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International Journal of Fatigue 27 (2005) 828–834

International Journal of Fatigue
www.elsevier.com/locate/ijfatigue

Probabilistic crack growth behavior of aluminum 2024-T351 alloy using the 'unified' approach

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Received 9 March 2004; received in revised form 11 August 2004; accepted 4 December 2004

Abstract

In a previous paper, a deterministic experimental crack growth model for aluminum 2024-T351 alloy was formulated based on published experimental results, using the 'unified' approach. In the present paper, random equivalent initial flaw size (EIFS) values obtained from other experimental results are introduced to the model, and the crack growth probabilistic behavior is demonstrated. The EIFS values computed from published experimental results of 3-D cracked fastener holes are well-approximated by a Weibull distribution. This approximated EIFS distribution is used as a distribution of the initial cracks in a large number of computations for a 2-D case which is very similar to the 3-D one, and serves for demonstration purposes. A computation program was written to numerically solve the behavior of crack lengths vs. the number of load cycles. It is shown that part of the initial cracks do not propagate, as their initial value is smaller than the required threshold criteria set by the 'unified' approach. A dispersion in the number of load cycles required to obtain a given crack length is shown. Although the coefficient of variation (COV) of this dispersion is smaller than the COV of the initial random cracks, it may be of concern to designers, as the life period of the design may change by a factor of more than 3.

Keywords: Probabilistic crack growth; Fatigue crack growth; Fracture mechanics; Aluminum 2024-T351 alloy; Unified approach

1. Introduction

Crack growth behavior is a major issue in the prediction and maintenance of aerospace structures, as well as other structural elements in mechanical and civil engineering projects. Prediction of expected life of a structural element due to a combination of a constant (static) and an alternating (fatigue) loadings is of major concern to the designers. Prediction of remaining life of the structural elements influences the decisions of maintenance engineers (checking intervals, corrections, replacements).

Fracture mechanics has been used as the main tool with which such problems have been treated. During the last three decades, fracture mechanics scientists and engineers have made tremendous advances, from the basic practical approach dominated by Paris–Erdogan law, to more and more sophisticated crack growth models. Mathematical and metallurgical models (both deterministic and probabilistic), experimental analysis of simple models and testing of complex structures have resulted in thousands of publications, dozens of models for crack growth and life prediction, maintenance decision-making processes and numerous computer codes for crack growth analysis.

A major concern of fracture mechanics is the influence of the load ratio on the behavior of cracks. In 'real life' both static and alternating (i.e. vibrations) loadings exist simultaneously. This is expressed by the load ratio R, which is classically defined as:

$$R = \frac{S_{min}}{S_{max}} \quad (1)$$

S_{min} and S_{max} are the minimal and maximal applied stresses, respectively, in the far field. Thus, $R = -1$ refers to 'pure' vibrations (mean value is zero), $R = 0$ is a loading between zero level ($S_{min} = 0$) and a maximum value (S_{max}).

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doi:10.1016/j.ijfatigue.2004.12.003

Experiments have shown that the value of R influences the crack growth rate (da/dn, where a is the crack length and n is the number of load cycles). It was argued that the reason for this influence is the crack closure effect. Crack closure was first introduced by Elber [1,2]. Since then, many publications treated the phenomena, suggesting models for the closure phenomena (i.e. Newman [3]) and methods to measure the driving force due to crack closure. The ASTM introduced a standard method (ASTM standard E647) for its measurement, and numerous numerical codes for its computation were developed (i.e. Newman [4], Harter [5]). The crack closure is also claimed to be the reason for the different (and sometimes contradicting) behavior of very short cracks and microstructure cracks. In the last decade, some experimental results have suggested that the role of closure in the crack growth process might have been exaggerated. Measurements of closure stresses were done in 10 separate labs (Phillips [6], ASTM [7]), with completely differing results. Experiments done in vacuum did not show the R effects on the results (i.e. Clerivet et al. [8], Shih et al. [9], Vasudevan et al. [10]). Some approaches, which are considered controversial, have been published claiming that the crack-growth driving forces depend not only on the change in the stress intensity factor (SIF) ΔK, but on additional (mainly local internal) stresses.

One of these approaches, the so called 'unified' approach, is described in many papers by Vasudevan, Sadananda et al. (i.e. [11–16] and cited references). According to these works the growth of the crack depend on both ΔK and K_{max}, and in order for a crack to grow, two thresholds values must be met. According to this approach, the local driving force of short cracks is comprised of two stresses-one originated from the far field stress intensity factor and the other-from local internal stresses close to the crack tip. These local stresses 'create' local R values near the crack tip, which are different from the far field R value. The internal stresses were measured (Sadananda et al. [17]) and compared to finite element computations. By using this approach, the behavior of both short cracks and long cracks can be treated using one 'unified' growth law. This approach is supported by data analysis of many previous experimental results for many materials described by numerous authors and laboratories.

In Maymon [18], a crack growth model for aluminum 2024-T351 alloy was formulated, based on the 'unified' approach and the experimental results described in Kujawski [19] (which are based on experiments described by Pang et al. [20] and Lee et al. [21]). Deterministic crack growth curves of crack length vs. load cycles were obtained. An initial crack length below which cracks do not propagate were found as a function of the loading stress and the stress ratio R.

Crack growth depends on material properties (such as microstructure, initial flaws, grain boundaries etc.), geometrical properties of the structural element, and loading conditions. As most of these parameters behave randomly, the crack growth behavior should be treated using probabilistic methods. A special attention must be given to the initial crack lengths, or initial flaws, as well as to the stochastic behavior of the propagation process.

Initial flaws in a structural element originate from the material production phase and from environmental loading conditions. One of the approaches is the equivalent initial flaw size (EIFS) approach, in which initial flaws in the structure are evaluated backwards from measurements of crack lengths during a loading process. In Yang et al. [22], distributions of initial flaws in fastener holes were computed using the experimental results for time to crack initiation (TTCI) performed in Wright Patterson AFL (Norohna et al. [23]) The distributions obtained can be approximated by a Weibull cumulative distribution function (CDF). In Barter et al. [24], distribution of inclusions that initiated fatigue cracking in 7050-T7451 aluminum alloy specimens was approximated by a lognormal CDF. In Liao et al. [25], EIFS values for lap splice riveted specimens of 2024-T4 alloy were approximated by a Weibull CDF, and in DeBartolo et al. [26] initial flaw sizes for three aluminum alloys were approximated by a lognormal CDF. In Harlow [27] probabilistic pitting behavior due to corrosion is described.

The stochastic behavior of crack growth was described in many publications. In Lin et al. [28,29], a stochastic process was added to the crack growth model, compared to experimental results of Norohna [23], and used by many other authors (i.e. Maymon [30]) to include stochastic effects of the crack growth process. In Bogdanoff and Cozin [31] some probabilistic models of cumulative damage are described.

In the present paper, the 'unified' model described in Maymon [18] is used to demonstrate the effects of random initial EIFS distribution. The CDF of the EIFS was taken from Yang [22] and was approximated by a Weibull distribution. Crack lengths for a 2-D symmetric cracks in a fastener hole were calculated as a function of the load cycles. Dispersions in the growth behavior and in the time to failure are discussed.

2. Deterministic model for 2024-T351, the unified approach

Some highlights of the model presented in Maymon [18] are presented in this section. Data from the regular tests (long cracks) was plotted on a $\Delta K - K_{max}$ plane. This is a planar projection (on the $\Delta K - K_{max}$ plane) of a 3-D plot, where the z axis is da/dn. On this plot, points of equal R lie on straight line, whose slope is $(1-R)$. A family of experimental data points for the L shaped curves is thus obtained.

The experimental results were smoothed. The L shaped curves were drawn for the smoothed data, and 'virtual data points' from the smoothed curves were selected. These are shown in Fig. 1. A straight line was passed through