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Study of layup influences on the nonlinear behavior of composites by evaluation of ply stiffness reduction

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ABSTRACT

The influence of the stacking sequence on the nonlinear response of composite laminates is investigated. It is shown that a layup dependency solely emerges from damage evolution mechanisms, whereas damage initiation and viscoelastic and viscoplastic strain accumulation are not affected by the layup. This is a result of a proposed procedure that enables the evaluation of the stiffness reduction on lamina level. The residual ply stiffness components can be determined at large deformations and for various laminates under in-plane loading conditions. A finite element study is utilized to characterize the properties of a ply containing discrete cracks. The relationship between transverse and shear stiffness reduction is derived from the FE results. This allows the combined determination of the residual lamina moduli from an axial laminate stiffness. The analysis approach is validated by angle-ply specimens with different layups.

1. Introduction

The precise simulation of the stress–strain response is essential for a reliable prediction of the structural integrity of components made of fiber-reinforced polymer-matrix composites (PMCs). For numerous loading conditions, unidirectional continuous fiber-reinforced composites exhibit nonlinear mechanical response. Loaded in fiber direction, the modulus of a laminate increases slightly with the tensile stress [1]. Failure occurs at comparatively low achievable strains. Laminated plies subjected to transverse or shear loads exhibit a nonlinear material behavior due to the polymer properties. Several demands for a composite design require the structural ability for large deformations. This motivates the application of laminates loaded off-axis to the fibers. These laminates are governed by a matrix dominated constitutive behavior and thus, offer the ability to employ their ductile mechanical characteristics. Accordingly, angle-ply laminates offer the opportunity to investigate the influence of polymer features on the mechanical behavior of PMCs.

Various concurrently acting mechanisms are responsible for the degree of nonlinearity. The mechanical behavior of polymeric materials is significantly time dependent. This results in viscoelastic and viscoplastic strain accumulation [2,3]. Another influencing factor of nonlinear behavior are damage processes during loading history [4–6]. A growing inter-fiber crack development results in laminate stiffness reduction, especially at large strains. Moreover, fiber rotation leads to an altering mechanical response of the material [6–8]. Considering the sources of nonlinearity and their interaction depending on the laminate stacking sequence is crucial for the accurate development of a constitutive modeling approach.

In the present study, the constitutive response of a composite by means of homogenized damaged continuum properties is investigated. The effective moduli on laminate and lamina level are considered as the elastic material response from the direct state coupling through the concept of effective stress [9]. The effective lamina properties are derived from measurements of the laminate axial modulus from angle-ply tension tests. This enables the investigation of the material response up to large deformations. For angle-ply laminates, an analysis of the variation of the elastic modulus is more sensitive compared to an edge crack counting approach, often applied for cross-ply laminates [10–13].

The influence of the free-edge effect on the strength of angle-ply specimens is subject of extensive investigations [14,15]. As shown by Kress [16], a sequence of stacked $+\theta$ and $-\theta$ plies causes increased interlaminar shear stresses at the edge of the specimens. Moreover, the intralaminar stresses differ between the edges and the center of the laminate. The transverse and shear stress component increase, which causes an inter-fiber failure onset at the specimen edge. Sket et al. [17] have conducted extensive X-ray computed tomography studies of the damage progression of ±45° laminates. They showed that cracks are initially developed at the

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specimen edge and barely extend into the specimen center. For sufficiently wide samples, these cracks have little effect on the laminate constitutive behavior. A crack counting approach that provides relations between the effective moduli of the cracked layer versus crack density has to account for the varying length of the cracks. Thus, the proposed experimental approach for the determination of the lamina stiffness components of angle-ply laminates involves measuring the laminate stiffness of loading-reloading cycles, and incorporating a relationship between the constitutive parameters on laminate and lamina level.

The stiffness reduction of a 0°/90° cross-ply laminate with transverse inter-fiber cracks can be observed and measured by standardized uniaxial tension tests. Their unique feature is that only fiber longitudinal and transverse tension loads are acting and cracks span across the whole width of the specimen. Laminate stiffness variations can be reduced to a problem of linear elastic material behavior combined with the development of matrix cracks. In laminates with off-axis plies, especially with angle-ply layups, notable shear deformation occurs. In many cases a combined normal-shear stress state acts in lamina principal material directions. Due to the lack of an effective method to measure the shear stiffness reduction caused by matrix cracking, only a few experimental results have been reported [18,19]. The stiffness measurement has to be critically examined. A change in the elastic properties can be the result of damage processes or caused by the polymer features or fiber rotation in the specimen. Some attempts were made to achieve a pure shear stress state in a specimen. A reported test fixture is the rail shear test [20,21]. This test is very sensitive to the deformation, due to induced bending. Especially for large deformations, no pure shear stress state is provided [22]. The effective stiffness evaluation from conducted ±45° tensile coupon tests, based on the presented procedure of Rosen [23], is inaccurate as well. The combined stress state influences the results, when fiber rotation alters the initial laminate-lamina stiffness relationship. In the present study the stiffness reduction of several angle-ply laminates is investigated. A procedure is proposed that enables the combined evaluation of in-plane normal and shear stiffness reduction. Moreover, the numerical-experimental approach is applicable for large deformations. This is important, as no reliable experimental data on stiffness reduction at large strains are currently available.

Most reported studies in the literature dealing with the prediction of stiffness reduction due to matrix cracking focused solely on laminate response. The objective of the present paper is the investigation of the laminate layup influence on the nonlinear constitutive behavior of composites. The constitutive behavior of the laminated plies has to be considered, in order to provide a physical based explanation for experimentally determined differences of the nonlinear response. The proposed test and analysis approach allows to assess the reduction of particular ply stiffness components for different layups and arbitrary in-plane load combinations. Knowing the influence of damage mechanisms on ply properties is important for a correct laminate analysis. The procedure can be used for the validation of material models representing the behavior of composite laminates.

2. Constitutive behavior of angle-ply laminates

The global stress–strain behavior of in-plane loaded $\pm\theta$ angle-ply laminates can be described by the laminated plate theory. It is assumed, that damage growth in angle-ply laminates is homogenous for plies of the same thickness. This results in uniform evolution of the effective ply properties. The laminate is assumed to be symmetric, orthotropic and balanced until failure. Damage evolves from inter-fiber crack development without delamination. Based on these assumptions, the continuum stress–strain relation can be defined as:

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{pmatrix} = \left[\widehat{\boldsymbol{S}}\right]_{lam} \begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{pmatrix}, \tag{1}$$

where $\left[\widehat{\boldsymbol{S}}\right]_{lam}$ is the effective laminate compliance matrix including homogenized damage. For symmetric and balanced angle-ply laminates it is defined as:

$$\left[\widehat{\boldsymbol{S}}\right]_{lam} = \begin{bmatrix} \widehat{S}_{11} & \widehat{S}_{12} & \widehat{S}_{16} \\ \widehat{S}_{12} & \widehat{S}_{22} & \widehat{S}_{26} \\ \widehat{S}_{16} & \widehat{S}_{26} & \widehat{S}_{66} \end{bmatrix} = \begin{bmatrix} \frac{1}{\widehat{E}_x} & -\frac{\hat{\nu}_{xy}}{\widehat{E}_x} & 0 \\ -\frac{\hat{\nu}_{xy}}{\widehat{E}_x} & \frac{1}{\widehat{E}_y} & 0 \\ 0 & 0 & \frac{1}{\widehat{G}_{xy}} \end{bmatrix}. \tag{2}$$

With a direct state coupling the laminate stress–strain behavior is defined through effective lamina stiffness matrices of the single plies:

$$\{\boldsymbol{\sigma}\}_{xy} = \frac{1}{n}\sum_{k=1}^{n}[\boldsymbol{T}]_k^{-1}\left[\widehat{\boldsymbol{Q}}\right]_k[\boldsymbol{T}]_k\{\boldsymbol{\varepsilon}\}_{xy}, \tag{3}$$

where n is the number of plies in the laminate.

$$[\boldsymbol{T}]_k = \begin{bmatrix} \cos^2(\theta') & \sin^2(\theta') & \sin(\theta')\cos(\theta') \\ \sin^2(\theta') & \cos^2(\theta') & -\sin(\theta')\cos(\theta') \\ -2\sin(\theta')\cos(\theta') & 2\sin(\theta')\cos(\theta') & \cos^2(\theta')-\sin^2(\theta') \end{bmatrix}$$

is the transformation matrix of the$k$-th ply, where θ' is the fiber orientation angle related to the deformed state. The effective lamina stiffness matrix $\left[\widehat{\boldsymbol{Q}}\right]_k$ is similarly defined for each ply in the laminate:

$$\left[\widehat{\boldsymbol{Q}}\right]_k = \begin{bmatrix} \widehat{Q}_{11} & \widehat{Q}_{12} & \widehat{Q}_{16} \\ \widehat{Q}_{12} & \widehat{Q}_{22} & \widehat{Q}_{26} \\ \widehat{Q}_{16} & \widehat{Q}_{26} & \widehat{Q}_{66} \end{bmatrix} = \begin{bmatrix} \widehat{Q}_{11}(\widehat{E}_1,\hat{\nu}_{12},\hat{\nu}_{21}) & \widehat{Q}_{12}(\widehat{E}_1,\hat{\nu}_{12},\hat{\nu}_{21}) & 0 \\ \widehat{Q}_{12}(\widehat{E}_1,\hat{\nu}_{12},\hat{\nu}_{21}) & \widehat{Q}_{22}(\widehat{E}_2,\hat{\nu}_{12},\hat{\nu}_{21}) & 0 \\ 0 & 0 & \widehat{Q}_{66}(\widehat{G}_{12}) \end{bmatrix}. \tag{4}$$

With Eqs. (1)–(4) the coupling of the effective laminate and lamina moduli can be described. Accordingly, the variation of the homogenized axial laminate modulus $\widehat{E}_x$ depends on the ply-based change of the stiffness matrix components. As indicated in Eq. (4), they can be represented by a functional relation to the behavior of the effective material constants. As shown in [22], the residual lamina properties are laminate dependent. Related parameters, such as crack density, thickness of the cracked plies and constraint conditions due to stacking directions of adjacent plies have to be taken into account. They have a significant influence on the lamina effective stiffness matrix and, as a consequence, on the changing relationship of the elastic constants. Measuring the effective axial stiffness evaluates the homogenized behavior of a laminate only.

A direct coupling of the laminate and lamina constitutive behavior during damage progression neglecting the laminate influences is severely limited. Either a laminate stiffness reduction results exclusively from a variation of a single lamina property or the evolution of the relationship between the effective ply properties is known. The measurement of the residual stiffness from ±45° tension specimens, as shown in [24–26], fulfills the first condition, but is limited to this particular layup and small deformations. For laminates with combined stress states, as investigated in the pre-