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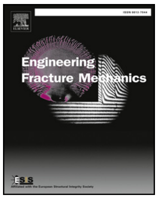

# Residual fatigue life analysis and comparison of an aluminum lithium alloy structural repair for aviation applications

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## ABSTRACT

A method for residual-fatigue-life estimation of repaired aluminium–lithium alloy structures designed for use in aerospace applications is presented. Crack propagation was investigated using the Abaqus software package while the stress intensity factor was calculated using the FRANC3D package. Paris equation was applied to estimate the fatigue-crack growth rate. The residual fatigue life of and corresponding a–N curve for the repaired structure were obtained via post-processing under varying conditions of repair-structure shape, size, position, and stress levels. Results demonstrate that structural repairs possessing relative width, height, and thickness values of 35.7%, 50%, and 83.3%, respectively, tend to increase the residual fatigue life of the overall structure.

## 1. Introduction

With increasing demand for aircraft comfort, security, and reduced operating costs, new and greater challenges concerning aircraft design and manufacturing technology tend to continuously increase. Weight reduction is another crucial aspect of aircraft design, as demonstrated by the 20% improvement in efficiency of the Boeing 787 aircraft primarily achieved via gross-weight reduction [1]. Design and manufacture of large integrated components has become an important technique to reduce the gross weight and thereby operating costs of an aircraft. Such integrated structures, however, are susceptible to crack formation, thereby causing difficulties in meeting the prescribed standards of damage tolerance. To this end, selective repair is a key technique that serves to effectively solve this problem.

Over the years, methods used to repair damaged aircraft structures as well as life-extending methodologies applied on aging aircraft structures have gained increased attention in many countries. However, fatigue analysis and residual-fatigue-life prediction of selectively repaired aluminium–lithium alloy structures are difficult to perform. Numerous factors impact the crack-growth rate in selectively repaired structures, thereby causing difficulties in the accurate prediction of their fatigue life. For example, residual thermal stresses caused by different types of thermal expansion, and quality of cementation post repairs tend to impact fatigue performance of repair structures. Furthermore, degumming, caused by rubber nonlinearity, change in rubber properties, and stress concentration affects fatigue performance of reinforced structures. Consequently, fatigue analysis and fatigue-life prediction of repaired aluminium–lithium alloy structures have become critical problems that require immediate attention [2,3]. Studies concerning application of the composite patch repair technology to aircraft structures have been performed using aluminium alloy sheet structures measuring less than 5 mm in thickness [4–6]. Toudeshky [7], by performing a study concerning the effect of patch layers on the propagation rate of thick-plate repaired structures, observed that the fatigue life estimated using mid-plane structural

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## Nomenclature

| | |
|---|---|
| $a$ | crack length |
| $A$ | integral area for area J-integral |
| $c$ | material constant of the Paris' law |
| $J$ | $J$ integral |
| $Ki$ | stress intensity factor, $i = I,II,III$ |
| $m_{ij}$ | parameters depending on material properties and orientation |
| $M^{(1,2)}$ | M integral |
| $n$ | material constant of the Paris' law |
| $N$ | cycling number (life) |
| $N_{ij}$ | matrix depending on material properties and orientation |
| $q$ | weight function, $0 \leqslant q \leqslant 1$ |
| $q_t$ | value of the q-function along the crack front |
| $W^{(k)}$ | strain energy density |
| $W^{(1,2)}$ | interaction strain energy density |
| $\Delta K$ | amplitude of stress intensity factor |
| $\varepsilon_{ij}$ | strain tensor |
| $u_i$ | displacement vector |
| $\sigma_{ij}$ | stress tensor |
| $Y(\alpha/\omega)$ | shape correction factor used in James-Anderson method |
| $\omega$ | plate width |
| $\delta_{ij}$ | Kronecker delta |
| $\Gamma$ | integral loop for J-integral |
| $\Im$ | imaginary part of the bracketed quantities |

parameters was longer compared to that of an unrepaired structure. Bouiadjra et al. [8,9] studied the effect of differently shaped patches, based on the finite element method, and observed that the crack-tip stress-intensity factor of a hexagonal patch repair was small for crack lengths measuring 5–20 mm. The residual fatigue life of the structure was also observed to have improved. Mall et al. [10] adopted a two-dimensional finite-element approach to analyse the crack-propagation behaviour of a composite plate having thin as well as thick patches, and it was observed that the fatigue life of thin and thick patches were, respectively, 10 and 4 times superior to that of the unrepaired plate. Poursaeidi and Bakhtiari [11] investigated fatigue-crack growth within a first-stage compressor blade. The stress intensity factor, although difficult to analyse, plays a key role in determination of the residual fatigue life of repaired structures. Analysis of the stress intensity factor concerning the crack tip before and after repair is an important method in determining the efficiency of a composite material patch repair [12–13]. Tai et al. [14] also adopted the finite element approach to calculate the stress intensity factor of a composite-material crack tip formed within an aluminium alloy plate measuring 11.43 mm in thickness. Papanikos et al. [15] studied the stress intensity factor of crack tips within adhesive materials along with damage accumulation within degumming areas. Dolbow et al. [16] calculated the compound stress intensity factor of functionally graded materials based on the interaction integral and extended finite element methods. Xiao and Karihaloo [17] proposed a means for calculating the stress intensity factor using the extended finite element method without the need for post-processing; however, their method was found to be inconvenient when simulating crack propagation, as it was only applicable for determining the stress intensity factor of a static crack. Giner and Sukumar [18] further analysed crack propagation using Abaqus and subsequently derived the stress intensity factor via post-processing.

In the proposed study, crack propagation was simulated using the FRANC3D software without post-processing, and the stress intensity factor was subsequently obtained. Secondary development of the extended finite element method function was not

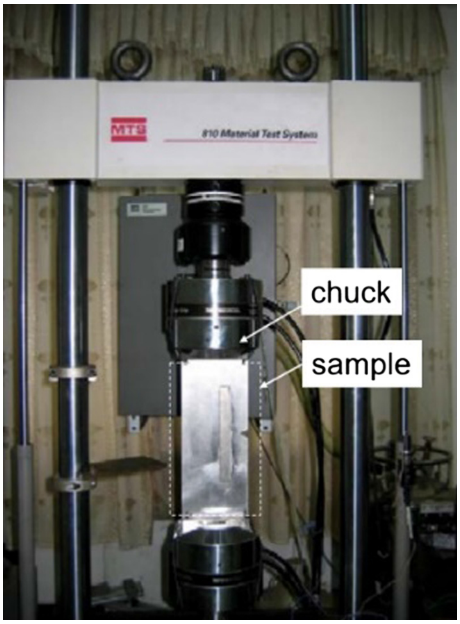

**Fig. 1.** MTS 810 material test machine.