Stress-state dependent cohesive model for fatigue crack growth

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ABSTRACT. In the cohesive framework, a stress-state dependent cohesive model, combined with an irreversible damage parameter has been used in simulation of fatigue crack growth initiation and continued growth. The model is implemented as interface elements and plane strain simulations of crack initiation and growth under cyclic loading are performed. The stress-state of neighboring continuum elements is used in the traction-separation behavior of the cohesive elements. The model is shown to be able to reproduce the typical initiation life as well as fatigue crack growth curves. Further, the effect of the cohesive fatigue parameter on the initiation life and crack growth rates is established.

KEYWORDS. Cohesive zone model; Fatigue; Triaxiality; Stress state.

INTRODUCTION

P rogressive growth of microstructural damage under sub-critical loads makes fatigue one of the most critical modes of failure. Over the years, diverse approaches have been adopted with the objective of better prediction of fatigue failure. Classical approaches such as Paris law that are based on finding empirical relations between the amplitude of the stress intensity factor and the crack growth rate, firstly, are predictive only for crack growth under very idealized conditions but also lack the ability to predict the initiation life of a fatigue crack near a stress-concentrator. Safe operation and life assessment of ageing components and structures, thus, require not only a better understanding of the factors that influence the initiation and growth of damage under cyclic loading but also development of predictive models that account for these effects.

As an alternative to classical fracture mechanics based characterization of fatigue crack growth, the cohesive zone model (CZM) has been receiving increasing attention for modeling fatigue damage growth ahead of a macroscopic crack [3-5]. More recently, a stress-dependent model that is able to incorporate the dominant role of stress-states in prediction of failure due to fatigue damage has been proposed [2]. In this model, the constitutive behavior of the process zone was described by a stress-state dependent traction-separation law that was combined with an irreversible damage parameter, whose evolution was based on

continuum damage laws requiring two fatigue model parameters. While the model was able to capture the typical features of fatigue failure under uniaxial and proportionate bi-axial loads, the implementation of the model, determination of the model parameters and its validation with experimental data on fatigue crack growth was left as a future task.

In the present work, the stress state dependent model along with an irreversible damage parameter is implemented as cohesive element. A cohesive model for a plane strain modified CT specimen analyzed for fatigue failure is presented for an aluminum alloy material. The mechanical properties and the corresponding cohesive properties for the monotonic nature of the traction separation law are taken from monotonic fracture properties of aluminum. The fatigue crack growth predictions of the model for different fatigue parameters are presented. The effect of the cohesive fatigue parameters on crack growth curves is established.

STRESS-STATE DEPENDENT COHESIVE MODEL FOR FATIGUE

In the present work, the simulation of fatigue crack initiation in a modified compact test specimen and its continued growth is based on the fatigue cohesive model proposed by Jha and Banerjee [2]. The model assumes that the damage mechanisms that lead to failure are localized in a thin layer (process zone). The constitutive behavior of this thin layer is represented by a triaxiality dependent cohesive law that is updated with an irreversible damage parameter to account for the progressive cyclic damage. The triaxiality dependent relation between the traction, T_n, and the normalized separation, $\widehat{\delta_n}$, are taken to have three distinct expressions to represent linear, hardening and softening behavior for increasing separation between the bounding surfaces as:

$$
\begin{aligned}
T_{n,o} &= (1+\sqrt{3}\,H_{eff})\left(\frac{2E}{3}\right)\widehat{\delta_n} & 0 < \widehat{\delta_n} \leq \widehat{\delta_{n1}} \\[2ex]
&= (1+\sqrt{3}\,H_{eff})\,\frac{\sigma_y}{\sqrt{3}}\left(\frac{2E}{\sqrt{3}\sigma_y}\widehat{\delta_n}\right)^n & \widehat{\delta_{n1}} \leq \widehat{\delta_n} \leq \widehat{\delta_{n2}} \\[2ex]
&= \sigma_{max}\,exp\left(-0.01\left(\frac{\widehat{\delta_n}-\widehat{\delta_{n2}}}{\widehat{\delta_{n2}}}\right)^4\right) & \widehat{\delta_{n2}} \leq \widehat{\delta_n} \leq 10\widehat{\delta_{n2}}
\end{aligned}
$$

where $\widehat{\delta_{n1}} = \dfrac{\sqrt{3}\sigma_y}{2E}$ and $\widehat{\delta_{n2}} = \dfrac{\sqrt{3}}{2}\left(Ce^{-1.5H_{eff}}+\dfrac{\sigma_y}{E}\right)$. Here, H_{eff} is an effective triaxiality parameter defined to incorporate the effects of triaxiality [7], and C and S are model parameters that are used to define upper and lower bounds on the equivalent plastic strain required for failure during monotonic fracture respectively.

To incorporate the accumulation of incremental damage due to cyclic loading, a damage evolution law proposed by Roe and Siegmund [1] was used. The accumulation of damage parameter was taken to start once a deformation measure, accumulated separation ($\overline{\Delta_n}$), is greater than a critical magnitude (δ_o), which is implemented through Heaviside function. The accumulated separation is calculated by $\overline{\Delta_n} = \int\left|\dot{\delta_n}\right|dt$ and the critical magnitude (δ_o) is the separation at maximum stress (σ_{max}). The increment of damage is related to the increment of deformation weighted by the current load level while the incremental deformation is normalized by accumulated cohesive length (δ_Σ). Also, the model assumes that there exists an endurance limit, σ_F, which is a stress level below which cyclic loading can proceed infinitely without failure. The evolution equation for the damage parameter is taken to be:

$$
\dot{D_c} = \frac{|\dot{\delta_n}|}{\delta_\Sigma}\left[\frac{T_n}{\sigma_{max}}-\frac{\sigma_F}{\sigma_{max,o}}\right]H\left(\frac{\overline{\Delta_n}}{\delta_o}-1\right)
$$

Cohesive endurance limit, σ_F and accumulated cohesive length, δ_Σ are two fatigue parameters of this model. σ_{max} is the current maximum stress that can be taken by the process zone after the onset of damage accumulation. It is calculated by $\sigma_{max} = \sigma_{max,o}(1-D_c)$. Then the damage is translated as the degradation of the process zone by updating its constitutive

behavior. The current traction is calculated by $T_n = T_{n,o}(1 - D_c)$. Here it is assumed that, the tangential separation is less significant when compared to normal separation, therefore the contribution of shear traction on damage is ignored in the proposed model.

A description of the cohesive zone behavior under unloading and reloading is provided by a linear function similar to the linear part of TSL, modified to retain opening displacement continuity and use the current elastic modulus as:

$$T_n(t + \Delta t) = T_n(t) + \left(1 + \sqrt{3}H_{eff}\right)\frac{2E}{3}(1 - D_c)\left(\widehat{\delta}_n(t + \Delta t) - (\widehat{\delta}_n(t))\right)$$

During unloading, to avoid interpenetration of cohesive surfaces, which is physically unrealistic, higher stiffness is incorporated for negative normal separation. In the present model, the frictional interactions have been ignored.

The cohesive model is implemented as a user-element through a user-subroutine (UEL) in ABAQUS V6.10. The cohesive element formulation as per Gao and Bower [6] is modified to include the stress-state dependence, fatigue damage evolution and criteria for failure of a cohesive element representing crack growth.

The damage in every increment is calculated according to the evolution equation depending on the incremental separation. The damage calculated in every increment over one cycle is accumulated using an additional damage variable (DD). To avoid longer computational times, it is assumed that the damage accumulated in each cycle is similar valued to next (n-1) cycles, where 'n' is a chosen number of cycles that is significantly smaller than the number of cycles taken from initiation of crack to final failure. As a consequence, after every i^{th} cycle the damage is updated to be $D_c = D_c^{i-1} + n * DD$ and the total number of cycles, $N = N^{i-1} + n$.

Failure of cohesive element is taken to occur under two conditions. The first condition is based on traction, where if the traction of cohesive element is less than a specified low value of traction. The second condition is based on the accumulated damage, when the damage accumulated within a cohesive element reaches a threshold value the element is considered to have failed.
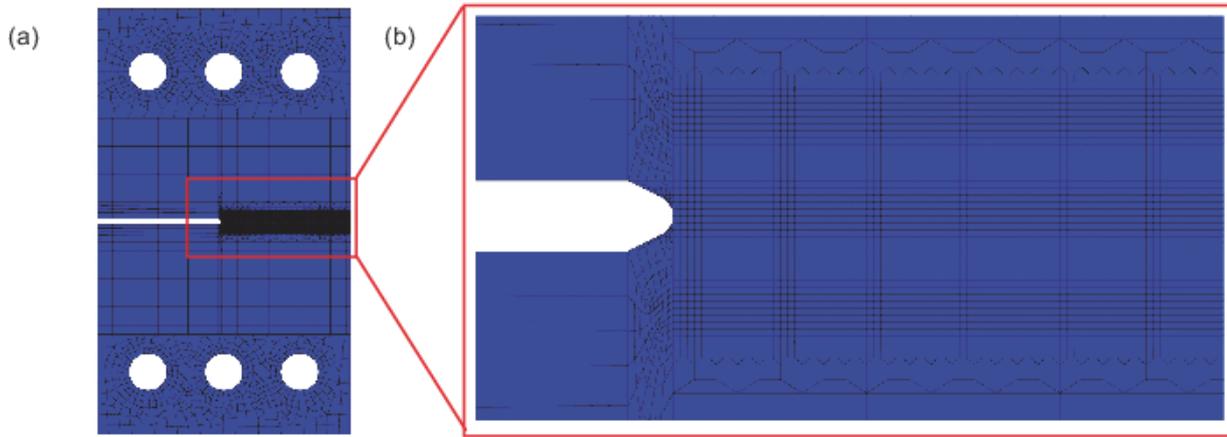

Figure 1: (a) FEM model (b) Mesh around the crack tip.

A modified compact tension (CT) specimen geometry with a width, W =74 mm and thickness, B =22 mm is used for analysis as shown in Fig. 1. A plain strain finite element mesh based on the specimen geometry was created and the cohesive elements are inserted along the process zone. The elastic-plastic mechanical properties used in this investigation are that of Aluminum alloy (E=70000 MPa, ν=0.33) and the model parameters are taken as, S=4.32 and C=0.432 as per Faizan and Banerjee [9]. Mode-1 fatigue loading with an amplitude range of 1-8 KN is applied on the plain strain FEM model. Fatigue crack growth curve predictions of the model were generated for different model parameters.

A crack growth curve prediction of the model with parameters σ_F =0.25, δ_Σ =10, Δ_{th} = 1 is shown in Fig. 2 (a) and the corresponding damage evolution of the first five elements ahead of the crack tip is shown in Fig. 2 (b). It is observed that the element 3 attains the threshold damage (D=0.002) first followed by element 2 and then element 1, which eventually leads to the crack propagation causing the further elements to fail in the similar manner. The stress field ahead of the crack tip is shown in Fig. 3. The plastic wakes forming locally along the crack path is shown in Fig. 4. The formation of

these regions could be correlated with the instabilities observed in the crack growth curves as the regions with localized plastic strains in the wake correspond to the cycles that have low crack growth rate while the cycles having fast crack growth rate resulted in virtually no plastic strain in the wake.
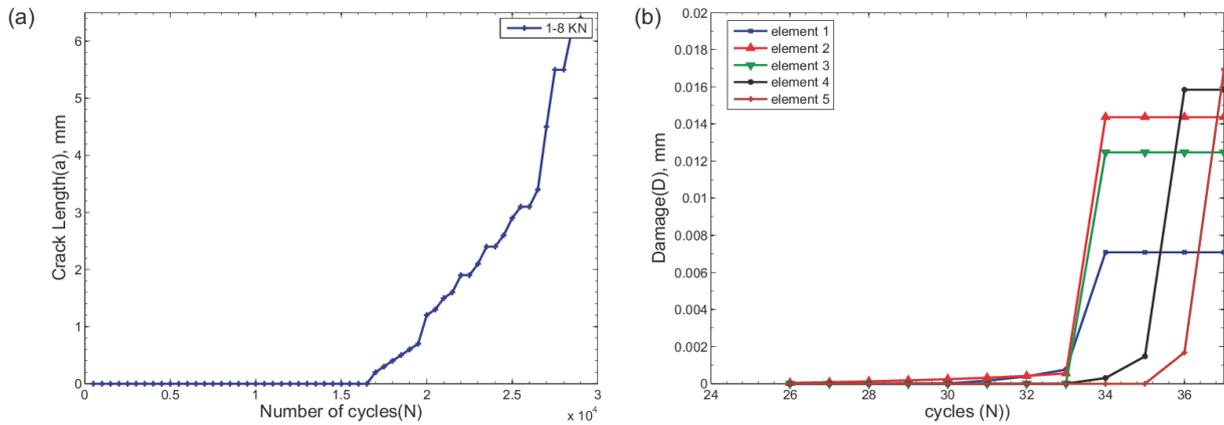

Figure 2: a) Fatigue crack growth curve (1-8 KN) b) Damage evolution in the elements ahead of crack tip.
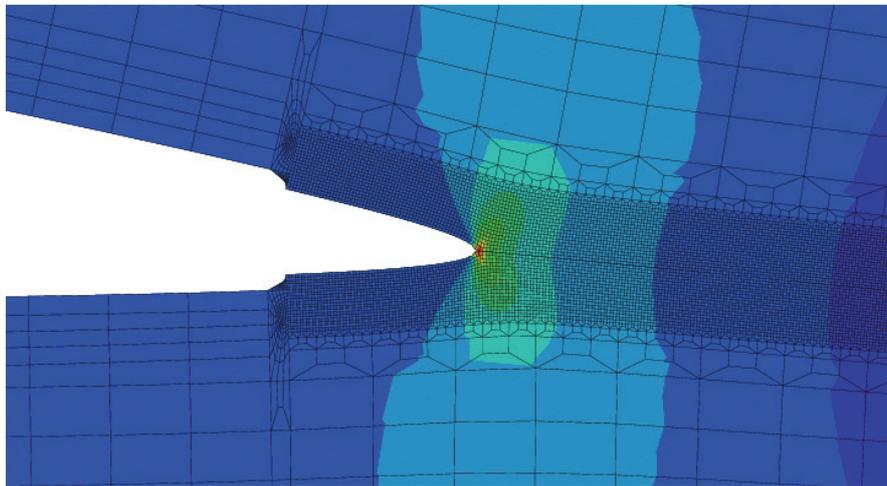

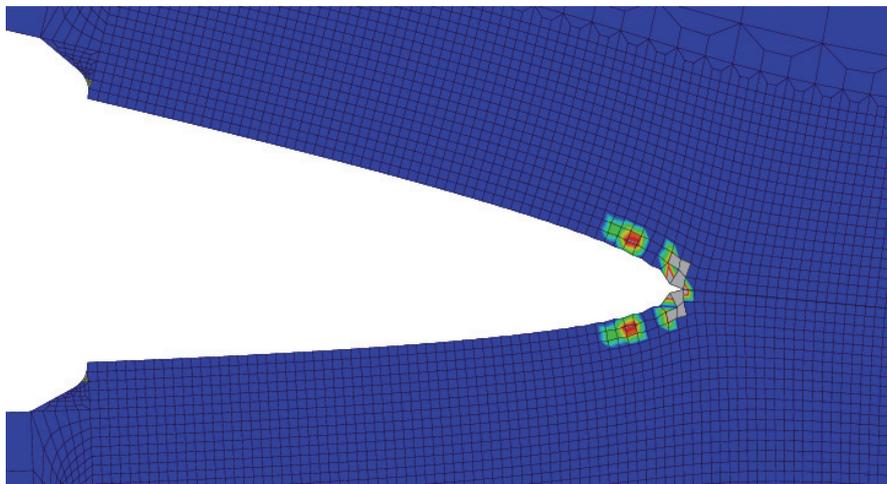Figure 3: Stress contour (σ_{yy}) ahead of the crack tip.

Figure 4: Contour of equivalent plastic strain.

RESULTS AND DISCUSSION

A parametric study was carried out to establish the effect of stress state on crack growth kinetics and determine the effect of model parameters on FCG curves. The effect of the parameters cohesive length (δ_Σ), threshold (Δ_{th}) and cohesive endurance limit (σ_F) are discussed in detail in this section.

The effect of cohesive length (δΣ) parameter on the crack growth curve

The effect of the cohesive length parameter, δ_Σ, in the model is established by keeping the other parameters cohesive endurance limit (σ_F) and threshold (Δ_{th}), constant for the cohesive length ranging between $2\delta_{n2}$ and $20\delta_{n2}$.
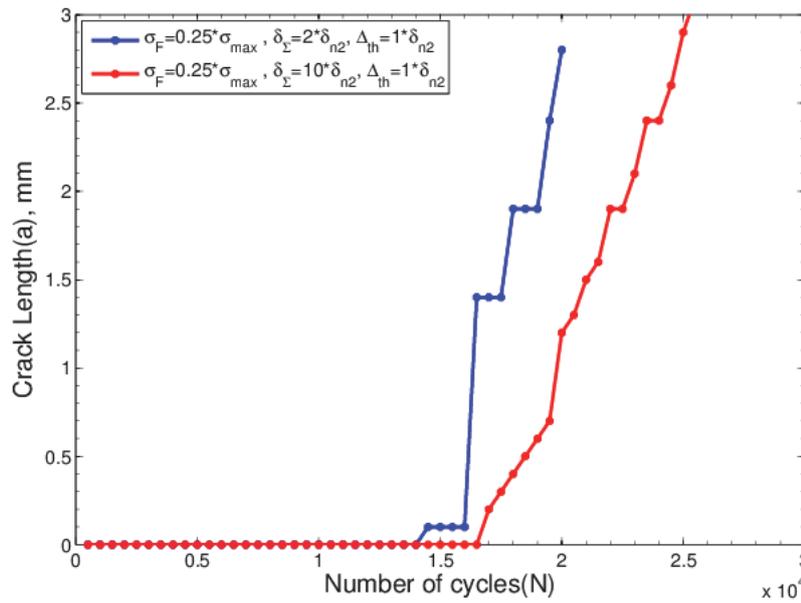

Figure 5: Effect of cohesive length (δΣ) parameter on the fatigue crack growth curve.

In the crack growth curves, as seen in Fig. 5 for the chosen set of parameters, with increasing cohesive length, the accumulation of damage is slower and thus the initiation of crack as well as the rate of crack growth is comparatively slower.

The effect of threshold parameter (Δth) parameter on the crack growth curve

The effect of the threshold parameter, Δ_{th}, in the model is seen by keeping the parameters cohesive endurance limit (σ_F) and cohesive length (δ_Σ) constant and varying the threshold (Δ_{th}). In Fig. 6, it is observed that threshold (Δ_{th}) has a strong influence on the crack initiation, for Δ_{th} = (1.25δ_{n2}) the crack initiation is delayed by almost 4000 cycles when compared to Δ_{th} = (1.0δ_{n2}). The effect of the threshold parameter on the rate of crack growth, however, is comparatively less significant.

The effect of cohesive endurance limit (σF) parameter on the crack growth curve

The effect of the cohesive endurance limit parameter, σ_F, in the model is established by keeping the other parameters cohesive length (δ_Σ) and threshold (Δ_{th}) constant and varying the cohesive endurance limit values.

As shown in Fig. 7, it is observed that cohesive endurance limit (σ_F) shows significant influence on the crack initiation. As the cohesive endurance limit is increased, there is a delay in crack initiation. It also shows a significant effect on the crack growth rate. As observed, lower the cohesive endurance limit faster is the crack growth rate.
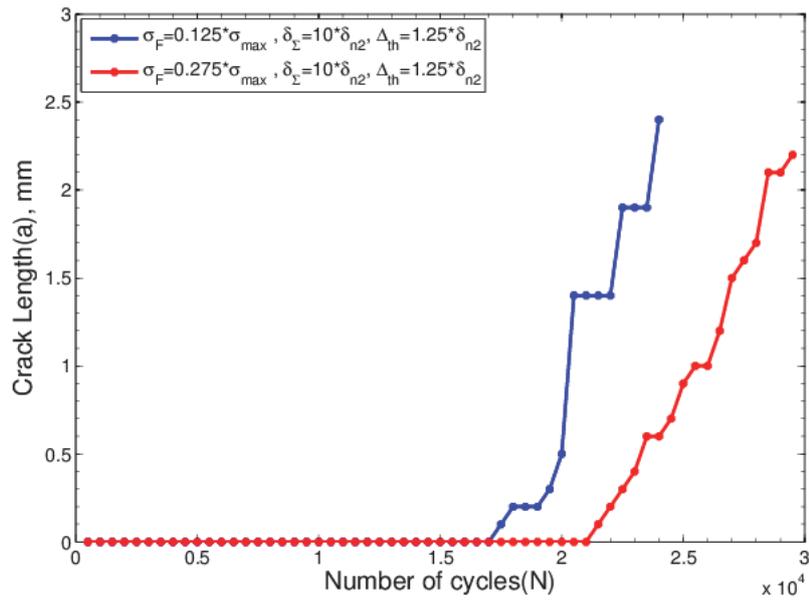
Figure 6: Effect of threshold (Δ_{th}) parameter on the fatigue crack growth curve.
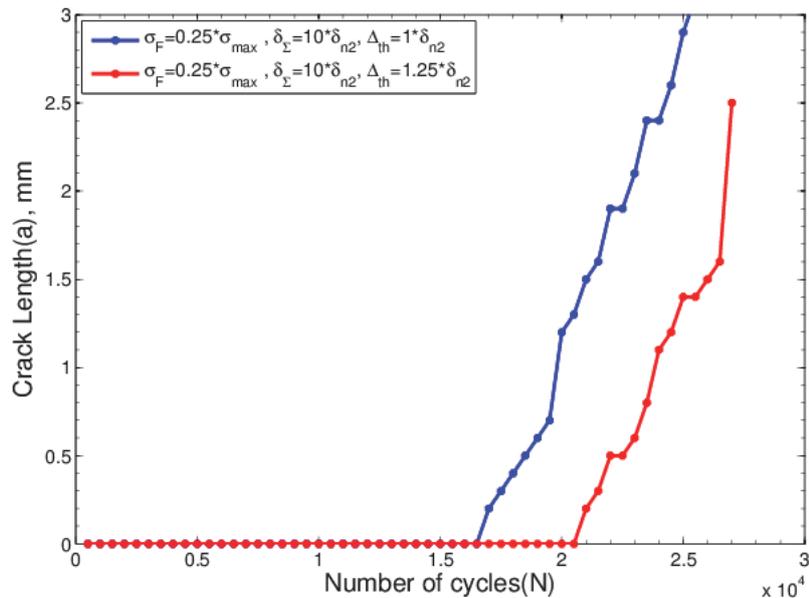

Figure 7: Effect of cohesive endurance limit (σ_F) parameter on the fatigue crack growth curve.

CONCLUDING REMARKS

A stress-state dependent cohesive model for fatigue is used in simulation of fatigue crack initiation and growth in a representative aluminum alloy. The model was shown to be capable of predicting both initiation and propagation reasonably well compared to as observed in the experiments [8]. From the parametric study it is observed that increase in the parameter, cohesive endurance strength (σ_F), is causing a delay in the crack initiation with significantly lower crack growth rates. A similar effect of the parameter,

threshold (Δ_{th}), is observed where higher the threshold value, more the delay in the crack initiation. However the effect of threshold parameter on crack growth rates is negligible. The parameter accumulated cohesive length (δ_Σ) with increase in its value exhibits slower crack growth rate and delay in the initiation of the fatigue crack.

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