Micromechanical Damage Modeling of Long Fiber Reinforced Composites With the Parametric Method of Cells

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Micromechanical damage modeling is presented with the parametric high-fidelity generalized method of cells for a long fiber reinforced composite. Two models for a planar single fiber repeating unit cell, including damage, are proposed. The first one, implemented with the spatial continuum damage mechanics, is based on the idea that volumetric defects occur in the material phases. The other one, modeled with the interface damage mechanics, is founded on the view that cracks as surface-like defects cause the stress degradation. The potential and ability of both approaches to predict damage in first-order homogenization is shown by comparing the simulation results with each other as well as with test data under uniaxial and biaxial stress loading.

1 Micromechanical Models

Two micromechanical models are proposed to describe the fundamental failure processes in long fiber reinforced composites. The first one, based on the spatial continuum damage mechanics (CDM), introduces a scalar damage variable $D^{(\beta)}$ into HOOKE's generalized model for each subcell $\Omega^{(\beta)}$ of the discretized repeating unit cell (RUC) to represent volumetric damage, see [1] and Fig. 1 left. This model is able to capture strain softening in the fiber and in the matrix. The other approach, which can additionally represent fiber-matrix debonding, is founded on the interface damage mechanics (IDM) to model cracks, i. e., surface-like defects, see [2] and Fig. 1 right. The locations of crack initiation and growth are predefined with interfaces $\mathcal{S}^{(k)}$ inserted along all internal boundaries of the discretized RUC. In these interfaces, a scalar damage variable $D^{(k)}$ governs the stress degradation. The subcells do not damage in this approach but follow HOOKE's model.

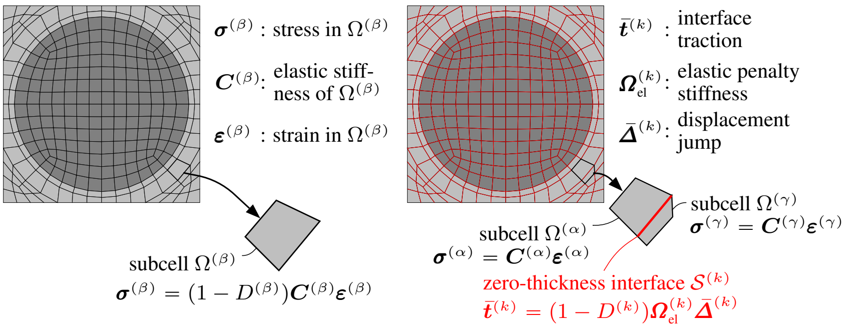

Fig. 1: left – RUC with continuum damage, right – RUC with interface damage

The continuity and periodicity of tractions and displacements along the subcell boundaries of the RUC, as well as the static equilibrium in each subcell need to be satisfied in the high-fidelity generalized method of cells (HFGMC) in an integral average, see [1, 3]. A system of nonlinear equations is obtained by evaluating these conditions and taking evolving continuum damage into account. It is solved with a staggered solution scheme, see [1]. The interfacial jump condition with averaged quantities, denoted by $\overline{(\bullet)}$ in Fig. 1 right, replaces the displacement continuity for a compliant interface between two neighboring subcells. Then, the underlying conditions of the HFGMC also lead to a system of nonlinear equations due to the interface damage, which is solved by NEWTON's method, see [2]. A staggered solution scheme is used if convergence fails.

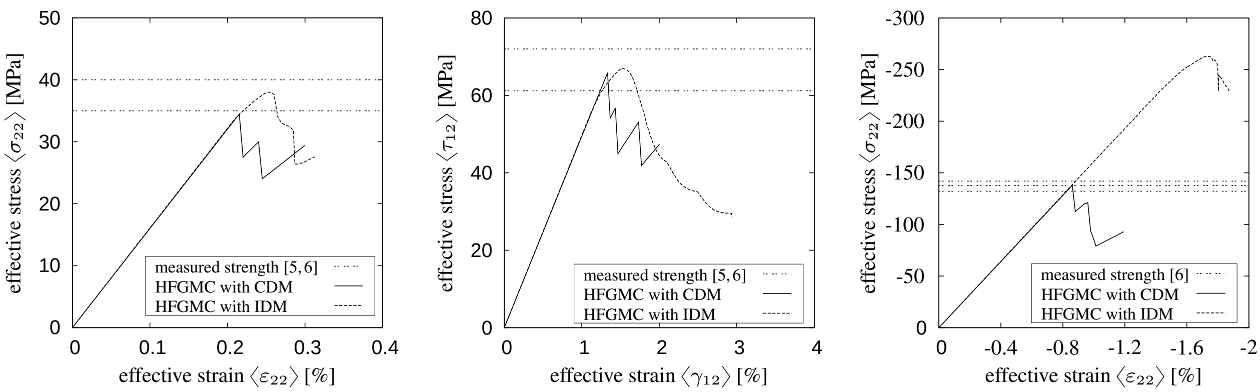

Fig. 2: Verification, left – transverse tension, center – longitudinal shear, right – transverse compression

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2 Failure Prediction

The failure prediction with the micromechanical models proposed is shown for a composite of E-glass 21×K43 Gevetex with LY556/HT907/DY063 resin. This long fiber reinforced material is subjected to different load combinations of transverse tension, transverse compression, and longitudinal shear. The elasticity constants of the isotropic fiber and matrix are published in [5, p. 1012–3]. Values for the macroscopic strength are listed in [5, p. 1012] and [6, p. 1491]. A progressive continuum damage model is used for the evolution of $D^{(\beta)}$, see [1] for more details. The damage parameters of this model, determined for the aforementioned composite, are also given therein. The micromechanical model of the RUC with interfaces excludes fiber damage a priori because this type of failure does not occur under the load cases considered. The interfaces in the matrix as well as those along the fiber-matrix phase transition obey the traction-separation model proposed in [4]. Using the same notation for the damage parameters as in [4], values of $T_0 = 75\,\text{MPa}$, $\eta = 1.6$, $u_0 = 0.025\,\mu\text{m}$, and $\alpha = 3$ were identified for the interfaces lying in the matrix, as well as $T_0 = 61\,\text{MPa}$, $\eta = 1.6393$, $u_0 = 0.01\,\mu\text{m}$, and $\alpha = 6.5$ for the interfaces along the fiber-matrix phase transition. The parameter identification for both micromechanical RUC models with damage was conducted by hand, and with the objective of predicting the measured strength in the uniaxial load cases. Fig. 2 left and center show that both models yield the experimental strength values for transverse tension and longitudinal shear. In the latter case, both RUC models show damage in the same zone on the microscale but with a different magnitude, see Fig. 3 left and right. The continuum damage approach can also represent the compressive strength, compared with the interface ansatz, see Fig. 2 right. The interface model taken from [4] excludes damage initiation and damage growth due to compressive loading.

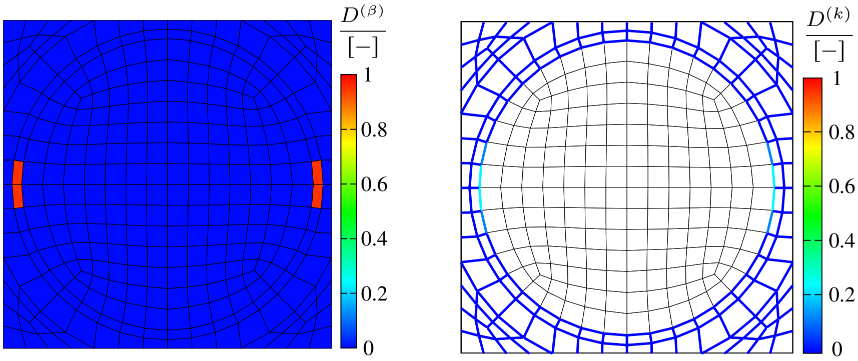

Fig. 3: Microscopic damage distribution at the macroscopic stress maximum under longitudinal shear, left – RUC with continuum damage, right – RUC with interface damage

The proposed models are also utilized to study the accuracy of their failure prediction under biaxial in-plane loading, see Fig. 4. The data points, obtained with the HFGMC, represent the maximum stress values in shear and transverse direction. The test data are given in [5, p. 1012] and [6, p. 1491]. PUCK's fracture criterion [7], which was adjusted to the aforementioned glass fiber composite, is also depicted in Fig. 4. All data are close in the first quadrant. However, the micromechanical results do not show the negative slope between $-70\,\text{MPa} \leqslant \langle\sigma_{22}\rangle \leqslant 0\,\text{MPa}$ and $\langle\tau_{12}\rangle > 0$, compared with the test data and the response of PUCK's model in this range. The prediction of the interface approach under a combination of longitudinal shear $\langle\tau_{12}\rangle \neq 0$ and transverse compression $\langle\sigma_{22}\rangle < 0$ also suffers as a result of the used interface model, as explained above.

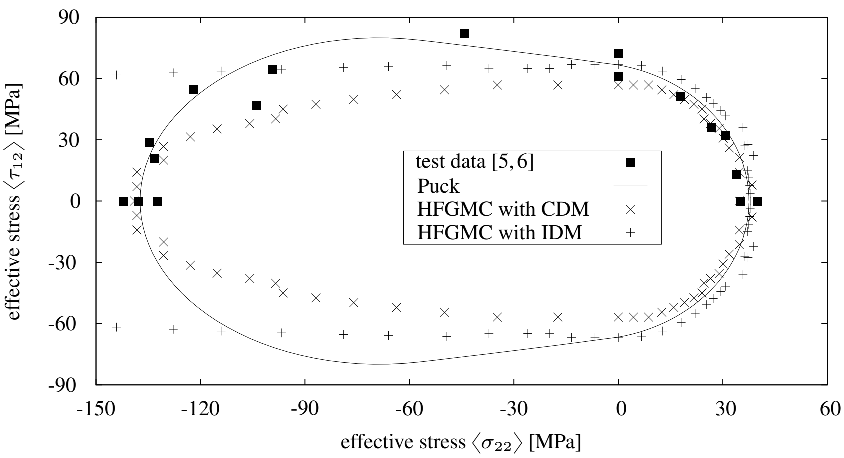

Fig. 4: Biaxial in-plane failure envelope

In summary, both micromechanical models presented are able to predict damage on the fiber-matrix level. In both of them, the homogenization captures the influence of damage on the effective stress-strain behavior. The computed values for the macroscopic strength are noticeably close to the test data. However, there is a need to improve both micromechanical RUC models with damage for the compressive range, as the biaxial failure envelope shows.

References

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