MECHANICAL BEHAVIOUR OF ANGLE-PLY LAMINATES

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Keywords: nonlinear constitutive behavior, angle-ply laminates, large deformations

Abstract

As a result of conservative design rules angle-ply laminates are currently not used in industrial application in spite of highly promising properties. To take advantage of their excellent constitutive properties, like quasi-ductile behavior and lightweight potential, in the future it is necessary to understand their behavior more thorough. A constitutive model is developed to describe the nonlinear response of laminates without fibers aligned in load direction. It is shown, that the effect of fiber rotation and damage is essential in consideration of large deformations. The evolution of yielding is described by two independent hardening curves either for longitudinal shear or transverse loading. A method for the experimental determination of the hardening curves is proposed based on uniaxial tests. To ensure the applicability to structural parts, the nonlinear constitutive model is validated by a large number of various angle-ply tension and off-axis compression tests, fabricated of the same carbon/epoxy IM7-8552 material. Extra wide specimen geometry was used for the conducted angle-ply tension tests to prevent delamination failure. Different types of specimens with single ply clustering and double ply clustering respectively have been investigated to take into account the influence of the layer thickeness on the response. The implemented model shows excellent correlation even at very large shear strains of up to 14%.

1. Introduction

The precise simulation of the stress-strain response prior to failure is essential to predict the ultimate failure of the laminate. Otherwise, incorrect stress states are determined, leading to misinterpretation of locus and time of damage initiation and progression. The constitutive response of composites prior to ultimate failure is determined by the interaction of 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 viscoelastic and viscoplastic deformations, fiber deflection 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. To avoid a considerable influence of time and temperature, the experiments are conducted quasi-static on low strain rates and room temperature. Equivalently, the constitutive model is implemented in the context of rate-independent plasticity with isotropic hardening to predict the material response for large deformations at quasi-static conditions. To show the interaction of the sources, influencing the nonlinear response, the calculation procedure of the material subroutine is illustrated schematically in Fig. 1. For an efficient analysis, the constitutive model is formulated to represent a macroscopic homogenized material.

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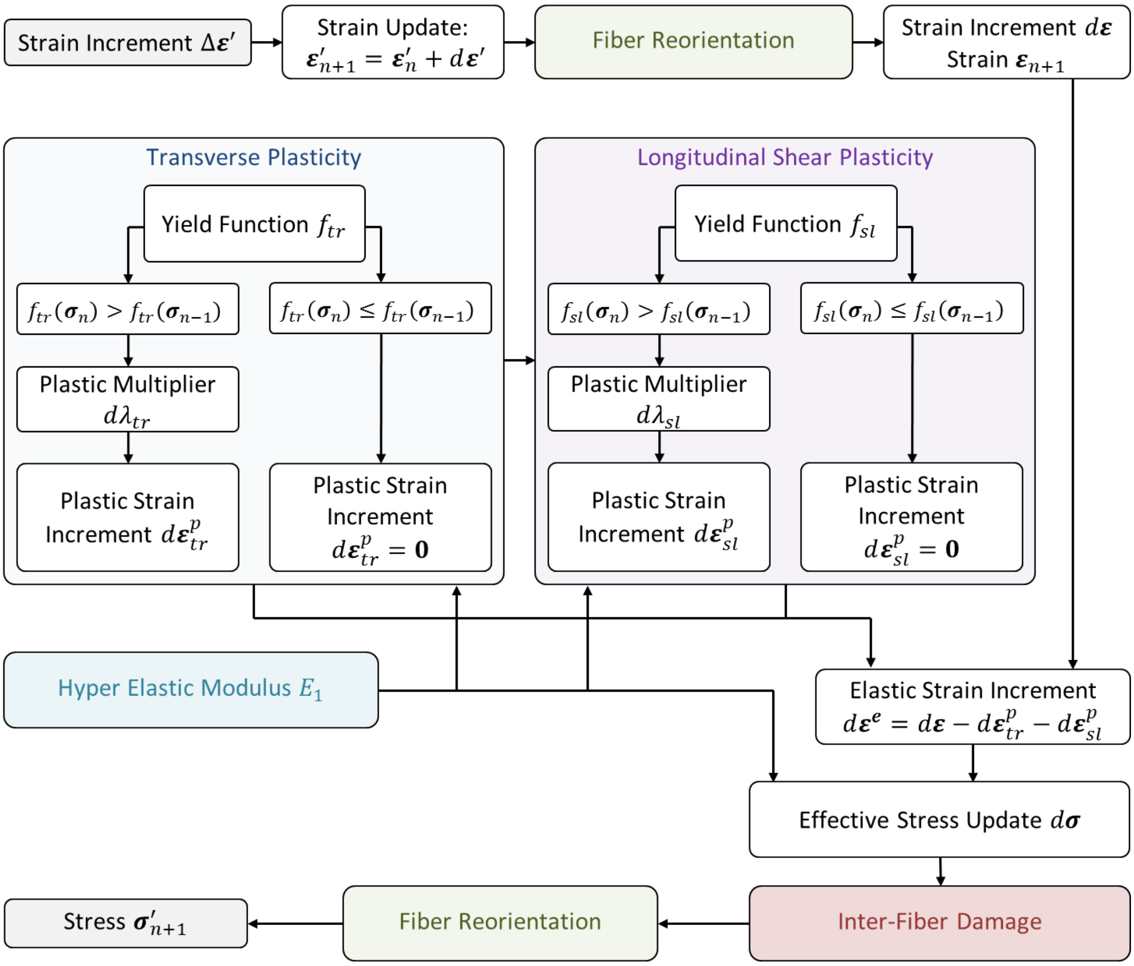

Figure 1. Flowchart of the calculation approach.

2. Deformation Induced Fiber Reorientation

The deformation induced reorientation of the fibers influences the constitutive behavior of composites especially at large deformations [1-4]. But for laminates with a large poison ratio, fiber rotation results in a considerable stiffening even at low deformations. The angle of the deformation induced rotation θ arises from the current deformation state

$$\theta = \arctan(\varepsilon'_{12}). \tag{1}$$

The strain components $\boldsymbol{\varepsilon}'_{12}$ and $\boldsymbol{\varepsilon}'_{13}$ are defined in the non-rotated coordinate system $\{\mathbf{1}', \mathbf{2}', \mathbf{3}'\}$, where the $\mathbf{1}'$-direction is aligned in fiber direction of the non-deformed state. According to the condition $\boldsymbol{n}_1^{\boldsymbol{\theta}} = \mathbf{0}$, the rotation tensor $\boldsymbol{R}$ can be written as

$$\boldsymbol{R}(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{2}$$

The actual strain, considering fiber reorientation, can be calculated incrementally

$$\boldsymbol{\varepsilon}_{n+1} = \boldsymbol{\varepsilon}_n + \boldsymbol{R}(\theta)^T \, d\boldsymbol{\varepsilon}' \, \boldsymbol{R}(\theta). \tag{3}$$

With the local strains present for the current time increment, the stress state can be calculated by application of the constitutive model, as shown in Fig. 1. The last step of the calculation procedure is the retransformation of the stress increment into the initial non-rotated coordinate system $\{\mathbf{1}', \mathbf{2}', \mathbf{3}'\}$

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$$\boldsymbol{\sigma}'_{n+1} = \boldsymbol{\sigma}'_n + \boldsymbol{R}(-\theta)^T \, d\boldsymbol{\sigma} \, \boldsymbol{R}(-\theta). \tag{4}$$

3. Fiber Hyper Elasticity

In literature the tensile behavior in fiber direction of carbon composites is usually assumed to be linearly elastic up to failure. However, the Young's modulus in fiber direction increases proportionally with the tensile stress [5]. This behavior can also be observed for single non-impregnated fibers [6]. According to this experimental observable feature the Young's modulus in fiber direction E_1 is defined as

$$E_1 = E_1^0 + k_f \, \sigma_{11}. \tag{5}$$

where E_1^0 is the initial Young's modulus and the constant k_f controlls the stiffening due to tensile load. As the material model is defined for explicit forward Euler time integration, for σ_{11} the value of the last time step is used. The material behavior in fiber direction is defined hyper elastic, so that the unloading path follows the loading path in the stress strain relation.

4. Partly Interactive Plasticity Model

The partly interactive plasticity model has been published for three-dimensional stress states [1]. The model includes two independent non-associative flow rules to describe yielding due to transverse and longitudinal shear loading, respectively. As material imput the model requires the corresponding two mastercurves and two additionalparameters accounting for the hydrostatic sensitivity of the neat resin. In this paper only the yield function and the plastic potential are given. A detailed description of the model and information about the determination of the required input data is given in [1]. The yield function $\boldsymbol{f_2}$ concerns the nonlinear behavior observed under transverse normal ply loads and is defined as

$$f_2 = \sigma_{22} + \alpha_{tr} \, \frac{1}{3}\left(\frac{E_m}{E_1}\sigma_{11} + \sigma_{22}\right). \tag{6}$$

The plastic potential used for the flow rule is defined non-associative.

$$g_2 = \sigma_{22}. \tag{7}$$

To describe the plastic deformation caused by in-plane shear, the following yield function is defined

$$f_{12} = |\sigma_{12}| + \alpha_{sl} \, \frac{1}{3}\left(\frac{E_m}{E_1}\sigma_{11} + \sigma_{22}\right). \tag{8}$$

The corresponding non-associative plastic potential reads

$$g_{12} = |\sigma_{12}|. \tag{9}$$

5. Inter-Fiber Damage

Angle-ply laminates are one of the most widely used test specimens to evaluate the stress-strain response of composite materials. Especially $\pm 45°$ laminates are often used to obtain pure shear properties [8]. This kind of laminate possesses the ability, to carry loads far in excess of initial damage events. To determine reliable data of the nonlinear load response, the influence of damage on the laminate stiffness has to be integrated in an accurate model.

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6.1. Inter-Fiber Damage Initiation

For the layer wise detection of inter-fiber damage initiation in laminates the plane stress Puck Criterion [8] is suitable in principle. However, the constraint effect of the surrounding plies must be considered. Therefore, in-situ strength values depending on the ply thickness need to be determined. The in-situ transverse tensile strength has been determined by analyzing micrographs of different loaded cross-ply laminates. The in-situ shear stress has been estimated based on ±45° tension tests with single and double ply-clustering. For pure transversal compressive loads, damage is not active in the present model. For a unidirectional specimen fracture appears on a plane with an angle of about 54°. In a laminate, this failure mechanism would induce an inter-ply delamination between plies of differing fiber orientations. Remarkably, within the experimental study, such a failure mode has not been found. Prepared micrographs of $\pm\mathbf{45}°$ specimens exhibit only vertical cracks. Based on these observations, the proposed damage initiation criterion exclusively detects shear failure. Therefore, only Mode B of the Puck Criterion is used to detect inter-fiber damage initiation under combined in-plane shear and transverse compressive load.

6.2. Inter-Fiber Damage Progression

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. Therefore, two scalar damage variables are introduced. The affected stresses are directly degraded through multiplication with the relating variables. The relation between the undamaged effective stresses and the smeared nominal stresses is given by

$$\sigma_{22} = (1 - d_2)\sigma_{22}^{eff}, \tag{10}$$

$$\sigma_{12} = (1 - d_{12})\sigma_{12}^{eff}. \tag{11}$$

The damage variables are calculated by simple approach, where the difference of the current strain to the strain at damage initiation is multiplied by a constant. For transverse tension and in-plane shear different constants are necessary. If a transverse compressive stress is acting, the damage variable d_2 is set to zero.

$$d_2 = k_2\left(\varepsilon_{22} - \varepsilon_{22}\left(\frac{\boldsymbol{\sigma}}{f_E}\right)\right), \tag{12}$$

$$d_{12} = k_{12}\left(\varepsilon_{12} - \varepsilon_{12}\left(\frac{\boldsymbol{\sigma}}{f_E}\right)\right). \tag{13}$$

To prevent material healing the damage variables are only updated then they increase. During unloading the material model exhibits linear elastic behavior without additional damage and yielding. For subsequent reloading the stress-strain response is consistent with the unloading curve until the yield surface or damage initiation is reached. Thus, energy creation is avoided.

7. Results

Within the study, several tension tests of angle-ply laminates have been conducted. This kind of experiment enables combined stress states at high shear strains in the specimen. Due to a wide specimen geometry, large axial strains can be obtained and thereon the verification of the model applicability up to large deformations is possible. Plates of angle-ply laminates were fabricated in a hot press machine with steel spacers to assure a constant thickness distribution of 2.0mm. The plates were produced according to the standard curing cycle. The material used for the experimental study is Hexcel IM7-8552 unidirectional carbon/epoxy prepreg with a single ply thickness of 0.125mm. Two

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different layups have been tested for each off-axis angle. One with single ply clustering, where the plies are stacked alternating and one with double ply clustering, where allways two plies with the same fiber orientation are stacked together. The laminated plates were cut into specimens with a length of 350 mm and a width of 50mm. The size of the specimens was selected to avoid a substantial dependence of edge delamination on the constitutive behavior. A gauge length of 250mm minimizes an influence of the clamped support. Three samples for each layup were sliced from the fabricated plates. A glass fiber/epoxy material was used for the end-tabs. The dimensions of the end tabs are 50x50mm and the thickness is 1.0mm. The specimens were tested under tension in a load frame at a cross-head strain-rate of 0.0001s-1. All tests were conducted under displacement control. The strain was captured using an optical system ensuring a full-field strain measurement.

The presented angle-ply tests for the IM7-8552 carbon/epoxy material are simulated with the explicit finite element solver of Abaqus. The described material model has been embedded using a user-defined material. The material parameters are given in Table 1. The master curves for the plasticity model are given in [1].

Table 1. Material properties for IM7-8552 used for the simulations

Longitudinal Stiffness	E_1	163	[GPa]
Fiber Hyper Elasticity Parameter	k_f	20	[-]
Transverse Stiffness	E_2	9	[GPa]
In-plane Poisson`s Ratio	ν_{12}	0.32	[-]
In-plane Shear Stiffness	G_{12}	5.29	[GPa]
Hydrostatic Sensitivity – Transverse Plasticity	α_{tr}	0.42	[-]
Hydrostatic Sensitivity – In-Plane Shear Plasticity	α_{sl}	0.25	[-]
Transverse Tension Strength Single Clustered	YT	86	[MPa]
Transverse Tension Strength Double Clustered	YT	63	[MPa]
In-plane Shear Strength Single Clustered	SL	93	[MPa]
In-plane Shear Strength Double Clustered	SL	83	[MPa]
Puck Inclination Parameter	$p_{\perp\parallel}^{t}$	0.27	[-]
Puck Inclination Parameter	$p_{\perp\parallel}^{c}$	0.27	[-]
Damage Parameter - Transverse Tension	k_2	70	[-]
Damage Parameter - In-Plane Shear	k_{12}	2.4	[-]

The verification is stated by a comparison of the remote stress-strain response. The focus of this validation is the nonlinear material behavior of the specimens and not the strength, since the numerical model does not contain an ultimate failure criterion. As shown in Fig. 2, the presented results indicate the excellent correlation between the predicted and measured responses. Therefore the model provides a basis to evaluate the sources for the nonlinear constitutive behavior. Moreover, the interactions of the different mechanisms can be considered, which cause the actual stress-strain response. For larger axial strains, fiber reorientation generally provokes an increased stiffness for the angle-ply tension specimens. If damage occurs in the material, the stiffness of the laminates is reduced. This effect is present only for some of the specimens. Within the present study, also ply thickness dependent effects on the laminate response were investigated. It is shown that a layup dependency solely emerges from inter-fiber damage mechanisms, whereas plastic strain accumulation is not affected by the ply

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thickness.

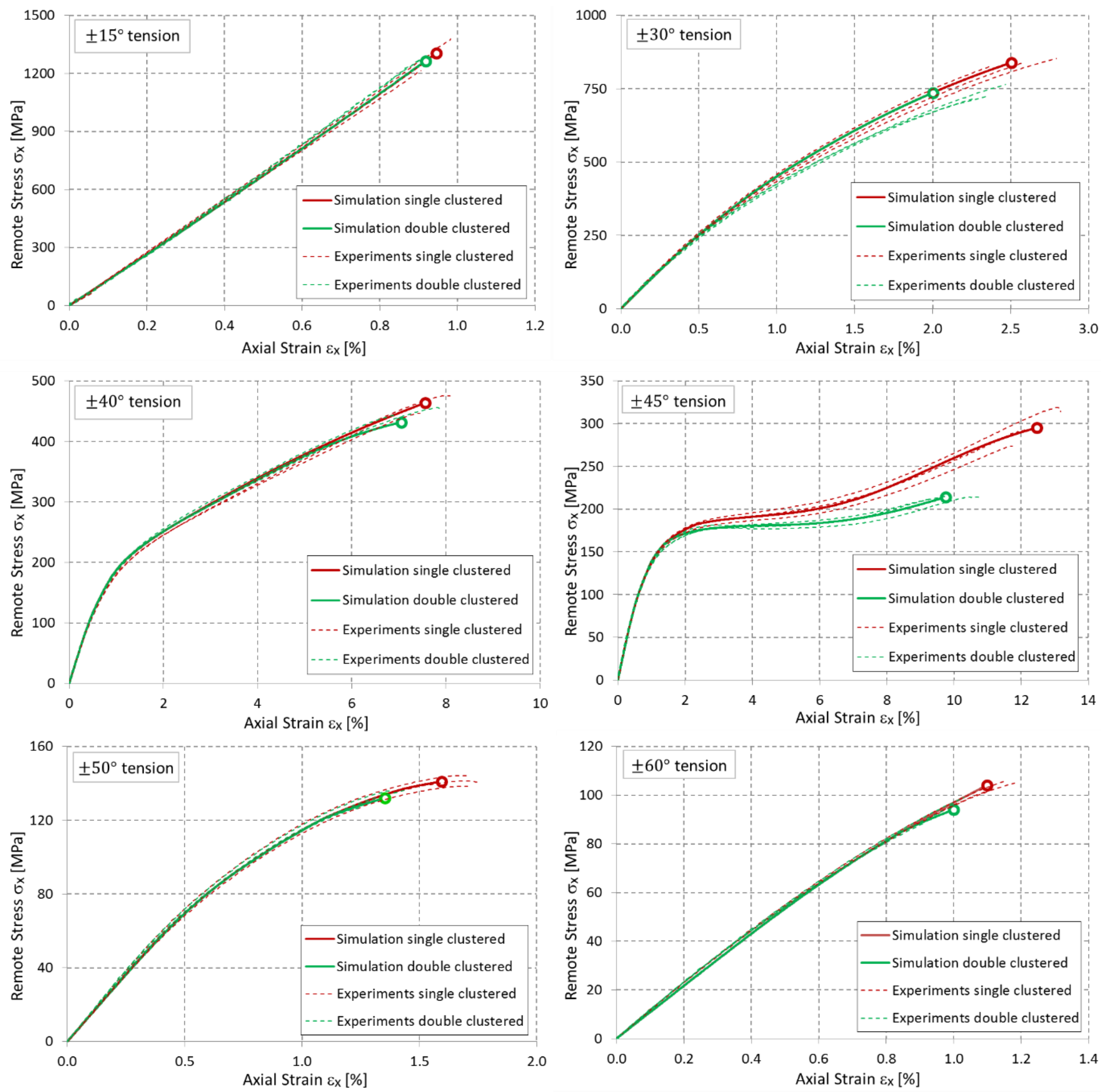

Figure 2. Remote axial stress-strain response of angle-ply tension specimens for IM7-8552.

3. Conclusions

A nonlinear material model for composite laminates able to represent large deformations has been developed. Displacement-induced fiber rotation and inter-fiber damage are considered, as these effects characterize the laminate response at high strain levels. The hardening is described by two independent master curves either for in-plane shear or transverse normal load. For an efficient analysis, the model has been implemented as a user-defined subroutine for the explicit FEA solver of Abaqus. For a comprehensive validation, the model has been compared to conducted angle-ply tension tests. A large specimen width was chosen to avoid delamination failure of the angle-ply laminates. Comparisons between the simulated and experimental observed material response show excellent correlation for all specimens. The exact prediction of various different nonlinear stress-strain characteristics demonstrates the reliable applicability of the presented model. It is further shown that solely inter-fiber damage mechanisms are affected by the ply thickness. Plastic flow is not affected by layup effects like ply thickness and the angle difference between adjacent plies.

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