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International Journal of Fatigue 28 (2006) 1803–1819
International Journal of Fatigue
www.elsevier.com/locate/ijfatigue

# Proposed modifications to the Wheeler retardation model for multiple overloading fatigue life prediction

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Received 14 May 2005; received in revised form 25 August 2005; accepted 26 December 2005
Available online 22 March 2006

**Abstract**

A number of modifications to the Wheeler fatigue crack retardation model were proposed. The modifications allow the model to account for the delay retardation due to applied overloads, initial crack growth acceleration immediately following an overload, overload interaction and the net section yielding effect observed in the fatigue crack growth retardation behaviour of many materials. The modified model was used to predict the fatigue life of a series of single and multiple overloading fatigue tests conducted on 350 WT steel. The results showed that the modified model predicted the fatigue lives with a greater accuracy than the original model.


*Keywords:* Fatigue crack growth retardation; Wheeler model; Delay retardation; Initial acceleration; Overload interaction; Net section yielding; Multiple overloading; 350 WT steel

## 1. Introduction

Fatigue induced crack acts as a severe stress raiser in a structure, forming a zone of plastic deformation and residual stresses ahead of the crack tip. This zone can also be called a load interaction zone since the residual stresses within the zone interfere with the applied stresses to the crack and thereby affecting its fatigue crack growth rates. A well known load interaction effect is the retardation of the fatigue crack growth rates following the application of single or multiple tensile overloads within constant amplitude fatigue loading. This occurs due to the presence of a larger zone of compressive residual stresses ahead of the crack tip produced by the overloads, resulting in crack tip blunting, crack closure and increased level of crack opening stress in the subsequent fatigue cycles. Here, the crack opening stress is defined as the stress at which the crack surfaces are fully separated. Since the crack would not propagate while fully closed, an increased level of crack opening stress increases the stress required for crack propagation and reduces the effectiveness of a load cycle.

Fig. 1 shows a typical crack growth rate curve showing retardation following a single tensile overload. For a number of materials, it has been observed that an initial acceleration of the fatigue crack growth rate occurs immediately after an overload. The crack growth rate then decelerates to a minimum value at some point ahead of the overload application, at which point the rate gradually returns to its steady state value [1–4]. The phenomenon is also known as "delay retardation". In addition, when multiple tensile overloads are closely applied, they may interact with each other to either enhance or reduce to overall crack growth retardation. Such overload interaction is dependent on the relative magnitude and the spacing between the overloads [5–10], or the frequency of the overload application [11–15]. In other words, the overall crack growth retardation may be maximized by applying overloads at certain distances apart or at certain frequencies. At the same time, due to the aforementioned initial crack growth acceleration immediately following an overload, overloads that are applied too closely or too frequently can lead to decreased overall crack growth retardation or even crack growth

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0142-1123/$ - see front matter 
doi:10.1016/j.ijfatigue.2005.12.007

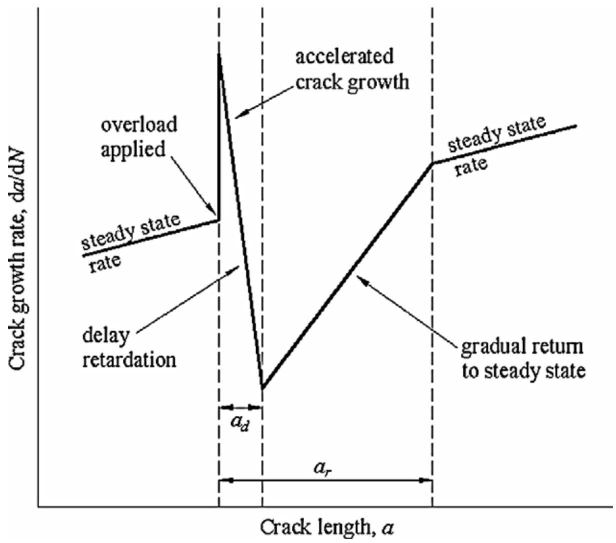


Fig. 1. Schematic crack growth rate curve showing delayed retardation following tensile overload.

acceleration. Furthermore, it was observed in the experimental portion of our work that crack growth retardation is reduced in the latter stage of the fatigue life when the net section stress of the specimen approaches the yield strength of the material.

Many researchers have proposed various models to describe the overload retardation behaviour. Generally, these retardation models may be classified into two main categories: crack tip plasticity models and crack closure models. The crack tip plasticity models are based on the assumption that crack growth retardation occurs due to the large plastic zone developed during overloading. The residual compressive stresses formed in this zone will reduce the magnitude of the tensile stresses during the next fatigue cycle and tend to delay the crack growth. A number of retardation models belong to this category.

The Wheeler model [16] predicts the retardation in the crack growth rate following an overload by modifying the constant amplitude growth rate. The model modifies the constant amplitude growth rate by an experimentally determined retardation parameter, which is a function of the ratio of the current plastic zone size to the plastic zone size created by the overload. A number of modifications [2,17,18] have been proposed to the model to account for the delay retardation phenomenon. In addition, the Wheeler model was found to provide satisfactory prediction of the overload retardation for 350 WT steel [19,20], which is the material used in the present investigation.

The Willenborg model [5,19,21–23], on the other hand, does not incorporate any empirical parameters but uses the material yield stress to give a plastic zone size. The amount of retardation is determined as a function of the stress intensity factor necessary to cancel the effect of the overload plastic zone. The model computes an effective stress intensity factor that is being reduced by the compressive residual stress. However, the Willenborg model was found to be not reliable for predicting the overload retardation for 350 WT steel [19].

The multi-parameter yield zone model [25,26], proposed by Johnson, is a modification to the Willenborg model. The model is able to account for the crack growth retardation, acceleration and underload effects, but requires four load interaction parameters. The parameters are selected from the simple overload test observations and are provides the best fit of the predicted to the experimental test results of these simple tests.

The EXPOL model [27], proposed by Nicholas et al., is similar to both the Wheeler and Willenborg model both in theory and capabilities. The model reduces the applied stress intensity factor to an effective stress intensity factor by an exponential function, which has two experimentally determined parameters. In addition, the model accounts for the initial crack growth acceleration immediately following an overload by simply adding an experimentally observed crack jump following the overload.

The Kim and Shim model [28] is a purely empirical model that is similar to the Wheeler model. The model also introduces a retardation coefficient, which is simply defined as the ratio of the experimentally determined retarded crack growth rate to the constant amplitude crack growth rate. The model is able to simulate delay retardation, but require the duration of delay retardation and complete retardation and the minimum crack growth rate during retardation to be recorded from experiment.

The Pavlou model [29] is another retardation that uses a retardation factor to modified the constant amplitude crack growth rate. The model takes into account the influence of the degree of material strain hardening within the overload plastic zone on the fatigue crack growth rate. This is accomplished by defining the retardation factor as a function of the changing yield strength due to strain hardening within the overload plastic zone. Similar to the Wheeler and Willenborg models, it appears that the Pavlou model does not simulate delay retardation.

Finally, Lang [10,30] proposed that the load interaction effects are governed by the residual compressive stresses and are accounted for by the crack propagation stress intensity factor. The crack propagation stress intensity factor is used to compute an effective stress intensity factor. It must be determined and monitored either experimentally by the crack propagation load measurement method or by the finite element method [31]. The model has been used for prediction in both single and multiple overloading situations as well as for overloading followed by unloading and underloading.

The second main category of retardation models, the crack closure models, are based on Elber's experimental observation [32] that, as a result of the tensile plastic deformation left in the wake of a fatigue crack, a partial closure of the crack faces occurs during part of a fatigue load cycle. Since crack propagation can only occur during the time for which the crack is fully open, the formation of crack closure reduces the range of the applied stress that is effective