Modified NASGRO equation for physically short cracks

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A typical fatigue crack growth curve consists of the threshold region, the Paris region (linear in a logarithmically scaled diagram) and the transition region from the Paris region to unstable crack growth. For cracks exceeding a certain material-dependent length, this curve depends only on the load ratio \(R\) and is well described by commonly accepted crack growth models such as the Forman/Mettu (NASGRO) equation. However, cracks below this length typically grow significantly faster due to the absence of crack-closure effects, leading to an additional dependence of the crack growth curve on the crack extension \(\Delta a\). In this paper, a simple analytical model for describing the crack growth behavior for any crack length and load ratios between \(-3\) and 0.5.

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1. Introduction

To estimate life-time or inspection intervals of components it is crucial to obtain a reliable estimate for the growth of fatigue cracks which may potentially pre-exist or have been initiated during operation. The analytical description of crack growth under cyclic loading, with the maximum stress \(\sigma_{\text{max}}\) the minimum stress \(\sigma_{\text{min}}\) and the stress range \(\Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}}\) as well as the respective stress intensity factors \(K_{\text{max}}\), \(K_{\text{min}}\), \(\Delta K\) for any load ratio \(R = \sigma_{\text{min}}/\sigma_{\text{max}} = K_{\text{min}}/K_{\text{max}}\) and crack extension \(\Delta a\), is based on the crack growth equations according to Erdogan/Ratwani [1] and Forman/Mettu [2] including Newman’s model for plasticity-induced crack closure [3]. A summary and short discussion of these equations can be found in [4]. It is known that short cracks are able to grow below the threshold for long crack growth, and that they can grow significantly faster than long cracks at the same cyclic stress intensity factor range [5–7]. Commonly used crack growth models cannot describe short crack growth with sufficient accuracy or do not consider this behavior at all, which may lead to non-conservative lifetime predictions (cf. Fig. 1) with potentially disastrous consequences. There are different types of short cracks which are broadly classified in microstructurally short cracks, mechanically short cracks, physically short cracks and chemically short cracks [5]. Microstructurally short cracks are comparable in size to the scale of the characteristic microstructural dimension. Mechanically short cracks are comparable to the near-tip plastic zone, or are engulfed by the plastic strain field of a notch. Physically short cracks are significantly larger than the characteristic microstructural dimension and the scale of local plasticity, and typically have lengths smaller than a millimeter or two. Chemically short cracks exhibit apparent anomalies in their propagation rate below a certain crack size [5]. The purpose of the present contribution is to create a crack growth model which is able to describe the growth rate of cracks of arbitrary length under the condition of small scale yielding, i.e., for physically short cracks. At first, the approach describing the crack growth behavior by considering the build-up of crack closure will be described (Section 2), followed by experimental verification of the modified NASGRO equation (Section 3).

2. Analytical description of the crack growth behavior

The following considerations on crack growth behavior are based on a mechanical model as shown in Fig. 2a. Starting from a sharp notch with depth \(a_0\), a crack of length \(\Delta a\) is growing. The sharp notch can be regarded as a crack of length \(a_0\) which is not subject to any crack closure. Therefore the stress intensity factor range is calculated via \(\Delta K = \Delta a (\pi a)^{1/2}\) using the total crack length \(a = a_0 + \Delta a\), whereas the build-up of crack closure does only occur on the crack extension \(\Delta a\). In what follows, the NASGRO equation according to Forman/Mettu [2],
Nomenclature

- \( \alpha \) constraint factor, \( \alpha = 1 \) for plane stress and \( \alpha = 3 \) for plane strain
- \( \Delta a \) crack extension length
- \( a_0 \) notch depth
- \( a_{0H} \) fictitious length scale following El Haddad
- \( a \) total crack length
- \( A_b, A_1, A_2, A_3 \) polynomial coefficients of Newman’s crack opening function
- \( B \) thickness of specimen
- \( C \) crack growth constant
- \( C_{th} \) curve control coefficient
- \( da/dN \) fatigue crack growth rate
- \( f \) crack opening function
- \( F \) crack velocity factor
- \( F_{lc} \) crack velocity factor according to long cracks
- \( F_a \) applied load amplitude
- \( J_i \) initiation fracture toughness
- \( \Delta K \) stress intensity factor range
- \( \Delta K_0 \) stress intensity factor range for long crack growth at \( R = 0 \)
- \( \Delta K_{th} \) threshold of stress intensity factor range for crack propagation
- \( \Delta K_{th,eff} \) intrinsic (effective) threshold stress intensity factor range
- \( \Delta K_{th} \) long crack growth threshold stress intensity factor range
- \( K \) stress intensity factor
- \( K_c \) fracture toughness
- \( K_{\text{max}} \) maximum stress intensity factor
- \( K_{\text{min}} \) minimum stress intensity factor
- \( k_{ro} \) opening stress intensity factor
- \( l_i \) fictitious length scale
- \( L \) length of specimen
- \( m \) Paris exponent
- \( p, q \) empirical constants describing the curvatures that occur near the threshold and near the instability region of the crack growth curve, respectively
- \( R \) load ratio
- \( S \) span
- \( \Delta \sigma \) stress range
- \( \sigma_f \) flow stress (average between uniaxial yield stress and uniaxial tensile strength)
- \( \sigma_{\text{max}} \) maximum applied stress
- \( \sigma_{\text{min}} \) minimum applied stress
- \( v_i \) weighting factors
- \( W \) width of specimen

\[
\frac{da}{dN} = C \cdot F \cdot \Delta K^m \cdot \left( \frac{1 - \frac{\Delta K}{\Delta K_0}}{1 - \frac{\Delta K}{\Delta K_{\text{th}}}} \right)^p = C \cdot F \cdot \Delta K^m \cdot \frac{\Delta K_0}{(K_c - K_{\text{max}})^p},
\]

will be discussed and then modified to take account of the short crack behavior (i.e., the deviation from the long crack propagation behavior for small \( \Delta a \)).

Eq. (1) represents all three branches of the crack growth curve (Fig. 2b): the fatigue crack growth threshold \( \Delta K_{th} \) gives the position of branch I; the parameters \( C \) and \( m \) and the crack velocity factor \( F \) discussed below describe the Paris region (branch II); the fracture toughness \( K_c \) determines the transition to unstable crack growth (branch III). In addition, the curvatures of the transitions between the different branches can be adjusted by means of the parameters \( p \) and \( q \).

However, the exact position of each of the three branches is influenced by the load ratio \( R \); although not denoted explicitly in Eq. (2), the threshold \( \Delta K_{th} \) (describing branch I) and the crack velocity factor \( F \) (describing the location of branch II) depend on \( R \). Likewise, the location of branch III in the \( da/dN \) vs. \( \Delta K \) curve also depends on \( R \), because \( K_{\text{max}} = \Delta K/(1-R) \). Therefore, for \( K_{\text{max}} = K_c \) one obtains \( \Delta K = (1-R) K_c \). All influences from load ratio and crack opening behavior will be discussed in more detail below. Setting \( p = m = q = 1 \) independent of \( R \) for simplicity, one obtains

\[
\frac{da}{dN} = C \cdot F \cdot \frac{\Delta K - \Delta K_{th}}{1 - \frac{\Delta K}{\Delta K_{th}}} = C \cdot F \cdot \frac{\Delta K - \Delta K_{th}}{1 - \frac{\Delta K_{th}}{K_c}}.
\]

To adjust the simplified NASGRO Eq. (2) to the behavior of short cracks, one has to take into account

- that short cracks are able to grow below the threshold for long crack growth and
- that short cracks grow significantly faster than long cracks at the same stress intensity factor range, most notably in the low and medium near threshold regime, the Paris region.

The former effect can be modeled by introducing a dependence on the crack extension \( \Delta a \) into the expression for the crack growth threshold \( \Delta K_{th} \), the latter effect by modifying the crack velocity factor \( F \) according to the influence of \( \Delta a \).

2.1. Analytical description in the threshold region

In the original formulation of the NASGRO Eqs. [2,4], the dependence of the threshold for crack growth propagation on the load ratio \( R \) is approximated by

\[
\Delta K_{th} = \Delta K_0 \sqrt{\frac{a}{a + a_{0H}}} \left[ \frac{1 - f}{1 - A_0(1 - R)} \right]^{-(1 + C R)},
\]
where $\Delta K_0$ is the threshold for long crack growth at $R = 0$, and $C_{th}$ and $A_0$ are additional adjustment parameters.

The crack opening function $f = K_{op}/K_{max}$, i.e., the ratio of crack opening stress versus maximum applied stress, is used to model the influence of various crack closure mechanisms. Newman [3] achieved, based on finite element simulations of plasticity-induced crack closure for long cracks, the following analytical approximation for the crack opening function:

$$f = \begin{cases} \max(R; A_0 + A_1 R + A_2 R^2 + A_3 R^3) & \text{for } R \geq 0, \\ A_0 + A_1 R & \text{for } -2 \leq R < 0, \\ A_0 - 2A_1 & \text{for } R < -2 \end{cases}$$

With

$$A_0 = (0.825 - 0.34x + 0.05x^2) \left(\frac{\sigma_{op}}{\sigma_y}\right)^{1/2},$$

$$A_1 = (0.415 - 0.071x) \frac{\sigma_{op}}{\sigma_y},$$

$$A_2 = 1 - A_0 - A_1 - A_3,$$

$$A_3 = 2A_0 + A_1 - 1.$$  

In what follows, the values $\sigma_{max}/\sigma_y = 0.3$ and $x = 3$ are assigned, as it applies for approximate plane strain condition and largely elastic crack behavior; for a more detailed discussion of these parameters see [3,4].

In Eq. (3), $a_{0,th}$ is a fictitious intrinsic length scale based on the concept of El Haddad [8] for the approximate consideration of short crack effects. As a consequence of this approximation a crack of total length $a = 0$ shows a threshold value of 0. Such an increase of $\Delta K_{th}$ with crack extension might be interpreted by the build-up of crack closure until $a = a_{0,th}$. At least in the presence of an initial notch $a_0$, see Fig. 2a, this concept proves to be unsustainable because only the crack extension $\Delta a$ and not the total crack length $a$ is relevant to the build-up of crack closure effects. Furthermore, also in the absence of crack closure the threshold value is not 0 but equal to the effective threshold for crack propagation $\Delta K_{th,eff}$. For these reasons, the application of the El Haddad correction is not considered (i.e., $a_{0,th} = 0$), and one obtains

$$\Delta K_{th,lc} = \Delta K_0 \left[1 - f \left(\frac{1 - a}{1 - R}\right) \right]$$

(6)

In what follows, Eq. (6) is exclusively used to describe the $R$ dependence of the long crack threshold.

For the description of the threshold build-up starting from the intrinsic value of $\Delta K_{th,eff}$ at a crack extension of $\Delta a = 0$ to the long crack growth threshold $\Delta K_{th,lc}$ at large $\Delta a$, the empirical approach

$$\Delta K_{th} = \Delta K_{th,eff} + (\Delta K_{th,lc} - \Delta K_{th,eff}) \cdot \left[1 - \sum_{i=1}^{n} v_i \cdot \exp \left(\frac{-\Delta a}{l_i}\right) \right]$$

(7)

with the constraint

$$\sum_{i=1}^{n} v_i = 1$$

(8)

is proposed. The $l_i$ can be interpreted as fictitious length scales for the formation of crack closure effects (see Fig. 3), similar to $a_{0,lc}$, and may be determined in conjunction with the $n_i$ by fitting of the experimentally obtained crack growth resistance curve ($\Delta K_{th}$ plotted against $\Delta a$), as shown later. The basic physical idea behind this approach is that each closure mechanism requires a certain crack extension length to build up completely. A similar approach has been proposed by McEvily [9], using a single fictitious length related to the crack opening stress intensity factor.

2.2. Analytical description in the Paris region

In the original formulation of the NASGRO equation [2,4], the crack velocity factor

![Fig. 2. (a) Schematic illustration of the used mechanical model and (b) typical shape of fatigue crack growth curve for long cracks for a constant load ratio $R$.](image)

![Fig. 3. Illustration of the build-up of crack closure due to plasticity induced crack closure and roughness induced crack closure mechanisms with fictitious length scales $l_i$.](image)
describes the position of region II depending on the load ratio $R$ for long cracks (large crack extensions $\Delta a$).

For cracks with arbitrary crack extension $\Delta a$, an empirical approach for the crack velocity factor $F$ is developed similar to the adjustment in the threshold region. Because the crack growth rate is influenced by the same crack closure mechanisms as the crack growth threshold, in analogy to Eq. (7) the approximation

$$F = 1 - (1 - F_{lc}) \cdot \left[ 1 - \sum_{i=1}^{n} \nu_i \cdot \exp \left( -\frac{\Delta a}{L_i} \right) \right]$$

(10)

With

$$F_{lc} = \left( \frac{1 - f}{1 - R} \right)^m$$

(11)

and unchanged values for the $I_i$ and $\nu_i$ is chosen in place of Eq. (9).

Finally it should be noted that in reality the relative contributions of crack closure – i.e. the values of $\nu_1$ and $\nu_2$ – depend on $\Delta K$ and $R$. In addition the characteristic lengths to build up the different crack closure mechanisms are functions of $\Delta K$ and $R$. Therefore the $I_i$ and $\nu_i$ are affected by $\Delta K$ and $R$. The assumption that the $\nu_1$ and $I_1$ are independent of $\Delta K$ should be well fulfilled near the threshold and lower Paris regime. In this case the different contributions of crack closure are similar to those at the threshold. However in the mid and upper Paris regime this is different. The plasticity induced crack closure becomes more dominant compared to roughness and oxide induced crack closure, i.e., the relative contributions of plasticity induced crack closure $\nu_1$ increases and the relative contribution of roughness and oxide induced crack closure $\nu_2$ and $\nu_3$ decrease. Furthermore, the characteristic length $l_i$ to build up plasticity induced crack closure increases, because the plastic zone size increases. If $l_i < l_j$ and $v_i = v_j$ (see next section), the increase of $l_i$ is partly compensated by the change of the ratio $v_i/l_j$. Hence the simplification that $F$ does not depend on $\Delta K$ should give a satisfactory approximation of the real increase of crack closure in the near threshold as well as in the Paris regime.

Fig. 4b shows the dependence of the crack velocity factor $F$ on the load ratio $R$ and the crack extension $\Delta a$ in graphical form. At all load ratios $R$ below 0.5, a clear difference between short and long crack behavior is recognized.

The crack velocity factor $F$ is based on Newman’s crack opening function $f$, Fig. 4a, and adjusted according to the crack extension, cf. Eqs. (10) and (11). Basically, $F = 1$ is assigned to the unreduced growth rate of a crack where no crack shielding occurs, i.e., where the maximum stress intensity factor in a load cycle $K_{max}$ acts to its full extent as a driving force for crack opening $K_{op}$, or where $f = K_{op}/K_{max} = 1$. Wherever crack closure mechanisms are present, one obtains $f < 1$ and $F < 1$.

3. Experimental verification

For model calibration, experiments on typical standard fracture mechanic samples – i.e. deep notched specimens – were tested. For the verification of the proposed equation to describe the fatigue crack propagation, in addition different fatigue experiments on short notches were performed.

3.1. Material and experimental procedure

As material for the experimental investigations, the QT steel 25CrMo4 widely used for drivetrain components was chosen. The material has a bainitic microstructure and a hardness of ~245 HV10. In the tensile test, a 0.2% offset yield stress of 512 MPa, a tensile strength of 674 MPa, and an elongationat fracture of 18.9% are obtained.

For determining the fatigue crack propagation behavior, SENB (Single Edge Notched Bending) specimens measuring $L = 100$ mm, $B = 6$ mm, $W = 20$ mm (cf. Fig. 5a) with different notch depths $a_0$ (0.35 mm, 1 mm, 5.3 mm) were machined. The latter one corresponds to a sample for a standard fatigue crack growth experiment. The notches were sharpened by means of razor blade polishing with diamond paste (1 μm). The samples were then compression pre-cracked at a load ratio of $R = 10$ to obtain a fatigue pre-crack (cf. Fig. 5b). Due to tensile residual stresses from compression pre-cracking, the pre-crack is fully open so that crack closure effects can be excluded at the beginning of the crack growth experiment, see also [10,11]. The applied stress intensity to generate the pre-crack was taken as small as possible – $\Delta K$ of about 20 MPa m$^{1/2}$ – in order to reduce the residual stress affected region in front of the pre-crack, and more than $10^6$ cycles were used. The pre-crack measured from the notch root has typically a length between 20 and 80 μm. The notch root radius was usually smaller than 10 μm hence standard fracture mechanics equations to determine $\Delta K$ could be applied.
The experiments are performed at room temperature under laboratory conditions for three different load ratios \( R = 0.5, -1 \) and \(-3\). The samples are subjected to cyclic loading under eight-point bending (cf. Fig. 6) in a resonance test rig at a testing frequency of 108 Hz. The crack growth is measured using the direct current potential drop due to the Seebeck effect at material junctions is excluded by periodic switching of the direction of the electric current and subsequent averaging. Crack arrest was defined as the (averaged) crack growth rate falling below a value of at most \( 6 \times 10^{-8} \) mm/cycle.

![Fig. 5. (a) SENB specimen with thickness \( B = 6 \) mm, length \( L = 100 \) mm and width \( W = 20 \) mm and (b) notch details: I machined notch, II razor blade polishing, III compression pre-crack.](image)

The experiments are conducted under step-wise increasing constant loads as proposed by Tabernig [12]. The procedure is schematically illustrated in Fig. 7. For load amplitudes which correspond to \( \Delta K \) values smaller than the effective threshold \( \Delta K_{th, eff} \), no crack propagation is observed. For load amplitudes which correspond to \( \Delta K \) values larger than \( \Delta K_{th, eff} \), the crack starts to propagate. The crack grows initially, but after a certain crack extension \( \Delta a \) crack arrest occurs due to the build-up of crack closure. Subsequently, the load is increased so that the crack can grow further. In this way, the resistance curve for the threshold of stress intensity factor range is obtained point by point (Fig. 7 and 8). As soon as the crack starts to grow through, one gets the crack growth curve. At that crack extension, crack closure has already built up completely.

The crack growth rates during these tests depend on the increased stress intensity range due to crack extension on the one hand, and on the increased crack growth threshold due to the build-up of crack closure effects on the other hand. At very small crack extensions, the change in stress intensity range is negligible and crack closure effects build up rapidly, which leads to an immediate decrease of the crack growth rate and to crack arrest. For larger crack extensions, the build-up of crack closure becomes much slower (the resistance curve becomes very flat); under these conditions, the increase in stress intensity range due to crack extension may initially be more pronounced than the increase of the threshold value, which leads to an initial increase in crack growth rate until sufficient crack closure has developed, as in the case \( F_a = 1379 \) N in Fig. 8.

3.2. Experimental results

Since all experiments started with closure free pre-cracks the results show the expected behavior as illustrated in Fig. 7. For short crack extension the crack grows initially at stress intensity factor ranges below the threshold for the stress intensity factor range for long cracks. Due to the build-up of crack closure crack arrest occurs eventually. Fig. 8 shows exemplarily the results for a specimen with an initial notch depth of 5.12 mm tested at a load ratio of \( R = -1 \). In this experiment, crack arrest occurs at four load amplitudes. The crack extensions \( \Delta a \) where the crack stops to propagate and the corresponding \( \Delta K \) provide in this case four points of the resistance curve for the threshold of stress intensity factor range. The asymptotic value (for large \( \Delta a \)) of the resistance curve for \( \Delta K_{th} \) is obtained from the threshold branch of the fatigue crack growth curve. The effective threshold – the starting point of the resistance curve for \( \Delta K_{th} \) – has not been determined at all load ratios and crack lengths, as it is known to be typically about 2.5 MPa m\(^{1/2}\) for ferritic steels.

3.3. Parameter determination

At first, the parameters for the load ratio dependent threshold of long cracks \( \Delta K_{th,L} \) in Eq. (6) are determined. To this purpose, the long crack thresholds \( \Delta K_{th,L} (R) \) are first extracted from the resistance curves recorded at different load ratios \( R \) (Fig. 9) and then plotted against the load ratio \( R \) (Fig. 10). Least-squares fitting of Eq. (6) to the data points in Fig. 10 allows to determine the adjustment parameter \( C_{th} \).

As it is assumed that the build-up of crack closure is similar at different load ratios, the fictitious length scales describing the build-up of crack closure can be estimated for a single resistance curve; in the present case, the resistance curve at \( R = -1 \) is chosen. \( \Delta K_{th,eff} \) and \( \Delta K_{th,lc} \) can be read directly from the resistance curve, cf. Fig. 9. The length scales \( l_1 \) and \( l_2 \) together with the weighting factors \( v_1, v_2 \) are obtained by least-squares fitting of Eq. (7).
Now, the only remaining parameters are the crack growth constant $C$, the Paris exponent $m$, and the fracture toughness $K_c$. $K_c$ is calculated using $J_i$ from an experimentally determined static crack resistance curve [4]. $C$ and $m$ are obtained by least-squares fitting of Eq. (2). The crack velocity factor $F$ is calculated according to

$$
\Delta K < \Delta K_{th, eff} < \Delta K < \Delta K_{th,k}
$$

Fig. 7. Schematic illustration of the loading procedure of a test to determine the $R$-curve for the fatigue crack propagation threshold and the fatigue crack growth curve at a constant load ratio [12].

Fig. 8. Experimental results for a constant load test at $R = -1$ with an initial notch depth of 5.12 mm; crack growth rate and derived points of the cyclic crack resistance curve.

Fig. 9. Crack resistance curves: crack growth threshold $\Delta K_{th}$ vs. crack extension $\Delta a$ for different load ratios $R$ – experimental data points and analytically predicted curves from Eq. (7).

Fig. 10. Load ratio dependent long crack growth threshold – experimental data points and analytically predicted curve from Eq. (6).
Eq. (10) with $F_{lc}$ from Eq. (11), and $D_{K_{th}}$ is calculated according to Eq. (7) with $D_{K_{th,lc}}$ from Eq. (6). Newman’s crack opening function $f$, Eq. (4), is used without any modification. The model parameters determined from the experiment are summarized in Table 1.

3.4. Comparison of experimental results and model predictions

In Fig. 11 the predictions of the proposed analytical crack growth model are shown for a crack starting from a very sharp notch ($\Delta a = 0$ mm) and for a crack after substantial growth ($\Delta a = 10$ mm), which can be seen as the limiting cases of a very short crack (no closure effects) and a crack where closure effects are fully present. This implies for constant amplitude loading and small scale yielding condition that no crack can grow faster than a very short crack (dashed line), and that no crack can grow slower than a long crack (full line) at a given load ratio $R$. It should be noted that the crack growth rate of a very short crack is in the threshold region (branch I) and in the Paris region (branch II) independent from the load ratio $R$; this can also easily be seen if the crack velocity factor $F$ is evaluated for $\Delta a = 0$ (cf. Eq. (10) and Fig. 4b).

The proposed equation permits to describe quite well the $R$ dependence of long cracks and the fatigue crack growth behavior in deep sharp notches (the crack stopping behavior), as shown in Fig. 11 and 12. However, more essential is the description of the propagation behavior from small flaws, as depicted in Fig. 1. The growth of a short crack starting from a notch of depth $a_0 = 0.812$ mm ($R = -1$) is calculated and compared with the measured data. Good agreement between measurement and calculation is observed, cf. Fig. 13. The left limiting curve corresponds to a crack extension $\Delta a = 0$ (short crack behavior), the right to a very large $\Delta a$ (long crack behavior). In the first two load steps the crack slows down and stops (curves 1, 2) due to the build-up of crack closure. Only after a further increase of the load amplitude the crack grows, after an initial slight deceleration, finally through, in the course of which it approaches the behavior of long cracks (curve 3).

The growth of a crack starting from a sharp notch of depth $a_0 \sim 4$ mm ($R = -1$) in the Paris region is also calculated and compared with the measured data (Fig. 14). The calculation inclines to about two times higher crack growth rates. It is supposed that this behavior is due to the much higher constant load in this test, leading to a larger plastic zone and increased plasticity-induced crack closure compared to the tests at stepwise increasing constant load used for model calibration.

4. Conclusions

It has been shown that, by mean of an analytical model for the build-up of crack closure effects with increasing crack extension $\Delta a$, a modified NASGRO crack growth equation can predict the crack growth rate for arbitrary crack lengths. With this model it is possible
to predict fatigue lifetime or necessary inspection intervals more accurately in the context of damage tolerant design and fitness-for-purpose assessments. It will be interesting to show whether the fictitious length scales, which have here been determined by curve fitting, can be related to flow stress and microstructural parameters; these investigations and experiments for load ratios $R < 0.5$ and $R > 0.5$ are currently performed. Still, even without this direct relation to physical length scales, the model has already proven useful for predicting the behavior of short cracks; in this sense, it will be interesting to explore potential conceptual links to the theory of critical distances as introduced by Taylor [13].

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