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International Journal of Fatigue 29 (2007) 677–686
International Journal of Fatigue
www.elsevier.com/locate/ijfatigue

Fatigue modeling for aircraft structures containing natural exfoliation corrosion

M. Liao *, G. Renaud, N.C. Bellinger

Structures and Materials Performance Laboratory, Institute for Aerospace Research, National Research Council Canada, 1200 Montreal Road, M-14, Ottawa, Ont., Canada K1A 0R6

Received 23 December 2005; received in revised form 14 June 2006; accepted 2 July 2006
Available online 12 September 2006

Abstract

This paper presents the results of testing and modeling studies on the remaining fatigue life of aircraft wing skins containing natural exfoliation corrosion. Dogbone specimens were manufactured from 7075-T6511 upper wing panels containing natural exfoliation. The maximum depth of the exfoliation damage was determined by an ultrasonic non-destructive inspection (NDI). Fatigue tests were carried out under fully reversed constant amplitude loading ($R = -1.0$), and fractographic analyses were performed to examine the cracking mechanisms in the exfoliation region. Based on the test findings, a simplified fatigue model was developed to estimate the remaining fatigue life of the corroded specimens. In this model, the exfoliation damage was assumed as a surface crack with a depth that was presumably available from an NDI or grindout database. The comparison indicates that the simplified model gave a good estimation for the remaining fatigue life of the naturally exfoliated specimens.

Keywords: Exfoliation corrosion; Prior corrosion and fatigue; Life prediction; Aluminium alloys; Fractography

1. Introduction

Exfoliation corrosion (exfoliation) is a form of severe intergranular corrosion (IGC) that occurs at the boundaries of grains elongated in the rolling direction. In aircraft materials, exfoliation corrosion is most common in the heat-treatable Al–Zn–Mg–Cu (7000 series), Al–Cu–Mg (2000 series), and Al–Mg alloys, but it has also been observed in Al–Mg–Si alloys [1,2]. Generally, exfoliation occurs when there is a combination of three factors: a highly directional microstructure, a preferential anodic path, and a specific type of corrosive environment [1].

The current ‘‘find-it-fix-it’’ approach to corrosion maintenance requires that even the smallest of corrosion damage be removed by grindout. The grinding of corroded material can be carried out until the allowable limit is reached, at which stage the skin may require repair or replacement at a significant cost to the operator. While this approach is very costly, the effects of the maintenance actions on structural integrity are not well understood. A new corrosion management philosophy has been proposed with the intent of anticipating, planning, and managing corrosion, which stands in sharp contrast to the ‘‘find-it-fix-it’’ approach [3]. To implement this new philosophy, analytical models need to be developed to evaluate the impact that exfoliation has on structural integrity.

In some previous research, various static tests were carried out on naturally pre-exfoliated specimens to evaluate the effect of exfoliation on the residual strength. The test results showed that natural exfoliation may not have a detrimental effect on the residual strength in the elastic and near plastic regimes such as the compressive yield and bearing strength; however, it may have an effect on the strength in the large plastic region such as the compression stress at 4% compressive deformation [4]. Some modeling capabilities have also been developed to quantify the effects of natural exfoliation on residual strength [4–6]. Concerning

* Corresponding author.
E-mail address: min.liao@nrc-cnrc.gc.ca (M. Liao).

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doi:10.1016/j.ijfatigue.2006.07.003

fatigue, some studies indicated that natural prior exfoliation reduced the fatigue life of aircraft structures by 40–60% under constant amplitude loading [7] or low-high block loading [8]. Another test showed that fatigue crack growth rate was enhanced by prior exfoliation from service [9]. However, recent tests have indicated that a compression-dominated spectrum loading, which was the representative loading for the upper wing skin of a large transport aircraft, had benign effects on the remaining fatigue life of exfoliated skins [10,11]. Thus far, the effects of natural exfoliation on fatigue life are not well understood yet due to various factors such as loading spectrum, structural locations, and complicated cracking mechanisms associated with different levels of exfoliation and corrosion pitting [5,7–12]. On the modeling side, several fatigue models were developed for estimating the fatigue life of *artificially* exfoliated specimens [13–15], but very little efforts were pursued to address the effects of *natural exfoliation* on the fatigue properties of aircraft material and structures.

In this paper, fatigue tests on naturally exfoliated 7075-T6511 specimens, which were finished in a previous NRC project, are briefly reported. The results from the tests are then used for examining an existing fatigue model developed from artificially exfoliation tests. Finally, a practical fatigue model for estimating the remaining fatigue life of the naturally exfoliated specimen is presented.

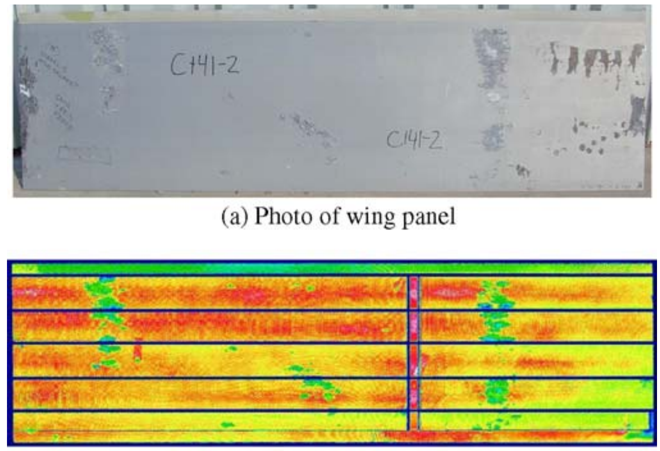
2. Testing

2.1. Fatigue tests

The materials for the test specimens were cut from various 7075-T6511 upper wing skin panels, which were manufactured for the C141 aircraft. These panels, which became corroded in storage and therefore were never used in service, contained various levels of exfoliation ranging from barely visible to extensive. Extensive damage characterization was performed on sections taken from the skins and progressive polishing showed that the exfoliation formed from IGC that originated at corrosion pits [16]. All the wing skins were inspected using ultrasonic (UT) non-destructive inspection (NDI) techniques from the back (non-corroded) side and some of the results are shown in Fig. 1.

The fatigue specimens were basically designed according to the ASTM E647 standard with some modifications made so that the specimen could cover a reasonable size of exfoliation and also would not buckle under compression loading. The specimen configuration is presented in Fig. 2. Quantitative ultrasonic NDI was carried out from the non-corroded surface of each specimen to determine the maximum depth of the exfoliation. For example, Fig. 3 presents two specimen photos, and the corresponding NDI images taken from the back face. The maximum exfoliation depth was found to be 0.84 mm (0.033 in.), which is about 21% of the nominal thickness.

Fatigue tests were carried out under fully reversed constant amplitude loading until failure. The maximum gross section tensile stress was 165 MPa (24 ksi) and the stress ratio R was -1. The tests were carried out in both dry air (<20% RH) and saturated air (>90% RH). In total, twenty-seven (27) specimens were tested. The test results, including the number of cycles to failure versus maximum depth of exfoliation or exfoliation volume, are presented in Fig. 4. Although the later fractographic analysis found that not all crack origins were at the maximum exfoliation damages, the maximum depth of exfoliation was considered as a convenient and conservative parameter to correlate with the remaining fatigue life. Also it should be noted that some specimens failed from the non-corroded corner at the end of a fillet, even though these specimens had exfoli-



(a) Photo of wing panel

(b) Image from ultrasonic NDI

Fig. 1. One of the wing panels used for tests, C141-6A.

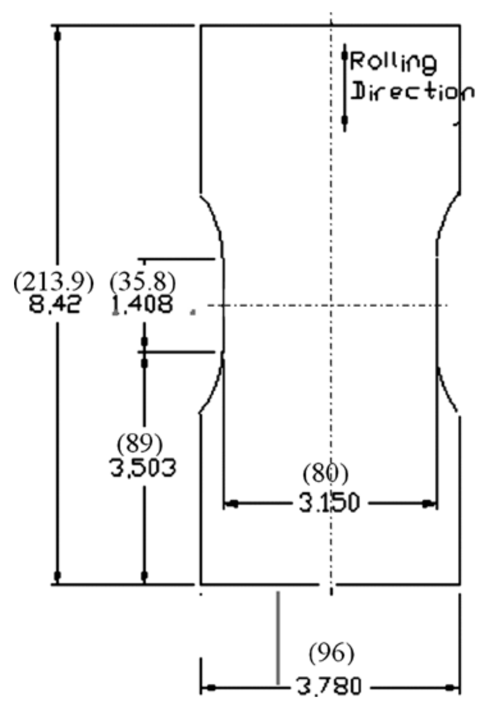


Fig. 2. Schematic of specimen configuration (unit:(mm)/in.), the thickness was as received and around 4.0 mm (0.16 in.).