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Mechanism based nonlinear constitutive model for composite laminates subjected to large deformations

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ABSTRACT

A nonlinear constitutive model for composite laminates is developed with the focus on the distinction among inducing mechanisms. 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 in-plane shear or transverse normal load. A method for the experimental determination of the hardening curves is proposed based on uniaxial tests. To ensure the applicability to structural parts, the numerical 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. The implemented model shows excellent correlation even at very large shear strains of up to 14%.

1. Introduction

To take advantage of the excellent properties of fiber reinforced plastics (FRP), the application is predominantly in thin structures of unidirectional (UD) plies with continuous fibers. Since structural parts typically have to be designed for numerous load cases, a weight-efficient layup does not allow fibers aligned in all directions of acting force fluxes. This causes a nonlinear material response. Additionally, some specific load cases require high failure strains, obtainable by off-axis plies. Depending on the layup, the constitutive behavior of UD laminates is significantly influenced by different processes and their interactions. An accurate analysis of the structural integrity of CFRP components requires the consideration of all phenomena influencing the constitutive material behavior. The precise simulation of the stress–strain response prior to failure is essential to predict the ultimate failure of a structure. Otherwise, incorrect stress states are determined, leading to misinterpretation of locus and time of damage initiation and progression.

For the evaluation of the nonlinear behavior of fiber reinforced plastics and effects of various stress interactions, several tests are conceivable. In order to investigate bi-axial in-plane combined shear and normal stress states, an off-axis compression (OAC) or tension (OAT) test can be conducted on unidirectional laminates [1]. Combined bi-axial tests with two load actuators are presented in [2]. Equivalently, an interaction of in-plane shear and normal stress or different normal stress components, especially transverse to the fiber, is achievable. Angle-ply [$\pm\theta$] laminates are a further possibility to provide a bi-axial stress state, as shown in [3,4]. Fig. 1 shows the local stress state composed of shear stress and normal stress transverse to the fibers within different angle-ply laminates. The advantage of using angle-ply laminates is the significant nonlinear constitutive behavior as well as the robust stress–strain characteristic and the avoidance of structural instability modes. Moreover, as indicated in Fig. 1, angle-ply laminates are subjected to a highly non-proportional interaction of the local stress components that do not occur in unidirectional off-axis tests. Combined tri-axial stress states can be provided by complex specimen geometries, but such a stress state is non-uniform and not specific. Another experimental procedure generating tri-axial stress states is to conduct the tests under applied hydrostatic pressure [5].

Current yield criterions for the representation of the nonlinear material behavior of fiber-reinforced polymers are predominantly based on the deviatoric yield criterion for orthotropic solids, known as Hill's criterion [6] or the Drucker–Prager yield criterion [7], which accounts additionally for the hydrostatic stress state. Both criteria are theoretically formulated as fully interactive in the yield behavior of the considered stress components.

Hill [6] presented a generalized yield criterion for orthotropic material behavior. It is based on a fully quadratic stress interaction neglecting linear stress terms. The yield locus is defined by 6 parameters which can be determined experimentally. Hill proposed 3 uniaxial tension tests in the principal directions

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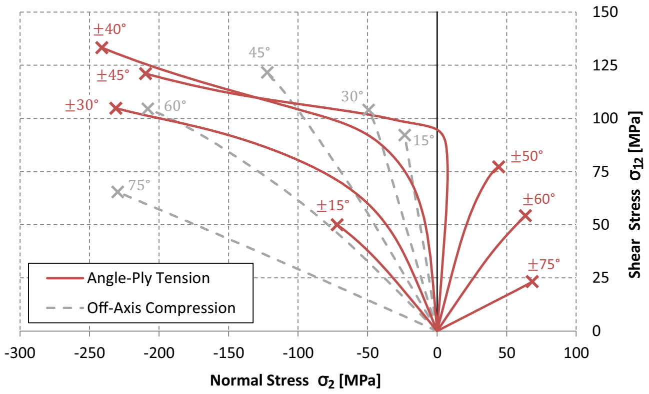

Fig. 1. Local stress evolutions based on experimental results of angle-ply tension and off-axis-compression [1] specimens.

orthogonal to the planes of orthotropy and 3 pure shear tests in the planes of orthotropy. Xi [8] proposed a yield criterion based on a simplification of Hill's work related to FRP's. With the assumption of transverse isotropy and an assumed linear elastic behavior in fiber direction, the number of required parameters is reduced to two. As they are considered as intrinsic material constants, one hardening decisive effective stress–strain curve is defined, based on 5 different uni- and bi-axial test setups. A further reduction of Hill's yield criterion for the application on FRP's is proposed by Sun [4]. Due to a fixed specification of several yield parameters, only one parameter has to be provided. Similar to [8], a single effective stress–strain curve is proposed to assign the hardening behavior under various stress states. Sun [4] proposed a set of in-plane off-axis tests in order to define the hardening curve. As shown in [9] for unidirectional CFRP laminates of IM7-8552, it is not possible to match OAC and OAT results with only one single hardening curve. The application of two curves would provoke a knee in the stress–strain curve for a [±45]-laminate at the transition of tension and compression regime. A direct formulation of a yield criterion for FRP's is presented by Boehler [10] based on invariants formulation in the context of the generalized theory of transversely isotropic solids. Spencer [11] proposed a criterion taking into account only quadratic stress interactions. The criterion exclusively consists of deviatoric stress invariants, as he assumes an independence of hydrostatic stress. Moreover, yielding is not affected by stresses in fiber direction, as only fiber independent stress invariants are used. In a recent paper, Vogler [11] stated a tri-axial yield criterion including an additional invariant that contains linear non-deviatoric stress terms, transverse to the fiber. The criterion is equivalent to Hill's criterion neglecting stress terms in fiber direction, but accounts opposite to Hill for a transverse axial compression and tension sensitivity. For the determination of hardening parameters under combination of various stress states, he proposed six different test setups. An in-plane and transverse shear test, one transverse uniaxial compression and tension test and one bi-axial compression and tension test. The model is validated on in-plane off-axis compression tests.

A second group of yield criteria is based on the experimentally-detected dependence of polymers on hydrostatic pressure [13]. A yield criterion for FRP's according to this effect is shown by Vyas [14]. He proposed an adopted Drucker–Prager criterion, taking into account the transverse stress components for hydrostatic sensitivity and assuming linear elastic behavior in fiber direction.

A rather different modeling approach is presented by Flatscher [15] for plane stress conditions. He distinguishes between two different mechanisms for plastic strain accumulation of in-plane shear and transverse compression. Both mechanisms are considered separately on a specific shear plane oriented on fracture planes defined by Puck's failure criterion. For both mechanisms, a separate flow rule and its own hardening behavior is assigned. The idea to separate yielding is inevitable, especially considering the same development in the field of composite failure.

Although, several material models are available for composite design, it is obvious that there is a lack of experimental verification. The validation of a constitutive model based on a small number of different tests or a barely varying experimental setup with similar loading states in all specimens does not ensure its general applicability. As shown in [9] and [12], fundamentally different plasticity approaches are able to match the same series of UD off-axis compression tests. Due to the fact that experimental results considering more than bi-axial stress combinations are not available and not necessary for most composite structural applications, within the present study, a new nonlinear constitutive model for plane stress conditions is developed. For a considerable experimental foundation, the developed constitutive model is verified with conducted tension tests of several angle-ply laminates and off-axis-compression tests found in literature [1]. Extra wide specimen geometry minimizes the propagation of free edge delamination and allows for the observation of the material response at large axial strains. An experimental validation including several materials requires the determination of different parameters for the constitutive model. Thus, it increases the risk of deficient modeling. In the present study the conducted and considered test results are exclusively for carbon fiber/epoxy composite IM7-8552.

For an efficient analysis, the constitutive model is formulated to represent a macroscopic homogenized material. The presumed sources for nonlinear material behavior are evaluated in order to identify the contribution of nonlinear strain accumulation, fiber rotation and damage processes. Furthermore, different probable influencing interactions are subjected to a critical discussion concerning physical relevance relating to the application within the scope of this numerical and experimental study. Current models from the literature do not sufficiently represent essential influencing mechanisms on the nonlinear response. Some models account for fiber rotation, others for damage, but no model adequately considers both relevant sources and their interactions. Thus, current constitutive models for composites are not applicable for large deformations.

2. Constitutive behavior

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. 2. The numerical