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Numerical analysis of layered fiber composites accounting for the onset of delamination

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ABSTRACT

Since delamination is a major failure mode of layered composites, predicting its initiation is essential for the design of composite structures. Evaluating delamination onset criteria based on stress–strength relations requires an accurate representation of the through-the-thickness stress distribution, which is delicate for thin shell-like structures. Therefore, in this paper, a solid-shell finite element is utilized, which allows for incorporating a fully three-dimensional, anisotropic, micro-mechanically motivated material model, still being suited for application to thin structures. Moreover, locking phenomena are cured by using both the enhanced assumed strain (EAS) and the assumed natural strain (ANS) concept, and numerical efficiency is ensured through reduced integration.

1. Introduction

In many technical applications in the field of lightweight constructions, fiber-reinforced composites are gaining importance due to their most beneficial characteristics, the very high Young's modulus and low density. These are particularly leveraged in shell-like structures of lightweight constructions. The composites considered in this paper consist of multiple layers, each of which is composed of a fiber-reinforced thermoset matrix material. Besides this anisotropic structure, the stress–strain behavior of fiber composite materials is highly non-linear. Moreover, the response of the materials in tension and compression can differ significantly.

To represent this complex material behavior the model proposed by Reese in [1] for fiber-reinforced rubber-like composites has been adopted, in which the transition from the micro-scale to the macro-scale is formulated in a general manner. Therefore, this model is not restricted to rubber-like materials but also suitable for the carbon fiber-reinforced plastics (CFRP) considered here.

Structural collapse in fiber composite structures is caused by the evolution of either matrix transverse cracking, fiber fracture, or delamination. From these different damage modes, the delamination is particularly important, because it drastically reduces the bending stiffness of the structure and promotes local buckling in case of compressive loads [2,3]. Including delamination into the computation of composite structures requires the definition of an appropriate criterion for its onset as well as the prediction of its growth after an initial crack has evolved.

For the initiation of delamination, different criteria exist, formulated in dependence of stress-resistance relations, e.g. [4–8]. After onset of delamination, the high stress gradients appearing at the crack front prohibit employing solely stress-based criteria. Thus, fracture mechanics approaches are often used for simulating the delamination propagation, such as the virtual crack closure technique, [9–11]. As an alternative, delamination growth can be treated within the framework of damage mechanics using cohesive zone models, which are incorporated into the finite element simulation by interface elements, e.g. [12–15]. However, in this paper, the onset of delamination is addressed based on stress-resistance relations.

Since fiber-reinforced composites are mostly applied in thin shell-like structures, the element formulation demands providing a suitable shape for thin structures while displaying realistically the three-dimensional stress states. Although shell formulations exist, which take into account the through-the-thickness stretching, see e.g. [16,17], the implementation of three-dimensional material models is much simpler in the context of solid elements. On the other hand, the latter typically provide a poor performance when being applied to thin shell-like structures. In particular, there are different locking phenomena to be coped with, which cause an overestimation of the stress state and an underestimation of the deformation. Using solid-shell elements represents one strategy to overcome this problem by combining the advantages of both solid elements and shell elements at the same time. Further, applying the enhanced assumed strain (EAS) concept eliminates the

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volumetric locking in case of (nearly) incompressible materials as well as the Poisson thickness locking, which occurs in bending problems of shell-like structures due to the non-constant distribution of transverse normal strain over the thickness.

In literature, one can find several solid-shell formulations incorporating the EAS concept, see e.g. [18–20], to name only a few. To cure the transverse shear locking, which is present in standard eight-node hexahedral elements, the assumed natural strain (ANS) method is applied. In the context of full integration formulations, the ANS can be found e.g. in [21,22], and for reduced integration solid-shell formulations e.g. in [23–26]. The formulation presented in this paper is based on the works of Schwarze and Reese [24–26].

For laminated layered composites, the accurate determination of the through-the-thickness stress distribution was recently investigated by several authors. For instance, in [27] an improved shell formulation was used for this, whereas in [28] the investigations were based on the solid-shell concept. For a more elaborate literature overview, the reader is referred to the review papers [29–31] and the references therein. However, to our knowledge no solid-shell formulations exist, which consider the orthotropic behavior of fiber composites with woven fabric accounting for different fiber directions.

This paper is based on [32], where for better comprehensibility the wording has been improved and additional figures have been included. Further, since experimental validation is out of scope of this work, the addition of a second numerical example seemed to be advisable.

2. Orthotropic material model

The fiber composites examined in this paper consist of stacked layers, each of which is composed of a woven fabric embedded in a matrix material. The anisotropic material behavior of such composites is taken into account by using the micro-mechanically motivated model proposed in [1]. Describing the matrix by the Neo-Hooke material model allows for incorporating rubber-like matrix materials with sufficient accuracy, whereas viscous effects of e.g. epoxy resin cannot be represented. However, in the following, the basics of the continuum model are summarized. Therein, parameters are chosen to represent approximately the behavior of carbon fibers in an epoxy resin matrix.

2.1. Concept of structural tensors

Introducing the deformation gradient $\mathbf{F}$, the deformation of a continuous body is represented by the right Cauchy-Green tensor

$$\mathbf{C} = \mathbf{F}^T\mathbf{F} \tag{1}$$

The characterization of a hyperelastic body is then given by the existence of a scalar potential, which is the stored energy function $W = W(\mathbf{C})$, such that

$$\mathbf{S} = 2\frac{\partial W(\mathbf{C})}{\partial \mathbf{C}} \tag{2}$$

is the second Piola–Kirchhoff stress tensor. In the case of orthotropic material behavior, the energy function $W(\mathbf{C})$ reduces to an isotropic function of $\mathbf{C}$ and the structural tensors $\mathbf{M}_1$ and $\mathbf{M}_2$, which are defined by

$$\mathbf{M}_1 = \boldsymbol{n}_1 \otimes \boldsymbol{n}_1 \quad \text{and} \quad \mathbf{M}_2 = \boldsymbol{n}_2 \otimes \boldsymbol{n}_2 \tag{3}$$

where the vectors $\boldsymbol{n}_1$ and $\boldsymbol{n}_2$ are oriented in parallel direction to the fibers as shown in Fig. 2. For a discussion of the theoretical background, the reader is referred to [33] and the references therein. Then, the strain energy function W can be represented in dependence of the following invariants:

$$I_1 = \operatorname{tr}\mathbf{C} \qquad I_2 = \frac{1}{2}\left[(\operatorname{tr}\mathbf{C})^2 - \operatorname{tr}\left(\mathbf{C}^2\right)\right] \quad I_3 = \det\mathbf{C} \tag{4a}$$

$$I_4 = \operatorname{tr}(\mathbf{C}\mathbf{M}_1) \quad I_5 = \operatorname{tr}\left(\mathbf{C}^2\mathbf{M}_1\right) \tag{4b}$$

$$I_6 = \operatorname{tr}(\mathbf{C}\mathbf{M}_2) \quad I_7 = \operatorname{tr}\left(\mathbf{C}^2\mathbf{M}_2\right) \tag{4c}$$

2.2. Strain energy function

In this work, the anisotropic model from Reese [1] is adopted, which assumes that the fibers do not carry any load in case of compression but only in tension, which is not realistic for the CFRP considered here. Therefore, this model is slightly modified, such that the matrix acts as an elastic continuous support for the embedded fibers. Hence, the compressive behavior is considered approximately the same as the tensile one. Further, plastic contributions are not needed to be taken into account for carbon fibers. Moreover, the fiber volume fractions $0 \leqslant \varphi_1$ and $0 \leqslant \varphi_2$ for the two families of fibers are introduced, where $\varphi_1 + \varphi_2 \leqslant 1$ holds. Except of this, we adopt the mentioned model and use the following strain energy function:

$$W = (1-\varphi_1-\varphi_2)W_{NH}(I_1,I_3) + W_{ani}(\varphi_1,\varphi_2,I_1,I_2,I_4,I_5,I_6,I_7) \tag{5}$$

Here, W_{NH} denotes the Neo-Hookean part displaying the isotropic case in the small strain regime. Denoting the Lamé constants by μ and Λ, the strain energy function is given by

$$W_{NH}(I_1,I_3) = \frac{\mu}{2}(I_1-3) - \mu\ln\sqrt{I_3} + \frac{\Lambda}{4}\left(I_3 - 1 - 2\ln\sqrt{I_3}\right) \tag{6}$$

The anisotropic behavior of the fabric is introduced by the part

$$\begin{aligned} W_{ani}(\varphi_1,\varphi_2,I_1,I_2,I_4,I_5,I_6,I_7) = {}& K_1^{iso}(I_1-3)^{\alpha_1} + K_2^{iso}(I_2-3)^{\alpha_2} \\ & + \varphi_1\left[K_1^{ani\,1}(I_4-1)^{\beta_1} + K_2^{ani\,1}(I_5-1)^{\beta_2}\right] \\ & + \varphi_2\left[K_1^{ani\,2}(I_6-1)^{\gamma_1} + K_2^{ani\,2}(I_7-1)^{\gamma_2}\right] \\ & + K^{coup\;ani}(I_4-1)^{\xi}(I_6-1)^{\xi} \end{aligned} \tag{7}$$

The exponents α_i, β_i, γ_i, (i = 1, 2), and ξ are chosen to be integers larger than 2. Together with the values K_1^{iso}, K_2^{iso}, $K_1^{ani\,1}$, $K_2^{ani\,1}$, $K_1^{ani\,2}$, $K_2^{ani\,2}$, and $K^{coup\;ani}$, they constitute the set of material parameters of the current model. Notably, in [1] further coupling terms have been introduced, which have hardly influenced the results, and therefore are dropped here.

Furthermore, the isotropic material response is already sufficiently described by the Neo-Hookean part, such that K_1^{iso} and K_2^{iso} can be neglected. The other parameters have to be fitted to experimental data. In the case of unidirectional fibers, this can be done by tensile tests in different fiber orientations (see [34]), whereas in [1] numerical experiments are performed for the woven composites. For the latter, appropriate representative volume elements (RVE) need to be defined, as illustrated in Fig. 1.

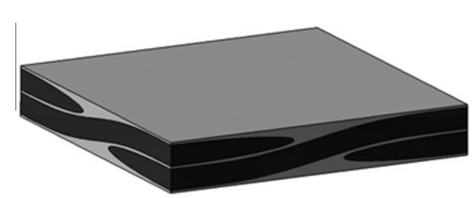

Fig. 1. Representative volume element (RVE) of woven composite.