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van der Meer, Frans

Publication date
2016

Document Version
Final published version

Published in
Proceedings of the 17th European Conference on Composite Materials

MICROMECHANICS-BASED VALIDATION OF A MESOMODEL FOR MATRIX NONLINEARITY

F.P. van der Meer

Faculty of Civil Engineering and Geosciences, Delft University of Technology
PO Box 5048, 2600 GA Delft, The Netherlands
Email: f.p.vandermeer@tudelft.nl

Keywords: Micromechanics, Matrix nonlinearity, Orthotropic model, Plasticity, Damage

Abstract
The performance of a mesomechanical constitutive law for composites is assessed through comparison with micromechanical model results. In this paper, results are presented for non-monotonic strain histories obtained from mesomechanical simulation of a shear dominated delamination test.

1. Introduction

Modeling of failure in composite laminates is mostly done on the mesolevel, which means that plies are modeled as an homogeneous orthotropic continua. Fibers are not explicitly modeled, but implicitly present in the principal directions of the orthotropy. The mesolevel is attractive because it allows for analysis of complete test coupons, while distinction between different failure processes inside and between individual plies remains possible. Another relevant level of observation for composites is the microlevel, where fibers and matrix are modeled explicitly. Microlevel models typically require less inputs, because description of the behavior of fibers and matrix is more simple than that of the composite material. Moreover, the different dissipative processes during failure, viz. matrix plasticity, matrix cracking, fiber breakage, and fiber/matrix debonding can all be modeled on the microscale. Multiscale techniques where a mesolevel model can be coupled to a micromechanical model potentially allow for micromechanics-based coupon level simulations. However, these techniques are computationally very expensive. Therefore, there will remain need for accurate homogenized mesolevel models.

In this contribution, a micromechanical model is used to validate a homogenized orthotropic model for mesolevel analysis of matrix plasticity and failure. The advantage of using micromechanics for validation is that arbitrary stress states and histories can be applied, which is difficult in a laboratory settings. The micromodel is first used to generate the basic data that is needed as input for the mesomodel. In a separate publication[1], the performance of the homogenized model for monotonic biaxial stress states is assessed by comparison with micromodel results. In this paper, the capability of the mesomodel to represent non-calibrated stress histories is investigated by comparing the prediction of the constitutive law with micromodel results for non-monotonic strain histories.

2. Methods

The pressure-dependent plasticity model proposed by Melro et al. [2] for the matrix material in micromechanical analysis of composites is used on the microlevel. A periodic representative volume element (RVE) with quasi-random distribution of 25 fibers and fiber volume fraction of 0.6 is generated with dis-

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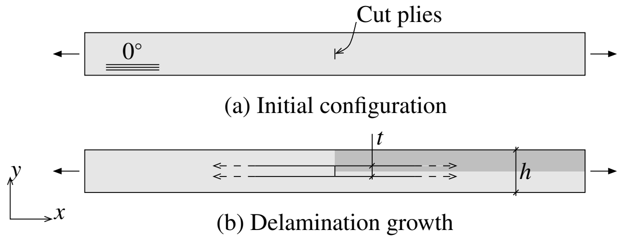

Figure 1. The transverse crack tension (TCT) test.

crete element simulator Hades. The micromodel response is compared to the homogenized constitutive model proposed by Vogler et al. [3].

First, the RVE is subjected to six fundamental stress states to generate hardening curves. The six hardening curves corresponding to uniaxial tension, uniaxial compression, biaxial tension, biaxial compression, longitudinal shear and transverse shear are used as input for the homogenized model.

Next, the RVE is subjected to a range of different stress states and results are compared to the constitutive behavior of the homogenized material model. In this paper results are shown from an analysis where a realistic non-monotonic strain history is prescribed. The mesomodel is used for simulation of a transverse crack tensile (TCT) test, which is a shear dominated test where the stress around the crack tip experiences changing stress ratios.

One quarter of a specimen with thickness $h = 1.27$ mm, notch length $t = 0.254$ mm and total length of 10 mm is modeled (see Figure 1). The calibrated homogenized plasticity model is used in combination with interface elements with a cohesive law for delamination. The TCT test is a mode II test, which means that shear nonlinearity is relevant, while the stress state around the crack tip is not a state of pure shear, which means that non-monotonic stress histories are present. The mixed-mode cohesive law by Turon et al. [4, 5] is used. The shear and tensile strength are set equal to 60 MPa and the mode I and mode II fracture energy are 0.4 and 0.8 N/mm respectively with a linear interpolation (interaction coefficient $\eta = 1$). In the mesomodel analysis, a process with stable crack growth at constant load level is obtained, in line with simulations without friction reported in [6].

The strain and stress history is recorded in every integration point as well as the local energy dissipation. The history of volumetric energy dissipation E, which has units J/m^3 or Pa is computed locally as:

$$E(t) = \int_{\tau=0}^{t} \boldsymbol{\sigma} \cdot \dot{\boldsymbol{\varepsilon}}^{\mathrm{p}} \, \mathrm{d}\tau \tag{1}$$

Subsequently, a single micromodel analysis is performed for every mesolevel integration point. The strain history from the corresponding point is applied as boundary condition. Averaged stress and dissipation in the micromodel are recorded for comparison with the mesomodel results. For the micromodels, the volumetric dissipation is computed with averaged stress and strain histories, where homogenized plastic strain is computed from the averaged stress and averaged strain with the homogenized elastic stiffness matrix.

Note that this differs from FE^2 analysis [7] in the fact that no iterations are performed to ensure equilibrium between neighboring micromodels. Nevertheless, this procedure gives a first order estimate of the difference between the homogenized model and FE^2 analysis. If the micromodel gives a stress close to the stress computed in the mesomodel for the same strain history, the unbalance between stress states in neighboring micromodels remains small.

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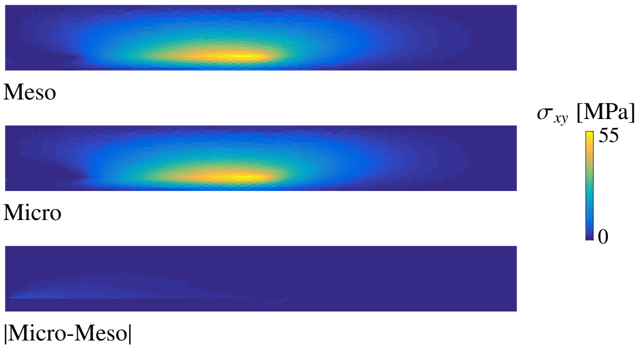

Figure 2. Comparison between σ_{xy} field from mesolevel analysis of TCT test and reconstructed σ_{xy} field from micromechanical analyses with the same averaged strain histories.

Figure 3. Comparison between σ_{xx} field from mesolevel analysis of TCT test and reconstructed σ_{xx} field from micromechanical analyses with the same averaged strain histories.

3. Results

The stresses computed in the different micromodels are related to the corresponding elements in order to visually compare the meso and micromodel response as fields. In Figures 2–4 stress fields from a single time step are plotted. The stress concentration in the shear stress field (Fig. 2) indicates the location of the crack tip and cohesive zone for this time step. It is observed, that the stress state around the cohesive zone is complex, with stress ratios of $\sigma_{xx}/\sigma_{xy} \approx 10$ and $\sigma_{xy}/\sigma_{yy} \approx 5$. Furthermore, for the primary stress components σ_{xy} and σ_{xx} the difference between meso and micromodels is small. In the σ_{yy} field obtained from the aggregated micromodel responses (Fig. 4), the disequilibrium can be observed in the discontinuity of this stress component across the crack surface. The relative difference between meso and micro stress values is larger for this component. This difference is related to discrepancies in direction of plastic strain for combined longitudinal shear and transverse loading [1]. The fact that the unbalance is visible is also due to the relatively small absolute values for this stress component.

Finally, dissipation history is investigated. Energy dissipation during crack growth is a relevant quantity for a test like the TCT test, because this test is designed to measure fracture energy. Mesolevel or multiscale simulations give information on what happens in the tests and on how much of the measured fracture energy should be ascribed to bulk plasticity rather than to the formation of new crack surface. Comparison of mesomodel dissipation to the dissipation in a micromodel subjected to the same averaged strain history gives insight in how reliable the mesomodel is for such investigation.

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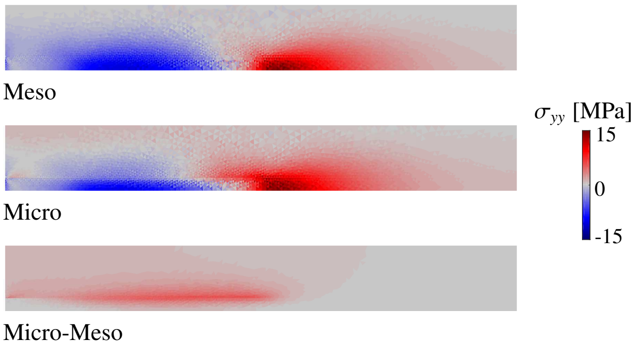

Figure 4. Comparison between σ_{yy} field from mesolevel analysis of TCT test and reconstructed σ_{yy} field from micromechanical analyses with the same averaged strain histories.

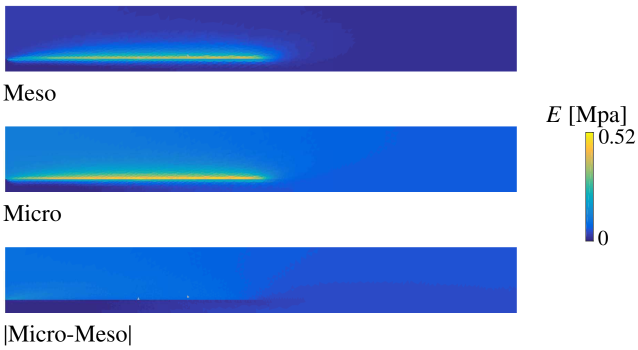

Figure 5. Comparison between dissipation field from mesolevel analysis of TCT test and reconstructed dissipation field from micromechanical analyses with the same averaged strain histories.

In Figure 5, the volumetric dissipation E is visualized for the same time step as the previous stress plots. It is observed that there is a significant difference in energy dissipation between the meso and micromodels. The difference is largest where the stress in fiber direction σ_{xx} is largest.

Because the energy dissipation in Eq. (1) is computed with a dot-product, it is possible to decompose this quantity into contributions associated with individual stress components. In Figure 6, the decomposed dissipation history is shown for a single mesolevel integration point along with the same quantities from the associated micromodel. A point just above the crack plane has been chosen with coordinates $x = 1.79$ mm and $y = 0.16$ mm. Labels xy, zz and yy each refer to one pair of neighboring lines in the graph, one line from the mesomodel and the other from the micromodel. For the xx component, only the micromodel contribution is shown, because the mesomodel dissipation in this direction remains equal to zero. The rise in energy dissipation around time step 25 is associated with the increase in shear stress as the crack approaches the considered integration point. The plateau that follows is associated with bulk unloading as softening takes place in the neighboring interface element.

Several observations can be made. The largest contributor to the energy dissipation is the longitudinal shear component. The visible difference between the meso and micromodel dissipation related to the xy-component is due to the influence of σ_{xx} on the longitudinal shear response. The dissipation associated with the yy-component is negative but very small. Note that negative values for an individual component are not unphysical, as long as the total dissipation rate remains positive. There is also significant dissipation associated with the zz-component, for which the plane strain condition holds. Differences in

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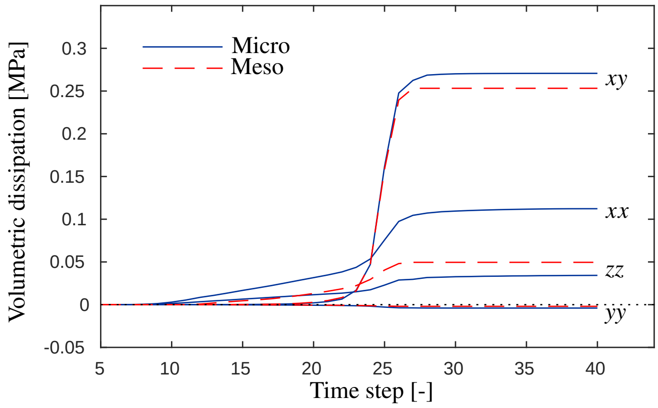

Figure 6. Decomposed dissipation history from mesolevel integration point and micromodel subjected to the same strain history.

dissipation between meso and micromodel related to xy and zz components approximately cancel each other out.

The most notable difference between meso and micromodel is the dissipation related to the xx-component. The dissipation in the micromodel starts around the tenth time step, which is prior to any delamination growth. The part of the dissipation that takes place in this phase of the test does not affect the measured fracture energy, but the dissipation related to the xx-component also shows a pronounced increase in the time steps where most of the shear dissipation takes place, even though the σ_{xx} does not increase further. The plasticity process is shear dominated, but because it takes place at $\sigma_{xx} \neq 0$, the rate of plastic strain in the micromodel has a nonzero component $\dot{\varepsilon}^{\mathrm{p}}_{xx}$.

In a data reduction scheme to compute fracture energy from an experimentally measured crack propagation load, this part of the dissipation would be included in the fracture energy, while it is missing in the mesomodel. Therefore, if one were to perform mesoscale simulation with Vogler's plasticity model to estimate the contribution of plasticity to the mode II fracture energy in the TCT test, a significant part of the dissipation is lost in the assumption that there is no plastic strain in fiber direction.

4. Conclusions

A methodology is proposed to compare a homogenized model against a micromodel for non-monotonic stress states without doing full FE^2 analysis. A mesomodel with homogenized constitutive law is used for crack growth analysis. Local strain histories are recorded and subsequently used for micromechanical analysis with periodic boundary conditions.

It is concluded from micromechanical simulations that the influence of stress in fiber direction has a significant influence on the plastic energy dissipation. In the considered homogenized model, this is not taken into account, which leads to an underprediction of the energy dissipation due to crack growth in the TCT test. Concerning other stress components, the agreement between homogenized model and micromodel is reasonably well for the investigated strain histories.

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