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AN ELASTO-PLASTO-DAMAGE CONSTITUTIVE PLY MODEL FOR FEM-ANALYSES OF LAMINATED COMPOSITE STRUCTURES

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ABSTRACT

Introduction:
For the purpose of light weight design, laminates made of fiber reinforced polymers (FRP) are becoming increasingly important. To tap the full potential of such material systems, reliable prediction of the mechanical behavior is desired. The present work is concerned with the prediction of the non-linear behavior of continuous fiber reinforced polymer plies embedded in laminates. The work is focused on matrix dominated phenomena which occur already before the ultimate load of the laminate is reached and lead to non-linearity in the overall laminate behavior.
Importance is attached to the reliable prediction of stiffness degradation and residual strains accumulated during loading. A constitutive model is proposed, implemented as material model within the Finite Element Method (FEM), and applied in structural analyses.

Constitutive Model:
Based on the work in [1], separate formulations concerning two phenomena, i.e. shear plasticity and brittle damage, are developed. The formulations are combined in an elasto-plasto-damage constitutive model for prescribing the ply behavior.
One part of the constitutive model concerns the prediction of residual strains which accumulate mainly under in-plane shear loads and transverse compression [1]. For this purpose, a phenomenological approach is used assuming plastic mechanisms for which scalar plasticity laws are proposed.
The other part of the constitutive model uses continuum damage mechanics to incorporate stiffness degradation and is based on considerations for brittle failure as postulated by Puck. To account for the effect of brittle matrix cracks, fictitious penny-shaped voids are assumed inside the transversally isotropic ply material. For loads which lead to crack closure, the voids turn into inclusions with non-zero stiffness. Even so, they are referred to as “voids” in the following. The voids are not intended to represent actual cracks, but provide a method to incorporate brittle damage mechanisms in tensorial formulation into the model. The proposed approach associates various stiffness degradations in different

directions with the applied loading and, therefore, is able to capture the anisotropic nature of damage [1].

Implementation:
To make the constitutive model available in structural analyses, it is implemented as user defined material within the commercial FEM code Abaqus/Standard (SIMULIA, Providence, RI, USA).
In order to account for residual strains, the ply material is taken to be anisotropic elasto-plastic. As soon as damage occurs, the elasto-plastic constitutive equations are applied to the still virgin material "between" the voids. To gain the strain state between the voids, the strain equivalence principle is used. This entirely decouples the computation of plastic strains from the computation of the degraded stiffness and, therefore, leads to an efficient implementation.
For the integration of the plasticity law, a return mapping algorithm is used. The effect of the voids on the material stiffness is predicted by recourse to a Mori-Tanaka Mean Field Method which gives the entire secant stiffness tensor. In order to account for different damage modes, several populations of voids are assumed and the void stiffness is assumed to be dependent on the current stress state. This way the effect of crack opening and closing is captured.
With the implemented constitutive model, arbitrary plane stress loading histories can be simulated. At the same time, the transitions between different modes of plastic shear deformations and different modes of damage are captured. The number of material parameters is kept small and only a few standard experiments are needed to calibrate the model.

Application:
To demonstrate the constitutive response given by the implemented material model, several stress-strain curves for proportional and non-proportional ply loadings are predicted. The comparison to coupon tests with various bi-axial loading histories from the literature shows good agreement. Both, anisotropic stiffness degradation as well as residual deformations are predicted satisfactorily.
The implemented material model is also used in FEM simulations of layered composite structures. The predictions for an open hole compression test are presented and compared to results available in the literature. In contrast to experiments, for each material point the FEM simulations allow to distinguish between the influence of residual strains and damage on the nonlinear material response. Additionally, the effect of plasticity is demonstrated by comparing the response predicted by the elasto-plasto-damage constitutive model to predictions in which only brittle damage is assumed.

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