Numerical simulation of delamination onset and growth in laminated composites

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October 5, 2006

Abstract

Delamination in fiber reinforced laminated composite structures is analyzed. The numerical simulation of delamination is divided into creation of a starting delamination and delamination growth. The starting delamination is predicted by a stress based failure criterion developed by Puck. Growth of the starting delamination is modeled by the Virtual Crack Closure Technique. A curved laminate is analyzed to demonstrate the proposed simulation procedure. A linear finite element analysis is performed to predict the starting delamination, whereas non-linear analysis are required for the simulation of delamination growth. The effect of the size of the starting delamination is studied and a critical size is found. From the simulations of the growth of various starting delaminations the maximum bearable load of the structure is predicted. Moreover, structures containing initial delaminations were analyzed, yielding conditions for crack growth stability. For the verification of the proposed simulation procedure, cohesive zone elements are used and the same results are achieved. However, the proposed simulation procedure is computationally markedly cheaper than the use of cohesive zone elements.


1 Introduction

Due to their great potential in weight saving, fiber reinforced laminated composites are becoming increasingly important in applications where low weight, high stiffness, and high strength is required, in particular the aircraft industry.

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Due to their complex structure, several failure modes occur in laminated composites. Depending on the failure location ply failure and delamination are distinguished. Delamination is caused by out-of-plane shear and normal stresses attributed to e.g. impact loads, free edge effects, ply drop-offs, or transverse loading.

The formation of a delamination in a flawless structure can be divided into two parts; delamination onset and delamination growth. For the prediction of delamination onset, methods based on material strength have been developed. The interlaminar stress state is computed and a strength criterion is utilized to predict onset of delamination, see e.g. Garg [1] for an overview. A special case of these methods is the First Ply Failure criterion developed by Puck [2, 3, 4, 5], where delamination is interpreted as a special mode of ply failure.

For the simulation of delamination growth, methods employing fracture mechanics have been developed. Linear Elastic Fracture Mechanics (LEFM) has been shown to be suitable for predicting delamination growth when material non-linearities can be neglected [6, 7]. However, LEFM can only be applied when a starting crack exists. For the prediction of delamination growth methods like the Virtual Crack Closure Technique (VCCT)[7, 8, 9], the J–integral [10], and the Virtual Crack Extension Technique [11] are used successfully.

Another approach for the numerical simulation of delamination is the Cohesive Zone Method (CZM) which uses the framework of damage mechanics and softening. A thin layer of matrix material is assumed to exist between plies. Delamination is interpreted as creation of a cohesive damage zone [12, 13] in front of the delamination front, separating the adjacent plies. Within the Finite Element Method (FEM) traction–separation laws are defined for the interface, see e.g. [14, 15]. The CZM can handle delamination onset as well as delamination growth. However, this method is numerically expensive and requires fine meshes in order to represent the damage zone adequately.

To overcome this drawback a combination of a First Ply Failure criterion and a fracture mechanics approach is proposed in this paper. The FEM is used to simulate delamination in a structure without initial delaminations and flaws. To predict delamination onset the failure criterion developed by Puck is used. Based on the results of the Puck criterion, a starting delamination is created. Growth of this starting delamination is simulated using the VCCT. In addition, growth of initial delaminations is studied. These delaminations may stem from the production process or previous loadings. The CZM is used for verification of the proposed simulation procedure.

2 Simulation Tools

For the structural analysis the FEM package ABAQUS/Standard (ABAQUS Inc., RI, USA) is used.

2.1 Puck Criterion

Delamination onset in a flawless structure is predicted employing a First Ply Failure criterion developed by Puck [2, 4, 3, 5]. It is a local strength criterion for three-axial stress states at the ply level. The criterion is built on a physically based, phenomenological model and is suitable for long fiber reinforced polymers. The Puck criterion is capable of predicting the risk of failure and
the corresponding failure mode. It distinguishes between fiber failure and several modes of Matrix Dominated Failure (MDF), where delamination is one of these MDF modes. The delamination strengths, typically, are estimated by slightly reducing the transverse ply strengths [3]. The criterion has been implemented in ABAQUS as a post processing tool [4, 5]. It evaluates the stresses in each Gauss point and predicts the spatial distribution of the risk of failure and the failure mode.

2.2 Virtual Crack Closure Technique

Delamination growth is modeled by the VCCT which is based on the Griffith crack growth criterion assuming LEFM [7, 8, 9]. According to the Griffith crack growth criterion, a crack grows if the energy released at crack propagation is equal or larger than the energy required to create new crack surface. The latter is called “critical energy release rate” and can be derived from experiments. The central assumption of the VCCT is, that the energy released when the crack is extended by a length, \( \Delta a \), and the energy required to close the crack over a length, \( \Delta a \), are identical. This assumption holds true only, if \( \Delta a \) is small compared to the total crack length and self similar crack growth takes place, i.e. the shape of the crack does not change significantly during crack growth. The energy rate for closing the crack is computed from the force at the crack tip and the crack opening displacement. If the computed energy rate is equal or greater than the critical energy release rate, the crack propagates.

By considering the components of the force and the displacement in the principal directions, the mode I, mode II, and mode III energy release rates can be computed. Various criteria have been developed to take the mode mix at the crack tip into account, see e.g. [7, 16] for details. In the present paper, a quadratic criterion is used.

The VCCT is available as an add on tool for ABAQUS and is implemented as a particular contact condition [17]. The tool is capable to assess the crack growth conditions and to extend the crack if indicated.

2.3 Simulation Procedure

To model delamination onset and growth, two FEM runs are required. First, a linear simulation is done to predict a starting delamination (i–iii). Second, a non-linear simulation is performed, delamination is triggered and the capabilities for the simulation of delamination growth are switched on (iv–vi).

(i) A linear elastic stress analysis is performed. (ii) The stresses are evaluated using the Puck criterion and the location as well as some size of a starting delamination is predicted. The question which size of the starting delamination is critical is discussed in detail in section 3.3. The load for delamination onset is computed from the highest risk of failure. (iii) At the location where the starting delamination is predicted, the FEM model is adapted accordingly. (iv) The FEM model is loaded up to the load that corresponds to the size of the starting delamination predicted before. (v) The starting delamination is created by opening the interface while keeping the load constant. (vi) The VCCT tool is activated and if the conditions for delamination growth are fulfilled, the delamination is extended. Depending on the structure and the prescribed loading stable growth, unstable growth, or no growth can take place.
2.4 Cohesive Zone Method

The CZM can handle onset and growth of delamination and is used for the verification of the proposed simulation procedure. The traction–separation law employed in the present work is shown in Fig. 1. It is described by the finite initial stiffness, $C_{\text{init}}$, the strengths of the interface, $t$, and the energy required to create new delaminated area, $G_c$. Interface elements employing the CZM and the traction–separation law described are available in ABAQUS.

3 Example

3.1 FEM model

An L–shaped structure made of a laminated composite with a 0/90 layup (15 plies total) is analyzed, see Fig. 2. The right leg of the laminate is fixed at the lower side and a horizontal displacement, $u$, is prescribed at the upper edge of the left leg. The structure has a considerable length in $z$–direction, thus, generalized plane strain conditions are assumed. A carbon/epoxy composite is considered, material data is taken from [18], see table 3.1. The strengths of the interface are assumed to be 10% lower than the ply strengths in transverse direction. The structure is modeled using continuum elements with linear shape functions. Each ply is represented with three elements over the ply thickness.

Figure 1: Traction–separation law for the Cohesive Zone Method.
Table 1: Material data of carbon/epoxy UD–layer, T300/976, data taken from [18].

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* following Puck’s guidelines for carbon fiber materials [19]

3.2 Delamination onset and growth

In the first step, the structure is loaded with a unit load and the stresses are evaluated using the Puck criterion. Figure 3 (left) shows, that the highest risk of failure is found at an interface in the curvature of the laminate. In Fig. 3 (right), the predicted failure mode is shown, indicating delamination at the critical location.

The size and the location of a starting delamination is derived from the spatial distribution of

Figure 2: Geometry and boundary conditions of the laminated structure, generalized plane strain conditions are assumed.
the risk of failure. In a first attempt, a load that corresponds to a starting delamination size of 20 elements is chosen. The effect of changing the load level, and thus the size of the starting delamination, is studied in detail in section 3.3.

In Fig. 4, the load–displacement curve is shown. At point 1, the starting delamination is opened. This leads to a decrease of the reaction force (point 2) due to the stiffness change. At point 2, the VCCT tool is activated. Between point 2 and point 3 unstable crack growth takes place at constant prescribed displacement. Beyond point 3 the load is increased, accompanied by stable crack growth up to point 4. From point 4 on unloading is simulated.

For verification of the proposed simulation procedure, the CZM is used. An FEM model is created, where each interface is represented by elements employing the CZM. The thickness of these elements is $1 \mu m$. The strengths of the interface are assumed to be 10% lower than the ply strengths in transverse direction. Ply strengths and energy release rates are given in table 3.1. As

![Risk of failure (left) and failure mode (right) predicted by the Puck criterion.](image1)

![Delamination in a curved laminate is simulated with a combination of Puck/VCCT and Cohesive Zone Elements.](image2)
initial stiffnesses, the transverse ply stiffnesses are used.
The results of the simulation employing the CZM show, that the location of the starting delamination is predicted correctly by the Puck criterion. Figure 4 shows, that the load–displacement curves are nearly identical for both simulations. The same holds for the delamination growth behavior with respect to size and direction. However, the simulation using the CZM lasts some 10 times longer than the proposed simulation procedure.

3.3 Size of the starting delamination

The Puck criterion predicts a certain size of the starting delamination for any load exceeding delamination onset. Four different load levels are considered, the corresponding starting delaminations are created and the delamination growth is studied. The same steps as described in Fig. 4 for the combination of Puck/VCCT are carried out and the results are shown in Fig. 5.

The introduction of an extra small starting delamination (12 elements) leads to a small reduction of the laminate stiffness, however, the delamination does not propagate at that load level. Instead, a substantial load increase is required to trigger delamination growth, which is unstable. The same behavior is observed for the small starting delamination (15 elements), except for the fact that the load increase to trigger delamination growth is smaller. For the medium starting delamination (20 elements), growth starts immediately at constant prescribed displacement. For the large starting delamination (25 elements), again, immediate growth is observed. The delamination growth takes place on a higher load level which corresponds to the size of the large starting delamination. Comparison of the load–displacement curves shows, that the displacement at delamination growth

Figure 5: Load–displacement curves of different sizes of the starting delaminations, the medium starting delamination is the critical one.
is lowest for the medium starting delamination (0.316 mm).
The load–displacement curves possess a lower envelope, see Fig. 5. From the envelope a conservative measure for safe loading conditions, with respect to delamination growth in an initially flawless laminate, is obtained.

3.4 Unstable crack growth

From the results of the VCCT, crack growth stability is judged. In Fig. 6 the delamination at the transition from stable to unstable growth is shown. For each FEM node in the delamination growth area the energy release rate computed by the VCCT and the critical energy release rate are shown. The comparison of these values reveals that more energy is released during delamination growth as being required to create new delaminated surface. This excess in energy indicates unstable crack growth.

Up to now, flawless laminates were analyzed and delamination growth was revealed to be unstable. To study the influence of delamination size on the crack growth stability, structures containing different sizes of initial delaminations are studied. The initial delaminations are present from the very beginning and located according to the previous results. The VCCT is also activated in the very beginning. The resulting load–displacement curves are shown in Fig. 7. The effect of the initial delaminations can be seen in the change of the initial stiffness and the peak load.

The load–displacement curves show that the small and the medium initial delamination grow in an unstable manner, whereas the large initial delamination grows in a stable manner. In other words, there is a limit size of a delamination at which the delamination growth changes from unstable to stable.

Since the initial delamination is placed at the most critical location its most detrimental effect can be assessed. This is relevant for the interpretation of the effect of delamination sizes that are

Figure 6: Energy release rate calculated by the VCCT and critical energy release rate in the delamination growth area.
too small to be detected by inspection methods. A "fictitious" load–displacement curve for a delamination process where the energy release rate at crack growth exactly equals the critical energy release rate can be derived. At the start point and the end point of unstable delamination growth this requirement is fulfilled. From these points, a load–displacement curve is approximated that shows a pronounced snap back behavior of the structure, Fig. 7.

4 Summary

Delamination in a laminated composite structure without flaws is simulated. The delamination process is divided into two parts; creation of a starting delamination and delamination growth. To predict a starting delamination, the Puck First Ply Failure criterion is used. Growth of the starting delamination is simulated using the VCCT. These procedure is applied in the analysis of an L–shaped structure. Based on the predictions of the Puck criterion various sizes of starting delaminations are derived and analyzed. The resulting load–displacement curves own a lower envelope, from which a measure for safe loading conditions is obtained. Furthermore, the results show that the delamination grows in an unstable manner. The effect of the size of an initial delamination on the crack growth stability is studied and a limit initial delamination size is found. Delaminations exceeding this size grow in a stable manner, delaminations

Figure 7: Delamination growth of various sizes of initial delaminations, indicating a snap back behavior of the structure.
below this size grow in an unstable manner. A further interpretation of these results reveals a pronounced snap back behavior of the structure. The comparison to a simulation using the CZM shows excellent agreement. Advantages of the proposed procedure are low computational costs and numerical robustness. The procedure allows to determine the critical size and location of a starting delamination and provides detailed information about the delamination growth stability.

Acknowledgement

The funding of the Austrian Aeronautics Research (AAR)/Network for Materials and Engineering by the Austrian Federal Ministry of Economics and Labor is gratefully acknowledged.

References