Proceedings of COBEM 2005
18th International Congress of Mechanical Engineering
November 6-11, 2005, Ouro Preto, MG

Crack Growth Retardation Effects in Civil Airplane Structures

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The accurate prediction of fatigue crack growth has long been recognized as of critical importance for the design of aeronautical structures. Modern transport airplanes have to be designed to meet damage tolerance requirements, established by international certification agencies. Under the damage tolerant design philosophy, the fatigue lives of structural members are predicted using Fracture Mechanics concepts, more specifically crack propagation calculations. Maintenance procedures are also dependent upon crack growth predictions, since inspection intervals are defined from propagation results combined with specific information on the selected NDE techniques to be used. Therefore, reliable predictions of fatigue crack propagation have great impact on the safe and economical operation of modern aircraft.

The prediction of fatigue crack propagation under complex, variable amplitude loading requires the modeling of the so-called retardation effects, which are basically due to the plastic zone ahead of the crack tip caused by overloads. This paper discusses the application of such models to predict crack growth in structural components of a transport airplane. A review of the traditional crack growth retardation models is presented. In order to assess the accuracy of the models current available in the literature, numerical simulations are performed and the results are compared to published data. Then, selected retardation models are used to predict crack growth in typical aeronautical components. The results are validated against experimental data from crack propagation tests in coupon specimens submitted to the standard MiniTWIST load spectrum.

Keywords: Crack Propagation, Fracture Mechanics, Load Sequence Effects, Crack Retardation, TWIST

1. Introduction

Due to the nature of the load spectra to which commercial aircraft are subjected, the load sequence effects have a great influence on the total life of a structural component. Usually, in the lack of a better understanding of this technology, the evaluation of crack propagation performed on aircraft by the industry does not take in account these load sequence effects. Such effects are known as crack retardation when they cause the reduction of the crack propagation rate. In most cases this approach is too conservative as has published Brot *et al* (2002). However, in some cases, if these sequence effects are not taken in account, it can lead to non-conservative results, affecting directly the safe operation of the aircraft as has noted McCLung *et al* (2002) for compressive dominated load spectrum.

Several models can be found in the literature in order to predict this behavior by changing the crack propagation rates in order to simulate the effect of load sequence. These models are generally based on adjustable parameters driven by the material characteristics and mainly by the applied load spectra according to Zhang *et al* (1987). The models are based on different formulations which can be as simple as considering a general retardation factor to be applied to the crack opening stress intensity factor or as complicated as taking into account the elasto-plastic behavior ahead of the crack caused by the overloads and the underloads .

2. Crack retardation models

Actual aircraft operation load usually results in a combination of high and low stresses with variable stress ratios. Any load cycle influence is affected by its history and can be described by two effects:

Retardation**:**

Retardation occurs after an overload peak, when the crack tip plastic zone caused by a load cycle is inside the crack tip plastic zone caused by the last load cycle, reducing the crack propagation rate.

Underload Effect**:**

The underload effect occurs when a compressive load (or even tension load) is lower than the lowest load found since the last overload. This effect causes the reduction of the retardation effects.

2.1 Wheeler Retardation Model

The Wheeler retardation model (*Wheeler et al* 1972) includes a correction parameter C_P to be added to the damage accumulation equation in order to slow crack growth after an overload which results in Eq.(1)

$$a_r = a_0 + \sum_{i=1}^{r} C_p f(\Delta K) \tag{1}$$

where a is the crack size and f(ΔK) is a function of the stress intensity factor range, defined as $K_{max} - K_{min}$.

The C_P parameter is bounded between 0 an 1 (starting at 0 just after an overload until it reaches the value of 1.0 in a late cycle). The C_P parameter is representative of a plastic zone evaluated according to a plane strain state at the crack tip according to Eq. (2)

$$r_0 = \frac{1}{6\pi}\left(\frac{K}{\sigma_y}\right)^2 \tag{2}$$

where σ_y is the yield stress and K is the stress intensity factor (SIF)

The C_P parameter is evaluated as shown in Eq. (3)

$$C_p = \left(\frac{Z_i}{Z_{ol} + a_{ol} - a_i}\right)^m \tag{3}$$

where:

$$C_p = 1 \Rightarrow Z_i + a_i \geq Z_{ol} + a_{ol} \tag{4}$$

The plastic zone size Z in the Wheeler model is evaluated at Eq.(2). M is an experimental parameter and provides the model the capacity to match experimental crack growth tests. All other parameters are defined on Figure 1

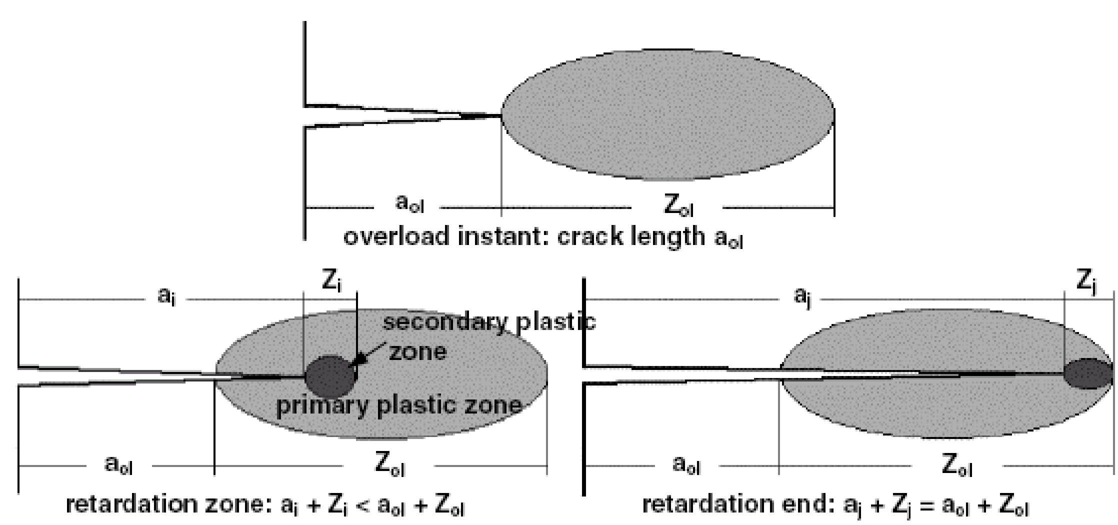

Figure 1: Plastic Zone Interaction (adapted from *Ebner et al,* 2004)

2.2 Willenborg Model

On the Willenborg model, (*Willenborg et al, 1971*) the retardation effect is considered directly on the R_{eff} function. An effective value of ΔK is evaluated from the crack tip residual stress after the application of an overload. Once the ΔK_{eff} is obtained it is used to evaluate an effective value of the stress ratio R (R_{eff}). There is no need of empirical factors.

On this model the current SIF (Stress Intensity Factor) is reduced by a residual stress factor K_{RW}, evaluated by Eq. (5)

$$K_{RW} = K_{ol}\sqrt{\frac{(Z_{ol} + a_{ol} - a_i)}{Z_{ol}}} - K_{\max} \qquad (5)$$

where K_{ol} is defined as the maximum overload SIF and the other parameters are defined in Figure 1.

The plastic zone in this model is evaluated according to a plane stress state (Eq.6)

$$r_0 = \frac{1}{2\pi}\left(\frac{K}{\sigma_y}\right)^2 \qquad (6)$$

The retardation effect is considered until the crack tip (a_i) reaches the plastic zone limit (Z_{ol} + a_{ol}), reducing the K_{RW} term to zero, canceling the SIF reduction effect. Both maximum and minimum SIF (K_{max} and K_{min}) are affected by the K_{RW} correction, resulting in $K_{eff,max}$ and $K_{eff,min}$ which are used to evaluate R_{eff} (which for negative values is considered as 0, thus making $\Delta K_{eff} = K_{eff,max}$)

2.3 Generalized Willenborg (GW)

This model is based on the Gallagher *et al* (1974) modification of the Willenborg model. The main difference of this model is the substitution of K_{RW} parameter by a K_R^G parameter evaluated according to Eq. (7)

$$K_R^G = \Phi K_{RW} \qquad (7)$$

where:

$$\Phi = \frac{1 - \frac{\Delta K_{th}}{\Delta K}}{\left(R_{SO} - 1\right)} \tag{8}$$

being R_{SO} the shut off value of the $K_{\max}^{ol} / K_{\max}$ ratio, which can be experimentally adjusted. When the R_{SO} value is exceeded, there is crack arrest and $K_{eff,max}$ is evaluated as Eq (9)

$$K_{eff,\max} = \frac{\Delta K_{th}}{\left(1 - R\right)} \tag{9}$$

2.4 Modified Generalized Willenborg (MGW)

The MGW (NASGRO, 2002) is a modification of the GW model in order to take in account the underload effects on retardation caused by compressive loads (or even tension loads).

On the MGW the $K_{eff,min}$ is evaluated after Eq.(10):

$$K_{eff,\min} = \begin{cases} \left(K_{\min} - K_R^G\right), & \text{if} \quad K_{\min} > K_R^G \\ 0 & , \text{if} \quad 0 < K_{\min} \le K_R^G \\ K_{\min} & , \text{if} \quad K_{\min} \le 0 \end{cases} \tag{10}$$

As can be seen on Eq.(10), ΔK_{eff} and R_{eff} are higher than the ones evaluated at the GW, therefore leading to a smaller retardation consideration.

However, the underload effects are only evaluated at the underload. In order to evaluate the underload effects after the underload the factor Φ_{MGW} is used instead of the factor Φ of the GW model and is defined at Eq.(11)

$$\Phi_{MGW} = \begin{cases} \min\left(1, \dfrac{2,523\phi_0}{1 + 3,5\left(0,25 - R_{ul}\right)^{0,6}}\right), \text{if} \ R_{ul} < 0,25 \\ 1,0 \qquad\qquad\qquad\qquad\qquad\quad , \text{if} \ R_{ul} > 0,25 \end{cases} \tag{11}$$

where R_{ul} is defined by Eq.(12):

$$R_{UL} = \frac{S_{UL}}{S_{OL}} \tag{12}$$

The factor Φ_0 is the factor Φ_{MGW} at R_{ul}=0 and is dependent on the material, and has to be experimentally evaluated. Values for Φ_0 can be found in the literature [NASGRO, 2002 and CASTRO *et al*, 2001] between 0.2 and 0.8.

The MGW model predicts reduction of retardation effects for loads up to 25% of the overload.

2.5 Strip Yield Model

The Strip Yield model (De Koning *et al*, 1997) is a mechanical model based on the hypothesis that a crack propagates through a plastic zone at the crack tip and the plastic deformation on this area will lead to load sequence effects such as retardation.

On the Strip Yield model, K_{op} is evaluated by a crack opening model based on the Strip Yield model (Dugdale *et al*, 1960)], modified to consider the plastic deformed material ahead of the crack. In this model all plastic deformation is considered to be in an infinitesimal strip along the crack path. The material within the strip is represented by a series of finite-width rigid-perfectly plastic bar elements.

The original Strip Yield model was only defined for a plane stress state, therefore in order to consider a more general stress state, the local yield stress (σ_y) is multiplied by a restriction factor α with values between 1.15 and 2.5 unless in compression cases where α is considered as 1.0. The α factor can be considered in two different approaches. The first one considers α constant along the plastic zone elements and the second one considers a parabolic variation of α along the plastic zone elements defined by finite element analysis. This present work considers the first approach, as all comparative analyses performed have shown no significant difference between the two hypotheses.

3. Comparison with Test Results

In order to evaluate the load sequence effects of a typical commercial aircraft spectra on a structural component made of a typical aeronautical alloy the retardation models have been evaluated using experimental data obtained from laboratory tests.

Two tests were performed using a MTS-810 test machine at CTA/IAE/ASA lab with a variable load spectra based on the MiniTWIST methodology (Lowak *et al*, 1979) with a reference stress of 31.2 Mpa in accordance with ASTM E647-002000). In order to reduce test time, the test frequency was set to 20Hz (this value was reduced to 1Hz at the compression cycles in order to avoid pin-slob).

The MiniTWIST load spectra is a short version of the TWIST (*Jonge et al*, 1973) load spectra which was developed in order to create a standardized load sequence for fatigue test programs. TWIST stands for **T**ransport **A**ircraft **WI**ng **ST**ructure and it based on the lower wing skin at the wing root due to its critical aspects. This methodology is based on the mean stress level in flight which was obtained by measuring several different commercial aircraft real wing loads over a wide range of weights, wing loads, cruising speeds and design flight distances.

The applied load spectra had 62.246 cycles divided in 10 blocks of 6.000 cycles (except for block 10 with 8.246 cycles). All blocks have been executed in sequence.

All measurements were made at an interval of 6.000 cycles until 170.000 cycles where the faster crack propagation required inspections intervals of 3.000 cycles. The crack was measured on both sides of the test specimen with a precision on 0,5mm (achieved by a magnifying glass and a graduated scale). All measurements were performed with test running in order to be able to see crack fully opened. Both sides of the crack have grown in a similar way.

The test specimens A and B were compact test specimen (C(T)) with Chevron notch, machined from Al 7050-T76511 alloy with the following dimensions, according to Figure 2:

- W = 80 mm
- D = 20 mm
- t = 5 mm
- c_0 = 18 mm

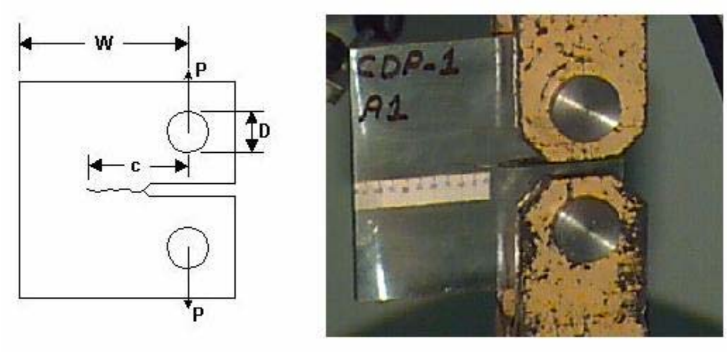

Figure 2: Test Specimen

The test results were evaluated using NASGRO software for all retardation models, except for the Wheeler model were the CRACK2000 (Mello *et al*, 1997) software has been used (this retardation model is not implemented at NASGRO). The results can be found on Figure 3, Figure 4 and Table 1.

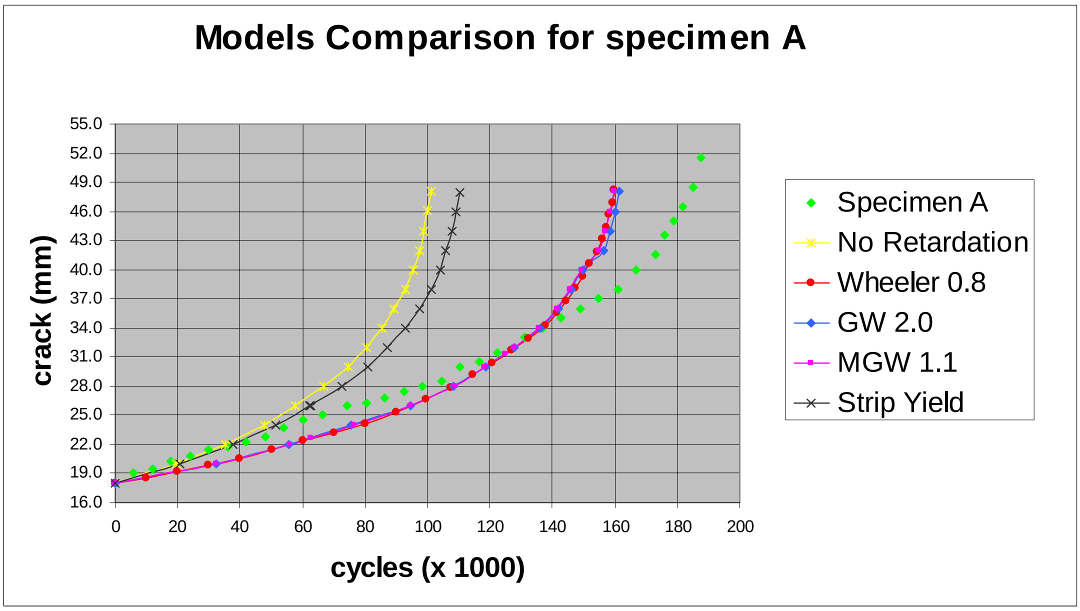

Figure 3: Models Comparison for Specimen A

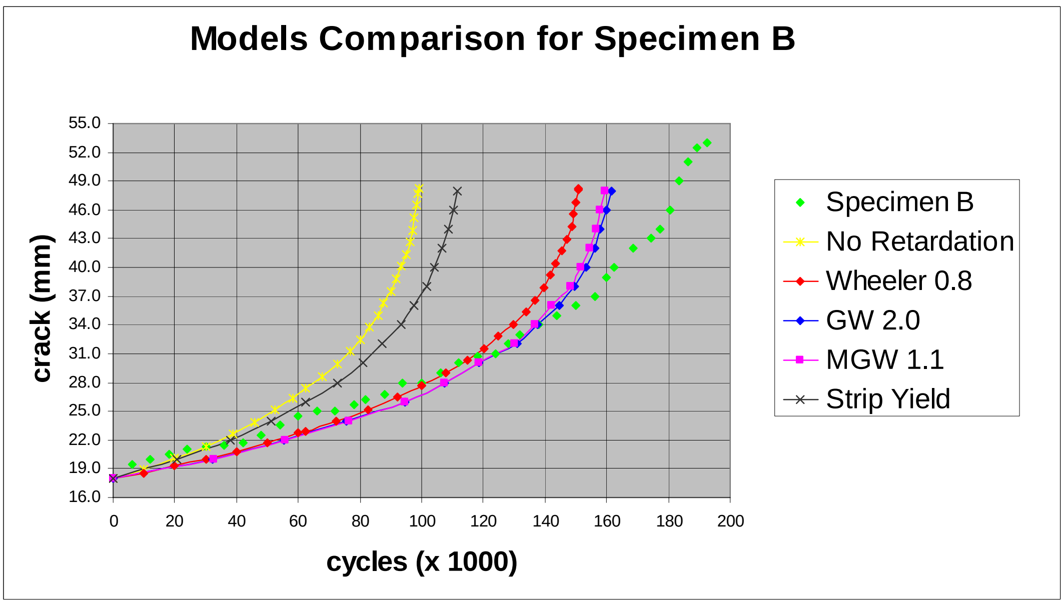

Figure 4: Models Comparison for Specimen B

Table 1: Test Results summary

	Test	no retardation	error (%)	Wheeler	error (%)
CDP A	184936	101153	45.30	159695	13.65
CDP B	183428	101299	44.77	150792	17.79

	Test	GW	error (%)	Strip Yield	error (%)
CDP A	184936	161470	12.69	110248.4	40.39
CDP B	183428	161564	11.92	111478	39.23

	Test	MGW	error (%)
CDP A	184936	159657	13.67
CDP B	183428	159391	13.10

4. Conclusions

From the results presented in Figure 3, Figure 4 and Table 1, the following conclusions can be made:

→ The Strip Yield which has no calibration parameter was found to be too conservative for the performed test conditions

→ The models based on the plastic zone ahead of the crack tip (GW, MGW and Wheeler) were found to be accurate in evaluating the retardation effects, having very similar propagation curves.

→ The underloads effects consideration performed by the MGW models do not show any significant difference regarding the other models (GW and Wheeler)

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6. Acknowledgments

The authors wish to acknowledge the Institute of Aeronautic and Space (CTA/IAE) for the support during the development of the present work. Special thanks to engineers Vanderley and Aminadab, from the Structural Tests Lab at IAE, for all their help in conducting the experiments.

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