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Cohesive zone model simulation of fatigue debonding along interfaces

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Abstract

In this work a cohesive zone model is developed to simulate fatigue crack propagation along bonded interfaces. The model is implemented by means of the USDFLD subroutine in the commercial software Abaqus. In particular, the crack growth increment is translated into a damage increment per cycle in the cohesive elements ahead of the crack tip. The computation of the strain energy release rate, not available in output for cohesive elements in Abaqus, was specifically implemented.

Keywords: Cohesive zone modelling, Fatigue crack growth, Finite element analysis, Bonded interfaces

1. Introduction

The design of advanced lightweight composite structures in the aeronautical, wind power generation, automotive or nautical fields for example, poses the problem of ensuring long-term lasting strength of materials and connections. In composite structures, the connections are made mainly by adhesive bonding and also the material itself may present bonded interfaces, such as in the case of a composite laminate.

Nomenclature

A	crack area
A_d	damaged area produced by voids or cracks within a Representative Interface Element (RIE)
A_e	area of a Representative Interface Element (RIE)

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A_{CZ}	total section area of cohesive elements where D > 0
B	fatigue crack growth rate coefficient
D	damage
MM	mixed mode ratio equal to $G_{II}/(G_I + G_{II})$
d	fatigue crack growth rate exponent
n_{CZ}	number of IPs lying within A_{CZ}
ΔD_{max}	user-defined value of damage increment

A numerical method able to reproduce the fatigue debonding evolution in a composite structures is therefore attractive to improve their performance. In order to do this, a relationship between the loading state of the component and the fatigue crack growth (FCG) rate of a defect is necessary. This relationship was given by Paris [1] in terms of crack growth rate as a function of the stress intensity factor, K. In the case of composites and adhesive joints it is traditionally written as a function of the range of applied strain energy release rate (ΔG) using the equation

$$\frac{dA}{dN} = B(\Delta G)^d \tag{1}$$

This method allows to predict the growth of a defect under fatigue loading provided that, in the case of complex real geometries, the strain energy release rate be computed numerically with the help of, for example, Finite Element (FE) simulation. The prediction of crack growth can be carried out by dividing the analysis in steps, each corresponding to user-defined crack growth increments. In the case of 3D simulations, a criterion to determine the crack propagation step is required since it is in general non-uniform along the crack front.

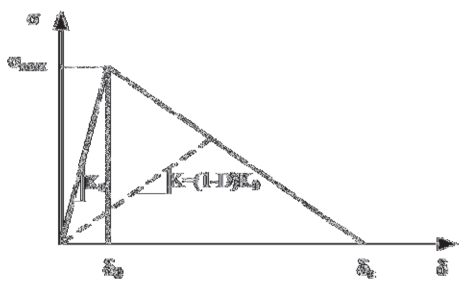


Fig. 1. Example of a triangular cohesive law.

On the other hand, the cohesive zone model of interfacial behavior (Fig. 1) is extensively used for the prediction of fracture propagation under quasi-static conditions, especially in the case of bonded joints and delamination in composites [2,3]. It consists simply of a relationship between the normal/tangential stress and opening/sliding of crack faces over a region ahead of the crack tip, where D is a state variable representing damage.

In the literature, a certain number of works can be found dealing with the simulation of the fatigue crack propagation using the cohesive zone model [4-8]. In order to take into account for the damage due to the fatigue, damage is made dependent also by the number of cycles. For example Maiti and Geubelle

[6] defined a relationship between the stiffness and the number of cycles in terms of a two-parameters power law. Roe and Siegmund [5] instead, simulated the crack growth at an interface, using a cycle by cycle simulation where damage is incremented according to the stress level reached in the previous cycle. In both cases, model parameters have always to be identified by comparison of FCG simulation and experiments, bringing with limitations on the transferability to cases different from those on which identification was made. In Turon et al. [4] instead, the cohesive law identified from quasi-static fracture tests is used while a relationship between damage evolution and macroscopic crack growth rate is established which needs only the coefficients of the Paris law of FCG tests. However, this model was implemented only in the case of geometries where the strain energy release rate could be computed analytically and was not dependent on the crack length.

This work starts from the framework presented by Turon et al. [4], but it is extended for any 2D geometry. Moreover, mixed mode criteria were introduced respectively for the cohesive zone in terms of traction-separation law and for the fatigue crack growth rate proposed respectively by Kenane and Benzegaggh [9], Curley [10], Quaresimin [11] and Abdel Wahab et al. [12].

2. Theory

According to Continuum Damage Mechanics [13], the damage D can be written as

$$D = \frac{A_d}{A_e} \tag{2}$$

In a FE simulation of the adhesive layer using cohesive elements, A_e is the area associated with an integration point (IP), i, of these elements. As shown in [4], an increment of the crack extension (dA) can be written as the sum of the increments dA_d^i of all the IPs lying in the cohesive zone A_{CZ}, yielding

$$dA = \sum_{i \in A_{CZ}} dA_d^i \tag{3}$$

therefore, the increment of the crack area with the number of cycle can be written as

$$\frac{dA}{dN} = \sum_{i \in A_{CZ}} \frac{dA_d^i}{dN} = n_{CZ} \frac{dA_d}{dN} = \frac{A_{CZ}}{A_e} \frac{dA_d}{dN} \tag{4}$$

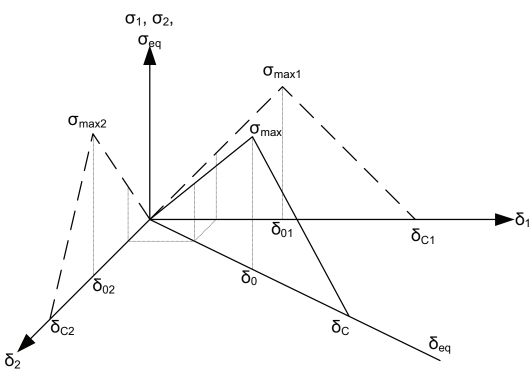


Fig. 2. Representation of the mixed mode cohesive law.

Using Eqns. 1 and 4 the increment of damage with the number of cycles becomes:

$$\frac{dD}{dN}=\frac{dD}{dA_d}\frac{dA_d}{dN}=\frac{1}{A_e}\frac{dA}{dN}\frac{A_e}{A_{CZ}}=\frac{1}{A_{CZ}}\frac{dA}{dN}=\frac{1}{A_{CZ}}B\Delta G^d \tag{5}$$

Mixed mode I/II conditions require the definition of a mixed mode cohesive law, Fig. 2, and it is necessary also to define a mixed mode FCG law. Concerning the cohesive law, the approach of Kenane and Benzeggagh [14] has been considered, while different mixed mode FCG laws were implemented in the model: Curley et al [10], Kenane and Benzeggagh [9], Quaresimin [11], Abdel Wahab et al [12]

3. Finite element implementation

The theory described previously is implemented into the commercial software Abaqus, using external routines interacting with the analysis solver. The analysis is divided in increments and each increment is assigned a number of cycles using the algorithm shown in Fig. 3.

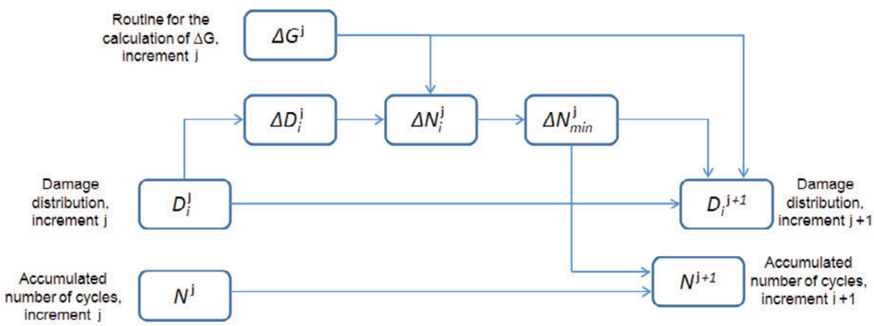


Fig. 3. Schematic representation of the algorithm used for the crack growth simulation.

At a generic increment (j), the elapsed number of cycles is N^j, and the damage at the i-th IP is D_i^j. An increment of the damage ΔD_i^j is then assigned to every IP in the cohesive zone as:

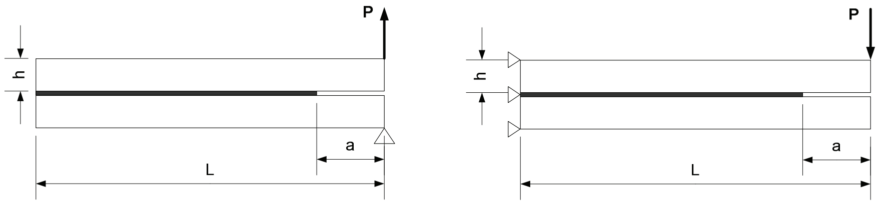
$$\begin{aligned}
&\Delta D_i^j=\Delta D_{\max} && \text{if } 1 - D_i^j > \Delta D_{\max}\\
&\Delta D_i^j=1-D_i^j && \text{if } 1 - D_i^j < \Delta D_{\max}
\end{aligned} \tag{6}$$

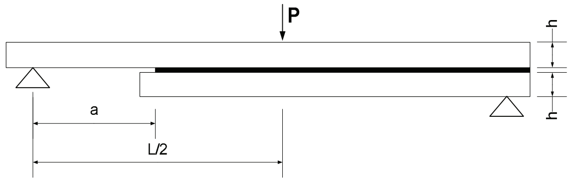
In the same increment, the subroutine calculates ΔG^j as the contour integral over a path surrounding the cohesive zone (in Abaqus the contour integral is not available for cohesive elements). A number of cycle ΔN_i^j is then computed for each IP using Eqn. 5 with ΔD^j and ΔG^j. The routine looks for the minimum among the ΔN_i^j of the IPs within the cohesive zone, ΔN^j_{min}, which is then set to be the number of cycle of the increment. Finally, the number of cycle and the damage distribution are updated.

4. Validation of the finite element implementation

In order to verify the accuracy and the robustness of the model, different joint geometries characterized by different mixed mode ratios were simulated. In particular, pure mode I condition are simulated with a Double Cantilever Beam (DCB) geometry, pure mode II conditions with an End Loaded Split (ELS) geometry and mixed mode I/II conditions with a Mixed Mode End Notched Flexure (MMENF) geometry as shown in Fig. 4. The adherends material is supposed to be aluminium with a

Young modulus equal to 70'000MPa and a Poisson's ratio equal to 0.3. The material parameters are taken from literature [4], for both the mixed mode cohesive law and FCG rate.





	DCB	ELS	MMENF
P [N/mm]	20	20	25
a [mm]	60	92	17
h [mm]	10	10	5
L [mm]	335	335	130

Fig. 4. Simulated geometries: DCB, ELS and MMENF.

The results of the simulations are compared with the analytical trends of FCG rate in case of DCB (MM=0), ELS (MM=1) and MMENF (MM=0.4) joints. The comparison is shown in Fig. 5 for the three geometries only in the case of the Kenane and Benzeggagh mixed mode FCG model, since the comparison worked in the same way with the other models implemented in the routine.

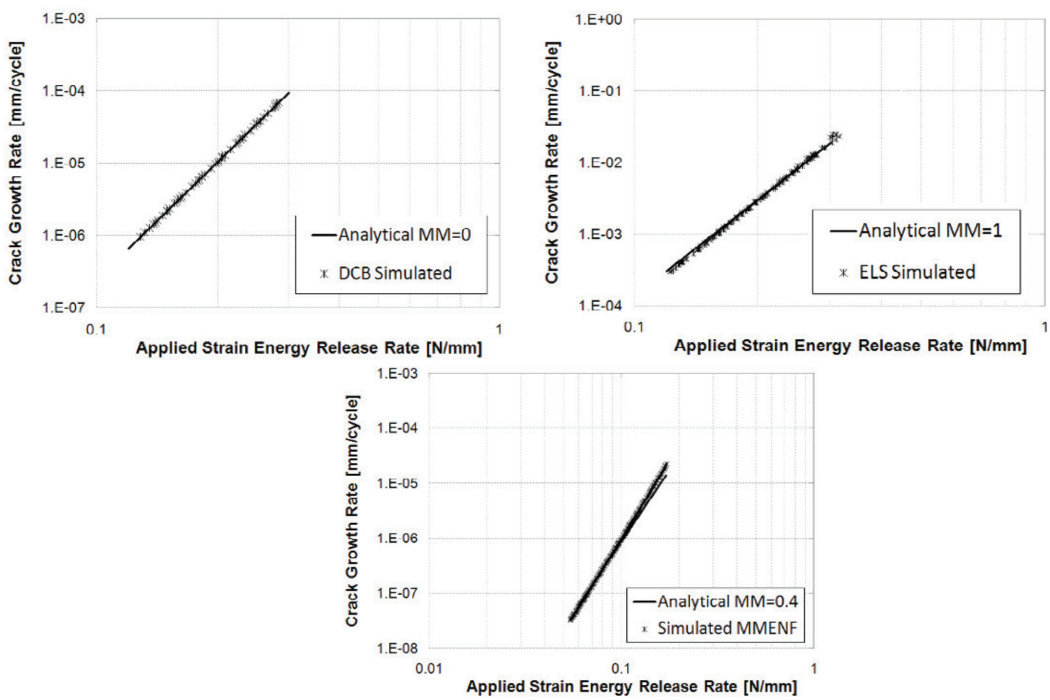


Fig. 5. Comparison between analytical and simulated trend in the case of DCB, ELS and MMENF geometries.

Under pure mode I or pure mode II the two sets of data are in very good agreement with each other over the entire range considered. For the mixed mode I/II condition instead, the simulation seems to overestimate slightly the reference trend. This occurs because the reference trend considers a constant mixed mode ratio over the entire range, while during the propagation, when the crack approaches the midpoint, the value of MM slightly increases, and this variation is captured by the simulation.

5. Conclusions

A procedure based on the cohesive zone model has been developed in this work for the simulation of fatigue crack growth at interfaces under different mixed mode I/II loading. It is completely automated, i.e. the fatigue crack propagation simulation is performed in a unique run. The procedure has been validated by comparison with analytical trends for different mixed mode conditions and mixed mode FCG models, giving very good results. Further enhancement will concern the extension of the procedure to 3D models.

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