ORAL REFERENCE: ICF100127OR

Influence of loading changes on the fatigue crack growth

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ABSTRACT

The basis for most of the concepts for predicting the life time of structures generally are tests, which are performed under both constant loading parameters (e.g. amplitude or mean stress) and Mode I conditions. But a component is exposed more or less loading changes during service loadings. Through these loading changes the so called interaction effects are induced, which are not taken into consideration by those standard tests. This means that the prediction of the life time could be too conservative.

In this paper the interaction effects of loading changes (e.g. overloads, block loadings and special service loadings) on the fatigue crack growth are investigated experimentally. The fatigue crack propagation tests have been performed on 7075 T6 aluminium alloy using CT specimens. In these tests the loading changes are interspersed in a basic loading with a constant amplitude. All experiments are controlled by the program system ^{FAM}Control. The experimental results show, that for all investigated loading changes ultimately a strong retardation of the crack growth occurs, which clearly depends on ratio of the loading changes.

KEYWORDS

fatigue crack growth, variable amplitude tests, retardation, acceleration, overload, block-loading, service-loading, Mixed Mode loading

INTRODUCTION

The quality of a product is of increasing importance for industrial applications, because costs arising from missing quality are enormous. Especially the missing quality, which is caused in the early phase of the development of a product are combined with high consequential costs. Not only economic but first of all the safety-engineering factors in this phase are important for a breakproof development of components and structures.

For this purpose the prediction of lifetime is a helpful instrument. The concepts, for example those by Wheeler [1], Willenborg [in 5] or Gray & Gallagher [3], used to predict the fatigue crack growth at variable amplitude loading in components are often based on tests with constant amplitude loadings, in which overloads are interspersed. However structures are exposed service loadings, which are composed of varying loading changes. These loading changes produce both acceleration and retardation, the so-called interaction effects. In this work some loading changes are experimentally investigated to form the basis of concepts for predicting lifetime of structures under real-life-conditions.

LOADING CHANGES DURING SERVICE LOADING

The loadings, under which a fatigue crack grows, can be divided up into two main parts: single-stage loading and service loading. With experiments under single-stage loadings statements can be made about the crack initiation, the crack path and starting of unstable crack growth. But it is impossible to predict the lifetime of a component under real-life conditions with service loadings. The service loadings again consists of single over-/underloads, over-/underloads sequences, block loading and combination loading. All these loading changes alone are interspersed into a single-stage loading. The combination loading is interspersed likewise in an constant amplitude loading, but is composed of the three other loading types. Moreover loading changes can result from a alteration of the load direction, so that all mentioned loading types must be investigated under Mixed Mode. In Figure 1 several loading changes are represented.

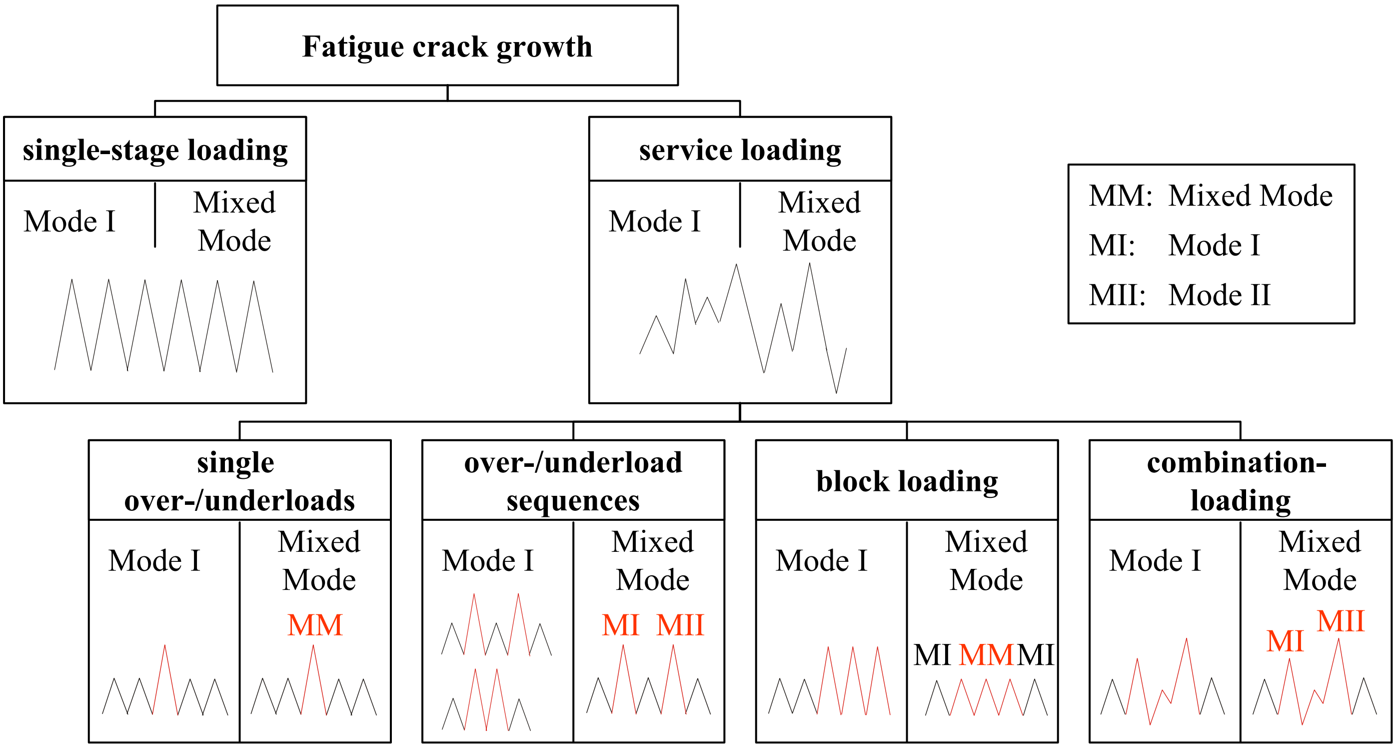

Figure 1: Systematisation of loading cases for fatigue crack growth

In this paper the results of single overloads, overload sequences, block loading and combination-loading under Mode I are presented. The overload ratio is defined as:

$$R_{ol} = \frac{K_{ol}}{K_{max}} \tag{1}$$

and the block loading ratio is defined analogous to the overload ratio as:

$$R_{block} = \frac{K_{block}}{K_{max}} \tag{2}$$

whereby K_{ol} and K_{block} are the maximum load of the overload resp. the block loading and K_{max} is the maximum load of the constant baseline level of the cyclic stress intensity factor, ΔK_{Bl}.

EXPERIMENTAL SETUP

The central unit of the experimental setup (Figure 2) is the servohydraulic testing system. The potential drop method (DC) is used for the measurement of the crack length. For both the measuring data logging and controlling of the experiments the program system ^{FAM}Control is used, which has been developed at the Institute of Applied Mechanics at the University of Paderborn. With ^{FAM}Control it is possible to perform all experiments fully automatic. Figure 3 shows the parameter window of ^{FAM}Control, in which the user can define all kinds of service loadings. During K-controlled tests, the load will adapted continuously to the crack length.

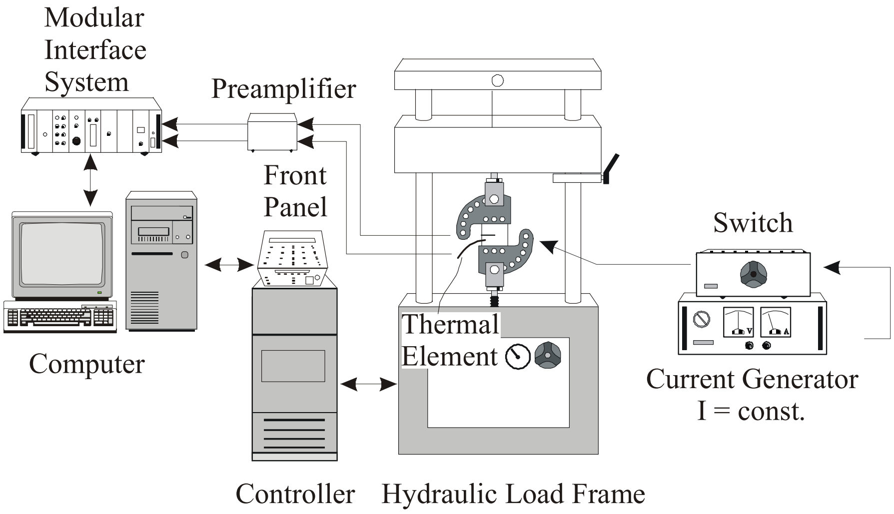

Figure 2: Schematic experimental setup

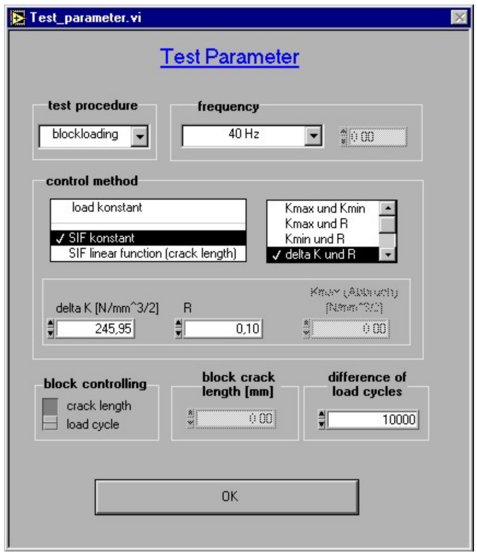

Figure 3: Parameter window of the program system ^{FAM}Control

The experiments have been carried out on the Aluminium alloy AlZnMgCu 1.5 (7075 T651) by means of CT specimens, which have been taken from a plate in T-L direction. The overloads have been interspersed in constant baseline levels, ΔK_{Bl} of 4, 7 and 10 MPam$^{1/2}$ and load ratio of 0.1. The experiments with block loadings and combined loadings have been performed with ΔK_{Bl} = 7 MPam$^{1/2}$ and R = 0.1.

RESULTS OF EXPERIMENTAL INVESTIGATIONS OF LOADING CHANGES

The effects of loading changes become obvious when observing the fatigue crack growth rate (FCGR). All measuring data are evaluated with the incremental polynomial method, as it is described in the ASTM E647 standard. In the transition between the loading changes the secant method has been applied, which results in a direct availability of the crack velocities after a loading change.

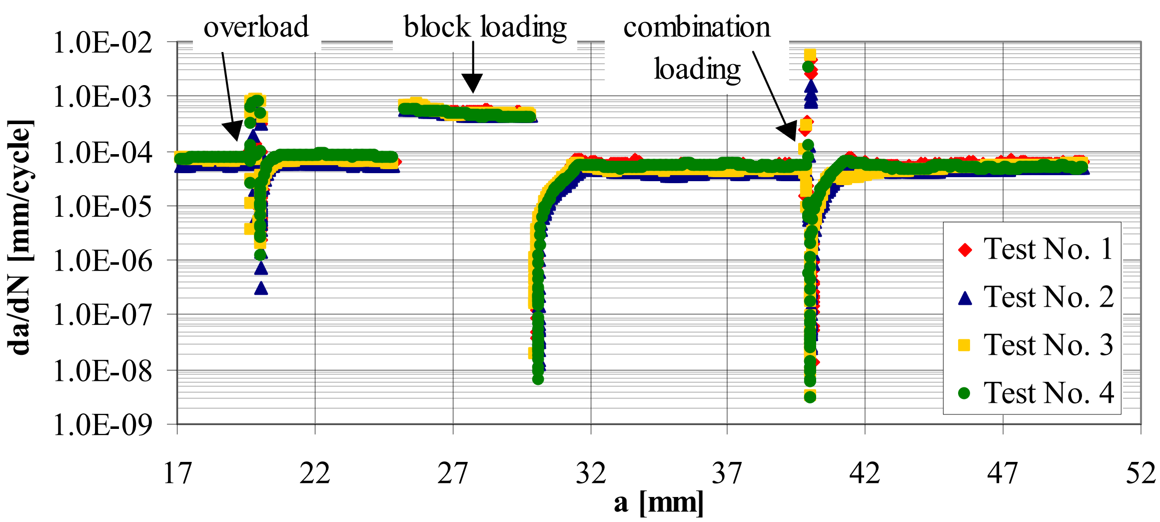

Figure 4: Crack growth rates for different loading changes with acceleration and retardation effects for several tests

Figure 4 illustrates the changes of the FCGR after loading changes with the same loading change ratio R_{ol} and R_{block} of 2.0, which are interspersed in a constant ΔK_{BI}. After a single overload the FCGR initially increases and then the crack growth retards. The block loading has two effects. At the beginning of the block the FCGR accelerates immediately and stays on this level over the whole duration of the block loading. After the block loading the FCGR decreases to a minimum and increases after a while to the base level. The combination loading consists of ten cycles of overloads with different overload ratios, but the maximum overload ratio amounts 2.5. In this case the FCGR increases, too, but decreases to a lower level as the minimum FCGR of the single overload and the block loading.
Figure 5 and Figure 6 show the crack length versus the load cycle curve, in which the typical load interaction effects are illustrated.

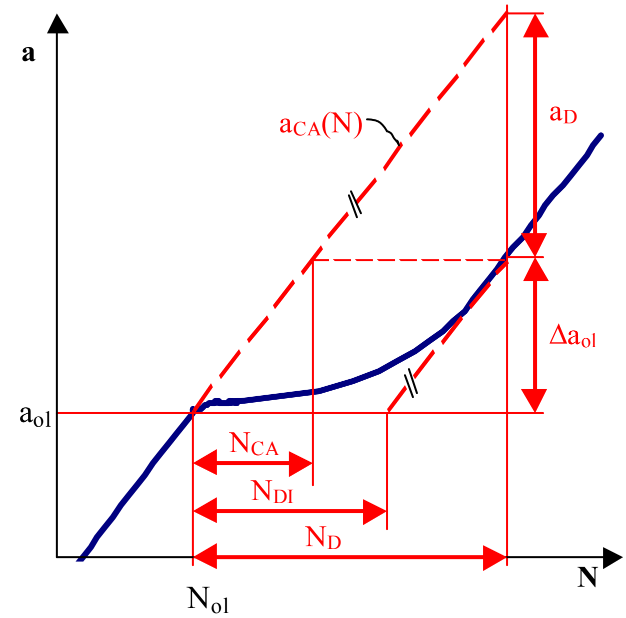

Figure 5: Characteristic parameters of interaction effects following an overload interspersed in a K-controlled-tests

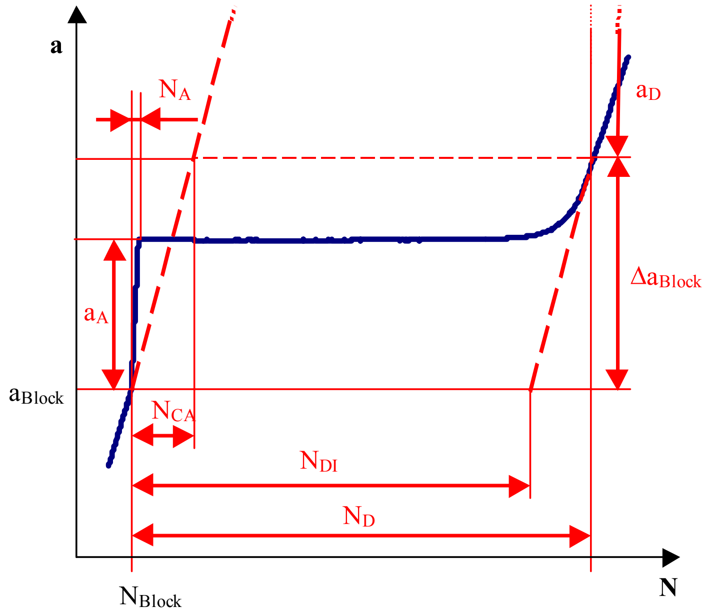

Figure 6: Characteristic parameters of interaction effects following an block loading interspersed in a K-controlled-tests

The magnitude of the retardation after an overload is usually measured by the delay cycles N_D or N_{DI}. N_D is the number of cycles until the FCGR of the constant amplitude loading is reached (comp. Figure 4). The cycle number N_{CA} indicates, how many load cycles are necessary for an overload-affected crack growth increment of Δa_{ol} in the absence of an overload. Instead of the delay cycle N_D sometimes the factor N_{DI} is used. N_{DI} is the number of delay cycles, which is adjusted by the N_{CA}. In addition to the mentioned retardation there exists a phase of acceleration for the block loading. This acceleration is described by the parameters N_A and a_A.
The results of the overload experiments shows, that the retardation effects increase with increasing overload ratios. That means, that the number of delay cycles and the overload-affected crack growth increment increases. This trend is also observed in many other publications [3-6]. Besides that the influence of the baseline level of the cyclic stress intensity factor is investigated. These tests have been performed with the baseline levels 4, 7 and 10 $MPam^{1/2}$. These experiments show, that the retardation effect raises with decreasing ΔK_{BI}.
Moreover Henn, Richard and Linnig [7] have carried out experiments with Mixed Mode overloads using CTS specimens [8]. These experiments prove, that if a Mixed Mode overload is interspersed into a Mode I loading, only the share of Mode I of this overload decides about the amount of retardation.
For the demarcation between tests with Mode I overload sequences and Mode I block loading a series of experiments have been performed. Therefore the number of overloads has been enhanced from a single overload to $n_{ol} = 50$, but the overload ratio is constant. Up to $n_{ol} = 22$ the number of delay cycles increases linearly. At $n_{ol} = 20$, 25 and 50 the fatigue crack arrests and the number of delay cycles reaches the technical

fatigue strength of Aluminium. This means, that from $n_{ol} = 20$ it does not make any difference if any overloads follow, so the limit for block loading has been reached.

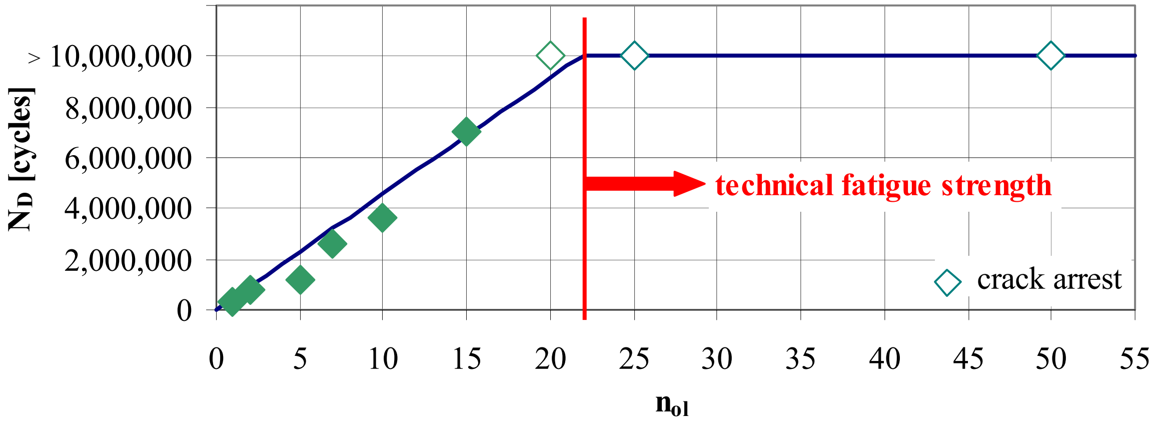

Figure 7: Number of delay cycles N_D over the number of overloads - Comparison between different overload sequences with the same baseline level $\Delta K_{Bl} = 7$ MPam$^{1/2}$ and the same overload ratio of 2.5

In Figure 8 the delay cycles of the experiments are illustrated. Compared to the tests with overloads the experiments with block loadings show a significant bigger retardation effect. From a block loading ratio of 2.2 the retardation is so high, that the technical fatigue strength of Aluminium is reached. The retardation of the combination loading, which consists of ten different load cycles, lies between that one of the overload and that one of the block loading.

Figure 9 shows the overload- resp. block-loading-affected crack growth increments. Both the overload-affected increment and the block-loading-affected increment increase linearly. In contrast to the overload-affected increments the block-loading-affected crack growth increments are much higher.

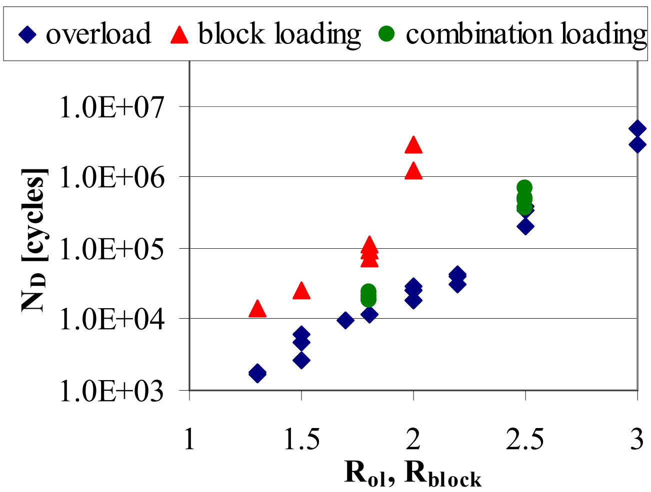

Figure 8: Number of delay cycles depending on the loading change ratio for overload and block loading

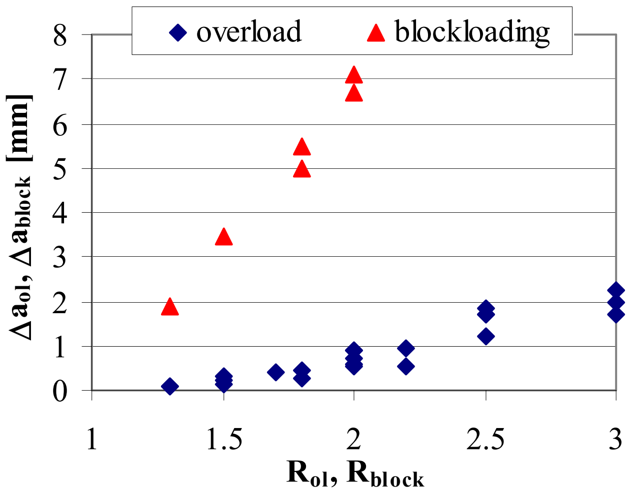

Figure 9: Delay distance depending on the loading change ratio for overload and block loading

The mentioned retardation occurs also under Mixed Mode loading changes. Experiments have been performed, in which the load direction is modified. In opposition to the pure Mode I loading the crack has kinked [9]. However, the crack growth retards after such a loading change from a pure Mode I loading to a Mixed Mode loading [9]. The change in the load direction and the consequences for the stress intensity factors are shown in Figure 10. It is obvious, that it comes up to a block loading. Further studies will be done, with which the influence of the share of Mode II will be investigated.

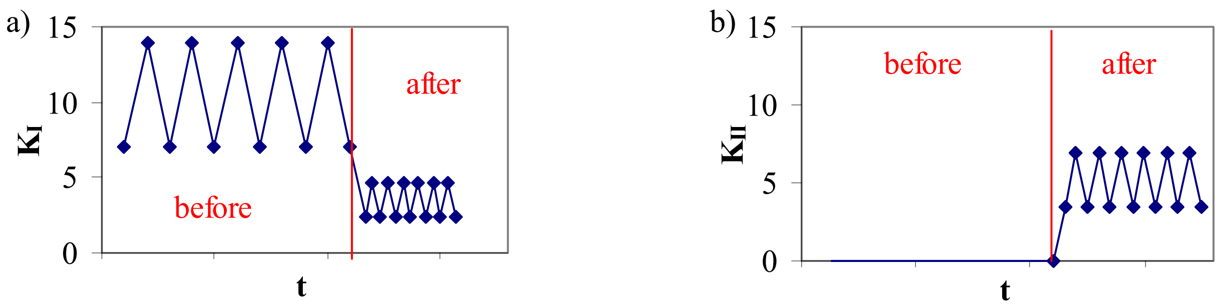

Figure 10: Stress intensity factors K_I (Figure 10a) and K_{II} (Figure 10b) before and after changing the load direction from Mode I to Mixed Mode loading

CONCLUSIONS

From the experiments and literature following conclusion can be drawn:

1. For the presented experiments the program system ^{FAM}Control has been developed. With ^{FAM}Control all experiments can be carried out fully automatic.
2. Loading changes produce both acceleration and retardation. This must be included into concepts for predicting the lifetime of components and structures.
3. The retardation effect of overloads arises with increasing overload ratio and decreasing ΔK_{BI}. Mixed Mode overloads, which are interspersed into a constant Mode I loading, likewise retard the crack growth, but only the share of Mode I of the Mixed Mode overload decides about the amount of the retardation.
4. Interspersed block loadings into a constant amplitude loading leads to acceleration. After block loadings the crack growth retards. The retardation of block loadings are much bigger than the ones of overloads.
5. A change from Mode I to Mixed Mode loading likewise retards the crack growth.
6. If a crack is subjected to either an overload or a block or a service loading the primary propagation direction remains unchanged. But under Mixed Mode fatigue loading a kinking of the cracks according to the K_{II}/K_I ratio can be observed.

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