Fatigue Crack Growth Analysis of Structural Components - the UniGrow Two-Parameter Driving Force Model

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ABSTRACT

A generalised step-by-step procedure for fatigue crack growth analysis of structural components subjected to variable amplitude loading spectra has been presented. The method has been illustrated by analysing fatigue growth of a planar corner crack in an attachment lug made of Al7050-T7451 alloy.

Stress intensity factors required for the fatigue crack growth analysis were calculated using the weight function method. In addition, so-called "load-shedding" effect was accounted for in order to determine appropriate magnitudes of the applied stress intensity factors. The rate of the load shedding was determined with the help of the FE method by funding the amount of the load transferred through the cracked ligament. The UniGrow fatigue crack growth model, based on the analysis the material stress-strain behaviour near the crack tip, has been used to simulate the fatigue crack growth under three variable amplitude loading spectra. The comparison between theoretical estimations and experimental data proved the ability of the UniGrow model to correctly predict fatigue crack growth behaviour of two-dimensional planar cracks under complex stress field and subjected to arbitrary variable amplitude loading.

BASICS OF THE UNIGROW FATIGUE CRACK GROWTH MODEL

The UniGrow fatigue crack growth model, proposed by Noroozi and Glinka [1], is based on the idea that the fatigue process near cracks and notches is governed by highly concentrated strains and stresses in the notch/crack tip region. Therefore, the fatigue crack growth can be subsequently considered as a process of successive crack increments resulting from material damage in the tip region. In addition the two parameter driving force postulated by Vasudevan et.al [2] was also incorporated.

It was postulated that the real material can be modeled as a set of elementary particles or material blocks of a finite dimension, ρ^*. The assumption of the elementary material block implies that the actual stress-strain and fatigue response of the material near the crack tip is such as the crack had a blunt tip with the radius of ρ^*. Therefore, the usual notch stress-strain analysis techniques can by applied in order to determine stresses and strains in the crack tip region.

The following assumptions and computational rules form the base for the UniGrow fatigue crack growth model.

- The material consists of elementary blocks of a finite dimension ρ^*.
- The fatigue crack is regarded as a deep notch with the tip radius ρ^*.
- The stress-strain analysis is based on the cyclic Ramberg-Osgood type material stress-strain curve [3].
- The number of cycles necessary to fail the material over the distance ρ^* ahead of the crack tip can be obtained using the Smith-Watson-Topper [4] fatigue damage parameter and the Manson-Coffin fatigue curve.
- The instantaneous fatigue crack growth rate can be determined as the ratio $da/dN = \rho^*/N$.

Based on the assumptions above Noroozi and Glinka [1] have analytically derived the fatigue crack growth expression in the form of

$$\frac{da}{dN} = C\left(\left(K_{\max,appl} + K_r\right)^p \left(\Delta K_{appl} + K_r\right)^{1-p}\right)^m \quad \textbf{(1)}$$

where, $K_{max,appl}$ and ΔK_{appl}, is the applied maximum stress intensity factor and the stress intensity range respectively, and Kr is the residual stress intensity factor accounting for the effect of crack tip residual stresses resulting from reversed plastic deformations.

Very similar fatigue crack growth equation has been proposed by Walker [5] and Kujawski [6] based on empirical fitting of observed constant amplitude fatigue crack growth data. However, the Walker and Kujawski expression do not take into account the fact that the correlation between the stress intensity factor and the crack tip stress/strain field is often altered by the residual stress resulting from reversed plastic deformations.

It was also found [7] that the instantaneous fatigue crack growth rate depends not only on the residual stresses produced by the recent loading cycle, but on a number of stress fields generated by preceding cycles. Therefore, a “memory rules” have been established [7] based on the experimental observations of fatigue crack growth under variable amplitude loading. Detailed description of the UniGrow model and additional verification data can be found in references [1, 7].

GEOMETRY OF THE COMPONENT AND MATERIAL DATA

Attachment lugs are often used in aircraft structures to connect different components of aircraft structures. In order to ensure operational safety of the aircraft it is necessary to perform fatigue crack growth analysis assuming the possibility of fatigue crack initiation and growth.

The attachment lug investigated below was made of Al 7050-T7451 aluminum alloy as specified in references [8, 9]. Eight constant amplitude fatigue crack growth data sets obtained at six different stress ratios were found in the literature (Figure 1-left). The

residual stress intensity factor K_r was determined for each experimental (da/dN) vs. (ΔK, R) data point and the 'master curve' was developed relating the crack growth rate and the total driving force Δκ (see Figure 1-right). The 'master curve' was subsequently divided into two segments and approximated by two linear pieces in the log-log scale.
Figure 2 shows the lug specimen tested under the variable amplitude loading spectrum. The lug was 10mm thick lug with the hole of radius r =13 mm and the outer radius of 35mm. A quarter-circular crack with initial dimensions of a=c=1mm was artificially made in the lug. As soon as the corner crack propagated through the whole thickness of the specimen it quickly transformed into an edge crack. A special stress intensity factor solution was needed in order to simulate the shape evolution of the growing crack.

DETERMINATION OF THE STRESS INTENSITY FACTOR

The stress field in the un-cracked attachment lug was determined with help of the Finite Element software package ABAQUS. The weight function [9] and the stress distribution from the un-cracked ligament were used for the calculation of the instantaneous stress intensity factor for the growing crack.

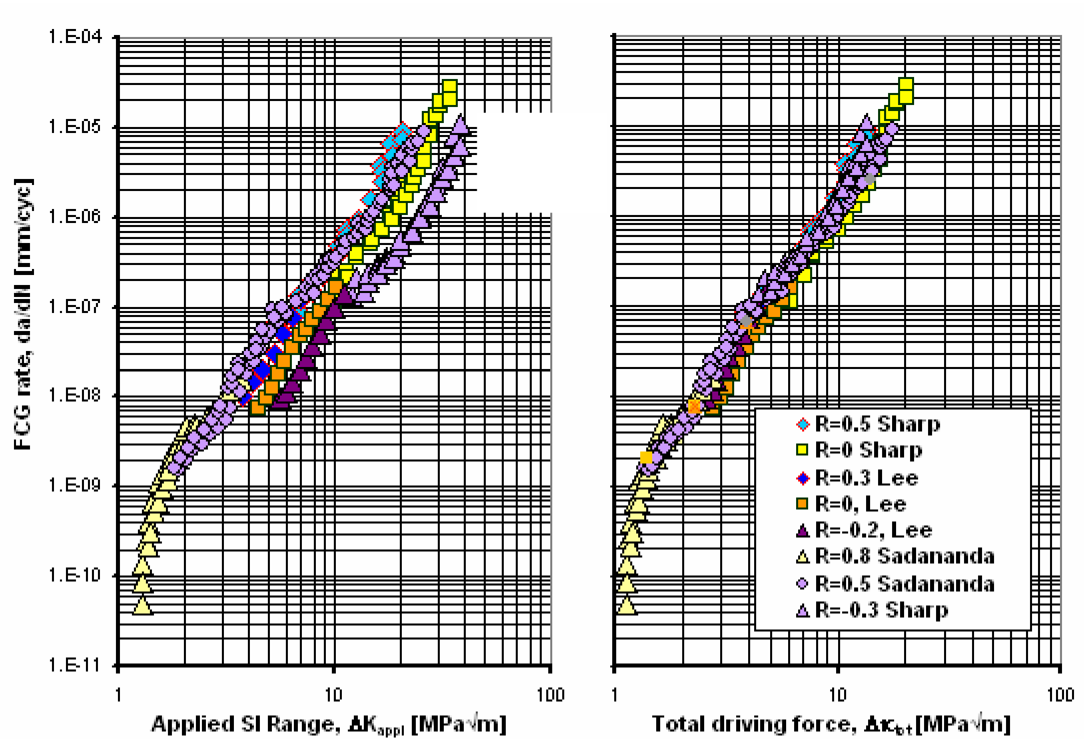

Figure 1: Experimental constant amplitude fatigue crack growth data in terms of the applied stress intensity range (left) and the total two-parameter driving force (right).

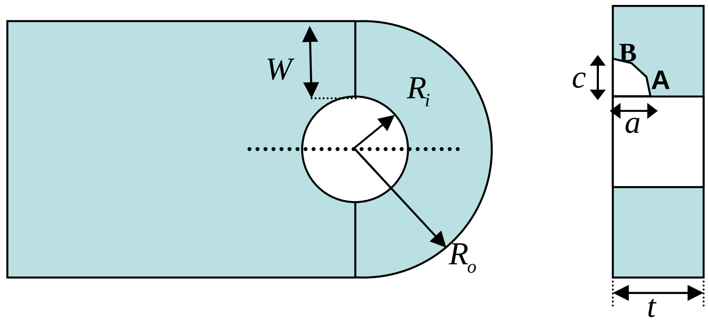

Figure 2: Geometry of the attachment lug with an initial quarter-circular crack

In order to simulate evolution of the crack shape the stress intensity factor at point A and B (Fig. 2) needed to be determined.

$$K^A = \int_0^c \sigma(y) m_A(y,c)\,dy \quad K^B = \int_0^c \sigma(y) m_B(y,c)\,dy \tag{2}$$

where σ(y) is the hoop stress distribution across the ligament and weight functions m_A and m_B are given in reference [9].

LOAD SHEDDING

The weight function method mentioned in above requires as an input the stress field in an un-cracked body induced by the applied load. This approach is valid as long as the cracked section is taking the same amount of load while crack propagates. However, in the case of a single crack in a lug (Figure 3), the cracked ligament "W2" becomes weaker than the un-cracked one "W1"and therefore part of the applied load transferred initially through ligament 'W2' is shifted to ligament "W1".

It has been shown using finite element analysis that this effect is relatively small as long as crack stays quarter-elliptical, but becomes significant when crack breaks through the whole thickness of the lug.

Since the magnitude of the stress field in the ligament depends on the magnitude of the load transferred through the ligament it can be shown that the instantaneous stress distribution can be written as ,$\sigma(x) = LS(c) * L * \sigma_n(x)$ where $\sigma_n(x)$ is the normalized stress field, L is the initial applied load, and $LS(c)$ is the load shading factor. Consequently the stress intensity factor for a crack in a lug can be written as:

$$K(c) = \int_0^a LS(c) * L * \sigma_n(x) * m(c,x)\,dx = LS(c) * K_{initial}(c)\,. \tag{3}$$

In order to determine the load shedding factor, a complete 3D finite element analysis was performed for three different edge cracks of depth 5mm, 10mm, and 15mm.

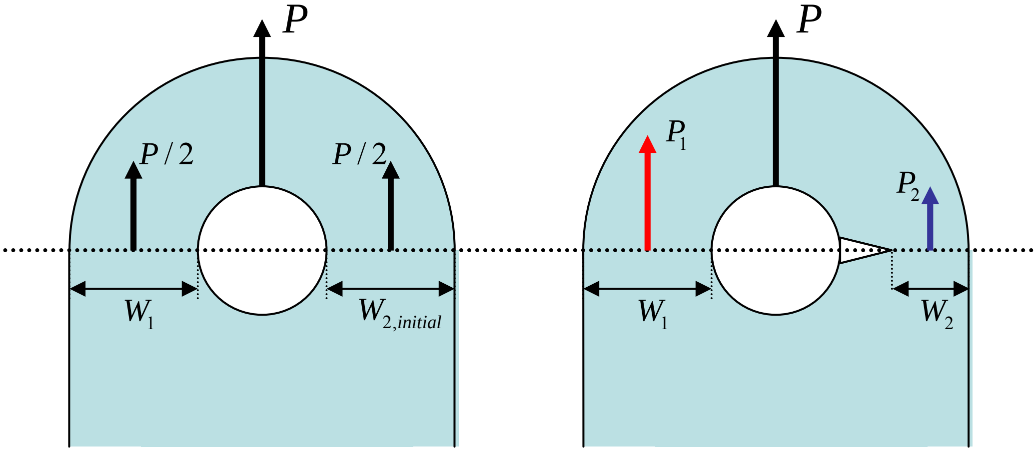

Figure 3: Schematic illustration of the load shedding effect

However, accurate modelling of the stress field near the crack tip in this case was not necessary and relatively coarse finite element mesh can be used over the entire ligament. The resulting stresses in the cracked and un-cracked ligament are presented in Figure 4.

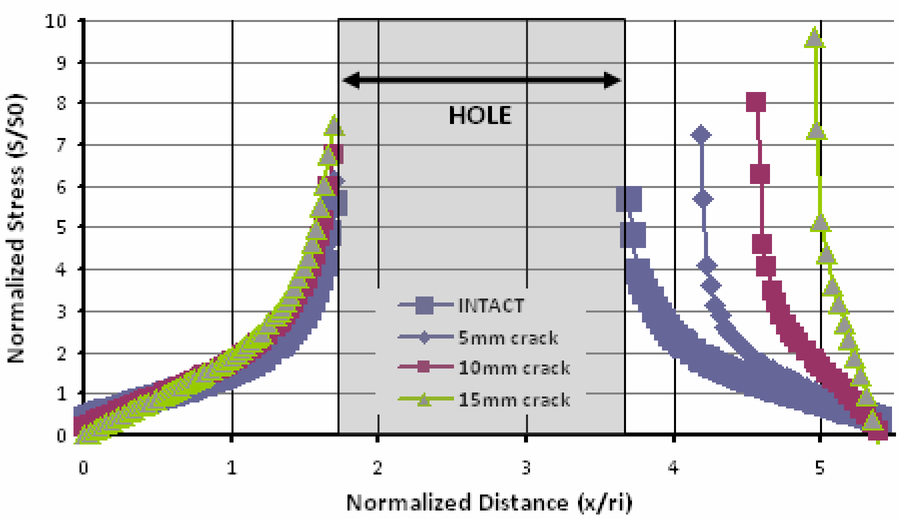

Figure 4: Stress fields for three different crack depths in the cracked ligament

The stress field obtained for un-cracked ligaments was used as a base for the determination of the stress intensity factor. However, the distribution was scaled in due course by the load shedding factor LC but without any change of the form of the original distribution. The amount of the load transferred from the cracked to the un-cracked ligament was determined by integrating the stress field over the remaining cross-section area of the cracked ligament. The evolution (Fig. 5) of the load in the cracked and un-cracked ligaments as crack propagates through the "W2" section. The results (Fig. 5) indicate that at the crack depth c=15mm the load taken by the cracked cross-section was reduced by around 20%. Based on the data presented in Fig 5 the load shedding parameter was subsequently fitted into the expression $LS = 1 - A(c/W - B)^q$ with A=0.45, B=0.238 and q=0.65.

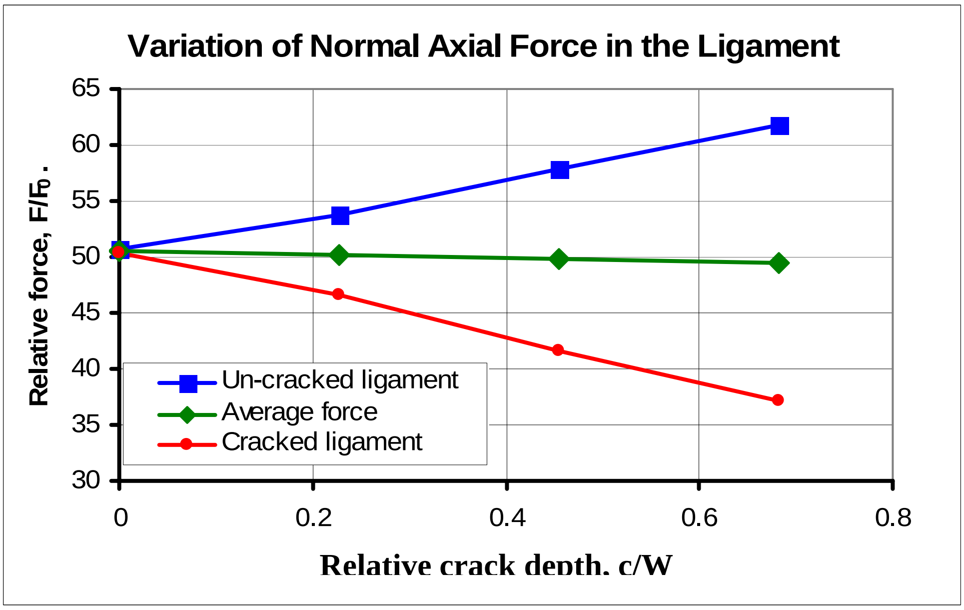

Figure 5: The shift of load from the cracked to the un-cracked ligament (the shedding)

RESULTS AND DISCUSSION

The fatigue crack growth analysis was carried out for the variable loading spectrum described in reference [8] and shown in Figure 6. The loading spectrum contained 2154 reversals and it was predominantly tensile with occasional high overloads and under-loads.

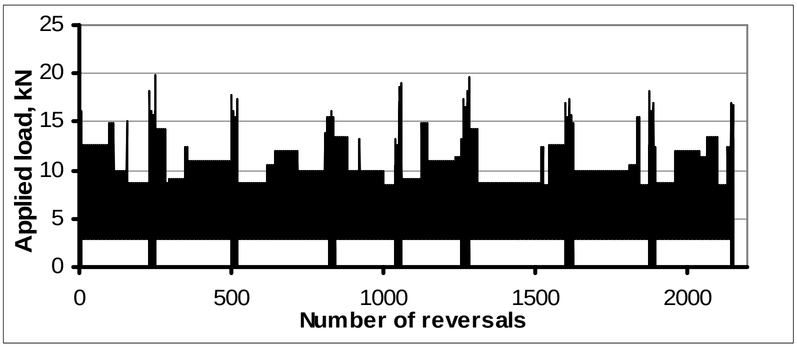

Figure 6: Applied loading spectrum

Theoretical estimations and experimental data of the fatigue crack growth through the lug ligament are shown in Figure 7. The first set of data was obtained from the lug tested under the original loading spectrum which was denoted, according to the reference [8] nomenclature, as being 100% clipped.

The data denoted as being 80% clipped were obtained for the loading spectrum with all high peaks reduced (truncated) to the 80% of the highest peak in the original (100% clipped) spectrum while all lower stress peaks remained unchanged.

The truncation of the loading spectrum from the top reduces residual stresses produced by overloads but also eliminates cycles with high stress intensity ranges and high maxima which significantly contribute to the fatigue crack propagation. Thus, it is interesting to see which effect may dominate. The retardation effect of multiple overloads can be quantified by comparing the fatigue lives corresponding to the truncated loading spectrum with that obtained under the original loading spectrum (Fig. 7). In this particular case the truncation resulted in shorter fatigue life and it was correctly predicted by the UniGrow model. Good agreement between computed and

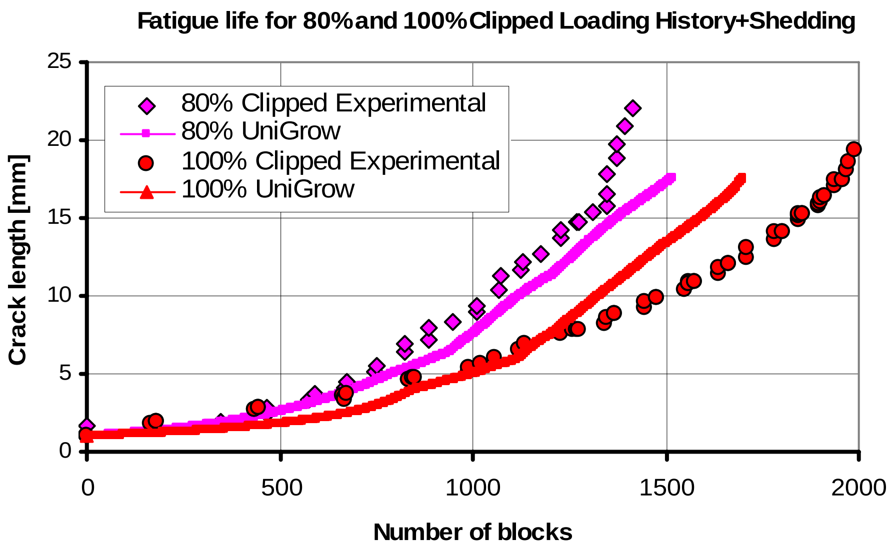

Figure 7: Fatigue crack growth estimations and the experimental data for the original and the truncated load spectrum

experimentally measured extension of fatigue cracks (c-N data) indicate that the model correctly simulates the effect of both overloads, under-loads and their sequence.

CONCLUSIONS

The analysis presented above shows that various effects influencing fatigue crack growth resulting from the application of cyclic variable amplitude loading can be modeled by considering the influence of residual stresses caused by reversed cyclic plastic deformation in the crack tip region. The analysis needs to be carried out on the cycle-by-cycle basis accounting for the load/stress history effects.

It has been also shown that the use of 'memory rules' and the two-parameter driving force enables accurate simulation of fatigue lives of cracked bodies subjected to complex variable amplitude service loading spectra.

The importance of the load shedding in the lug has been quantified by accounting for the decrease of the resultant load in the cracked cross-section. Exclusion of this effect in the fatigue crack growth analysis can result in conservative estimation of the fatigue crack growth life.

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