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Effective Block Approach for Aircraft Damage Tolerance Analyses

W. Z. Zhuang,[*] M. McDonald, M. Phillips, and L. Molent
Defence Science and Technology Organisation, Melbourne, Victoria 3207, Australia

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A damage tolerance analysis method for aircraft structural integrity, designated as the effective block approach, has been developed and subsequently applied to predict the fatigue crack growth life of aircraft structures subjected to flight spectrum loading. The predictions by the method were made not based on constant-amplitude crack growth data, but instead relied on spectrum crack growth data obtained from previous full-scale fatigue tests or representative coupon fatigue tests. The spectrum crack growth data were normally measured from observations of the fracture surfaces by quantitative fractography. Verification and consistency studies of the method were performed against fatigue test results under different flight spectra. The predicted fatigue lives and inspection intervals for fracture-critical locations in aircraft structures were found to be in close agreement with representative coupon and full-scale fatigue tests. This study has demonstrated that the method provided significant advantages in damage tolerance analysis over conventional fatigue lifing approaches for military aircraft structures and components. It was also found that the work has improved the value of structural integrity advice provided for some Royal Australian Air Force air platforms and supports the safe operation of the fleets through to their planned withdrawal date.

Nomenclature

a = crack length or depth
C = coefficient constant (for Paris-based empirical crack growth model)
$C_{\mathrm{A-TS}}$ = Paris constant obtained from analyzed fatigue crack growth data for tested spectrum
$C_{\mathrm{A-UTS}}$ = Paris constant obtained from analyzed fatigue crack growth data for untested spectrum
$C_{\mathrm{T-TS}}$ = Paris constant obtained from tested fatigue crack growth data for tested spectrum
$C_{\mathrm{T-UTS}}$ = Paris constant obtained from tested fatigue crack growth data for untested spectrum
$\mathrm{d}a/\mathrm{d}N$ = rate of crack growth (change in crack length per constant-amplitude cycle)
$\mathrm{d}a/\mathrm{d}t$ = rate of crack growth (change in crack length per spectrum flight hour)
K = stress intensity factor at a crack tip
K_c = critical stress intensity factor
K_{Ic} = critical stress intensity factor under plane strain conditions
K_{ref} = reference stress intensity factor at a crack tip
m = exponent constant (for Paris-based empirical crack growth model)
$m_{\mathrm{A-TS}}$ = exponent constant obtained from analyzed fatigue crack growth data for tested spectrum
$m_{\mathrm{A-UTS}}$ = exponent constant obtained from analyzed fatigue crack growth data for untested spectrum
$m_{\mathrm{T-TS}}$ = exponent constant obtained from tested fatigue crack growth data for tested spectrum
$m_{\mathrm{T-UTS}}$ = exponent constant obtained from tested fatigue crack growth data for untested spectrum
β = beta (geometry and load condition) factor
ΔK = stress intensity factor range at a crack tip (for constant-amplitude loading)
σ_{ref} = reference stress

I. Introduction

MILITARY aircraft often encounter highly variable environmental conditions and operate under different mission profiles that can result in fatigue failure in aircraft structures. To help maintain aircraft structural integrity until the planned withdrawal date, the Defence Science and Technology Organisation (DSTO) has conducted a range of scientific studies, including full-scale fatigue tests on aircraft structures and relevant component/coupon fatigue tests, under representative flight spectra. The objectives of these activities, amongst others, were to substantiate the service life and/or to predict inspection intervals for the fracture-critical structures and components. To achieve these goals, robust analytical fatigue lifing tools are required and DSTO is developing new approaches for fatigue crack growth (FCG) prediction under flight spectrum loading [1–5].

Fatigue crack propagation in aircraft structures under flight spectrum loading or variable-amplitude (VA) loading is traditionally predicted based on crack growth rates obtained from constant-amplitude (CA) fatigue testing using cycle-by-cycle approaches [6–11]. In contrast, this paper presents a damage tolerance analysis method for aircraft structures based on the crack growth information obtained under aircraft flight spectrum loading. This approach, named the effective block approach (EBA), predicts the FCG life of aircraft structures subjected to flight spectrum loading based on FCG rates obtained from full-scale fatigue tests or relevant coupon fatigue tests [2–5]. The flight spectrum FCG data were measured from observations of the fracture surfaces by the quantitative fractography (QF) process. The EBA method developed recently is able to account for some of the complex crack growth behaviors observed under different flight spectra [5,12]. To demonstrate its robustness, verification and consistency studies were performed using fatigue test results under different operational spectra. The predicted fatigue lives and inspection intervals for a number of fracture-critical locations in some aircraft structures were compared with representative components and coupon fatigue tests.

II. Effective Block Approach

The EBA predicts the FCG life of aircraft structures subjected to flight spectrum loading based on FCG rates obtained from previous full-scale fatigue tests and/or relevant coupon fatigue tests. The earliest version of this approach was proposed by Gallagher in the mid-1970s [13] with a cycle-by-cycle life calculation algorithm. The

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[*] Senior Research Scientist, Air Vehicles Division.