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Ciência & Tecnologia dos Materiais 27 (2015) 100–107

Ciência & Tecnologia dos MATERIAIS

http://ees.elsevier.com/ctmat

Special Issue IJSI 2014

Influence of the geometry on the fatigue performance of crenellated fuselage panels

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Abstract

Crenellation is a novel local engineering technique aimed at improving the fatigue performance of the airframe structures without increasing the weight. In this concept, a systematic thickness variation is applied to the fuselage skin to retard the fatigue crack growth. In order to achieve the best retardation effect, it is necessary optimize the crenellation geometry. As a result, a parameter study characterizing three independent geometric aspects of the crenellations was performed: the crenellation ratio c, the periodic length λ and a position parameter. The study was based on a FEA model validated by experiments. It is expected to give a sufficiently accurate prediction on fatigue life of different crenellation patterns. The obtained knowledge concerning the impact of those geometrical factors could provide guidance for future crenellation designs for industrial applications.

Keywords: fatigue life improvement; airframe structure; crenellations; geometric optimization

1. Introduction

Crenellation is an innovative concept aimed at improving the fatigue performance of fuselage panels with laser-beam welded stringers (Fig. 1) [1-6]. In this concept, the thickness of the fuselage skin is systematically varied while the structural weight remains unchanged. The purposely increased and reduced skin thickness introduces peaks and valleys in the stress intensity factor (SIF) profile along the crack path (Fig. 1c), which accordingly accelerate and retard the fatigue crack propagation as dictated by the Paris Law:

$$\frac{da}{dN} = C\Delta K^m \qquad (1)$$

where da/dN is the fatigue propagation rate and ΔK is the SIF range during a load cycle. In a well-designed crenellation, the fatigue life gain in the retardation region is much larger than the fatigue life loss in the acceleration region. This leads to an overall fatigue life improvement. Uz et al. [1,2] experimentally investigated the fatigue life improvement in crenellated fuselage panels with and without welded stringers (the crenellation geometry applied is depicted in Fig.1). In their experiments fatigue cracks were assumed to initiate at the welding site of the middle stinger in the center of the panel. It was demonstrated that from an initial half crack length of 37.5 mm to a final half crack length of 225 mm, the application of crenellations lead to a 9% increase of fatigue life in the un-stiffened panels and a 65% increase in stringer-stiffened panels.

The fatigue life improvement brought by crenellations is governed by the shape of the modified SIF profiles, which is in turn determined by the geometries of the crenellations. Thus it is necessary to identify the optimum geometric design of crenellations with the best fatigue resistance for future industrial applications. This aim can be achieved with the help of the finite element analysis (FEA), which is the well-established technique for estimating the SIF of cracks

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http://dx.doi.org/10.1016/j.ctmat.2015.06.003

in complex structures. Successful assessments of the fatigue performance of structures based on FEM simulation can be found in the work of previous researchers such as the assessment of integrally stiffened structure by Häusler et al. [7]. Once the reliability of the FEA models of a crenellated structure is validated by experiment in fatigue life prediction, it can be used to evaluate the fatigue performance of different crenellation patterns with arbitrary geometric designs.

The previous study on the geometric optimization for crenellated structures is rather limited. Uz *et al.* [8] did some optimization work by an approach coupling FEA with artificial neutral network methodologies. It was found the fatigue life is always improved by the introduction of crenellations. In addition the improvement of fatigue life is enhanced by increasing the thickness ratio between the thick and thin regions at a constant area ratio between the two regions.

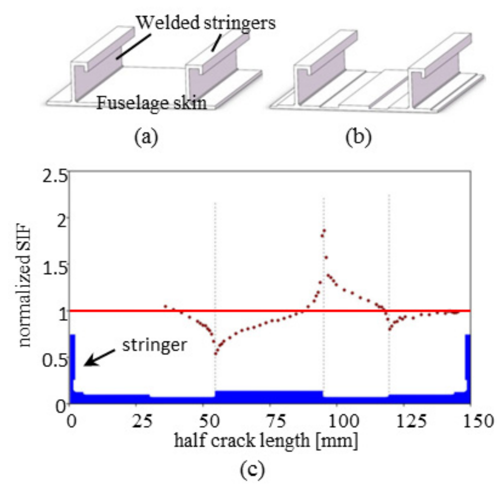

Fig. 1. (a) Flat and (b) crenellated structure with the same weight. (c) SIF profile of a center through crack in crenellated stiffened panel normalized to the SIF values of a reference panel (red line) with the same structural weight (after [1]).

However, the optimization of Uz et al. was limited to one specific configuration (one pad-up between each two stringer as depicted in Fig. 1b) [8], in which the parameters optimized are from the detailed geometrical dimensions in this configuration. In this study feature-based parameters are used, each of which independently describe one characteristic aspect of crenellations. Those parameters can define the crenellation pattern with more flexibility and thus allow a broader exploration of the solution space.

2. Experimental

2.1. Approaches of this study

The aim of the study in extension to previous work is to investigate the fatigue performance of crenellated panels under biaxial loads, which is the typical loading state of the fuselage skin under service conditions. The long-term cyclic loading due to the repetitive fuselage pressurizations, which is closely related with the fatigue problem of the fuselage [9, 10], can be experimentally realized by using the biaxial testing machine and cruciform specimens. FEA models for such an experimental setup were established and validated by biaxial fatigue tests carried out on flat and crenellated panels. After validation, new crenellation patterns with varied geometric parameters were implemented in the models, from which the SIF profiles with crack extension were extracted. Based on the SIF profiles fatigue life of corresponding crenellated structures were estimated by integrating the inverse of da/dN expression according to equation 1, that is :

$$N = \int_{a_0}^{a_f} \frac{1}{C\Delta K^m} da \qquad (2)$$

where N is the number of cycles to grow the crack from initial length of a_0 to a final length of a_f. The influence of those geometric parameters on fatigue life can be thus identified.

2.2. Specimens and experimental setup

In this work biaxial fatigue tests were firstly carried out on two flat panels (thickness: 1.9 mm, 2.9 mm) and a crenellated panel (equivalent thickness: 2.9 mm) in order to validate the FEA models (Table 1). Those validation tests were also part of the experimental work investigating the fatigue performance of crenellated structure under biaxial loading conditions, the results of which has been published in [11].

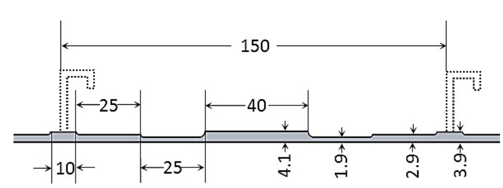

Fig. 2. Geometries of a crenellated sheet with welded stringers (unit: mm).

The specimens are 560 mm × 560 mm square panels, which were cut from a 4.5 mm thick AA2139 sheet with T351 heat treatment. The outer region of the