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Fatigue and crack-growth analyses of riveted lap-joints in a retired aircraft

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ABSTRACT

For aluminum alloys, research has shown that fatigue behavior of notched and unnotched specimens can be characterized by fatigue–crack growth from micro-structural features, such as inclusion-particle sizes. A crack-growth model using small- and large-crack data was used to calculate fatigue lives and crack growth in lap-joints in laboratory specimens. The tightness of the rivets dictated the type of crack configurations that occurred in the joint and equivalent initial flaw sizes (EIFS) were selected to fit the fatigue test data. These crack configurations and EIFS values were then used to predict fatigue lives in fuselage lap-joints in a retired passenger aircraft and for curved panels cut from the retired aircraft. The paper demonstrates that fuselage lap-joint fatigue-life-prediction methods based on fatigue–crack growth alone (i.e. with accounting for any time spent in crack nucleation) are very adequate to model the lifetimes in fuselage riveted lap joints.

1. Introduction

The Federal Aviation Administration (FAA) and Delta Air Lines [1–6] had teamed to conduct a destructive evaluation of a retired narrow-body passenger aircraft that had nearly 60,000 revenue service flights (one design service goal). Some objectives of the program were to characterize the state of multiple-site damage (MSD) at riveted fastener holes in the fuselage of an aircraft at the design service goal; and to develop or verify analysis methods that can correlate and predict the state of MSD at any point in time. For the retired aircraft, observations from the destructive examination of the fuselage joints indicated that one side of the aircraft appeared to have tight (within specifications) rivets with no detectable cracks present, whereas on the other side of the aircraft the rivets appear to have under-driven rivets with a large number of cracks present [5,6]. For these cracks, faying surface origins were predominant, despite a majority of rivets being under driven. A large number of cracks have been examined with a scanning-electron-microscope (SEM) to count striations and to back-track the cracking history to reconstruct the crack length against flight cycle behavior [4]. The measured crack length against flight cycle results tended to fall within a fairly narrow band considering the complexity of real aircraft structural joints under actual operational loads and service environments. Several curved fuselage panels were cut from the other side of the fuselage and two panels with lap joints that had tight, correctly driven rivets were tested using the Full-scale Aircraft Structural Test Evaluation and Research facility (FASTER) at the FAA William J. Hughes Technical Center, Atlantic City, NJ. The FASTER facility uses a pressure box to fatigue test large fuselage panel by cyclic hydraulic loading. Prior to testing, both panels were verified to be crack free to the extent detectable by high frequency eddy current non-destructive test methods. These pressure box tests extended the fatigue cycles already experienced by these two panels during aircraft revenue service of 59,497 cycles, and added 43,500 cycles in one case and 120,000 cycles in another case. Both extended fatigue tests showed that these two panels with the very tight joints were extremely durable with no cracks formed at the end of the extended test cycles. These widely differing fatigue lives in the relatively loose joints with the under driven rivets versus the tight joints with the correctly driven rivets, had to be modeled and shown to be amenable for analyses in consistent manner.

Some of the first approaches to improve the calculation of fatigue lives of riveted lap-joints were made in the mid-1960s [7,8]. These approaches were based on stress-life (S–N) behavior and the calculation of local stress concentrations due to rivet loading, by-pass loading, and local bending. The effects of hole preparation (drilling, reaming, or cold-working) and of hole filling (rivets, bolts, or interference-fit fasteners) were accounted for by using either empirical factors derived from fatigue tests [8] or, more recently,

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Nomenclature

a	crack depth in thickness (B) direction (mm)
a_i	initial flaw or crack depth in B-direction (mm)
B	specimen thickness (mm)
C_i	coefficients in multi-linear crack-growth equation ($i = 1$ to m)
c	crack half-length in width (W) direction (mm)
c_i	initial flaw or crack half-length in W-direction (mm)
D	rivet-hole diameter (mm)
F	boundary-correction factor
K	stress-intensity factor (MPa$\sqrt{m}$)
K_o	crack-opening stress-intensity factor (MPa$\sqrt{m}$)
L_i	riveted joint load factors
M	bending moment (N m)
N	number of cycles
N_f	number of cycles to failure
n_i	powers in multi-linear crack-growth equation ($i = 1$ to m)
P	rivet force (N)
R	stress ratio ($S_{\min}/S_{\max}$)
r	hole radius (mm)
S	remote applied stress (MPa)
S_b	fastener by-pass stress (MPa)
S_B	outer-fiber bending stress (MPa)
S_p	fastener bearing stress (MPa)
$S_{\max}$	maximum applied stress (MPa)
$S_{\min}$	minimum applied stress (MPa)
W	specimen half-width (mm)
w_r	rivet spacing (mm)
α	constraint factor
γ	bending factor
Δ	interference (μm)
ΔK	stress-intensity factor range (MPa$\sqrt{m}$)
ΔK_{eff}	effective stress-intensity factor range (MPa$\sqrt{m}$)
$(\Delta K_{\mathrm{eff}})_{\mathrm{T}}$	effective stress-intensity factor range at flat-to-slant transition (MPa$\sqrt{m}$)
λ	biaxial loading factor
σ_o	flow stress (average of σ_{ys} and σ_u) (MPa)
σ_{ys}	yield stress (0.2 percent offset) (MPa)
σ_u	ultimate tensile strength (MPa)

on the use of "reference" S–N curves [9] from fatigue tests conducted on joints made with the particular manufacturing process of interest.

The fracture-mechanics approach, used herein, is based on similar reasoning but calculates stress-intensity factors and crack-opening stresses for small cracks under rivet loading, by-pass loading, and local bending. Effects of hole preparation are accounted for by selection of an "equivalent initial flaw size (EIFS)"; and the effects of hole filling on the selection of an "effective" level of interference to account for riveting interference, clamp-up, and frictional effects. The selection of an EIFS also indirectly accounts for any nucleation cycles.

During the last two decades, research on small-crack behavior [10] and analysis methods [11], especially for aluminum alloys, have shown that the entire fatigue process can be effectively modeled as "crack propagation" from a micro-structural discontinuity in the material (e.g. precipitate particles). Thus, for the lap-joint configuration, an initial flaw size exists that will characterize the material or manufacturing quality. The analysis methodology to predict crack growth from the micro-scale has been based on traditional fracture-mechanics and crack-closure concepts. (Small-crack theory is the use of small-crack data accounting for micro-structural effects on crack growth in the low-rate regime and using a closure model to capture the transient closure effects as a small crack grows and develops a plastic wake.) Herein, these principles will be applied to the lap-joint configuration using some of the results obtained from the two- and three-dimensional analyses of the NLR lap-joint specimen [12]. Stress-intensity factors for small corner and through cracks growing under rivet loading, by-pass loading, and local bending have been developed [12]. The crack-closure model [13] will be used to calculate crack-opening stresses for a crack growing from an open hole, but using the stress-intensity factors for the lap-joint specimen. The rivet liftoff stress (applied stress required to separate the rivet from the fastener hole) will be used to account for rivet contact at the minimum load. (Ideally, a closure model should be developed to model the rivet in the hole and account for interference and contact analytically, but this is beyond the scope of the present paper.) Effects of hole preparation (e.g. tool marks or burrs) are accounted for by the selection of an EIFS; and the effects of hole filling on the selection of an "effective" level of interference to account for riveting interference, clamp-up, and frictional effects.

The objective of this paper is to use FASTRAN [13] and small-crack theory to calculate fatigue lives and crack growth in laboratory lap-joint specimens made of 2024-T3 clad aluminum alloy. Tightness of the rivets led to different crack configurations (corner cracks at the rivet hole or surface cracks along the fraying surface) and different EIFS values. Two types of laboratory specimens were analyzed: (1) three-rivet-row countersunk specimens and (2) two-rivet-row countersunk specimens with a doubler. Several rivet conditions were considered: (1) standard-driven rivets, (2) tight or over-driven rivets, and (3) under-driven rivets. The appropriate crack configuration and the EIFS values were then used to calculate crack growth in the retired aircraft and curved fuselage test panels cut from the aircraft and tested in the FASTER Test Facility at the FAA William J. Hughes Technical Center [14]. Comparisons are made between AFGROW [15] and FASTRAN for crack growth in the retired aircraft and the reconstructed crack-length-against-flight-pressure-cycle history. Fatigue life and crack-growth behavior are also predicted on the curved fuselage test panels and compared with test results.

2. Stress analysis of cracks at rivet-loaded fastener holes

Stress-intensity factors for a corner crack or a through crack emanating from a typical fastener-loaded hole under remote applied stress ($S = S_p + S_b$), remote outer-fiber bending stress (S_B) due to bending moment (M), by-pass stress (S_b), fastener load ($S_p = P/(w_r B)$), where w_r is rivet spacing and B is sheet thickness), and interference (Δ), as shown in Fig. 1, are given in Ref. [12]. The influence of biaxial loading (λS_b) on stress-intensity factors for cracks emanating from the fastener hole are given in the Appendix. One of the restrictions for the corner-crack equations is that the crack aspect ratio, a/c, is fixed, and the influence of rivet interference is based on a simple approximation [12]. Stress-intensity factor equations for a surface crack in a plate under remote tension (S_t) and bending (S_B) stresses are given in Ref. [16].

To calculate the growth of a corner crack initiating at a critically-loaded rivet hole in a lap-joint (see Fig. 1), the stress-intensity factors for rivet loading (S_p), by-pass loading (S_b), local bending (M or σ_b), and interference (Δ) must be obtained and added as

$$K = K_p + K_b + K_M + K_\Delta \qquad (1)$$