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Observations on fatigue crack growth in a range of materials

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ABSTRACT

Variants of the Frost–Dugdale crack growth law now form the basis of one of the fleet management tools in use within the Royal Australian Air Force (RAAF) Directorate General for Technical Airworthiness (DGTA) for the management of cracking in RAAF Combat Aircraft. To help understand the basis for this methodology the present paper examines the crack length versus cycles histories associated with a range of materials, viz: Mil Annealed Ti–6Al–4V, a high strength aerospace steel, several aerospace quality aluminium alloys and several rail wheel steels, subjected to constant amplitude loading. This paper also examines the crack length histories obtained in surface flawed 7050-T7451 and Ti–6Al–4V specimens under operational flight load spectra, in the Boeing 767 and 757 Material Characterisation test program, in a Northrop–Grumman study into crack growth under a representative fighter spectrum, in the Aloha Airlines accident, in several full scale fatigue tests and in-service cracking in rail wheels. In each case it is shown that crack growth conforms to the Generalised Frost–Dugdale crack growth law and that for spectra that consist of a number of repeated block loads the crack length history follows a form similar to that used to manage the RAAF Combat Aircraft fleet.

1. Introduction

It is commonly thought that the increment in the crack length per cycle, da/dN, can be related to the stress intensity factor range, ΔK ($=K_{max} - K_{min}$) where K_{max} is the maximum stress intensity factor in the cycle and K_{min} is the minimum stress intensity factor in the cycle, and/or the maximum stress intensity factor K_{max}. This approach was first suggested in 1961 by Paris et al. [1], who related the crack extension per cycle (da/dN) to the maximum stress intensity factor K_{max} and subsequently led [2] to the well known Paris equation:

$$da/dN = C(\Delta K)^m \tag{1}$$

where a is the crack length, N is the number of cycles and C and m are experimentally obtained and are considered to be a constant for a particular material and environment. Over the years this relationship, which works well in the mid-growth range or "Paris Region" region, has continued to be modified to account for a variety of observations [3], including R ratio ($R = K_{min}/K_{max}$) and K_{max} effects [4,5], and crack closure [6].

The Paris crack growth law and its subsequent variants are all based on the similitude hypothesis which states that:

two different cracks, in the same material and in specimens with the same thickness, with the same stress intensity factor range ΔK and K_{max}, will grow at the same rate.

However, it has been suggested that this hypothesis is not necessarily true in Region I where crack growth can be a function of the test geometry [7–13].

At this point it is important to recall that the Paris equation was not the first law developed to describe fatigue crack growth. This honour can be attributed to Shanley [14] who, on the basis of his experience as an airworthiness engineer, proposed a simple linear relationship between the log of the crack length (a) and the number of cycles (N), viz:

$$\ln(a) = \psi N + \ln(a_i) \quad \text{or } a = a_i e^{\psi N} \tag{2}$$

where ψ is a parameter that is geometry, material and load dependent, and a_i is the initial crack-like flaw size (the depth/length of the crack at the start of loading, i.e. at $N = 0$). Frost and Dugdale [15,16] subsequently found that, for centre cracked panels, ψ could be expressed as:

$$\psi = \lambda(\Delta\sigma)^\alpha \tag{3}$$

where λ is a constant, $\Delta\sigma$ ($=\sigma_{max} - \sigma_{min}$) is the stress range, σ_{max} is the maximum stress in the cycle, σ_{min} is the minimum stress in the cycle and $\alpha = 3$. Hence the Frost–Dugdale model can be written as:

$$da/dN = \lambda a(\Delta\sigma)^3 \tag{4}$$

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