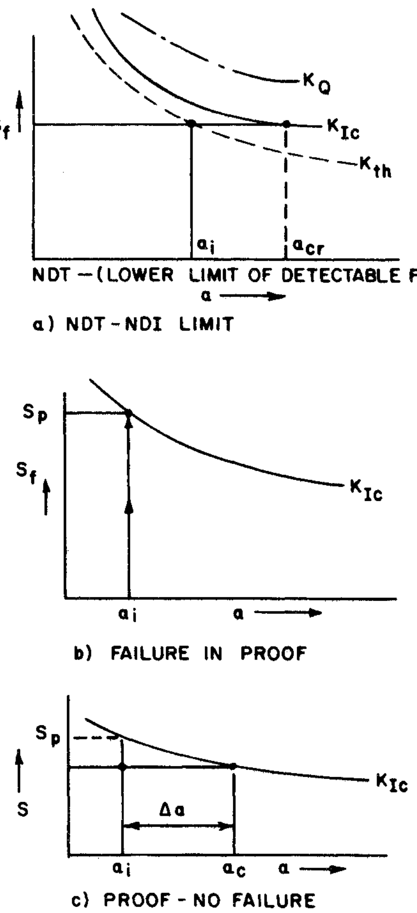

Fig. 2 Establishing flaw size by NDT/NDI or proof testing.

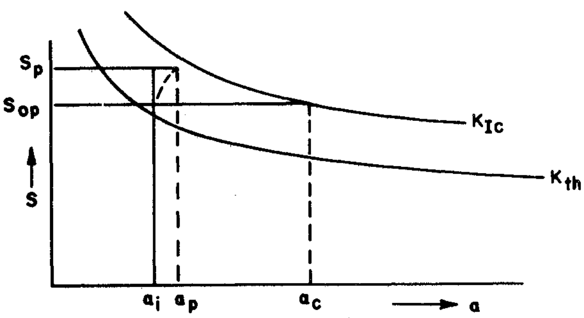

Fig. 3 Flaw growth during proof (initial overload).

If the initial flaw size (a_i) present is known and is greater than a_{th}, then the rate of subcritical flaw growth under projected operating conditions can be used to predict the life. For example, Figs. 1b and 1c illustrate the use of subcritical flaw growth data to explain crack propagation under sustained load conditions.

In Fig. 1b, an initial flaw (a_i) is at a sustained tensile load in a corrosive environment at S_{op}. The presence of the critical flaw a_i under the sustained tensile stress S_{op} in the corrosive environment develops a critical stress intensity greater than K_{Iscc}. The critical stress intensity factor K_{Iscc} is a value below which no crack propagation will take place in the environment being considered. The time for the flaw to grow from a_i to a_{cop} and the stress intensity to increase from K_{Ii} to K_{Ic} for fracture will occur as indicated in Fig. 1c. It is clear from this discussion that if the initial flaw size is known as well as the crack growth rate, then the life can be predicted.

In Fig. 1d the threshold stress intensity K_{th} is exceeded under the influence of an alternating operating stress because of the presence of the flaw of size a_i. The upper portion of the

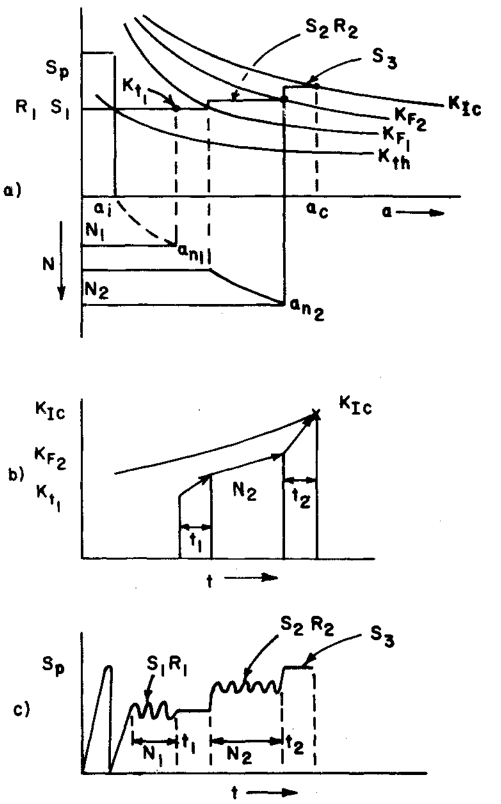

Fig. 4 Combination of fatigue-crack growth and sustained load flaw growth.

figure shows how the initial flaw propagates to a critical size a_{cop}. This causes an increase in stress intensity to the critical value for failure, K_{Ic}. The lower portion of Fig. 1d shows how the initial flaw grows to a critical size as N, the number of cycles of alternating stress applied, increases.

The change in flaw size with change in operating stress cycles da/dN and the increase in stress intensity ΔK are influenced by alternating stress ΔS, stress range ratio $R = S_{min}/S_{max}$, and the environment. Thus, each material condition could respond differently. Values of da/dN can be obtained by numerically differentiating data similar to the lower portion of Fig. 1d. Values of ΔK can be determined by calculating the stress intensity at the maximum load value of the cycle and minimum load value of the cycle and taking the difference.

Data of this sort can be used for the prediction of fracture behavior of a material when its crack propagation rate and fracture toughness properties are known.

The determination of the initial defect size (a_i) is sometimes difficult because this measurement must be made by nondestructive inspection (NDI) or by proof testing. The limits of detectability of the size and orientation of small flaws in materials is still subject to considerable error on a statistical basis.

Use of the principles illustrated in Fig. 1 can be used to 1) select the material with the desired fracture toughness for the prescribed application (K_{Ic}, etc.); 2) set NDT/NDI requirements prior to service; 3) establish proof test criteria for the component prior to (or during) service; 4) establish inspection intervals. It should be fairly clear from the prior discussion how item 1 above can be handled as can items 2 and 4. In Fig. 2a, the limit of detectability of a minimize size flaw a_i is shown. If the presence of this flaw causes a stress intensity under an operating stress that is equal to or greater than K_{th}, the flaw will propagate. If the rate of propagation under the applied stress is large enough, the flaw can grow to a critical size a_c. Under this condition the stress intensity will increase to the critical value K_{Ic} at which failure will occur.

Data of initial flaw sizes determined by NDI, crack propagation rates and fracture toughness (stress intensity factor) for a given material can be used in the prediction of the life of a part made from the material.

In Fig. 2b the initial flaw a_i is large enough so that the critical stress intensity K_{Ic} is reached under the proof stress S_p. If, as shown in Fig. 2c, the initial flaw a_i is small enough such that a critical stress intensity is not developed under the proof stress S_p, failure will not occur in the proof test. This behavior will not guarantee that the part will have an infinite life. If the crack propagation rate is large enough under the influence of the operating stress the initial flaw a_i can grow to a critical size a_c. Under these conditions if an initial flaw not detected by proof testing can propagate to a critical size, failure can occur under the operating stress when the critical stress intensity is reached.

It is preferable that a material, manufacturing, and design process can be used such that the events shown in Fig. 2c result. In this case, the initial flaw size is less than critical at proof. Thus, failure does not occur during the proof cycle. If the proof is completed, then it is known that no defect greater in size than a_i can be present, since if it was it would have failed at the proof stress S_p. Thus all crack sizes a greater than a_i have effectively been screened. All that remains then is to relate the initial crack size subsequent to proof to the growth that may result from service. If operating conditions and materials are selected such that growth during service does not reach a critical size, the life can be predicted. The frequency of inspection intervals can be predicted using the knowledge of initial and critical flaw sizes, crack propagation rates, and fracture toughness in the material.

One caution must be noted: it has been found by both Hoeppner[5] and Tiffany[8] that flaw growth can occur during proof testing as a function of the proof stress S_p and the hold time at proof stress. This observation not only has implications to "hold times" in proof testing but also in time effects during loading cycles. Thus, wave form effects could be extremely important for some materials. Hoeppner has shown in addition, how cryogenic proof testing might be used to screen small flaws. This procedure, however, may lead to other problems that have resulted in additional research.[9] The initial flaw growth during proof loading is illustrated in Fig. 3. The initial flaw a_i present at the start of proof, grows during loading and hold time to a_p. Thus it would normally be assumed that the flaw size after proof would be a_i, whereas it truly is a_p. It is apparent that knowledge of the flaw growth that may occur during proof and its effect on time or cycles to reach K_{Ic} by subcritical flaw growth must be available. Because if a_p is of such a size, with crack propagation rates large enough, it is possible for the crack growth induced by the proof overload to continue as a result of the operating

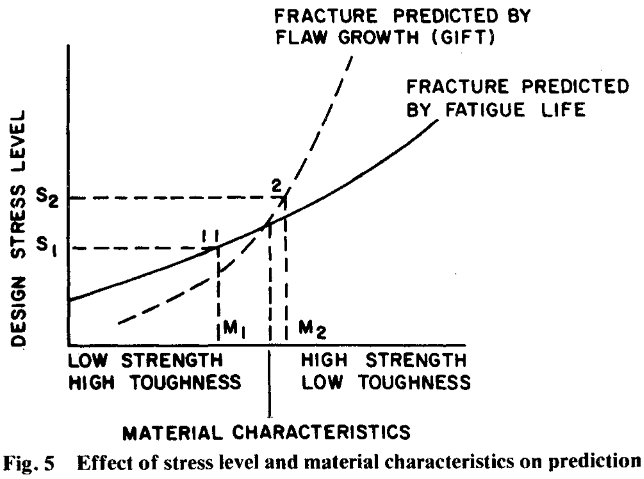

Fig. 5 Effect of stress level and material characteristics on prediction of fracture.

stress. Under these conditions the crack could reach a critical size a_c such that the critical stress intensity level K_{Ic} was equaled or exceeded and thus failure could occur.

The effect of mixed loading on subcritical flaw growth is shown in Fig. 4. The figure consists of four parts that illustrate the behavior of an initial flaw during 1) proof test, 2) fatigue loading, 3) sustained loading for a limited time, 4) fatigue loading at a higher stress and a different range ratio than 2, and 5) sustained loading at a higher stress than 4.

Fig. 4a is in two parts. The upper part shows that a material containing an initial flaw a_i survives the proof load and thus screens all flaws larger than a_i. Under fatigue loading at (S_I, R_I) the crack propagates from a_i to a_{nI}. Now under sustained loading at S_I for time t_I the crack propagates as K_{th} increases to K_I. Applying fatigue loading at S_2 with a range ratio R_2 causes continued crack propagation and an increase of stress intensity to K_{F2}. Now when a higher sustained load S_3 is applied for time t_2, the crack grows to the critical size, a_c, which under the applied stress increases the stress intensity to the critical value for failure K_{Ic}.

The propagation of the subcritical flaw under cyclic loading is shown in the lower portion of Fig. 4a. The increase in K with holding time under sustained loading is shown in Fig. 4b. The schematic loading cycles are illustrated in Fig. 4c. Data of this sort can be applied to the prediction of the life of a material.

The question that still remains and will require more thorough investigation is: Does the proof overload induce sufficient damage to start the crack propagation? Or does the fatigue cycling at (S,R), shown schematically in Fig. 4, cause the propagation and growth of the initial flaw? Information of this type can be used to establish lower limits of flaw size to be screened in various materials in an attempt to avoid fracture. Use of the da/dN versus K data, and the da/dt versus t data, in combination with K_{Ic}, can be used to establish recommended materials selection and application criteria, as well as recommended design practice for mixed-mode or plane-stress conditions. Material must be selected that provides the best compromise between such properties as static strength, stiffness, fatigue life, corrosion resistance, fracture toughness, and crack propagation resistance. Usually fracture toughness, and to a lesser extent, crack propagation resistance, are attained at the sacrifice of ultimate tensile strength. One of the major design considerations then becomes how much toughness and crack growth resistance are needed? For aircraft structural design, fracture mechanics analysis is supplemental to the more traditional fatigue life analysis, and partial answer to the above question can be attained by providing sufficient toughness and crack growth resistance so that the probability of failure due to the propagation of an undetectable initial flaw is of the same order as the probability of failure estimated from the fatigue analysis. Such a comparison is illustrated in Fig. 5.

In Figure 5, the prediction of fracture in design can be predicated upon conventional fatigue life analysis when the stress level is low enough S_I and a low strength-high toughness material M_I is used. This procedure is illustrated by point 1 on the figure and assumes a statistical body of laboratory data and field experience both are available.

Now, if a higher design stress level S_2 is required (to reduce weight or provide higher performance), then a higher strength material M_2 may be used. This material will have a lower fracture toughness and thus the same flaw size that could be tolerated in the first case could cause failure at the higher stress level in M_2 even though it is "stronger." Under these conditions, as shown by Fig. 5 at point 2, prediction of fracture must be done using the Griffith-Irwin Fracture Toughness (GIFT) analysis using subcritical flaw growth and fracture toughness data.

At the transition between low-strength and high-strength materials between points 1 and 2 on Fig. 5 a transition in the fracture behavior exists. In this area it is not clear whether prediction of fracture can be accomplished by either fatigue life considerations or subcritical flaw growth (GIFT) considerations.

Table 1 Some sources of defects in fabricated aircraft components

Defects existing in mill products
Chemical contamination
Inclusions
Laminations
Internal defects
Porosity
Cracks
Surface defects
Cracks
Laps
Pits
Scratches
Defects produced by processing
Machining
Grinding, honing, drilling
Cracks, scratches, gouges
Transformed regions
Welding
Planar defects due to residual stresses, incomplete fusion
Impurity segregation to liquid/solid boundary
Part geometry produces thermal stress on cooling
Plating
Coating defects-cracks, pits
Surface contamination
Hydrogen embrittlement

Initial Flaws

The size, shape, and location of probable initial flaws are influenced by metallurgical factors, product form, fabrication methods, and the ability of available inspection techniques to detect them on a reliability basis. Initial flaws in aircraft components can be present in the sheet, plate, or forged material or can be imparted during processing, as shown in Table 1. Nondestructive testing techniques employed to reveal the flaws include surface penetrant, X-ray, and ultrasonic. An Air Force Materials Lab. (AFML) contract performed at

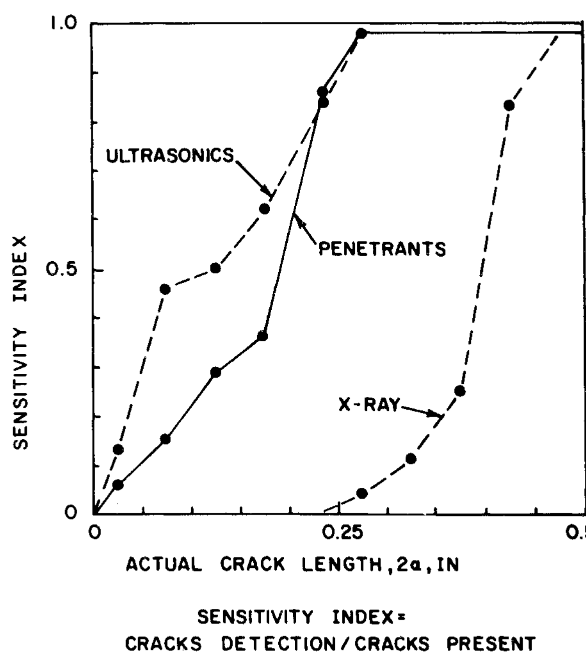

Fig. 6 Comparison of NDT inspection methods for aluminum cylinders.

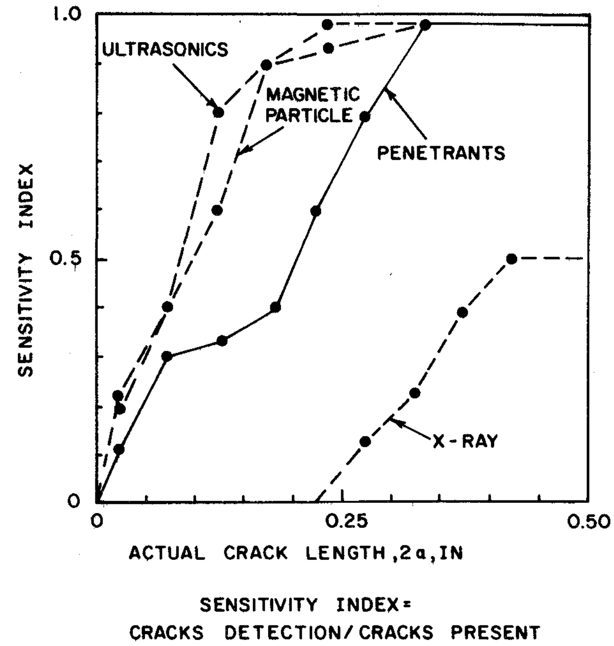

Fig. 7 Comparison of NDT inspection methods for steel cylinders.

Lockheed-Georgia Company[10] investigated the accuracy of determining flaw size, geometry, and location in typical aircraft components. Results for aluminum and steel parts are presented in Figs. 6 and 7, respectively.

The severity of initial flaws as sources of possible structural failures depends upon the probability of overloads in excess of the strength of the flawed structure and on the probability of overloads during subsequent flaw growth resulting from the combined effects of load and environmental spectra.

In the past it has been design practice to take measures to ensure the fatigue quality of a structure by specifying surface finish, heat treatment, fastener type, design details, etc. It is clear that the designer must also consider the flaw sensitivity of structure by specifying on the engineering drawing fabrication methods, inspection techniques, etc. to ensure that flaws of a greater severity than his design assumptions do not occur in the structure. An illustration of such material considerations and associated critical processing steps is presented in Table 2. Estimates of the maximum flaw size that can be permitted in a given structure can be made using available fracture mechanics analysis.

Periodic Inspection

After a flaw growth analysis has been completed, it must be judged whether the structure need or need not be subject to periodic inspection. Just as in fatigue life estimations, there are a number of unknowns that preclude an absolute determination of structural life. These include: variations in material properties; distribution of flaw size, shape, location, etc., actual load and environmental histories for an operational fleet of structure; and calculation unknowns such as sequential load and environmental effects. Thus an equivalent to a fatigue life reduction factor is needed. This can best be satisfied by establishing several inspection intervals within the estimated safe-life based on flaw size calculations. Preferably, these intervals should correspond to normal maintenance procedures. A portion of all design verification programs should yield information on the frequency of inspection required for the conditions studied.

Probabilistic approaches to fatigue life estimation have not been well developed for fatigue analysis. Although their desirability is understood, it will be some time before they can become effectively implemented. Therefore, as in fatigue analysis, crack growth-remaining strength analysis will

Table 2 Some material parameters and processing requirements

4340 Steel at 260-280 ksi strength level exhibits
Low resistance to crack growth
Increased susceptibility to mechanical damage
Decreased resistance to stress corrosion, H_2 embrittlement
Tempering temperature close to region that produces reduced impact properties
These factors result in critical processing operations
Casting or forging – inclusions, porosity
Welding – incomplete fusion, heat – affected zone
Heat Treatment – embrittlement, decarburization
Stress Relief – straightening, residual stress
Machining after heat treatment – hole drilling, grinding to produce untempered Martensite
Plating – H_2 embrittlement, poor adhesion, coating flaws
Ti-6Al-6V-2Sn, Ti-6Al-4V alloys exhibit
Low resistance to flaw growth in the presence of moisture
Susceptibility to environmental degradation by halogens, hydrogen, hydraulic fluids, cadmium metal
Ease of damage by fretting
Wide variation in fatigue data
These factors result in critical processing areas
Casting or forging – inclusions, porosity
Welding – contamination, incomplete fusion
Machining – imparting surface defects, removal of chlorinated oils (pickling), arc cutting burns
Fastening – protection against fretting
7075-T6 aluminum alloy exhibits
Susceptibility to galvanic and exfoliation corrosion
Poor resistance to stress corrosion, especially short transverse grain direction
Susceptibility to residual stress
These factors require
Use of overaged tempers in stress corrosion critical areas
Proper application of surface protection agents
Careful thermal and mechanical processing to avoid residual stresses and property degradation

initially be approached in terms of a maximum load to be carried by flawed structure. Realistically this should vary with operational requirements so that it reflects the probabilistic nature of these loads. For instance, since the number of relatively high loads in maneuver critical spectra are usually greater than in gust critical spectra, it would be necessary to specify a relatively higher tolerable K level for a fighter aircraft than for a transport in order to obtain the same level of reliability. Some initial assessment of the required strength of a flawed structure can be obtained by observing that in fail-safe design of commercial aircraft eighty percent of limit loads is the required strength for obviously damaged structure.

Concluding Remarks

It is anticipated that procedures similar to those illustrated in Figs. 1-5 can be established for the materials of interest in any structural application. This will allow the development of: recommended materials selection and application criteria; recommended design criteria; recommended data acquisition and presentation techniques; and recommended materials and process specification for fracture-resistant systems. Increased use of these procedures and further detailed requirements will reduce the incidence of unexpected events in structural design. It must be emphasized that the key to successful application of fracture mechanics is in the knowledge of loads and stresses and in the supportive data available.

Acknowledgment

The authors are grateful to the Lockheed California Company for continuing support. Dr. Hoeppner appreciates the continuing financial support of the Office of Naval Research, the Naval Ship Engineering Center, and the Alcoa Foundation.

References

[1]"Fracture Control of Metallic Pressure Vessels," NASA Structures Design Monograph, NASA SP8040, May 1970.

[2]Wilhelm, D. P., "Fracture Mechanics Guidelines for Aircraft Structural Applications," Air Force AFFDL-TR-69-111, Feb. 1970.

[3]Glorioso, S., "Lunar Module Pressure Vessel Operating Criteria Specification," NASA-MSC-SE-V-0024, Oct. 1968.

[4]Glorioso, S. and Ecord, G., "Fracture Mechanics Analysis of Apollo Block I Titanium Alloy Pressure Vessels (Command and Service Modules)," Apollo Working Paper No. 1325, 1967.

[5]Hoeppner, D. W., Pettit, D. E., Feddersen, C. E., and Hyler, W. S., "Flaw Growth Characteristics of Ti-6Al-4V Sheet in the Solution-Treated and Aged Condition," NASA CR-65811, Jan. 1968.

[6]Wessel, E. T., Clark, W. G., and Wilson, W. K., "Engineering Methods for the Design and Selection of Materials Against Fracture," Final Tech. Rept., U. S. Army Tank-Automotive Center, June 24, 1966.

[7]Liebowitz, H. (ed.), *Fracture, An Advanced Treatise*, Academic Press, New York, 1969.

[8]Tiffany, C. F., private communication, 1964.

[9]Schwartzberg, F. R., Gibb, R. H., and Beck, E. J., "Experimental Study of Pop-In Behavior of Surface-Flaw-Type Cracks," NASA-CR 108457, July 1970.

[10]Packman, P., Pearson, H., Owens, J., and Marchese, G., "The Applicability of a Fracture Mechanics-non-Destructive Testing Design Criterion," Air Force AFML-TR-68-32, 1968.

From the AIAA Progress in Astronautics and Aeronautics Series . . .

INSTRUMENTATION FOR AIRBREATHING PROPULSION—v. 34

Edited by Allen Fuhs, Naval Postgraduate School, and Marshall Kingery, Arnold Engineering Development Center

This volume presents thirty-nine studies in advanced instrumentation for turbojet engines, covering measurement and monitoring of internal inlet flow, compressor internal aerodynamics, turbojet, ramjet, and composite combustors, turbines, propulsion controls, and engine condition monitoring. Includes applications of techniques of holography, laser velocimetry, Raman scattering, fluorescence, and ultrasonics, in addition to refinements of existing techniques.

Both inflight and research instrumentation requirements are considered in evaluating what to measure and how to measure it. Critical new parameters for engine controls must be measured with improved instrumentation. Inlet flow monitoring covers transducers, test requirements, dynamic distortion, and advanced instrumentation applications. Compressor studies examine both basic phenomena and dynamic flow, with special monitoring parameters.

Combustor applications review the state-of-the-art, proposing flowfield diagnosis and holography to monitor jets, nozzles, droplets, sprays, and particle combustion. Turbine monitoring, propulsion control sensing and pyrometry, and total engine condition monitoring, with cost factors, conclude the coverage.

547 pp. 6 x 9, illus. $14.00 Mem. $20.00 List

TO ORDER WRITE: Publications Dept., AIAA, 1290 Avenue of the Americas, New York, N. Y. 10019