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LAMINATE DAMAGE MODEL FOR CFRP STRUCTURES

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Summary: *A material model for a progressive damage evolution analysis of composite laminates is presented. The model is developed in particular for layered elements, where the complete stacking is represented within one element. The difference to current models is that the laminate hardening is defined on ply-level and the laminate softening on laminate level. This allows the usage of an energy based stiffness degradation law during softening, to enable mesh-size independence. The model has been validated against open-hole tension tests with different hole-diameters and shows excellent correlation.*

1 INTRODUCTION

For the prediction of the maximum bearable load of a composite structure, damage models are necessary, since the first damage event often occurs much earlier than the ultimate failure of the laminate. Current continuum damage models for CFRP require very fine FE meshes, where each ply is represented by one layer of elements. Between the plies cohesive elements are used to model delamination [1]. For structural analyses often layered shell elements are used to minimize the numerical effort. The presented material model is developed in particular for this kind of discretization. The main difference to current models is that the strength and thus, the transition from the hardening to the softening regime is defined on laminate level and not on ply level. In other words, instead of the stiffness of the main load carrying ply, the homogenized laminate stiffness is reduced during softening.

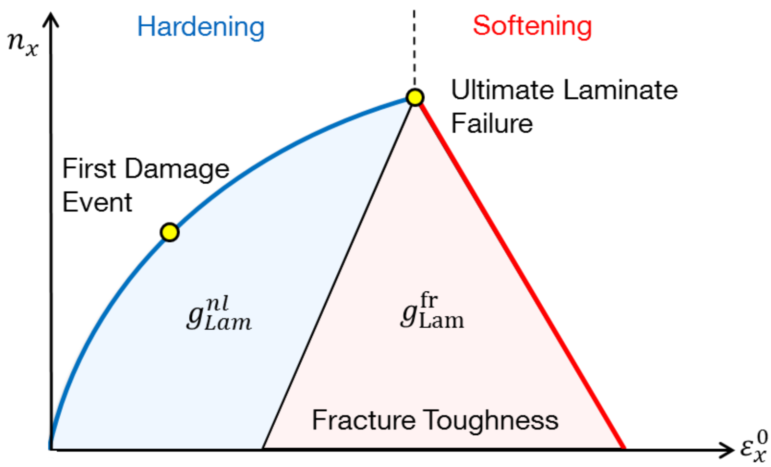

Figure 1: Constitutive behavior of a laminate.

In the hardening regime the laminate can show nonlinear material behavior, but the load can be further increased (see Figure 1). In the softening regime the stiffness of the laminate is reduced to represent the total separation of the laminate. An energy-based damage evolution law enables mesh-size independence.

In Figure 2 the schematic procedure of the presented material model is shown. The model is implemented for an explicit finite element simulation. In each time step the material model gets the global deformation at the discrete material points as input and determines the resultant forces and moments.

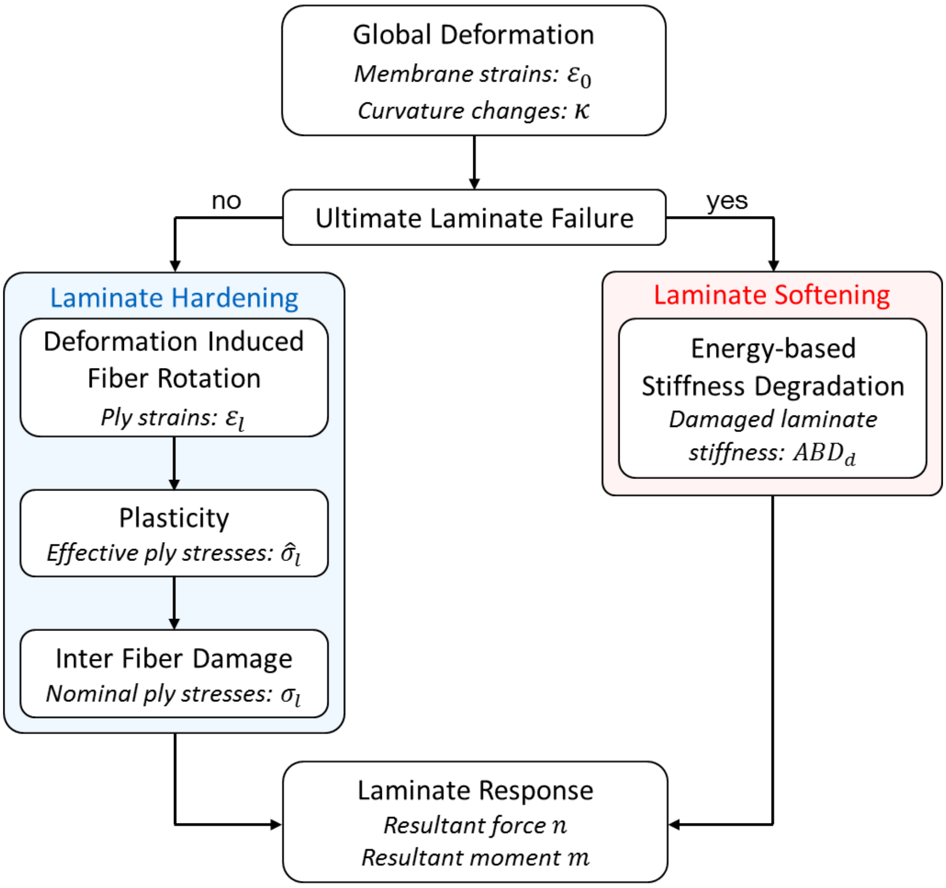

Figure 2: Schematic procedure of the Laminate Damage Model.

2 LAMINATE HARDENING

The constitutive response of composites prior to ultimate failure is influenced by several processes within the material constituents. Dependent on the prevailing direction and amount of the applied load in relation to fiber and matrix, several sources can be responsible for a nonlinear stress-strain behavior and characterize the specific degree of nonlinearity. These are an accumulation of plastic strains, deformation induced fiber reorientation and damage effects. The numerical simulation requires a material model that considers the micromechanical physics of the composite. The presented model accounts for all presumed sources interactively in order to stray from a mathematically-defined approach. A comprehensive description of the constitutive model representing laminate hardening is given in [2]. There, not only the derivation of the constitutive equations is given, but also a detailed literature review and discussion about the occurring mechanisms.

2.1 Fiber Rotation

A few studies account for the mechanism of fiber reorientation caused by large deformations [3-5]. Neglecting fiber rotation alters the stress-strain response, becoming worse for increased strains and impeding a reasonable failure analysis. Fiber rotation has a substantial influence on the nonlinear material behavior and on the true stress state. The fiber rotation angel θ_{def} is directly given by the shear strain:

$$\theta_{def} = \arctan\left(\tfrac{1}{2}\varepsilon_{12}\right). \tag{1}$$

The consideration of fiber rotation is particularly important when the laminate exhibits a huge transverse contraction or reaches large deformations. The effect of fiber rotation is illustrated in Figure 3 on the example of a ±30° angle-ply tension test.

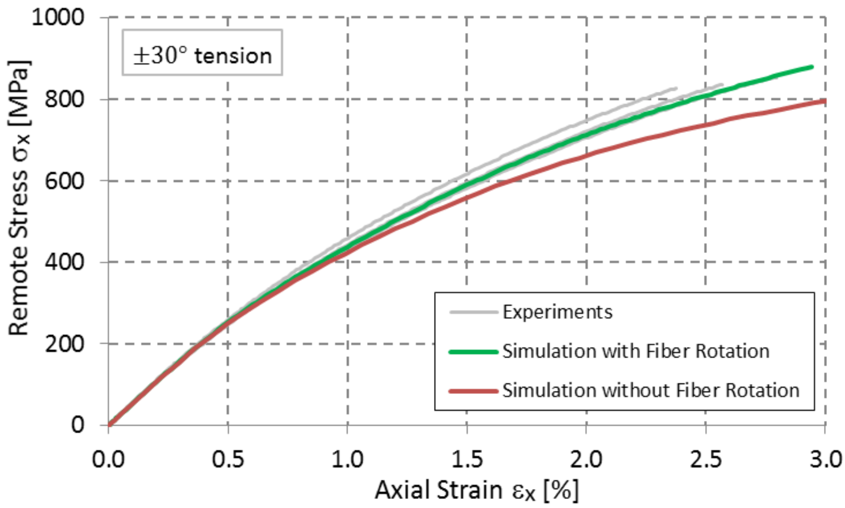

Figure 3: Axial response of a ±30° angle-ply tension test.

2.2 Plasticity

Longitudinal to the fiber, FRP's show linear elastic behavior until failure [6]. Transverse stresses and especially in-plane shear result in a nonlinear response. Different mechanisms, in relation to the stress components, promote yielding caused by directional straightening of polymer chains. Due to in-plane shear, sliding of fibers and resin occurs longitudinally. In contrast, the yield processes in reaction to transversal compression are taking place perpendicularly to the fibers. It follows that two master curves representing the effective stress-strain behavior for both mechanism are required for modelling plasticity. The model features no interaction of the respective stress components. A transverse compressive stress has a significant dependence on the shear strength of fiber reinforced composites. In contrast, no experimental dependency of transverse load on the shear stress-strain behavior is shown in [7, 8].

2.3 Inter Fiber Damage

Within a laminate the single plies can achieve stress states, under which pure unidirectional specimens would collapse. Exceeding this stress, the nonlinear material behavior is not only affected by fiber reorientation and plasticity, but additionally influenced by damage mechanisms. Achieving the inter-fiber strength, detected by common failure criteria like [9-11], micro damage initiates propagating until development of a complete through-thickness crack in a ply. With further loading, more parallel cracks are formed, inducing a growth in the crack density. Within the presented laminate inter-fiber damage model, the failure events are homogenized in the context of a continuum. The objective of the degradation analysis is to reduce the effective stress, calculated by the plasticity model, to determine the stress averaged over the ply's cross-section including damaged regions.

Once damage initiation is detected, it has to be verified if the load can be further increased. Either inter-fiber crack accumulation in the corresponding ply begins, or the strength of the laminate is reached. If the laminate strength is reached, the softening of the material starts leading to the total separation of the laminate.

The effect of inter fiber damage on the stress-strain response during laminate hardening is shown in Figure 4 on the example of a ±45° angle-ply tension test.

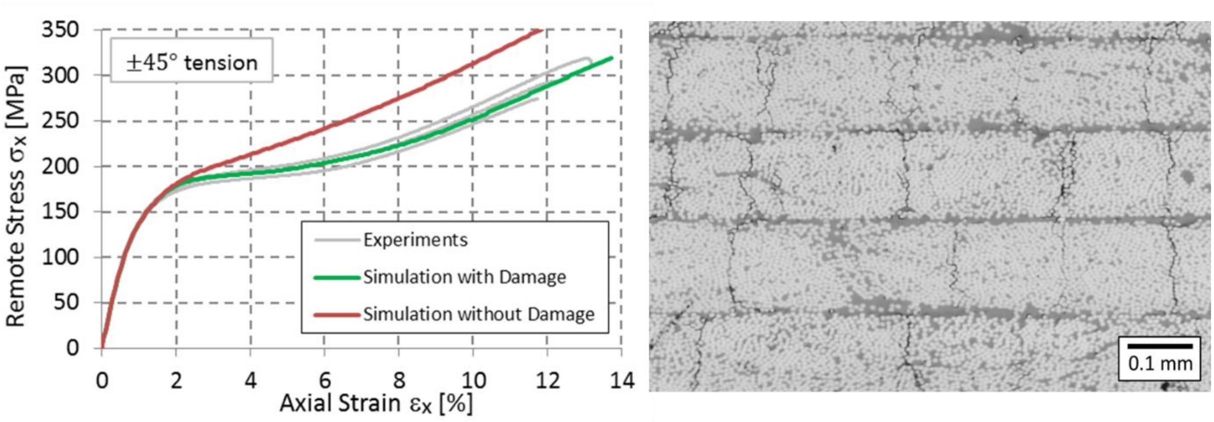

Figure 4: left: Axial response of a ±45° angle-ply tension test; right: Polished cross-section shortly before ultimate failure with matrix cracks in all plies

3 LAMINATE SOFTENING

The softening regime begins with the initiation of ultimate laminate failure. Fiber failure in at least one ply results always in ultimate laminate failure. Usually the residual laminate is not able to carry the load of the failed ply and the crack cannot be stopped by the adjacent plies. Using a fiber failure criterion as the ultimate laminate failure criteria works well, if the considered laminate contains fibers aligned in the main load direction. However, if there is no ply orientated in load direction, ultimate laminate failure usually occurs at a stress state, where no fiber failure is predicted. The ultimate failure of such a laminate can have several reasons. One reason is that the laminate stress-strain response gets descending due to cumulative inter fiber failure, leading to a localization of the process zone. For other load states the local stress state at the free edge of the considered structure is responsible. In the presented study the model is validated with quasi-isotropic open-hole tension test results. For this application a fiber failure criterion is suitable. In accordance with common failure criteria for unidirectional composites, the maximum stress criterion is used to detect fiber failure [9-11].

For a reliable prediction of the ultimate strength of a composite structure, in addition to the strength of the laminate its fracture toughness is necessary. Without the fracture toughness a stress concentration at a notch cannot be evaluated. In metal design this material parameter is often combined with the notch geometry to a notch factor for strength reduction.

In a finite element analysis the initiation of failure at a notch significantly depends on the mesh-size. To enable a mesh-size independent prediction of the ultimate strength the subsequent stiffness degradation has to compensate the mesh effect on damage initiation. Therefore, Bažant and Oh [12] proposed their crack band model, in which fracture is modeled as a band of parallel densely distributed micro-cracks (smeared crack band). In the presented model after reaching the strength the corresponding stiffness is reduced in such a way, that the stress-strain response shows a linear descent and the dissipated energy of a completely failed element matches the fracture toughness. The stress-strain response for fiber tensile failure is shown in Figure 5.

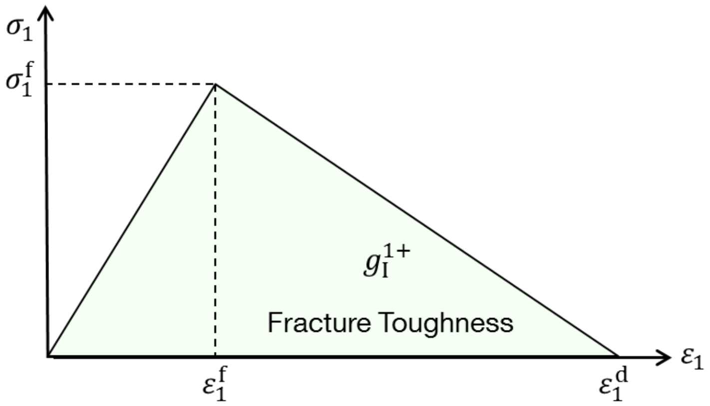

Figure 5: Axial response for fiber failure with linear softening.

The fracture energy per unit volume of the damaged element g_{I}^{1+} depends on the size of the element:

$$G_{\mathrm{I}}^{1+} \cdot A = g_{\mathrm{I}}^{1+} \cdot A \cdot l^* \quad \rightarrow \quad g_{\mathrm{I}}^{1+} = \frac{G_{\mathrm{I}}^{1+}}{l^*}. \tag{2}$$

The fracture surface A and the characteristic element length l^* are illustrated in Figure 6. The fracture toughness per unit area G_{I}^{1+} can be measured experimentally, as shown in [13].

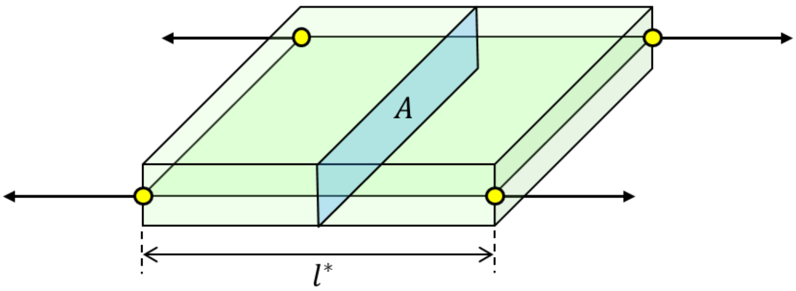

Figure 6: Finite shell element loaded in tension

On ply level, several constitutive models in literature adapt the theory of Bažant for unidirectional fiber reinforced composites [14-16]. However, to simulate the behavior of a laminate, this models only work associated with a fine modeling technic, where each ply is represented by at least one layer of elements and additional cohesive elements between the plies reproduce delamination [1]. To ensure its structural applicability, the presented laminate damage model is developed for layered shell elements (CLT elements). The difference to the ply-level defined model is, that the damage variable not only degrades the stiffness of the corresponding ply, but also the stiffness of the whole laminate. Therefore, the laminate's fracture toughness has been used instead of the fracture toughness of the ply. A simple model to predict the fracture toughness of multidirectional carbon–epoxy composite laminates using the fracture toughness of the 0°-ply is proposed in [17].

4 VALIDATION

To demonstrate the models applicability, open-hole tension tests are particularly suitable, as not only the strength of the laminate is validated, but also its fracture toughness. In [18] an experimental study of open-hole tension tests is presented. Within this investigation specimens with the same quasi-isotropic layup are varied in the hole-diameter and the specimen width. The hole-diameter to width and hole-diameter to length ratios are kept constant. The experimental results show a decrease of the open-hole tension strength with an increasing hole-size (see Figure 7). The presented laminate damage model achieves a very good agreement with the experiments. As material input for the model the data given by [18] is used. The mesh-size of the simulation models is 0.5mm for all diameters.

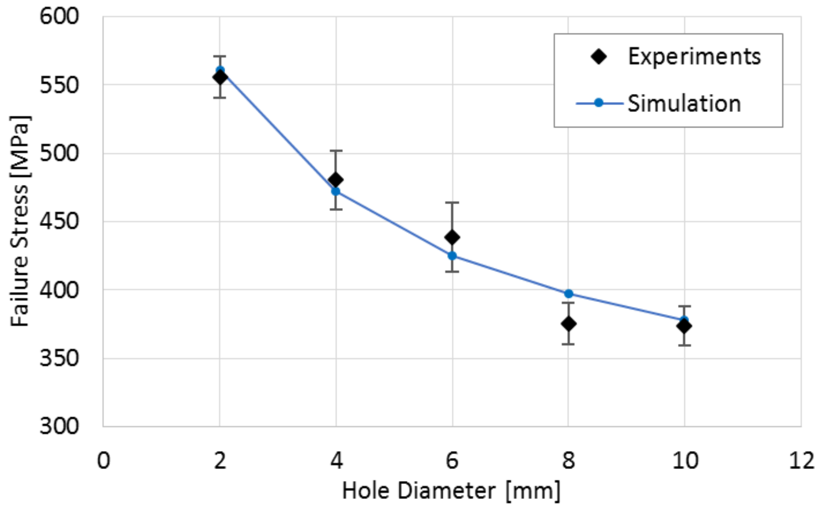

Figure 7: Open-hole tension strength for different hole diameters. Experiments from [18]

To evaluate the mesh-size independence of the model, the open-hole tension test with the 2mm hole was simulated with different mesh-refinements. The results of this study are given in Figure 8. The deviation in strength prediction of the different meshes is very slight according to the absolute value.

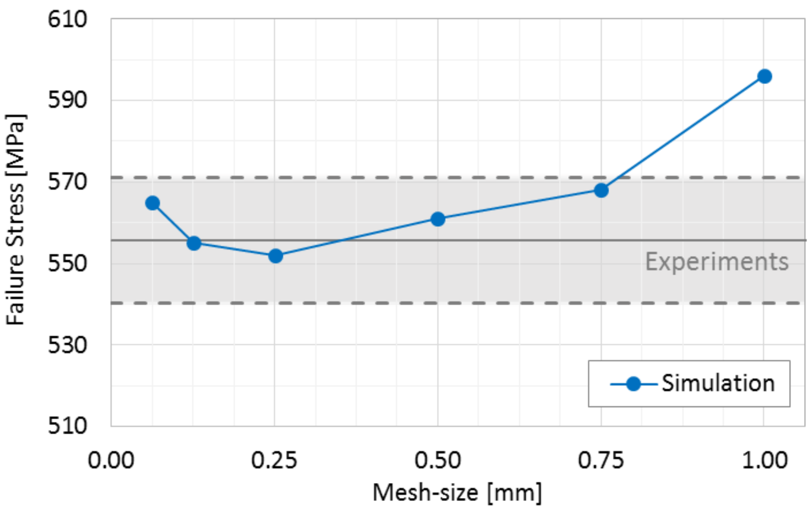

Figure 8: Open-hole tension strength for different mesh-sizes. Experiments from [18]

Applying an energy based stiffness degradation, leads to a maximum allowed element size, because the internal energy of an element at the point of damage initiation must not be greater than the fracture toughness. However, already for meshes with smaller elements than the maximum allowed, the predicted open-hole tension strength increases with a coarser mesh. If the discretization is too coarse close to a stress concentration, damage initiation occurs too late and the degradation analysis has no change to compensate the gap in damage initiation. A possibility to deal this problem is to reduce the corresponding strength value. But, this goes ahead with wrong predictions for homogeneous loaded regions of the laminate.

5 CONCLUSIONS

A material model for ultimate failure analysis of composite laminates is presented. The main difference to current failure and damage models for CFRPs is, that the softening is defined on laminate level. In other words, after reaching the fiber strength in one ply, leading to ultimate laminate failure, not only the stiffness of the corresponding ply is reduced, but also the stiffness of the whole laminate. Thus, the model is in particular applicable in combination with layered shell elements, where the complete stacking is represented within one element. For structural analyses often this discretization method is used to minimize the numerical effort. For validation an experimental study of open-hole tension tests with various hole-diameters was simulated. The model shows excellent correlation to the experiments and an extensive mesh size independence.

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