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The elucidation of load history editing effect on fatigue crack growth by crack closure concept

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Abstract

The principal goal of this investigation is to elucidate the effect of load history omission on fatigue crack growth behavior from experimental determinations of opening loads. A FALSTAFF pseudo-random spectrum and its shortened spectra based on an amplitude-based editing technique are used to see the effect with two types of 2124-T851 aluminum specimens having a corner crack and a through-thickness crack at a bolt hole. A constant amplitude cycle is appended at the end of the spectra to monitor the variations of opening loads with crack advances. The crack aspect ratio under a constant amplitude loading is somewhat different from that under a random loading but there is no noticeable effect of history editing on the aspect ratio. The more omission of small amplitude cycles, the higher the opening loads, and the longer fatigue lives. The load history editing effect is closely related to the crack closure phenomena.

Keywords: Fatigue crack growth; History editing; Crack closure; Random loading

1. Introduction

In many structures such as aircraft, numerous load carrying components are subjected to extensive random fatigue loading composed of millions of reversals. The loading results in fatigue crack propagation from stress concentrations such as bolt holes or initial defects. Accordingly, a fatigue design engineer should verify the structure's reliability to prevent a catastrophic failure. However, it is very time consuming to test with the original load history because there are numerous small amplitude cycles. Consequently, engineers want to truncate or eliminate non-damaging cycles from the original history collected in a field and accelerate a fatigue crack growth (FCG) test for the reason of time and cost. In addition, the engineers should know the crack growth patterns under different loading conditions in advance to do a safe design.

Conle and Topper [1] proposed a small cycle omission criteria for shortening of fatigue service histories. Buch [2] did an extensive study on the effect of some aircraft loading program modifications on the fatigue life of open holed specimens and found that in particular loading program cases rare load peaks may have not only a beneficial, but also a detrimental. Heuler and Seeger [3] edited three kinds of spectra by a procedure based on notch or local stress and compared the crack initiation and propagation lives using original and edited spectra. They found that omission of small cycles below a filter level of about 50% of the materials' constant amplitude endurance limit was allowable. Lanciotti and Lazzeri [4] studied the effects of truncating high loads and of omitting small cycles on crack propagation and compared with similar results in the literature. Stephens et al. [5] examined the use of a conventional strain range based editing model and proposed a new editing model based upon the Smith, Watson, and Topper (SWT) parameter. They combined strain amplitude and mean stress evaluation in the cycle omission, or gate, criterion, where all SWT parameter cycles less than the gate value are removed. Badaliance et al. [6] investigated the effects of fighter attack spectrum on composite fatigue life. They emphasized that retaining high loads in the spectra is

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important and cycles that have peaks less than 50% of limit load can be eliminated without significantly affecting the test results. Phillips [7] studied the effects of truncation on a compression-loaded spectrum and concluded that high loads should be retained and that large reduction in the low-load end of the spectra could be applied. Nyman et al. [8] also carried out a study regarding load-sequence effects on the fatigue life of composite structures and found that the elimination level can be set to approximately 50% of maximum range for in-plane loaded structures. Recently, Oh [9] applied another method called wavelet transform technique to perform a fatigue history editing and proved the technique can be applied in performing a fatigue history editing, especially in de-noising, spike removal and compression of data set. However, most of the above studies had concentrated only on the effects of spectrum variations on fatigue lives instead of proving major causes or underlying mechanism.

A loaded bolt hole (LBH) or fastener hole is very common in aircraft structures because there are many structures joined by bolting and riveting. Lin and Smith [10] performed the fatigue crack shape simulation for several initially quarter-elliptical corner cracks at three fastener holes of different radius and compared the aspect ratio changes with the results of Grandt and Macha [11]. However, experiments regarding the crack shape change under different loading spectra have not yet been performed.

It is well known that the crack propagation life occupies majority in the total life of structures designed by damage tolerant concept. Therefore, it is very important to know the effects of truncation on the fatigue crack propagation life as well as on the crack growth pattern from a designer's viewpoint. In this paper, the FCG behavior of 2124-T851 aluminum alloy specimen under original, 20, 30, and 35% edited FALSTAFF [12] loadings are investigated. During the test the crack opening loads are monitored by an analog subtraction circuit [13,14]. The goal of this study is to investigate the effect of load history editing on fatigue crack growth behavior and to explain the reason of the effect by crack closure concept.

2. Experimental details

2.1. Material

The material used in this study is aluminum alloy plate 2124-T851. The chemical compositions based on weight percentage are Cu 4.46, Mg 3.38, Zn 0.41, Mn 0.34, Fe 0.19, Ti 0.17, Si 0.12, Cr 0.08, remainder Al. The 0.2% proof stress is 414 MPa, the tensile strength 461 MPa, and fracture toughness 49.0 MPa$\sqrt{\text{m}}$. The Paris' [15] constant, C, and exponent, m, are 1.67×10^{-9} m/cycle and 3.43, respectively.

2.2. Specimens

Two types of specimen are used separately to simulate the crack growth behavior from a corner crack to a through-thickness crack. The corner cracked specimen (CCS) at a hole is used to simulate a crack emanating from a bolt hole. The test section is 61 mm long, 20 mm wide, and 3.81 mm thick and there is a hole of 4.85 mm diameter in the center of the section. An isosceles triangular notch of 0.5 mm long and 0.5 mm deep is made by electrical discharge machining (EDM). For the through-thickness specimen (TTS), all of the specimen geometries are the same as the case of CCS but an initial through-thickness notch of 0.71 mm long and 0.2 mm wide is introduced instead.

2.3. Experimental procedures

All of the tests are conducted by using a servo hydraulic testing machine, 100 kN load capacity, incorporated with a homemade Wood's alloy grip based on ASTM E606 [16] at frequencies from 3 to 13 Hz in the atmosphere. A strain survey confirming to ASTM E1012 [17] is carried out with eight strain gages to minimize bending stress. The bending is maintained within 3 up to 40% of a maximum load by adoption of Wood's alloy grip. The FCG tests under variable amplitude loading are preceded by the tests under constant amplitude loading for the CCS and the TTS. The stress intensity factors (SIF) are calculated by the equations proposed by Newman and Raju [18] for the CCS and NASA/LRC [19] for the TTS.

The normalized original FALSTAFF spectrum [12] (F0) has 35,966 peak-valley points and is shown in Fig. 1. This history is already edited by 6.3% of the maximum amplitude. The history is truncated by 20% (F1), 30% (F2), and 35% (F3) of the maximum amplitude and thus the compressed histories have 7050, 3756, and 2852 total points, respectively.

A real load is obtained by multiplying a respective peak load by the normalized history. The test conditions are arranged and shown in Table 1. A constant amplitude cycle, maximum of 5 kN and the stress ratio of −0.3, is added at

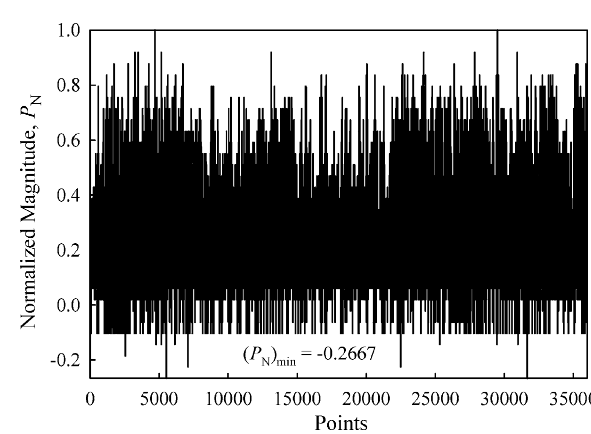

Fig. 1. Normalized original FALSTAFF history.