SAFE-LIFE ANALYSIS OF STRUCTURES SUBJECTED TO GENERAL IN-PLANE LOADINGS

N. N. Au

The Aerospace Corporation
Los Angeles, California 90009

ABSTRACT

The current methodology of safe-life analysis is based on the assumptions that the crack is aligned perpendicularly to the direction of loading and that the crack will propagate in a self-similar manner. In real structures, however, cracks are seldom oriented in this manner and the direction of crack propagation is generally not known as an a priori. These problems can be overcome by the strain-energy-density factor theory, or the $S_C$-theory. In this paper, the $S_C$-theory is applied to investigate the crack-growth characteristics of inclined cracks under general in-plane loadings. Equations are developed to enable the determination of safe-life in terms of structural allowables and crack-growth behavior of inclined cracks subjected to uniaxial tension, biaxial tension, and in-plane shear stress, acting either singly or in any specified combination. This versatility significantly increases the scope of application of fracture mechanics to the design, analysis, and development of weight-critical structures. An example problem is used to illustrate the safe-life analysis procedures. It is shown that the strain-energy-density factor range, $\Delta S$, is an effective parameter for use in predicting the safe-life of structures under the combined influence of crack geometry, complex loadings, and material properties. The resulting safe-life analysis accounts for the stress amplitude, mean stress, and the direction of crack propagation and is, therefore, a significant improvement over the conventional methodology. The influence of crack-angle orientation and mean stress on the predicted fatigue crack-growth life is also examined and discussed.

INTRODUCTION

Failure in a structure is often a complex interaction of metallurgy, mechanics, and chemistry. In aerospace structures, the three possible failure modes which have received the most attention from structures engineers and designers have been detrimental deformation, gross yielding, and elastic instability. In recent years, unexpected failures from subcritical crack growth and unstable crack extension have led to accelerated studies of cracks and crack-growth behaviors, and catapulted fracture mechanics as an important engineering tool in the design and development of modern high-performance structures.

The introduction of fracture mechanics into the structural design process significantly enhances our ability to design against the problem of brittle frac-
ture, fatigue failures, and stress-corrosion failures in aerospace structures. Through fracture mechanics, fracture-resistant design is made more quantitative. Material strengths and fracture properties can be balanced so that a lightweight structure can be designed and fabricated with sufficient damage-tolerance for long life and safety. Indeed, damage-tolerant and fatigue-resistant designs have become requirements for both military and commercial aerospace structures. Furthermore, with the advent of the Space Shuttle, fracture mechanics analysis and fracture control procedures are required by both the USAF Space Division and NASA on all their payloads using the Space Transportation System in order to prevent structural failures due to the initiation and propagation of flaws or crack-like defects.

One of the principal design philosophies widely used in the design of modern high-performance structures is the safe-life design approach. According to this design philosophy, crack propagation to failure will not occur during the specified service life of the structure. Safe-life structures are designed such that initial damage will grow at a stable, slow rate under service environment and not achieve a size large enough to cause rapid unstable propagation. Safety is assured by the maintenance of a slow rate of damage growth, a residual strength capability, and the assurance that subcritical damage will either be detected or will not reach unstable dimensions within the specified safe-life period. Safe-life is typically defined as at least four times the specified service life for space launch structures when they are not accessible for periodic inspection and repair of four times the interval between regularly scheduled inspection when they are readily accessible for periodic inspection and repair. This design philosophy is mandatory for all single load path structures, such as pressure vessels.

Safe-life analysis, as currently practiced in the industry, is typically conducted under the assumption that the structure has preexisting flaws or cracks of sizes defined by the acceptance proof test or by the selected nondestructive inspection techniques. A conventional stress analysis is first conducted to identify areas of low tensile margins of safety. These areas, along with areas of most likely occurrence of flaws, are then investigated for safe-life. The structure is said to be safe during its service life when the investigated areas, with the preexisting flaws placed in the most unfavorable orientation with respect to the applied stress and material properties and acted upon by the spectra of predicted operating loads and environments, meet specified safe-life requirements.

Clearly, the prediction of safe-life requires a knowledge of the loading spectra and the environments to which the structure is exposed. In addition, a knowledge is also required of the stress-intensity factor as a function of the crack size and geometry, the material fracture toughness, the crack-growth data in the expected operating environments, and the appropriate crack-growth model.

The current methodology to safe-life analysis suffers from several drawbacks which are the direct results of over-simplifying assumptions associated with loading conditions, crack orientation with respect to the applied stress, the direction of crack propagation, and a single mode of crack propagation. In addition, the effect of mean stress on fatigue crack propagation and fatigue life is not explicitly accounted for in the current methodology. In real structures, cracks are seldom aligned perpendicularly to the direction of loading. Real structures also are seldom subject to uniaxial loading alone. For these reasons, the direc-