ASSESSING THE OPERATION LOAD RANGE OF NON-LINEAR TEXTILE COMPOSITES BY MEANS OF STRESS ENVELOPES

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Abstract

The paper presents an energy based approach to estimate stress envelopes of composite unit cells exhibiting non-linear mechanisms. Based on non-linear simulations, these damage progression envelopes can be seen as an extension of the well known failure surfaces to cope with damage, plasticity, and delamination. To demonstrate the concept a 2/2 Twill weave featuring damage, plasticity, and softening in the homogenized tows as well as plasticity within the matrix pockets is subjected to biaxial and uniaxial load cases. Multiple non-linear simulations are conducted and the respective damage progression envelopes are constructed for two different energy levels.

1 Introduction

The growing demand for lightweight structural parts has been pushing the research on composites built from fiber reinforced polymers (FRP) for the last decades. To fully exploit the potential of such fiber reinforced composites the occurrence of damage and failure has to be identified and described in an appropriate way. In this context, several first ply failure (FPF) criteria have been developed, e.g. [1-3]. These criteria imply a linear elastic material behavior until failure. By means of such criteria, failure surfaces (also known as stress envelopes) can be computed in stress or strain space.

Since these “classical” failure surfaces are based on FPF criteria only, non-linear mechanisms, like plasticity, damage, and delamination are ignored during failure evaluation. If such a neglected mechanism leads to “failure” of the considered material point, no respective information is available.

Recently, some authors have derived classical failure surfaces for laminates featuring non-linear constitutive behavior, see e.g. [4]. To this end non-linear mechanisms are included in the constitutive laws but some FPF like criterion is used to assess the failure of the considered structure. In the field of textile composites, biaxial failure surfaces for a 2/2 twill weave discretized by three-dimensional continuum elements have been published by [5]. This model accounts for plasticity in the areas of unreinforced matrix and delamination between the tows. However, the included non-linear mechanisms might change the stress fields but are not treated as a cause of failure.

The present paper develops an extension of the classical failure surface to include non-linear effects into the stress envelopes. These envelopes are based on energy dissipation considerations and allow for a distinction between individual non-linear mechanisms like damage, plasticity, and delamination. The progression of these phenomena can be examined as well. In the following these extended stress envelopes are denoted as *damage progression envelopes*.

The approach is demonstrated by investigating the onset and progression of damage and plasticity in a single layer of woven textile composite subjected to biaxial in-plane stress states. Furthermore, the response to uniaxial in-plane tensile stress states is treaded as a function of the loading direction. Based on multiple non-linear simulations damage progression envelopes which account for the individual mechanisms are plotted in stress space.

2 Damage progression envelopes

The failure surfaces for fiber reinforced composites found in the literature are typically based on first ply failure criteria. These criteria use the stresses and strains, respectively, of the acting loading state to compute a scalar variable which is used to evaluate some risk or load factor. Depending on the choice of criteria applied, the failure surfaces are either based on polynomial approximations, e.g. [3], or are based on physical mechanisms, e.g. [1, 2]. The latter allow for a direct identification of the occurring failure mode. Failure surfaces and failure criteria, respectively, are typically used in conjunction with linear elastic materials and allow a fast evaluation of the applied loading conditions.

FPF criteria can be used in combination with multi scale approaches like lamination theory or unit cell investigations, to derive effective failure surfaces of structures at intermediate length scales (meso scale), see e.g. [6]. These effective failure surfaces can then be used to assess the severity of the stress state at a higher length scale, i.e. macro scale.

In the present approach damage progression envelopes are developed which can be seen as an extension of the well known failure surfaces. These envelopes are based on non-linear simulations and energy dissipation considerations. This allows for a distinct interpretation of the individual non-linear mechanisms, e.g. damage, plasticity, and delamination. Each phenomenon can be assessed individually and the sequence of occurrence results naturally. The approach is insensitive to localized stress peaks, occurring due to structural features or modeling issues as non-linear material models are used.

Damage progression envelopes are computed by means of a unit cell approach. To this end, multiple non-linear simulations are conducted “scanning” the stress space of interest. Typically, path dependent behavior can be expected which necessitates the assumption of radial load paths in stress and strain space, respectively.

A damage progression envelope is a combination of surfaces of equal relative dissipated energy. For the considered non-linear mechanisms the respective energy values, denoted as relative energy levels, are computed based on energy dissipations evaluated during the simulations. Figure 1 sketches uniaxial stress-strain curves and the dissipated energy densities due to damage and plasticity. These energy densities have to be integrated over the considered volume to get the energy values. The relative energy levels are defined as the ratio between these energies and the total energy in the system as

$$p_{\mathrm{dam}}(t) = \frac{w_{\mathrm{dam}}(t)}{w_{\mathrm{tot}}(t)} \quad \text{and} \quad p_{\mathrm{pla}}(t) = \frac{w_{\mathrm{pla}}(t)}{w_{\mathrm{tot}}(t)}, \tag{1}$$

with, t denoting the simulation time. The total energy, w_{tot}, is the sum of the energies associated with damage, w_{dam}, plasticity, w_{pla}, and elasticity, w_{el}.

Note that "artificial" energy contributions associated with the numerical solution procedure, like energy dissipated by the viscous regularization technique, are not to be included in the total energy.
If one of the ratios in Eq. (1) becomes nonzero, onset of the corresponding mechanism is detected. If the energy onset level is chosen sufficiently small, the approach resembles the application of a classical FPF criterion in terms of the damage mechanism and of a yield criterion in terms of plasticity theory, respectively. The evolution of the energy levels with respect to load increase represents the amounts of dissipated energy and can be used to give useful information on the influence of the individual mechanisms. Critical relative energy levels to predict safe operation ranges of the considered structure are to be defined based on distinguished load cases in combination with experiments. These load cases preferable feature one dominant mechanism only to separate the individual energy contributions.

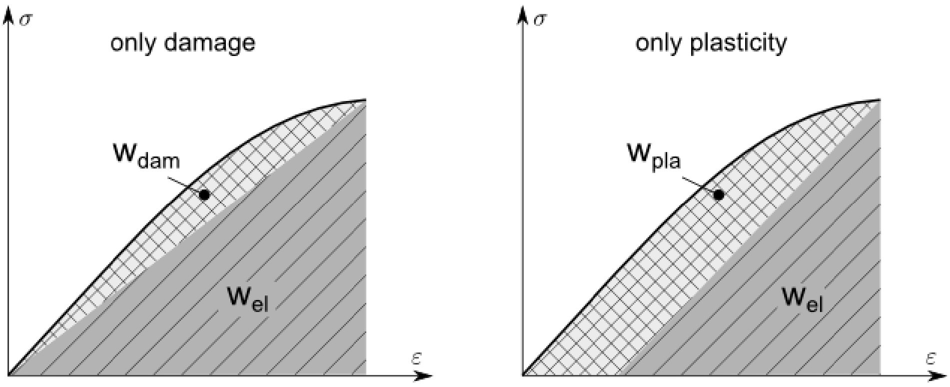

Figure 1. Uniaxial stress-strain curves of systems featuring either damage or plasticity as the only source of non-linearity. The dissipated energies densities are crosshatched and the corresponding recoverable strain energy density is shaded.

Using the relative energy levels surfaces of equal dissipated energy are constructed in the stress and strain space, respectively, to indicate the onset and evolution of the considered non-linear mechanisms. These surfaces can be combined to the damage progression envelope to represent ranges of safe operation. Besides the identification of an operation load range the individual surfaces enable insight into the development and sequence of the non-linear mechanisms acting in the investigated structure. If desired, the individual energy parts, $w_{\mathrm{dam}}(t)$ and $w_{\mathrm{pla}}(t)$, could be further split up into the underlying mechanisms (damage of the fibers, damage of the matrix material, delamination) and respective relative energy levels can be defined. In the following, only one relative energy level for damage and one for plasticity is used.
Damage progression envelopes can be used like classical failure surfaces. The stress and strain state, respectively, predicted by linear elastic simulations, is evaluated by means of a damage progression envelope. This envelope provides information on the non-linear mechanisms which would be active in a respective detailed non-linear simulation, but are neglected in the linear case. One has to be aware that, such non-linear mechanisms typically lead to stress redistribution. Moreover, the sensitivity of the non-linear mechanisms to load variation can be assessed.

3 Application example – 2/2 Twill weave
The approach is demonstrated by investigating the initiation and progression of damage and plasticity in a single layer of a 2/2 carbon/epoxy Twill weave. Since the computation of damage progression envelopes requires multiple non-linear (implicit) simulations an efficient

modeling and simulation strategy should be aimed at. In the present study a shell element based unit cell approach is applied which has been shown to be highly efficient in terms of computational performance and obtaining accurate results at the same time [7]. The individual tows are treated as unidirectional continuously reinforced composites. The behavior of these tows is modeled by a phenomenological non-linear constitutive law in which the fiber and matrix interaction is accounted for implicitly [8].

Damage progression envelopes are computed for two distinguished sub spaces of the in-plane stress space $(\sigma_{xx}, \sigma_{yy}, \sigma_{xy})$, i.e. biaxial stress states without shear stresses $(\sigma_{xx}, \sigma_{yy} \neq 0 \wedge \sigma_{xy} = 0)$ and a representative set of uniaxial in-plane tensile stress states $(\sigma_{\xi\xi} \neq 0 \wedge \sigma_{\eta\eta}, \sigma_{\xi\eta} = 0)$. In the later case, $\xi - \eta$ denotes a coordinate system rotated with respect to the global out-of-plane axis. Both cases are realized using force controlled loading and all conducted simulation runs allow for geometric non-linear deformations of the unit cell. All simulations are conducted using the commercial Finite Element package Abaqus/Standard 6.11 (Dassault Systèmes Simulia Corp., Providence, RI, USA).

In the present study, damage onset of the fibers, i.e. softening onset of the effective tow material in fiber direction is treaded as final failure and the occurrence of this mechanism terminates the simulation. Failure of the tows in fiber direction typically leads to global softening of the effective response This implies that in the current study damage evolution denotes only the matrix dominated damage modes.

3.1 Geometry and Mesh

The geometry of the considered weave is chosen to feature tows with a rectangular cross section and a piece-wise linear ondulation path. Figure 2 shows a sketch of the model weave including the dimensions (in mm).

The reference surfaces of the shell elements are meshed by 4-noded shell elements with linear interpolation functions. In thickness direction the Simpson scheme with five section points is used. The interfaces between these constituents are treated as being perfect. At the unit cell boundaries the nodes are coupled to achieve the plane periodic boundary conditions. A detailed description of the unit cell including the couplings and periodic boundary conditions can be found in [7].

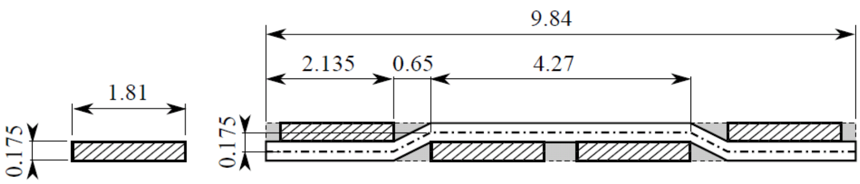

Figure 2. Cross section of the 2/2 Twill weave showing the piecewise linear ondulation path, rectangular tow cross sections (hatched), and matrix pockets (shaded) with dimensions in mm.

3.2 Material description

One of the key challenges for reasonable prediction of the non-linear mechanical behavior of fabric composites is to employ a proper constitutive material law for the tows. In this study the behavior of the tows is modeled by a phenomenological constitutive law for unidirectional FRP plies [8] which has been implemented as user defined material routine in Abaqus/Standard 6.11. It has been shown that this material model yields excellent predictions of the non-linear response of laminated structures [9]. The unreinforced matrix pockets are represented by an isotropic elastic-perfectly plastic linear Drucker-Prager model, as available in Abaqus/Standard 6.11. A circular shaped yield surface in the deviatoric plane and associated flow are assumed. Table 1 gives the material properties for the tows as well as matrix pockets. The tow data was chosen according to [8] and the matrix data was obtained from the supplier (Cytec).

Tows (60% fiber volume fraction)					**Matrix pockets**	
E_1	$E_2 = E_3$	$\nu_{12} = \nu_{13}$	ν_{23}	$G_{12} = G_{13}$	E_{Matrix}	ν_{Matrix}
146 GPa	9 GPa	0.34	0.61	4.27 GPa	3.52 GPa	0.37
R_{11}^{t}	R_{22}^{t}	R_{11}^{c}	R_{22}^{c}	R_{12}	σ_y^{t}	Friction angle Dilation angle
2100 MPa	1407 MPa	82 MPa	249 MPa	110 MPa	81.4 MPa	25°

Table 1. Material data for the tows and matrix pockets of the carbon/epoxy weave.

3.4 Results and Discussion – Biaxial stress state

Using the master node concept [10] normal stresses with respect to the initial configuration (1st Piola-Kirchhoff stresses) are applied to the unit cell, see Fig. 3 (left). The shear stress is set to be zero. An effective orthotropic material symmetry is expected, hence only half of the investigated stress space has to be simulated. Using the strategy defined in Sec. 2 the damage progression envelope is derived using two relative energy levels. The initiation level is set to 0.00001 and to visualize the progression of the individual modes a second level of 0.01 (=1%) is taken. Figure 3 (right) shows the predicted damage progression envelope. The dashed lines represent the initiation of the considered mechanism, plasticity (gray) and damage (black). The solid lines indicate the corresponding passing of the 1% level. The final failure, i.e. onset of fiber damage, is indicated by the thick gray line and the circles mark simulation runs with convergence problems.

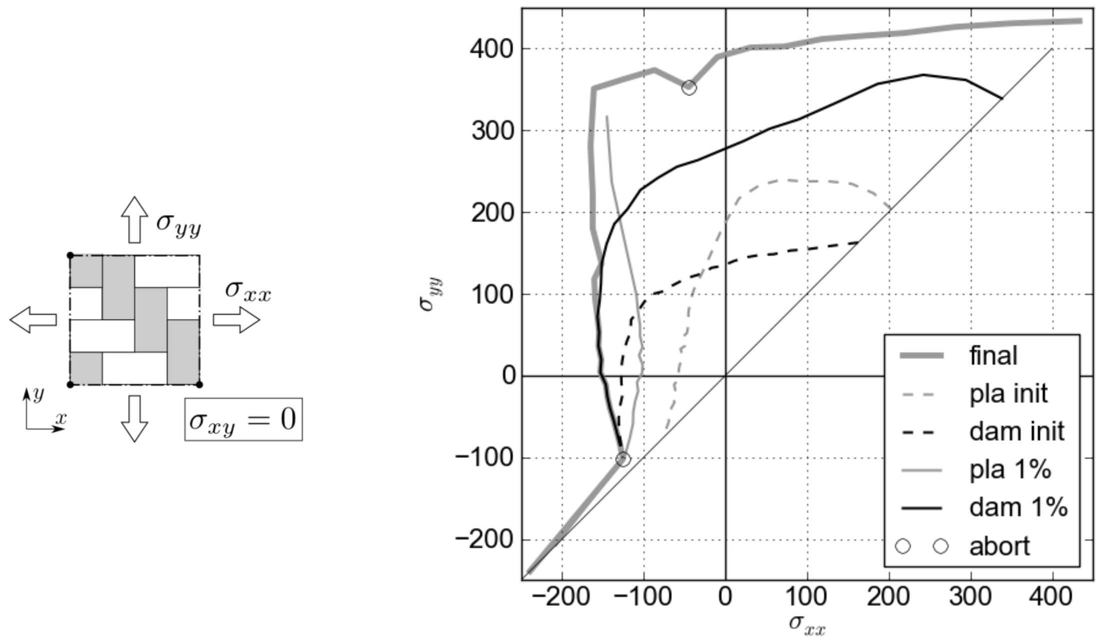

Figure 3. Sketch of the biaxial stress state (left) and the corresponding damage progression envelope in σ_{xx}-σ_{yy} space (right) indicating the initiation energy level, the 1% dissipated energy level, and the final failure.

The responses of the unit cell subjected to uniaxial tension in x and y direction, respectively, are equal and can be found on the ordinate. It can be seen that damage starts to initiate at about 140 MPa and reaches the 1% energy dissipation level at about 280 MPa. Plasticity initiates within the unit cell (about 190 MPa) but does not reach the 1% level during load increase. Similar considerations apply to the uniaxial compressive loading where plasticity is the more dominant mechanism. A biaxial tensile loading with equal stress values shows a similar sequence of the individual mechanisms as the uniaxial tensile case. However, all relative energy levels are shifted toward higher stress values. This suggests a better performance of the weave under such loading conditions. As only a single layer is investigated the unit cell shows poor performance if a compressive stress is applied.

3.5 Results and Discussion – In-plane uniaxial tensile stress state

The second loading range under investigation represents in-plane uniaxial stress states at loading angles $\varphi \in \{0, \frac{\pi}{2}\}$, see Fig. 4 (left). The range of φ is defined with respect to the expected orthotropic symmetry. To realize this loading condition, normal as well as shear stresses are applied using the master node concept. Since a geometrical non-linear simulation is conducted, it is important to ensure a constant loading direction φ during the analysis. Figure 4 (right) shows the damage progression envelope as a polar plot to visualize the response to uniaxial tensile stresses with respect to the loading angle. The same energy levels are used as in the previous subsection.

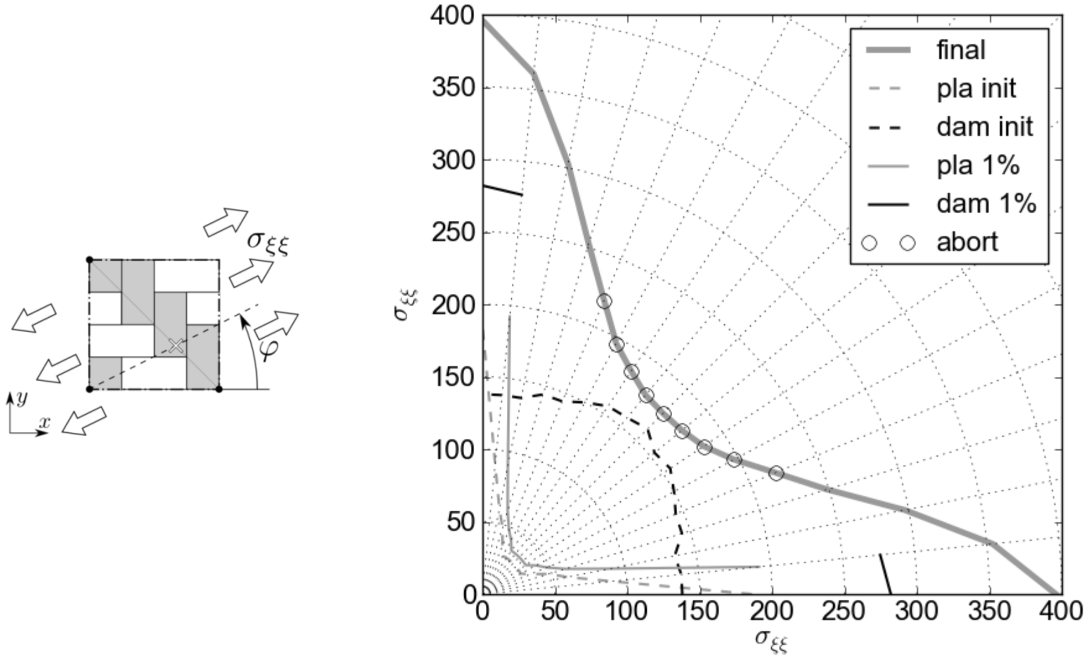

Figure 4. Sketch of the uniaxial loading conditions (left) and the corresponding polar plot of the damage progression envelope (right) indicating the initiation energy level, the 1% dissipated energy level, and the final failure.

The damage progression envelope (Fig. 4, right) highlights that loading directions different than the global x and y axis quickly lead to pronounced amounts of dissipated energy due to plasticity. Damage, on the other hand, initiates but has negligible influence in these load cases. The uniaxial stress state allows the plotting of stress-strain curves with respect to this distinguished direction. Figure 5 shows the predicted response in terms of linearized stress and strain measures for a 45º loading direction. The cross and triangle correspond to the plasticity mechanism. The first mark the onset and the latter the passing of the 1% energy level. As both symbols are right next to each other, energy dissipates at a high rate. This suggests that plasticity has a pronounced effect in this loading case which is confirmed by the unloading cycles. The initiation of damage is indicated by the circle. However, damage, evolving in the tows, has no notable influence on the predicted response. The horizontal tangent at high strains of the stress-strain curve explains why the force controlled simulations aborts with convergence problems at the peak load before fibers failure occurs. The same issue appears with load directions between 25º and 65º, see small circles in Fig. 4 (right).

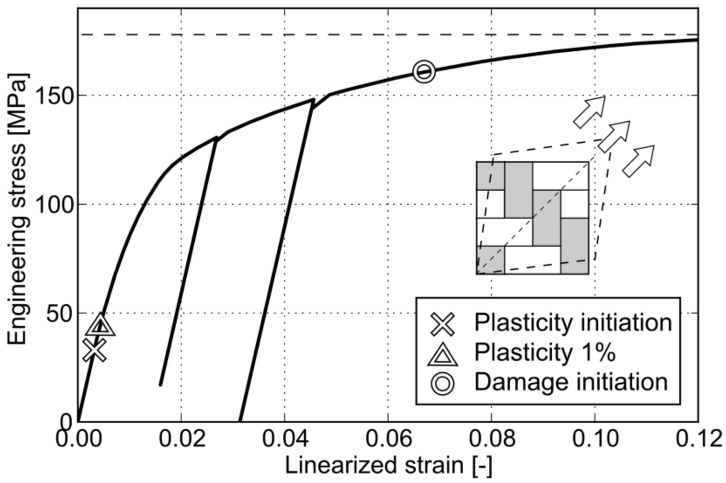

Figure 5. Predicted response of uniaxial in-plane tensile engineering stresses in the 45º direction vs. the corresponding linearized strain. The markers indicate specific energy levels.

4 Conclusions

An energy based concept to estimate safe operation ranges of composites exhibiting non-linear mechanisms is proposed. The damage progression envelopes allow for an efficient determination of reasonable operation ranges using scalar variables defined by dissipated energies. Furthermore, the sequential onset and progression of the individual mechanisms can be highlighted.

The approach is demonstrated by means of a twill weave unit cell featuring an elasto-plasto-damage tow material and an elasto-plastic matrix material. Biaxial and uniaxial load cases are conducted and respective damage progression envelopes are constructed. The results show the dependence of effects on different loading scenarios, e.g. that it is essential to account for plasticity effects within the treatment of textile composites, especially if dominant shear strains arise.

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