Fatigue Crack Propagation under Consecutive Load Cycles with Varying Mean Loads and Amplituedes

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The accumulation of fatigue damage on specimens and structures is still largely unknown, although much research has been done in this field. Nevertheless, especially in the transportation industry, structures, part of which are extremely light, are required. For the operation and safety of such structures, the knowledge of crack behaviour under service loading is very important, since the crack length, which is non-destructively measurable during inspection intervals gives quantitative information about the degree of structural damage and also of remaining life.

Crack propagation under constant amplitude loading

Various crack propagation equations have been proposed to correlate experimental crack growth data under constant amplitude loading. Some of these are based on stress intensity approach as proposed by Paris [1] and also by Roberts et. al. [2]. For more ductile materials, which exhibit larger plastic zones at the crack tip, the correlation of crack growth rate with crack opening displacement (COD) gave more suitable results [3]. Newer investigations have shown, that the behaviour of local stresses and deformations at the crack tip are strongly influenced by the fact, that cracks can open and close even under tension loading. In a model proposed by Elber [4] it is assumed, that the crack propagates during the consecutive load cycles only when it is fully open. Therefore, to evaluate the crack growth rate, not the full stress intensity range but the instantaneous range between the crack opening load and the maximum load in a load cycle (effective stress intensity range) is used. Finally, some investigations were performed using a specially developed extensometer and they showed, that the crack growth rate for various loading conditions was always the same, if the experimentally determined deformations at the crack tip were also the same. A crack growth rate equation, which takes into account this behaviour is given in [5].

Crack propagation under consecutive load cycles with varying mean loads and amplitudes

Compared to constant amplitude loading very few results dealing with the crack propagation behaviour under variable amplitude loading is available. Schijve et. al. used the linear cumulative damage hypothesis to describe the fatigue life within the crack stage [6]. Smith et. al. proposed a crack growth rate equation based on the average stress intensity range [7], which is similar to that proposed in [1]. An equation taking into account the crack closure behaviour has been developed for only simple two-step loading [8].

Investigations with biharmonic loading

In order to check the possibilities to predict the crack propagation behaviour under consecutive load cycles with varying mean loads and amplitudes on the basis of the above mentioned crack propagation theories, a series of tests with biharmonic loading was performed. A detailed description of the special loading conditions is given in [5]. In Fig. 1 the experimentally determined cycles to propagate a crack from 0, 5 to 10 mm relative to the corresponding cycles under constant amplitude loading with the same mean load and amplitude are shown. Also shown are the cycle ratios as they are predicted by the linear cumulative damage hypothesis and which are predicted by a linear summation of the single level crack growth rates using the crack propagation equations in [1, 2, 4]. For the determination of the effective stress intensity ranges in [4] the crack opening loads under biharmonic loading were used. The figure shows, that the predicted results deviate from the experimental. An application of the crack growth rate equation given in [7] predicts the same crack propagation behaviour for biharmonic loading, when the smaller load cycles inbetween the biharmonic load cycles are of the same amplitude but different mean loads. Fig. 1 shows clearly that it is not the case.

An extensive analysis of the deformations at the crack tip under biharmonic loading was performed using the above mentioned extensometer. These investigations showed, that the crack propagation was closely related to the total deformations caused by the consecutive load cycles. The experimentally determined deformations as a function of the applied load are shown in Fig. 2 as an example for a special type of biharmonic loading. Because of the crack closure behaviour the deformations due to the smaller load cycles inbetween the biharmonic load cycles with the same amplitude were larger in the case of higher mean load. A determination of the crack growth rates on the basis of the following equation:

$$\Delta l = \sum_{i=1}^{n} C \cdot V_{ges_i}^{4.5} \quad (1)$$

where Δl is the increase in crack length during n load cycles and V_{gesi} is the total deformation during one load cycle resulted in the behaviour shown in Fig. 3. A comparison with the experimentally determined values, which are also plotted in Fig. 3, confirms, that the predicted results follow the same trend as shown by the experimental results. A possible explanation for the still existing differences may lie with the deformation measurement device, which gives only the average deformation between the gauge length.

Crack propagation under reversed loading

In Fig. 4 are shown the cycle ratios in the crack stage under reversed loading. In the contrary to the crack propagation behaviour under zero to tension loading (Fig. 1) the crack life under biharminic loading can be prolonged as compared to the corresponding constant amplitude loading. This gives rise to the assumption, that there are additional influencing factors, which control the fatigue crack propagation behaviour under reversed loading.

References:

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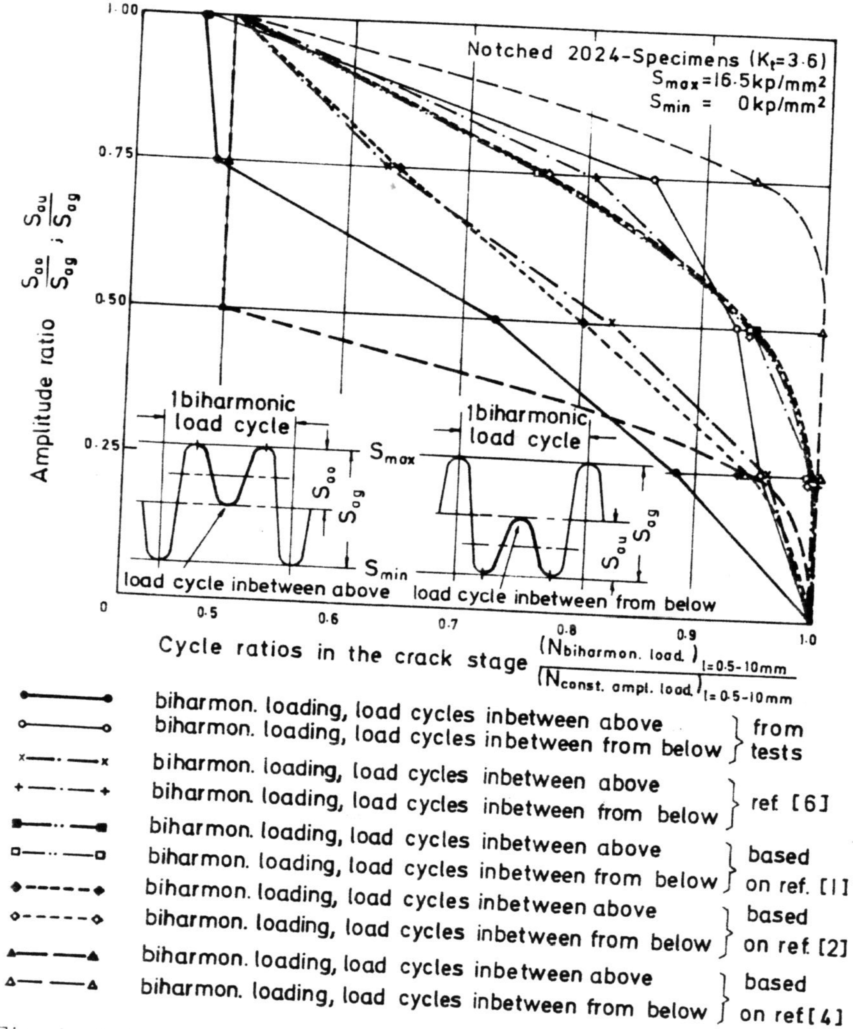

Fig. 1: Life behaviour in the crack stage (zero to tension loading)

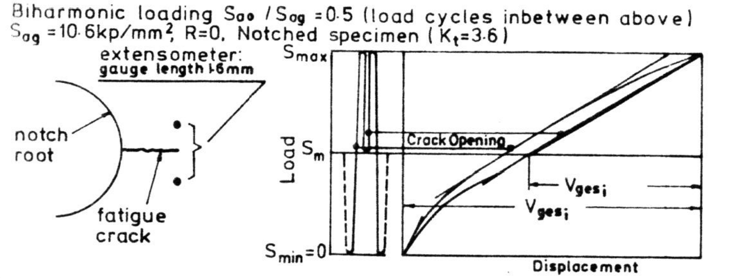

Fig. 2: Deformations measured at the crack tip (biharmonic loading)

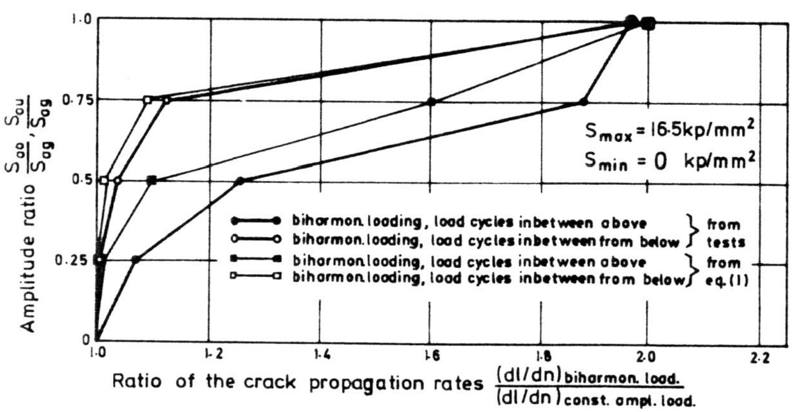

Fig. 3: Crack propagation behaviour under biharmonic loading

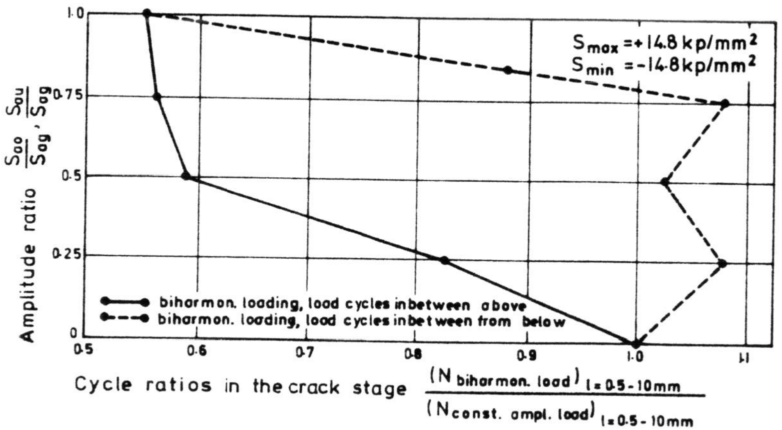

Fig. 4: Life behaviour in the crack stage (reversed loading)