International Journal of Fatigue 31 (2009) 538–543

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Effect of small cycles and load spectrum truncation on the fatigue life scatter in 7050 Al alloy

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ARTICLE INFO

Article history:
Received 5 November 2007
Received in revised form 25 March 2008
Accepted 31 March 2008
Available online 6 April 2008

Keywords:
Fatigue
Scatter factor
Aluminum alloy
Crack initiation

ABSTRACT

This work examines the effect of dynamic buffet loads (small cycles) on the scatter in the fatigue life of aircraft aluminum. Current life cycle management of fighter airframes assumes, without engineering evidence, that buffet loads cause an increase in the scatter factor used in safe-life calculations. Hence, the role of small cycles in spectra representative of the CF-188 aileron inboard hinge was examined in this study. The base load spectrum with the dynamic content was filtered to remove specified amounts of dynamic damage as determined by the CI89 strain-based cumulative fatigue damage program. The effect of this filtering on the scatter in crack initiation life and total fatigue life of double edge notched fatigue coupons of 7075-T7451 aluminum alloy were examined. The results indicate that inclusion of the dynamic loading caused the distribution of the crack initiation life to become bimodal. Each mode could be described with a log-normal distribution, the standard deviation of which was lower than the standard deviation obtained for the filtered load spectra. There was no evidence that the standard deviation increased with small cycle content, once the true nature of the distribution was taken into account. In fact, the standard deviation associated with the truncated spectrum was considerably larger. The bimodal distribution is positted to be a result of included particles near the surface on the fatigue limit of individual specimens.

1. Introduction

Certain parts of fighter aircraft structure are subject to high frequency, low amplitude load cycles called dynamic or buffet loading. There is concern that these low amplitude cycles may increase the variability in the fatigue life at long lives. This concern is reflected in the CF-188 Hornet fighter aircraft Structural Integrity Standard for Continuing Airworthiness policy which, on an interim basis, replaces original scatter factors in the range 2.3–2.9 with a scatter factor of 5.0 for parts subject to this kind of loading [1]. The value of 5 is chosen arbitrarily, and there are no specific data to justify this estimate. An increase in the scatter factor from 2.3 (0.1% chance of failure, $n = 3$, $\sigma = 0.1$) to 5.0 corresponds to a doubling of the standard deviation of the fatigue life. The aim of the larger study of which this work was part, was to measure the effect of dynamic loading on the standard deviation in the fatigue life of typical specimens used in life prediction methodologies for safe-life aircraft components. It was anticipated that these data could be used to justify a scatter factor lower than 5 for parts subjected to dynamic loading. If, for example, it could be demonstrated that dynamic loading had no effect on the standard deviation, then the scatter factor could be reduced to the original value. This would result in nearly doubling the allowable service life of the component.

An initial study [2] on Al7050-T7451 used a fatigue load spectrum derived from the aft engine hanger location of the CF-188 with different levels of small cycle truncation. The results showed that the distribution of the log of the crack initiation life was normal for various levels of truncation (up to 19% damage removed). However, when the spectrum was un-truncated, i.e., it retained the dynamic cycle content, the distribution of the log of the crack initiation life became bimodal as shown in Fig. 1. Each mode of the bimodal distribution appeared to be normally distributed with a standard deviation of 0.032 for the lower life mode and 0.057 for the upper. These two values were not statistically different and they are considerably less than the standard value of 0.1 used in the Canadian Forces (CF) lifing policy [1] and from the value of 0.112 found for the truncated spectrum filtered to remove 19% of the damage, as shown in Fig. 1. When only a small number of coupons are tested, the bimodal nature of the un-truncated spectrum distribution is not readily apparent. Although the life distribution was clearly not log-normal, the standard deviation obtained when the modes for the un-truncated spectrum were combined was 0.148, illustrated by a dashed line in Fig. 1. At first glance, this supports the notion that dynamic loading can increase in the scatter of the fatigue life data. However, this is not the case; since the distribution is not normal, the two modes are more accurately treated

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doi:10.1016/j.ijfatigue.2008.03.037

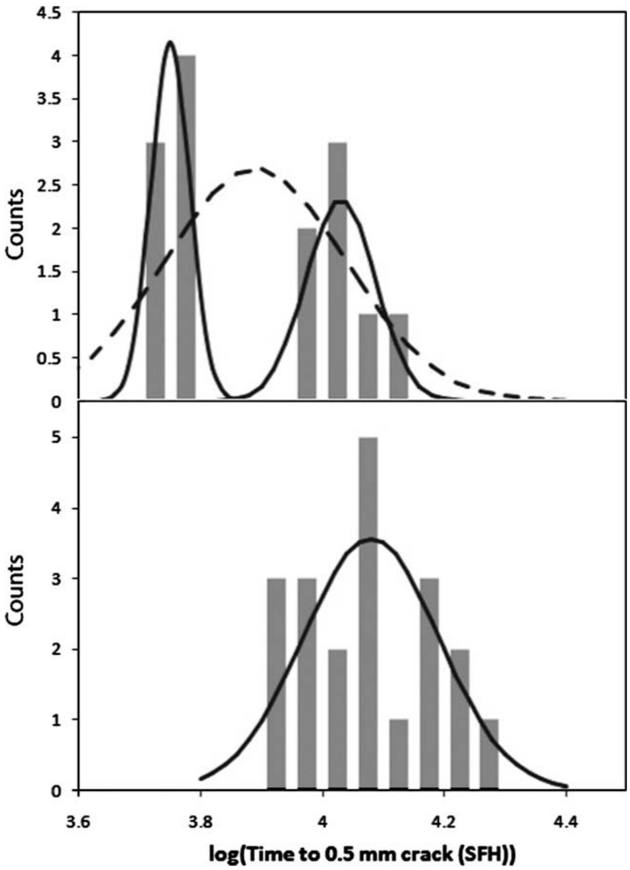

Fig. 1. Comparison of the fatigue life distributions for a spectrum with small cycles (M0) (top) and a filtered spectrum (M19) (bottom) [2]. The solid curves represent normal distribution fits to the data. The dashed curve is a normal distribution fit to all of the M0 data, ignoring the bimodal behaviour.

separately, and the lower life mode has a lower standard deviation than for the truncated spectra.

The present work sought to expand on the previous results by investigating whether or not the bimodal distribution was typical of load spectra with significant small cycle content or whether it was specific to the spectrum used in the previous study. In this work, spectra representative of the loads experienced by the CF-188 aileron inboard hinge were used to examine the effect of truncation on the distribution of the fatigue life.

2. Experimental approach

Double edge notched plate specimens of Al7050-T7411 with a stress concentration factor of 2.09 were fatigue tested in laboratory air using two loading spectra. A master flight spectrum of several million turning points was recorded over 300 h of actual flight. This master file was used to generate the loads at several critical locations in the CF-188 using transfer functions, mission mixing and profiling, and compiled to represent 652 simulated flying hours (SFH) for the aircraft. The spectra used in this work correspond to the loads experienced by the aileron inboard hinge of the CF-188, a wing location subjected to a significant quantity of high frequency low amplitude cycles (dynamic loading). Filtering small cycles from the spectrum reduces the total damage and increases the predicted fatigue life. The higher the magnitude of small cycles removed, the greater the average fatigue life will be. The baseline spectrum was obtained by filtering the master spectrum to produce an analytical crack initiation life that was 3% greater than for the master spectrum as predicted by the CI89 strain-based cumulative fatigue damage program [3–5]. This filtering was performed by eliminating small cycles below a truncation stress level. The value of this level was adjusted until the desired predicted life was obtained. A truncated spectrum was obtained by filtering the baseline spectrum to obtain a crack initiation life 11% greater than for the master spectrum as predicted by the CI89 program. The key parameters describing the spectra are shown in Table 1. The maximum notch root stress of 422 MPa is less than the yield stress of 470 MPa for this alloy. Fig. 2 shows the distribution of the cycles obtained using a rain flow analysis on the baseline spectrum. Fig. 3(left) shows a more detailed view of the plot for stress ranges below 130 MPa. The initial filtering from the master spectrum removed all cycles with a notch root stress range below 30 MPa. The right hand side of Fig. 3 shows the result of a rain flow analysis of the truncated spectrum. The effect of the truncation has been to remove all cycles with a stress range less than 60 MPa. The distribution of cycles as a function of mean stress and stress range in the truncated spectrum is virtually identical to that of the base spectrum for stress ranges above 130 MPa.

The initial specimens were machined from a single slab of Al 7050-T7451 102 mm (4 in.) thick. The slab was cut in half transverse to the rolling direction and then each half-slab was machined as shown in Figs. 4 and 5. Each specimen was labelled with two digits, the first for the layer (1–4) and the second for position within the layer (1–6 for the first half-slab and 18–23 for the other

Table 1
Comparison of baseline and truncated spectra for the aileron inboard hinge

	Spectrum	
	Baseline	Truncated
Max stress (K_tS_{max})	422 MPa	
Min stress (K_tS_{min})	−380 MPa	
Truncation level (% damage as determined by CI89)	3%	11%
Truncation level ($K_t\,\Delta S$) MPa	30	60
Reversals/block	894,484	275,338
Simulated flying hours per block	652	652
log(predicted crack initiation life (SFH))	Log(12,000) = 4.08	Log(12,926) = 4.11
log(predicted total life (SFH))	Log(18,000) = 4.26	Log(19,389) = 4.29

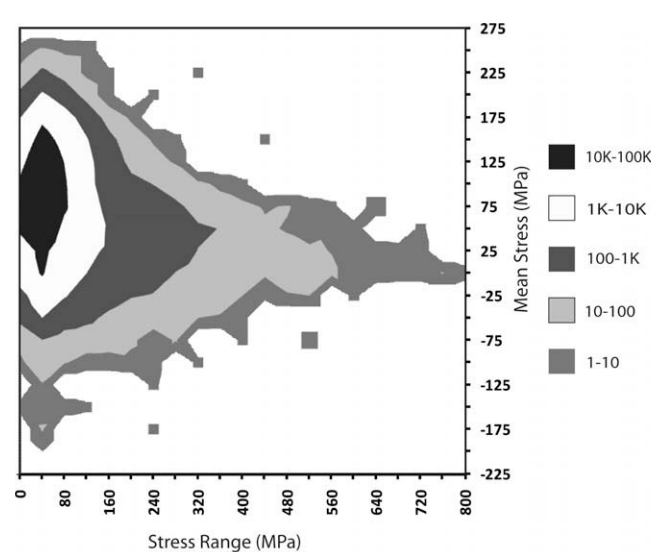

Fig. 2. Plot of log(number of cycles) versus mean stress and stress range for rain flow counted base spectrum. The numbers along the X and Y axes represent the lower bound on the bin into which the cycles have been partitioned.