Progressive Damage Modeling of Thick Laminated Composites: Robust Deterministic and Probabilistic Implementation

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Abstract: The objective of this work is to a) generate robust and physically reasonable Abaqus-based FEA solutions to model multi-step damage processes in laminated composite materials and structures and b) demonstrate their efficiency on representative examples. The examples are focused on scenarios of composites with complex networks of multiple interlaminar damages. Computational implementation is based on cohesive zone modeling approach allowing one to model both damage initiation and growth. Demonstration of computational robustness is shown on cases with increased levels of complexity starting with single damage statements, then with multiple damages, and finally, with probabilistic statements assuming statistical variability of properties representing different damage paths. For the probabilistic statement, method of Monte-Carlo simulation is applied, and developed Matlab/Python implementation is demonstrated. Systematic parametric studies for considered examples illustrate efficiency of the developed solutions for a relatively broad range of considered input parameters.

Keywords: Composites, Crack Propagation, Damage, Delamination, Probabilistic Design.

1. Introduction

Polymer-matrix composites (PMC) are widely used in numerous aircraft applications as critical load-bearing structures. For their analysis and design, damage tolerance assessments (DTA) are often applied with prime focus on evaluation of damage growth during service load conditions. Such assessments may significantly reduce over-conservatisms of more traditional approaches addressing instead damage initiation according to certain strength-based criteria.

In spite of well-documented and experimentally validated advantages of DTA-based approaches, there are potential challenges as well. One of them is definition of initial damages for follow-up assessment of their growth, where these flaws are either a) introduced in the weakest locations according to a stress analysis (i.e., considered as an input of modeling) or b) should be predicted as a part of the entire DTA (i.e., considered as an output of modeling). Scenario “b” with independent predictions of both damage initiation and growth, i.e., without any introduced...
assumptions, seems to be much more promising. However, it may be potentially associated with additional complexity and challenges of computational robustness.

The goal of this study, therefore, is focused on development of reliable DTA solutions for scenarios “b” using Abaqus-based capabilities and demonstration of their robust nature for a broad range of thick PMC structures. The demonstration is illustrated on problems of increased levels of complexity including statements with single damage, multiple damages, multiple damages with significant deterministic variations, and multiple damages with random properties.

This study is limited to problems with interlaminar damages and specifically addresses “thick” composite structures. Here, in contrast with a rather simplistic geometrical definition of “thick” PMC, a mechanical meaning of this word is assumed (Gurvich et al., 2016), i.e., for cases where applications of the classical laminated theory can be quite limited.

2. Approach

The cohesive zone (CZ) modeling approach is applied to model processes of both damage initiation and growth by simulating traction-separation failures at interfaces between layers. This approach considers several potential damage mechanisms acting simultaneously for the same structure. The first damage is associated with the weakest location. Then, after some damage growth and corresponding stress redistribution, the second damage can occur. Next, after potential growth of both first and second damages and similar stress redistribution, the third damage can appear. Such multi-step process of progressive damage continues until the complete limit of structural integrity. Similarly, it can continue until fulfilment of an introduced criterion relevant to a specific problem (e.g., critical displacement, stiffness reduction, number of damages, etc.).

Each failure mechanism is driven by two key assessments, namely, by a damage initiation criterion and a damage evolution law. The initial response of the cohesive element is assumed to be linear with respect to increasing traction. Once a damage initiation criterion is met, material damage occurs based on an adopted damage evolution law. Especially for CZ-based FEA, a choice of cohesive element removal (or deletion) at a complete damage state is added to the failure mechanism (Abaqus Elements, 2014). A recent version of Abaqus offers a cohesive surface model capability which significantly reduces the number of elements to analyze and alleviates the need of complex mesh setup. In this paper, CZ modeling using cohesive surface is applied.

3. Single Damage Scenario

The first example selected for modeling is a composite beam under three point bending load conditions with introduced interlaminar damage (Figure 1). The FEA model is expected to show further initiation and propagation of Mode II shear failure from a pre-determined damage location. The model is based on plain strain assumption and includes two thick packs of layers, cohesive surface setting between them, a vertical indenter on the top, and two round supports at the bottom. From the left to the white circle (the crack tip), the interface is open and set to slide (Figure 1). From this point towards to the right, cohesive surface setting is applied. Fine meshes are created near the damage initiation location with element sizes 6.25E-4 by 6.25E-3 inch² (Figure 1).
The quadratic nominal stress criterion, given by:

\[
\left( \frac{q_n}{N_0} \right)^2 + \left( \frac{q_s}{S_0} \right)^2 + \left( \frac{q_t}{T_0} \right)^2 = 1
\]  

is applied to track damage initiation in the cohesive surfaces. In Equation 1, the symbol \( < > \) implies Macaulay brackets indicating that only positive tractions are considered, and \( N_0, S_0, \) and \( T_0 \) are the interfacial normal, in-plane shear and anti-plane shear strengths, respectively. According to Equation 1, damage is deemed to have been initiated if the left-hand side of the equation, given by the corresponding parameter ‘CSQUADSCR’ (Abaqus Elements, 2014), attains a value equal to 1.0.

In theory, once Equation 1 is satisfied for a particular cohesive surface, it implies that the same surface can no longer resist further tractions. In other words, the load carrying capacity at the surface should vanish instantaneously. However, from a computational perspective, sudden relief of all its stiffness would lead to severe convergence problems. Therefore, the loss in stiffness is introduced gradually, as indicated by the negative slope of the traction-separation law. The domain of the traction-separation law corresponds to damage evolution, and under pure Mode I, Mode II or Mode III, once cohesive displacements attain corresponding final magnitudes given by either \( \delta_f^i, i = n, s, t \) (implying that the associated fracture energy has been dissipated), the surface cohesion is removed, signifying crack propagation. Under mixed-mode loading conditions on the other hand, an effective displacement, \( \delta_m = \sqrt{(\delta_n)^2 + (\delta_s)^2 + (\delta_t)^2} \), is first computed, and when the cohesive displacements attain the magnitude given by \( \delta_m \), the surface is no longer in cohesion. The evolution of damage is governed by the energy-based mixed-mode law (Benzagagh, 1996), which is implemented in Abaqus as:

\[
G_s^c + (G_s^c - G_n^c) \left( \frac{G_s}{G_T} \right)^{\eta} = G_c
\]

wherein, \( G_s = G_s + G_t \) and \( G_T = G_n + G_s + G_t \), and \( G_s^c \) and \( G_T^c \) are the mode-specific critical fracture toughness. Damage evolution in cohesive elements and surface is tracked via the parameter ‘SDEG’ in Abaqus (Abaqus Elements, 2014). For instance, under pure Mode I, ‘SDEG’ is given by:
In Equation 3, $\delta^n$ is the crack extension corresponding to the dissipation of the Mode I fracture energy. Similar conditions are also applicable under pure Mode II and Mode III loading conditions.

Unidirectional lay-up $[0]_n$ is considered in the demonstration example ($[0]$ corresponds to the beam orientation). Representative elastic and strength properties (NIAR, 2015) and characteristics of interlaminar toughness (Martin et al., 1998) are defined according to these published data. The normal, in-plane shear and anti-plane shear strengths of the cohesive surface are specified as $N_0 = 9,294.50 \text{ psi}$, $S_0 = T_0 = 13,209.50 \text{ psi}$. Additionally, the mode-specific critical fracture toughness for the cohesive surface is input as: $G^K = 1.0 \text{lbf/in. and } G^C = G^T = 4.5 \text{lbf/in.}$, with the exponent in Equation 2, $\eta = 2.5$. The stiffness of the cohesive surface was set to be $22.99 \times 10^9$, $1.3 \times 10^9$, $1.3 \times 10^9$ psi, respectively, assuming 0.001” thickness of the cohesive layer.

In the FEA model, the indenter is set to move 0.8” downward to introduce damage to the multi-layer beam. The entire indenter movement is partitioned into multiple small steps, and geometric nonlinearity is considered for numerical calculation. Figure 2 shows deflection and damage progression at several representative loading steps. As the indenter pressed the beam, the damage opening position (i.e., red circles) moved towards to the right, and interface between upper and lower packs became open, as the layers start to slide. The damage opening positions are identified according to CSQUADSCRT parameter which varies from 0 to 1. Figure 3b shows shear stress distribution ($S_{12}$) at the very early damage stages. Figures 3c-f capture damage initiation near the opening due to movement of the indenter, and its progression is clearly captured. The developed model ran in a stable manner in spite of the nonlinear geometry setting. Both damage initiation and progression are predicted as expected according to physical understanding.

4. Multi-Damage Deterministic Scenario

Demonstration of multi-damage deterministic case is performed on example of multiple (five) point bending (Robeson, 1997; Robeson, 1998) to mimic more complex load conditions with expected patterns of multiple damages (Gurvich et al., 2016). An example selected for modeling is a composite beam with four packs of layers under five-point bending (Figure 4). The model has three interfaces between layers, and the failure strength of each interface can vary depending on user inputs. The model is based on plain strain assumption and includes cohesive surface setting between all packs of layers, two vertical indenters on top, and three round supports at the bottom. Detailed geometry and dimension of the model is presented in Figure 4a. The interfaces between packs of layers are denoted as Intf1, Intf2, and Intf3 from top to bottom. Figure 4b shows mesh settings used in this example. All four layers are quad-meshed uniformly, and the element size was 2.5E-2 by 3.125E-3 inch².
Figure 2. Process of interlaminar crack growth at a) 0; b) 20%, c) 52%, d) 77.5%, and e) 100% of displacement-controlled load.
Figure 3. Distribution of shear stresses upon crack growth at a) 0; b) 1%, c) 2%, d) 3.5%, e) 5.75% and f) 9.125% of applied load.
A proposed FEA model is expected to show initiation and propagation of in-plain (Mode II) shear failure from different damage locations along three interfaces (Intf₁, Intf₂, and Intf₃) as shown in Figure 4c. The indenter is set to move 0.0475" downward to introduce damage to the multi-layered beam. The entire indenter movement is partitioned into multiple small steps, and geometric nonlinearity is considered for numerical calculation. It is notable that the model is developed in a way to accept different input parameters for shear strengths, allowing probabilistic approaches to be studied later. The shear strengths of Intf₂, N₀, S₀, and T₀ were set to be 2,323; 3,302; and 3,302 psi, respectively. To mimic potential variability of properties in a quasi-deterministic manner, properties of Intf₁ are reduced by half, and shear strengths of Intf₃ became double in this model. Thus, more damage growth along Intf₁ and possible no failure at Intf₃ are expected initially. Figure 4c clearly shows that Intf₁ contributes the most to carrying load from the indenters to the middle support.

In the cases with complex geometry, the presence of damage can be easily masked in graphics showing deformed shapes or stress distribution. As an alternative for damage monitoring, plots of parameters CSQUADSCRRT (0 to 1 scale, 1: damage initiation) and CSDMG (0 to 1 scale, 1: damage progression) are also provided in Figures 5, 6, and 7 as functions of load. For example, Figure 5 shows initiation and progression in Intf₁, at the moment of damage initiation (T_{init}) and end of indenter movement (T_{end}), and only initiation is shown along Intf₂. Damage is about to
Figure 5. Distribution of damage initiation (a) and evolution (b) along the beam length for interface Intf₁.

Figure 6. Distribution of damage initiation (a) and evolution (b) along the beam length for interface Intf₂.
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Figure 7. Distribution of damage initiation (a) and evolution (b) along the beam length for interface Intf3.

initiate, but the damage criterion is not met in Intf3 (Figure 5). The change of shear strengths can either reinforce or undermine interfaces, and the proposed model is able to demonstrate damage progression reflecting those changes in the interfaces.

5. Multi-Damage Probabilistic Scenario

In contrast with deterministic problems, probabilistic modeling is based on consideration of a broad variability of input parameters to represent their statistical scatter. Thus, the developed computational solutions have to be equally robust upon coupling with either Monte-Carlo simulation or other probabilistic solutions. The computational robustness of the multi-layered beam model within expected range of input variation is tested by varying key parameters. This test is performed prior to running the multi-damage probabilistic case.

Figure 8a shows a force-displacement chart as a function of stiffness variation of considered composite materials (each peak here represents a predicted damage). As expected, the 4-pack composite beam becomes more resistant to external loading as stiffness of the beam increases. The amount of force which introduces the first damage is almost the same for all cases. After the first damage, the occurrence of second and third failures varies based on introduced stiffness. Especially for higher stiffness cases (i.e., 2E and 4E cases), the interface between layers became relatively softer, and damage initiation and evolution process did not cause abrupt changes in the loading process (here, xE means that the stiffness is x time higher in a considered example than the baseline (BL) stiffness).
Figure 8. Processes of progressive damage predicted as functions of a) layer stiffness and b) interlaminar strength variations.
Figure 8b shows comparison among baseline (i.e., 100%) and cases with 75%, 125% and 150% of initiation related parameter changes. At lower strength cases, the interface became weaker, and rapid changes in the charts disappear. The occurrence of the first damage is delayed as interlaminar strength increased. In the baseline case, there are three damage steps. In 125% and 150% cases, the second and third damage steps are very close. As another example, Figure 9 shows representative distributions of shear stresses at different steps of damage. This example also clearly illustrates the progressive nature of interlaminar damage network. Robustness of considered examples indicates their applicability to probabilistic modeling, where variation of input data is introduced.

![Figure 9. Distribution of shear stresses as a function of progressive damage shown just b) before the 1st, c) after 1st, d) after 2nd, e) after 3rd cracks.](image)

Since FEA modeling in this project is based on Abaqus, applied integration for probabilistic analysis is based on available Abaqus tools and developed input/output solutions in Python and
Matlab. Abaqus supports parametric studies by providing script options in addition to a Complete Abaqus Environment (CAE) application. The fundamental process is to create a “.psf” file which denotes a parametric study function (PSF) and run the file in the Abaqus Command environment (Abaqus Scripting, 2014). Important input to PSF is an “.inp” file which contains definitions, conditions, and settings of an FE model. In the “.inp” users select parameters of their interest, and create related samples in the PSF. The PSF allows an automated process to test different parameters in the model, and helps selection of optimized parameters in common applications.

Based on these Abaqus options, a general Python-based script is developed in this study to link Abaqus with Monte Carlo simulation. Number of statistical simulations, selection of random variables, and their statistical parameters are defined by users and, therefore, can be easily modified for other similar problems of progressive DTA probabilistic modeling. Generated results are extracted from calculated .odb files (FEA direct output) and can be post-processed by different numerical software such as Excel or Matlab (Matlab is used in the present paper).

For demonstration of coupling probabilistic/FEA implementation a similar problem of five-point bending is considered with six different interfaces. Each interface is defined by random strength and toughness properties described by introduced Weibull distribution each. A quasi-deterministic parametric FEA model is developed to use using simulated quasi-random properties as input for the analysis. No statistical correlation between individual interfaces is assumed. This model is run independently for each statistical simulation case of a full progressive damage process each.

In contrast to the deterministic case, each statistical simulation produces separate quasi-random damage pattern. Figure 10, plotted for statistical populations with 20 simulations, shows a clear difference between these cases. In each simulation, the 1$^{st}$ damage occurred at different load and displacement levels. In summary, the developed probabilistic implementation of the progressive damage modeling seems to be quite robust and efficient.

6. Conclusions

Capabilities of progressive multi-step damage modeling in thick laminated composite structures with predominantly interlaminar failure are demonstrated using Abaqus/Standard cohesive zone based solutions. Robustness of solutions is illustrated for a broad range of composite problems including consideration of single damage, multiple damages, multiple damages with significant deterministic variation, and multiple damages with random properties. Coupling of the progressive damage solutions with probabilistic modeling is also successfully demonstrated using Python/Matlab based solutions.
Figure 10. Statistical populations of progressive damage processes predicted for 20 quasi-random simulations.

7. References


8. **Acknowledgements**

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