Symposium on Fatigue Testing and Analysis under Variable Amplitude Loading

Title: On the Crack Closure Modeling of Interaction Effects under Variable Amplitude Loading

Authors: M.A. Meggiolaro and J.T.P. Castro

Extended Abstract

Introduction

Load interaction effects on mode I fatigue crack propagation are discussed, considering overload-induced retardation effects on the crack growth rate based on the crack closure idea. A taxonomy of the load interaction models is presented. The stress state dependence of crack closure is discussed, and modifications to the traditional retardation models are proposed to better model such effects as crack arrest and crack acceleration due to compressive underloads. All load interaction models presented in this work have been extended to describe the behavior of surface cracks and implemented in a general-purpose fatigue design program named V i D a , developed to predict both initiation and propagation fatigue lives under complex loading by all classical design methods. The numerical implementation of these models is discussed, including practical details required to warrant their reliability. Using this software, the models and the proposed modifications are compared with experimental results from various load spectra, to evaluate their performance and main features. In particular, the proposed modifications to the Wheeler model showed a good agreement with the experimental data and a better response to varying characteristics of the loading spectra. In addition, assuming that crack closure is the only retardation mechanism, it is shown that the propagation rate **da/dN** should be a strong function of the specimen thickness **t**, which controls the dominant stress state at the crack tip. However, this thickness effect on **da/dN** has not been object of much concern in fatigue design nor in fatigue crack growth testing standards.

Load Interaction Models

Several mathematical models have been developed to account for load interaction effects in fatigue crack propagation based on Elber's crack closure idea. In these models, the retardation mechanism is considered to act only within the overload-induced plastic zone situated in front of the crack tip. The size of this overload plastic zone being (considerably) greater than the size of the plastic zone induced by subsequent load cycles, an increased compressive stress state would be set up inside that region, which would be then the main contributing factor for reducing the crack propagation rate under smaller succeeding load cycles [1-8].

Perhaps the best-known fatigue crack growth retardation models are those developed by Wheeler [9] and by Willenborg et al. [10]. Both use the same idea to decide whether the crack is retarded or not: under variable amplitude loading, fatigue crack growth retardation is predicted when the plastic zone of the i-th load event $\mathbf{Z_i}$ is embedded within the plastic zone $\mathbf{Z_{ol}}$ induced by a previous overload, and it is assumed dependent on the distance from the border of $\mathbf{Z_{ol}}$ to the tip of the i-th crack plastic zone $\mathbf{Z_i}$, see Fig. 1.

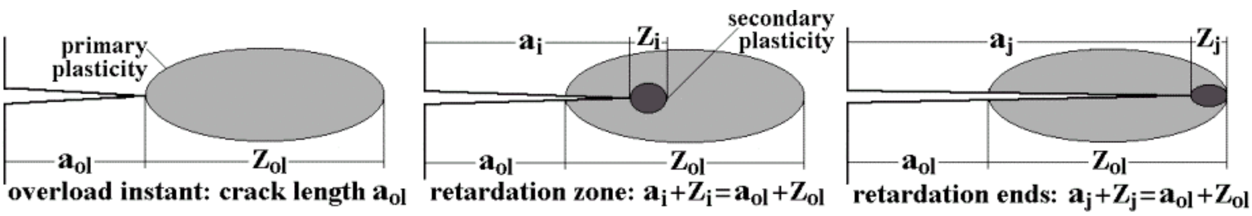


Figure 1 Yield zone crack growth retardation region used by Wheeler and by Willenborg

The main difference between the Wheeler and Willenborg models is that the latter quantifies the retardation effect by reducing $\mathbf{K_{max}}$ and $\mathbf{K_{min}}$ acting on the crack tip, while Wheeler accounts it by direct reduction of the crack propagation rate **da/dN**. Based on this and other differences, the load interaction models presented in this paper are divided in 4 categories:

(i) **da/dN** models, such as the Wheeler model, which use retardation functions to directly reduce the calculated crack propagation rate **da/dN**;

(ii) **ΔK** models, such as the Modified Wheeler model, which use retardation functions to reduce the stress intensity range **ΔK**;

(iii) $\mathbf{R_{eff}}$ models, such as the Willenborg model and its variations, which introduce an effective stress ratio $\mathbf{R_{eff}}$, calculated by reducing the maximum and minimum stress intensity factors $\mathbf{K_{max}}$ and $\mathbf{K_{min}}$ acting on the crack tip (however not necessarily changing the value of **ΔK**); and

(iv) $\mathbf{K_{op}}$ models, such as the Constant Closure and Strip Yield models, which use estimates of the opening stress intensity factor $\mathbf{K_{op}}$ to directly account for Elber-type crack closure.

Brief experimental details

The load interaction models presented in this work have been implemented in ViDa, a powerful software developed to automate the fatigue dimensioning process by ***all*** the traditional methods used in mechanical design [1, 5, 6]. This software has been developed to predict ***both*** initiation and propagation fatigue lives under complex loading by ***all*** classical design methods: **SN**, **IIW** (for welded structures) and **εN** to predict crack initiation, and **da/dN** for studying plane and 2D crack propagation, ***considering*** load sequence effects. In this section, the presented load interaction models and the proposed modifications are compared with experimental results from various load spectra.

Using ViDa, the crack propagation life of an 8-mm-thick center-cracked tensile specimen, made of a 7475-T7351 aluminum alloy, is calculated using several block loading histories, see Tab. (1). The calculated lives are compared to experimental tests performed by Zhang [11], who measured crack growth rates through scanning electron microscopy. Forman's crack growth equation [4] and Eq. (3) are used to compute crack growth (in mm), using $\mathbf{A = 6.9 \cdot 10^{-7}}$, $\mathbf{m = 2.212}$, $\mathbf{p = 0.5}$, $\mathbf{q = 1.0}$, $\mathbf{\Delta K_0 = 3MPa\sqrt{m}}$, and $\mathbf{K_C = 73MPa\sqrt{m}}$. All models are calibrated using the first loading history (except for the Willenborg model, without parameters to be adjusted), and a comparison is made through the remaining loading histories.

Experimental results and analysis

Table 1 Percentage errors in the test lives predicted by the load interaction models

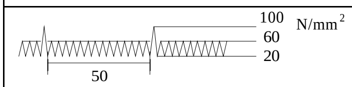
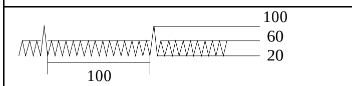
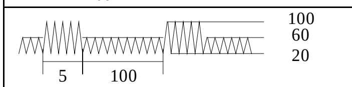
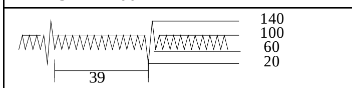
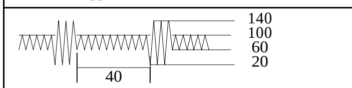
Loading history	Zhang's test life (cycles)	No Interaction	Wheeler	Generalized Wheeler	Willenborg	Generalized Willenborg	Modif. Gen. Willenborg	Constant Closure
	474,240	–17%	0%	0%	+293%	0%	0%	0%
	637,730	–36%	–22%	–22%	+269%	–22%	–22%	–22%
	409,620	–13%	+2.3%	+2.3%	+185%	+2.2%	+2.6%	+2.4%
	251,050	–27%	–18%	–18%	+27%	–20%	+24%	–75%
	149,890	–2.3%	+6.6%	+6.4%	+44%	+4.0%	+42%	–60%

Table 1 shows Zhang's test results and the percentage error of the predicted lives using several load interaction models. As expected, the Willenborg model resulted in poor predictions, since this model cannot be calibrated. The remaining models performed similarly for the second and third histories. However, as the maximum load increased from 100 to 140 MPa in the last two histories, the Modified Generalized Willenborg and the Constant Closure models showed increased errors. The Wheeler and Generalized Wheeler models performed very similarly, because the considered histories didn't include compressive underloads. These two models and the Generalized Willenborg model resulted in the best predictions for Zhang's histories. A qualitative comparison of the load interaction models, showing their main advantages and disadvantages, is presented in Table 2.

Table 2 Qualitative comparison of the load interaction models

	da/dN	**ΔK** models		**R_{eff}** models				**K_{op}** models	
	Wheeler	Modified Wheeler	Generalized Wheeler	Willenborg	Generalized Willenborg	Modif. Gen. Willenborg	Walk.Chang Willenborg	Constant Closure	Strip Yield
models crack retardation	√	√	√	√	√	√	√	√	√
models crack arrest		√	√	√	√	√	√	√	√
models crack acceleration			√			√	√	√	√
works for any load spectrum	√	√	√	√	√	√	√		√
works with any da/dN equation	√	√	√					√	
models primary plasticity		√	√						√
number of experimental parameters	1	1	1-2	0	1	1	1-2	1	5

Conclusion

In this work, load interaction effects on fatigue crack propagation were discussed. Overload-induced retardation effects were evaluated using several different models, and improvements to the traditional equations were proposed to recognize crack arrest and acceleration due to compressive underloads. The models were evaluated using a general-purpose fatigue design software named ViDa. Using this software, the presented load interaction models and the proposed modifications were compared with experimental results for various load spectra. In particular, the proposed modifications to the Wheeler model showed an excellent agreement with the experimental data.

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