# Fracture Mechanics Aircraft Structural Design Application and Related Research

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Fracture control requirements developed to ensure safety by reducing the probability of catastrophic failure due to undetected damage have been instituted by the USAF in the design of current and future systems. These requirements include provisions in appropriate aspects of material and processes selection, material procurement and control, non-destructive inspection and damage tolerance analyses and testing.

General Requirements: Requirements to perform crack propagation analyses on all primary safety of flight structure have been formulated (Figure 1). Each structure is classified according to type of approach selected to achieve damage tolerance, i.e., slow crack, or fail safe, and the type and frequency of in-service inspection. Analyses are performed to demonstrate that undetected initial production damage will not grow to catastrophic size prior to scheduled depot level inspection and that damage missed during any scheduled in-service inspection will not grow to critical size prior to the subsequent inspection. Final damage size is governed by the specified residual strength load, a variable depending upon inspection interval. In order to conduct these analyses, four new design allowables must be available to the analyst. Since the analysis must start with the maximum size crack-like defect which can remain undetected, this value takes on all the significance of a design allowable. Therefore, the probability and confidence level associated with detection of defects having a given size must be known for all applicable production and in-service inspections. Crack growth rate data must be available for all appropriate alloys, heat treatments, product forms, chemical environments, stress ratios, frequencies, and $\Delta K$ levels. The sustained stress intensity level below which crack growth will not occur must be known, as must the appropriate critical stress intensity factor, for all alloys, heat treatments and product forms.

Because the fracture mechanics design methodology is quite new, the necessary design data are not available with a statistical background sufficient to allow the luxury of testing on a sampling basis, as is done with conventional mechanical properties. Therefore, to attain the desired degree of structural safety, elaborate fracture control programs are presently required to ensure that the properties of materials in the as-fabricated structure are not inferior to those assumed by the analyst. The first step in the fracture control program is to identify and control those processing parameters necessary to produce raw materials possessing the requisite fracture toughness, stress corrosion resistance, and crack growth rate as well as conventional properties. Verification of proper processing must be accomplished at present by extensive fracture testing of raw materials such as plate, bar and extrusions. Extensive testing and very tight process control are also required during fabrication to ensure that methods employing heat, permanent deformation or chemical attack have not degraded the fracture properties. The role of non-destructive inspection (NDI) is recognized as crucial in ensuring structural safety. By working with the analyst, the NDI engineer must identify inspection requirements for every area of each component identified as fracture critical, and must prepare detailed inspection instructions which ensure that defects of the specified size will be detected with high probability and confidence. Where initial crack lengths used by the





analyst are smaller than allowed by the requirements, a demonstration program must be conducted using the inspection instruction with production equipment, conditions and personnel. The inspectors must be unaware that an evaluation is being conducted, and sufficient observations must be made of different flaw size ranges and unflawed control specimens so that a valid statistical evaluation of the results can be made.

In applying the requirements, these basic data coupled with analysis methods are used to establish allowable stresses so as to limit the safe crack growth to the bounds prescribed by the initial specified damage, the required growth period and the final critical damage size. This implies knowledge and understanding of variable amplitude load interaction effects, coupled load and environmental behavior and a mathematical model which suitably predicts this behavior. For multi-mission military aircraft, approximations must be made for flight stress profile simulation, location, size, shape and number of flaws to be considered, growth patterns, transitional behavior as surface cracks penetrate the thickness, failure sequence of individual elements in built up structure, and location and growth of damage in structure following arrest of a running crack or fracture of a fail safe load path.

Related Research Activities: Research is currently underway to upgrade our understanding of related fracture phenomenon and to improve the analysis capability. A major effort is determining the behavior of surface flaws and flaws emanating from open, filled, and loaded fastener holes, and to establish stress intensity solutions for these cases. Much of the testing is being conducted under flight simulation loading. Studies in growth delay and load interaction effects are quite numerous.

Delayed retardation patterns following overloads have been observed in aluminum and not in titanium. Important tasks are underway to improve existing growth retardation models which account for these variable patterns. Closure phenomena observed by many is one aspect being investigated. In many structures, fracture is controlled by other than plane strain conditions and use of $K_{IC}$ as a parameter is too conservative. Efforts are currently underway to improve the capability to predict mixed mode and plane stress fracture.

Projected future criteria are being evaluated in depth for their impact on existing structures including wing structure for cargo and fighter aircraft, and cargo aircraft pressurized fuselage structure. Numerous variables are being investigated including effects of material property variations, influence of initial flaw size, importance of multiple cracking assumptions, effect of in-service inspection frequency and capability, and criticality and cost of process controls on raw materials and fabrication. Efforts are in progress to identify environmental effects on crack growth rate, and to assess the interaction of in-service environments with metallurgical variables.

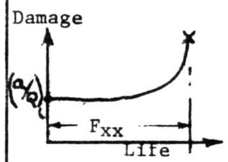
Conclusions - Problems and Concerns: Although significant work is being done in development of alloys with greatly improved resistance to fracture, applications of fracture mechanics criteria to aircraft design have helped to clarify the critical importance of research to identify the basic metallurgical mechanisms which will lead to improved resistance to crack growth and to the development of alloys which are relatively insensitive to the chemical environments in which aircraft operate. Considerable effort is needed to identify precisely the effect of processing and fabrication operations on crack growth rate and environmental sensitivity, and to develop economical procedures for





process controls and mechanical property retention validation. Load sequence effects on crack growth are difficult to predict even when the loads and ordering are known. The problem is compounded by the fact that exact loading is seldom known, and the level of simulation used is critical to the resultant growth calculations. Rationale for establishing confidence on growth predictions accounting for all the variables must be examined in order to preclude the assignment of arbitrary factors to growth calculations.

SAFE CRACK GROWTH REQUIREMENTS - INITIAL DAMAGE - $F_{xx}$

| Inspection \ Concept | I. Slow Crack Growth | II. Fail Safe Multiple Load Path | III. Fail Safe Crack Arrest | $(a/Q)_i$ = Assumed Initial Damage |
|---|---|---|---|---|
| A. In-Flight Evident | N/A | 2 x Frequency of Depot Level Inspection ( ½ Lifetime Typical) | | $(a/Q)_I = 0.10$ |
| B. Ground Evident | N/A | | | $(a/Q)_{II,III} = 0.03$ |
| C. Walk Around Visual | 2 x Frequency of Depot Level Inspection ( ½ Lifetime Typical) | | |   |
| D. Special Visual | | | | |
| E. Depot Base Level | | | | Failure |
| F. Non-Inspectable | 2 Life-times | 1 - Lifetime | 1 - Lifetime | I - Structure<br>II - Load Path<br>III - Critical $(a/Q)$ |

SAFE CRACK GROWTH REQUIREMENTS - IN-SERVICE DAMAGE

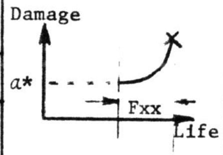
| Inspection \ Concept | I. Slow Crack Growth | II. Fail Safe Multiple Load Path | III. Fail Safe Crack Arrest | $a^*$ = Assumed In-Service Damage |
|---|---|---|---|---|
| A. In-Flight Evident | N/A | Return to Base | Return to Base | |
| B. Ground Evident | N/A | One Flight | One Flight | |
| C. Walk Around Visual | 5 x Frequency of Inspections (50 flights typical) | | |   |
| D. Special Visual | 2 x Frequency of Inspection (2 years typical | | | |
| E. Depot, Base Level | 2 x Frequency of Inspection (½ lifetime typical) | | | |
| F. Non-Inspectable | N/A | 1 - Lifetime | N/A | |

Figure 1 - Summary of Crack Growth Requirements