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FATIGUE LIFE OF A SINGLE LAP JOINT WITH AND WITHOUT SPECIAL EVENTS

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Abstract

The development of fatigue-resistant adhesive joints and adjacent parts remains challenging, particularly when simulating crack propagation under fatigue loading. Commercial software packages, such as ABQUS, include cohesive zone elements; however, they usually require user-defined subroutines for fatigue applications. This study combines multiple subroutines to predict the crack path across multiple lamina layers originating from a pre-crack. The interlaminar/adhesive subroutine employs a user-defined material model to assess cohesive stress and damage in the joint [1]. Additionally, a second user-defined subroutine developed at HAW Hamburg was used for intralaminar damage. Both subroutines were incorporated into the FEM software ABAQUS to enable information exchange between material models [2]. This allows the initiation of delamination from the matrix damage, in addition to a crack propagating through the lamina. The evaluation was conducted on a specimen measuring 100 mm × 150 mm, including a single-lap bonded joint. The specimens were subjected to cyclic tension at an R ratio of 0.1. For the impact assessment, a custom mapper developed by Wölfel was used to map the initial damage based on separate impact simulation results, enabling a distinct analysis method for fatigue. Using this method, a validated tool for predicting the fatigue life of a bonded joint was presented.

1. Introduction

To maximize the lightweight potential of carbon fiber reinforced plastics (CFRP), joints between parts can be bonded purely with adhesive, saving the weight of mechanical fasteners. To remove the mechanical fasteners, which also act as a crack-stopping feature in adhesively bonded joints, the fatigue behavior needs to be understood, analyzed, and be predictable.

Therefore, the objective of the research Project JoinDT is to develop a simulation methodology that enables damage-tolerant design of bonded CFRP joints in aerospace applications. The simulation of crack propagation in adhesive joints and adjacent parts is one part of achieving this predictability and is the focus of this particular work. Cohesive zone models are widely used to model delamination under cyclic and quasistatic loading. Various researchers have proposed constitutive models for high-cycle fatigue that integrate damage and fracture mechanics to describe the evolution of a damage variable. These models use the cohesive zone element to extract the strain energy release rate (ΔG), and the Paris law curve to determine the corresponding crack growth rate. Consequently, all the elements within the cohesive zone ahead of the crack tip are degrading. To satisfy the requirements of the global Paris Law, calculating the local damage rate for each Integration Point (IP) dictates the determination of the cohesive zone length ahead of the crack tip. Which, in turn, depends on the loading conditions and geometry. Kawashita et al. [1] proposed degrading only IP's that belong to the crack tip. Sachse et al.

[2, 3] developed this approach further to incorporate irregular meshes and adaptively determine the numerical fatigue frequencies.

This paper addresses the implementation of the fatigue damage formulation by Sachse [4] for adhesives as well as delamination growth in adhesively bonded joints and combines it with an intralaminar damage model developed at HAW Hamburg. Using a stacked approach for the composite allows the crack to jump between the different delamination layers. To achieve this, a previously published communication approach between user subroutines is used [5]. With this a bonded specimen, previously impacted, will be analyzed.

2. Simulation Method

For the delamination and cohesive crack growth simulations, a constitutive model for an 8-node three-dimensional cohesive zone element (CZE) was used. Detailed accounts of the simulation methods can be found in [6] and [7]. The model was implemented in a user-defined material subroutine for explicit time integration in the commercial software ABAQUS. It utilizes the standard cohesive zone approach for quasi-static loading and extends the model to account for damage caused by fatigue loading.

2.1 Constitutive Model for quasi-static loading

The Cohesive Zone Model (CZM) is widely used to simulate interfacial fractures under quasi-static loading. It summarizes the evolution of microcrack damage behind the crack tip in a damage variable that dictates the loss of cohesive stiffness.

Implemented in the Model is a tri-linear traction separation law, as shown in Figure 1 (left) which is implemented to correctly represent the ductile behavior of the adhesive, for the more brittle behavior of the matrix a bilinear traction separation law was sufficient.

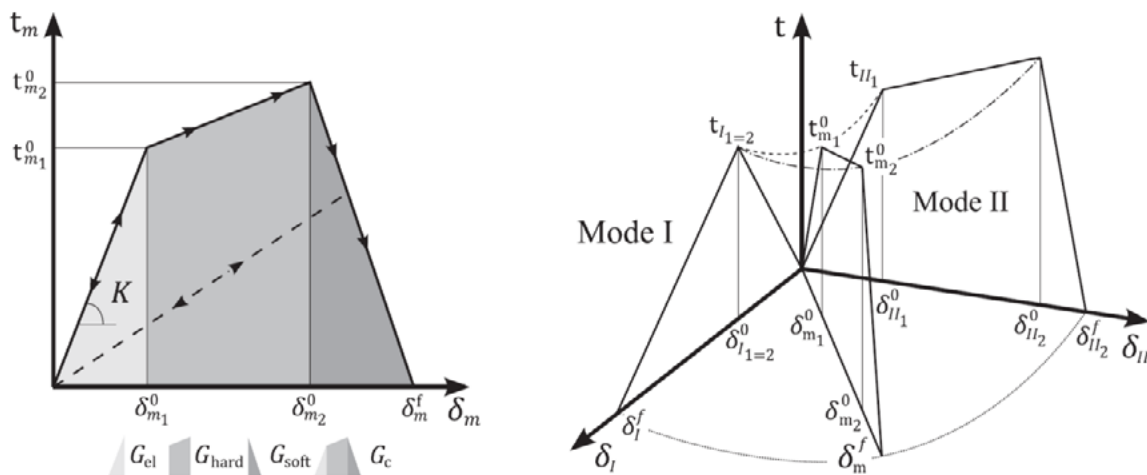


Figure 1: Mixed mode cohesive law (left) and composition from mode I and mode II loading (right) for static loading. from Sachse et al. [5]

Mixed-mode dependencies are implemented using the B-K type fitting functions for mixed-mode loading. The material parameters for the pure modes as well as the fitting parameters are determined experimentally.

2.2 Constitutive model for high-cycle fatigue damage

The fatigue model follows the approach of several other authors [8, 9, 10] and utilizes a load envelope approach to describe the individual cycles of fatigue loading. In the first loading step, the maximum amplitude load is applied quasi-statically. In the second step, the maximum load is held constant, and the fatigue model is activated. Figure 2 (left) compares the actual load curve to the load envelope representation. The total damage accumulation \dot{D}_{total} in the cohesive zone element corresponds to the sum of the quasi-static damage \dot{D}_{static} and the fatigue damage contribution $\dot{D}_{fatigue}$ [8]. The strain energy release rate amplitude is calculated from the instantaneous value of the strain energy release rate G_{max}^{inst} corresponding to the maximum applied fatigue load using the R-ratio from a fatigue test [11]:

$$\Delta G = (1 - R)^2 G_{max}^{inst} \quad (1)$$

Thus, the crack growth rate, da/dN can be determined using the Paris law curve derived from the experiments.

$$da/dN = C_1 \Delta G^{C_2} \quad (2)$$

With crack length a , the number of loading cycles N , and the Paris law constants C_1 and C_2 . The model is therefore limited to the region in which Paris' Law is constant; this region is depicted as region II in Figure 2 (right).

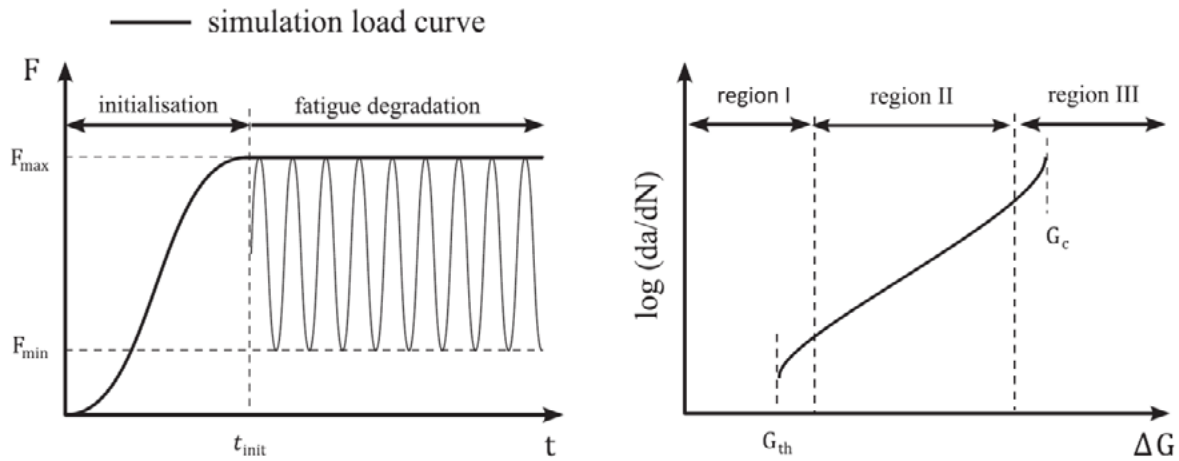


Figure 2: Comparison of numerical and experimental load curve (left) and Paris law curve (right) from [6]

To continuously describe the mixed-mode ratio dependent Paris Law, a dependency on the loading mode similar to the critical energy release rate G_c is introduced [12].

$$C_{i_m} = C_{i_l} + (C_{i_{II}} - C_{i_l}) MMR^{\eta_{c_i}}; i = 1, 2 \quad (3)$$

Where C_{i_l} and $C_{i_{II}}$ represent the Paris Law constants for pure mode loading, and η_{c_i} are curve-fitting parameters. Based on the mixed-mode crack growth rate da/dN , the equivalent fatigue damage accumulation is calculated, as described in [6].

$$D_{fatigue}^t = D_{fatigue}^{t-1} + \frac{dD_{fatigue}}{dN} f_{num} \Delta t \quad (4)$$

Where indication t is the current time step and f_{num} is defined as:

$$f_{num} = \frac{dN}{dt} \quad (5)$$

2.3 Crack tip monitoring

The crack tip front to which the fatigue damage is applied is continually monitored with flags in a global array to update its position. A neighborhood interaction was defined prior to the simulation with a Python script, including all IPs with which the IP shares a common edge.

For the layer-wise simulation of the composite material, this array is used by two user materials to allow for a crack growth in the thickness direction through intralaminar matrix cracking. This communication method has been described in more detail by Rose et al. [5].

2.4 Intralaminar material Model

To enable crack growth in the intralaminar regions of the individual ply's a 3-Dimensional Hashin Failure criterion was implemented. In the field of carbon fiber-reinforced plastics (CFRP), Hashin is a widely used failure criterion that has already been implemented in a 2D formulation in ABAQUS [3, 13]. The damage effect was considered by reducing the stiffness coefficients, as introduced by Kachanov [14]. The calculation of the damage variables for the individual forms of damage was based on Matzenmiller et al. [15] and adapted it in [3]. The relationship between effective stress $\hat{\sigma}$ and nominal stress σ is defined as follows: $\hat{\sigma} = M \sigma$. M is the so-called damage operator and has a diagonal form. The damage state is represented by damage variables d_i ($i = 1, \dots, 6$). Fiber damage is described by d_1 ; d_2 is associated with matrix damage in the plane, and d_3 is associated with matrix damage in the laminate thickness direction [16]. According to Pham et al. [16] it is assumed that the damage variables for shear, d_4, d_5 and d_6 are not independent, which is also supported by [3]. The three-dimensional stress space implementation for damage initiation aligns with the approach described in [16]. The parameters X_t and X_c denote the tensile and compressive strengths in the fiber direction, respectively, and Y_t and Y_c represent the matrix tensile and compressive strengths, respectively. S_{12}, S_{23} and S_{13} represent the in-plane and out-of-plane shear strength, respectively. The implementation used here is based on the method used in [16] with the use of a locally rotated coordinate system. The basis for this is Kachanov's approach [14].

In order to be able to represent the mechanical properties changing due to the damage, caused by static and fatigue loads to the material in the simulation, the stiffness properties are degraded. The degradation process is characterized by energy dissipation. A linear "softening law" (traction separation law) is used. The crack-band approach was adapted to minimize the mesh dependency of crack propagation. The element-specific characteristic length (LC) is introduced for this purpose. Based on the assumption that the dissipated energy of a fully failed element corresponds to the damage-mode-specific critical strain energy release rate G_i , the damage-mode-specific crack propagation can be described by the following equation:

$$\int \sigma_{eq}^i d(\epsilon_{eq}^i L_c) = G_i \quad (i = Ft, Fc, Mt, Mc) \tag{6}$$

where σ_{eq}^i is the equivalent stress and ϵ_{eq}^i is the equivalent strain of the respective damage mode ($i=Ft, Fc, Mt, Mc$). Figure 3 shows a representative softening law and coordinate system for the crack surface definition.

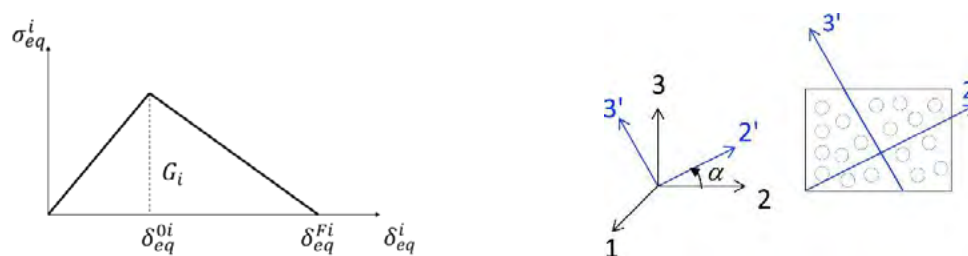


Figure 3: Softening law for each failure mode (left) and Principle stress coordinate system with the crack surface definition (right). [16]

where δ_{eq}^{0i} is the mode-specific displacement at damage initiation and δ_{eq}^{Fi} is the displacement at the total failure of the element. The mode-specific damage d_i for fiber tension (Ft), fiber compression (Fc), matrix tension (Mt), and matrix compression (Mc) were then implemented according to [16]. For crack propagation and the underlying communication for both user materials, the variables for matrix damage, MT, and MC are the most critical.

3. Material properties

The Specimens were composed of IM7-8552 prepreg material for the laminate bonded with EA9695 as the structural adhesive. The material properties used in this study were in accordance with those used [17] for intralaminar material modelling. The material properties of EA9695 were obtained from [17]. The Material values for Paris Law derived from the DCB, ENF, and CLS specimens following the method described in [4] and are given in Table 1 and Table 2.

Table 1. material properties for fatigue crack growth EA9695

C_{1I}	C_{1II}	C_{2I}	C_{2II}	η_{C_1}	η_{C_2}
-	-	-	-	-	-
2.67e+06	11.18	0.1405	3.929	4.01e-06	0.060

Table 2. material properties for fatigue crack growth IM7/8552

C_{1I}	C_{1II}	C_{2I}	C_{2II}	η_{C_1}	η_{C_2}
-	-	-	-	-	-
2.600	6.438	0.00695	2.262	0.122	0.479

4. Model description

To validate the simulation approach, a single-lap joint with outer dimensions of 100 mm × 150 mm was analyzed. The specimen contained a single lap joint with a 30 mm overlap. Both adherents are 16 ply laminate of IM7/8552 prepreg material with a quasiisotropic layup. The outer 30 mm which are clamped were omitted from the simulation model to reduce the model to 100 mm × 90 mm in size. Each ply was modeled with a layer of C3D8R solid elements utilizing the user-defined material model described in Section 2.4. To accommodate for delamination failure, the plies are connected with COH3D8 cohesive elements, which incorporate the user-defined material model described in sections 2.1-2.3. The adhesive layer was modeled using the same material model as the delamination layers, but with a different set of material parameters. Figure 4 depicts the simulation model with details of the stacked elements. The initial damage is mapped using a custom mapper developed at Wölfel, and the method is described in [18].

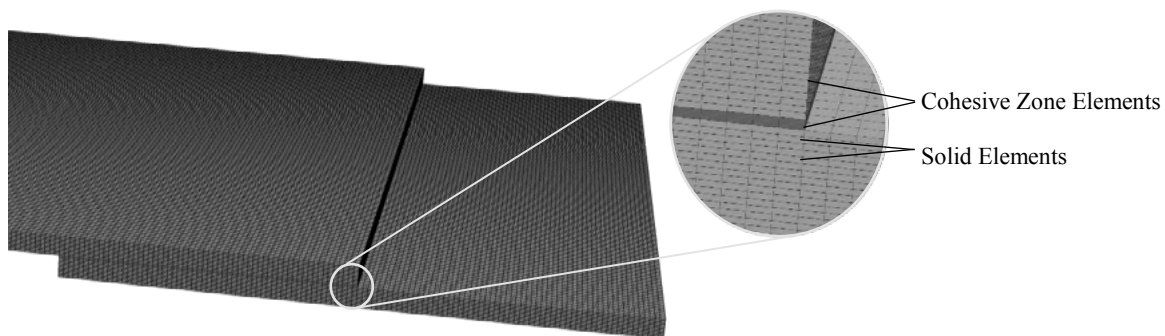


Figure 4. Simulation model for the fatigue analysis.

5. Results

To demonstrate the influence of the mapped impact damage on the Single Lap Tension After Impact (SLTAI) Specimen, the model was run with and without the initial damage provided by the mapping procedure.

In the undamaged model, an initial crack is modeled on the load concentration in the steps and propagates relatively evenly from both sides into the bonded area. The light blue coloration in Figure 5 indicates additional damage in the adherent above the delamination.

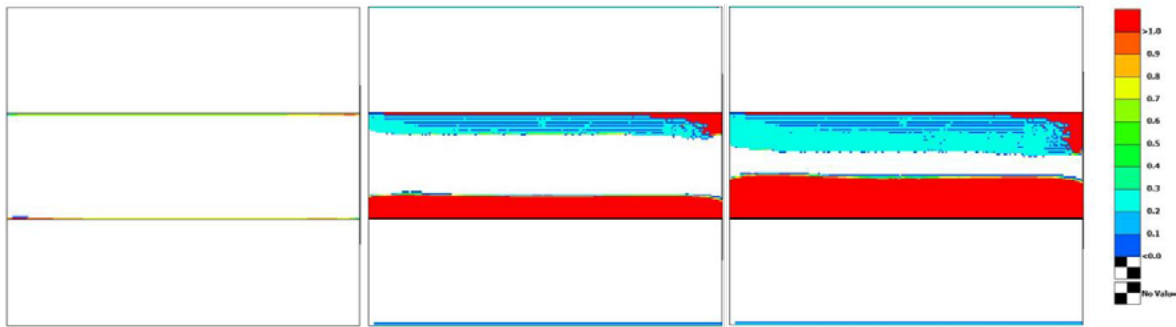


Figure 5: Fatigue damage progression of Single Lap Specimen with initial crack at step.

The simulation results for the mapped impact damage are shown in Figure 6. The state “Cycle:0” displays the pre-damaged specimen containing only the mapped impact damage. At cycle 3420, it is evident that the initial crack growth favors the step closer to the mapped impact damage. In addition, a second crack front is formed in the opposite step. To achieve this, the set threshold of intralaminar matrix damage was reached, and delamination in the adjacent cohesive elements was initiated through the communication between the user-materials. At cycle: 7980 the second crack front started growing as well, nevertheless the crack front under the impact location is progressing faster. This behavior can also be observed in the ultrasound images taken at intervals during the testing, which confirms the location of the predicted initial crack growth, as marked in Figure 6. However, the predicted cycle count underestimated the fatigue life observed during the tests.

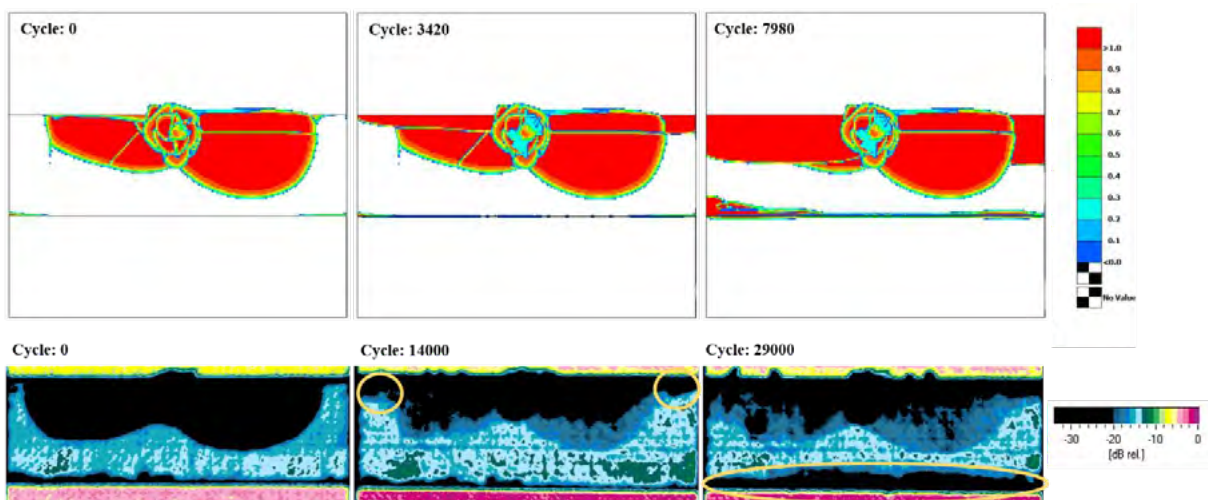


Figure 6: Comparison of the total damage progression in the simulation model and experimental tests through ultrasound images provided by Airbus Defence and Space.

6. Conclusions

The approach for the fatigue crack growth analysis, as presented, demonstrates the feasibility of such an analysis following an impact. The simulation method described exhibits its ability to initiate new delamination through the accumulation of intralaminar damage, which is made possible through communication between material models during runtime. The predicted damage pattern closely resembles the ultrasonic images obtained from the reference specimen during the fatigue test. Further investigations to verify the predicted crack path and fracture pattern will be conducted.

The discrepancy in the predicted crack growth rate may be attributed to various factors, which are currently under investigation. This may include the use of nominal dimensions in the simulation model, which differed slightly from those of the test specimen.

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