Abstract submitted for oral presentation at
7th ECCOMAS Congress Crete Island, 5–10 June 2016

Formulation and Implementation of an Orthotropic Constitutive Model for Coupled Elastoplastic - Damage

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The focus of this work is modeling the non-linear response of embedded plies within a fiber reinforced laminate due to matrix cracking and plasticity. Non-linearity prior to damage onset is assumed to be purely plastic, furthermore, a plane stress state is assumed with a homogeneous stress distribution inside the laminate plane. A coupled elastoplastic and damage approach is proposed where the non-linear response is modelled by introducing a set of internal variables describing the plasticity and damage behavior. The model problem is described by primary fields $\{\boldsymbol{\varepsilon}, \boldsymbol{\varepsilon}^p, \boldsymbol{d}, \alpha\}$ and the decoupled strain energy Ψ is defined as

$$\Psi = \Psi(\boldsymbol{\varepsilon}, \boldsymbol{\varepsilon}^p, \boldsymbol{d}, \alpha) = \frac{1}{2}\, \boldsymbol{\varepsilon}^e : \boldsymbol{E}(\boldsymbol{d}) : \boldsymbol{\varepsilon}^e + \Psi^p(\alpha) \tag{1}$$

Damage models capture the degradation of stiffness due to cracks/voids which are best described by a dimensionless quantity $\boldsymbol{d}(\boldsymbol{x}, t)$. These cracks grow in time from an initial undamaged state $\boldsymbol{d}(\boldsymbol{x}, 0) = \boldsymbol{0}$ to a fully damage state at $\boldsymbol{d}(\boldsymbol{x}, t) = \boldsymbol{1}$ thereby capturing the irreversabilty of damage mechanics. An orthotropic continuum damage formulation is employed here to describe the anisotropic effect of damage observed in composite materials. To define $\boldsymbol{d}$, three damage variables d_1, d_2, and d_3 are used corresponding to fiber, matrix and shear failure modes, respectively, where the shear failure mode is expressed as a function of fiber and matrix failure following [2]. A modified formulation is used to describe damage onset and damage progression as a function of thermodynamic dual driving force.
The material response prior to damage onset is assumed to be elasto-plastic and is captured by a plasticity formulation. The flow rule for plastic strain is specified by a modified yield function neglecting the deviatoric stress component in fiber direction which ensures the behavior in longitudinal direction to be linear elastic up to fracture. A backward/implicit Euler time integration scheme is applied. In the chosen formulation, the two processes of plasticity and damage are coupled only by effective stresses, $\bar{\boldsymbol{\sigma}} = \boldsymbol{\sigma}/(1 - \boldsymbol{d})$, which sets nominal stress in relation with the (higher) effective stress that acts in an undamaged material cross section. For a quantitative assessment of the model, predictions are evaluated in comparison with experimental data [3] and some existing damage models [1]. The stress-strain reponse focusing on matrix dominated loading conditions of an embedded ply, damage initiation and evolution, property degradation and non-linearity prior to damage onset are the issues addressed.

References

[1] C. Schuecker *et al.*[2010],”Comparison of Damage Models for Predicting the Non-linear Response of laminates under Matrix Dominated Loading Conditions”, NASA/TP-2010-216856

[2] E.J. Barbero *et al.*[2013],”Determination of material parameters for Abaqus progressive damage analysis of E-glass epoxy laminates”, Elsevier, Composites: Part B, **46,211–220**

[3] J. Varna *et al.*[2001],”A synergistic damage-mechanics analysis of transverse cracking in $[\pm\theta/90_4]_s$ laminates”, Comp.Sci and Tech, **58,1011–1022**