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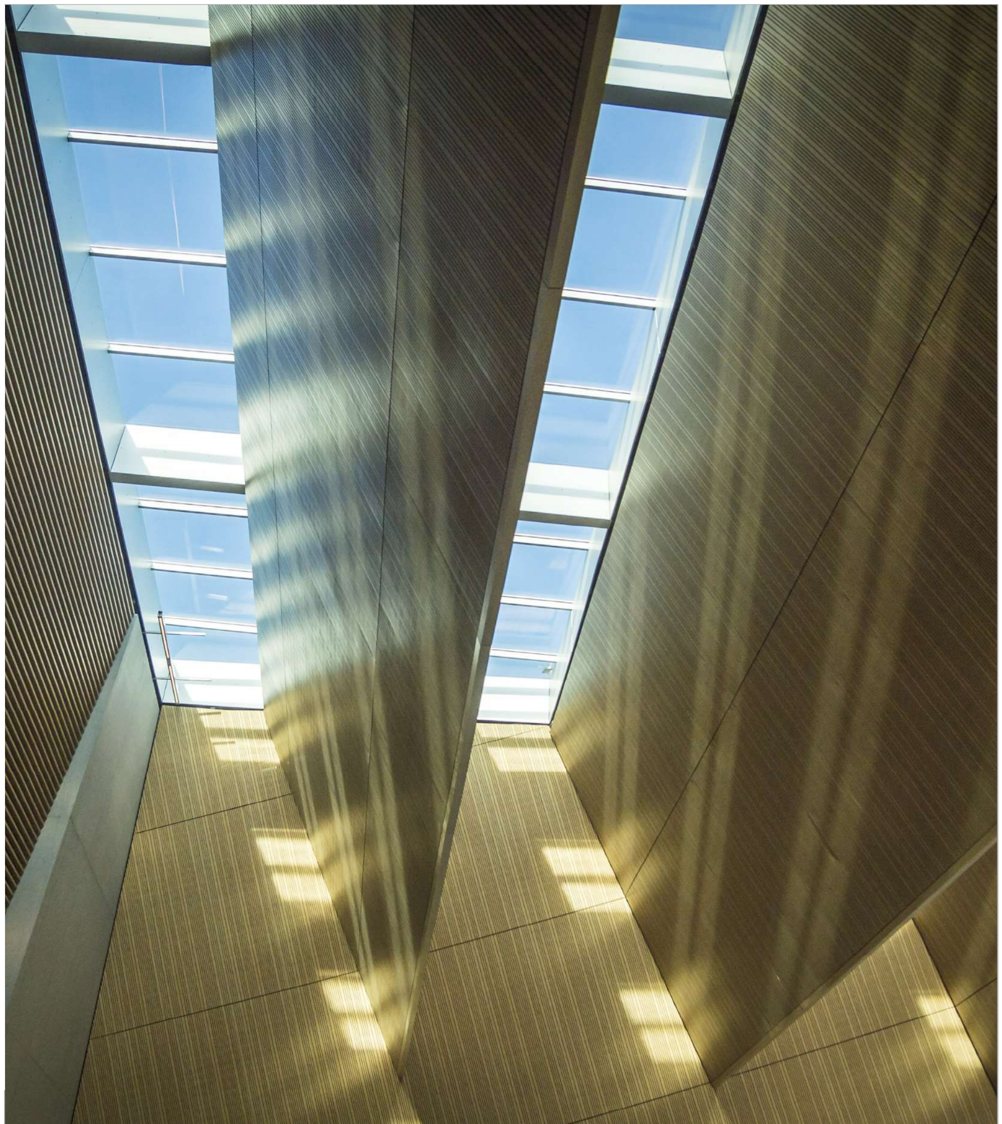

Proceedings of the 20th European Conference on Composite Materials

COMPOSITES MEET SUSTAINABILITY

Vol 4 – Modeling and Prediction

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CHARACTERIZATION OF MODE-II DELAMINATION FRACTURE ENERGY VIA COMPUTATIONAL HOMOGENIZATION

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Abstract: *It is well-known that the fracture energy for delamination is a function of the mode of fracture. Mode II delamination crack growth is accompanied with significantly higher energy dissipation than mode I delamination crack growth. It is not completely understood which physical processes drive this difference. In this study, a multiscale model based on computational homogenization (FE^2) is developed to shed light on the sources of energy dissipation for mode II crack growth. Distinction is made between matrix plasticity, matrix cracking and fiber/matrix debonding. In this paper, a study on a simplified micromodel is presented which allows for the validation of the results obtained with computational homogenization through comparison with direct numerical simulation (DNS) in which the microstructure is explicitly modeled in a monolithic model. In both DNS and FE^2 simulations, the amount of plastic energy dissipation that accompanies crack growth is quantified.*

Keywords: Micromechanics; multiscale modeling; delamination; plasticity; mode II

1. Introduction

The amount of energy required to grow a delamination crack in mode II is higher than it is in mode I. On the mesoscale, where the plies of composite laminates are modeled as homogeneous orthotropic material and the interface between the plies is modeled as a zero-thickness plane, this is usually accounted for by using phenomenological relations for the fracture energy as function of the mode of fracture. Although these models can describe the mode-dependence of the fracture energy, they do not offer an explanation for this phenomenon, which gives rise to the question whether the models generalize well to loading cases that are different from the fundamental experimental setups. In fact, there is evidence that the generalization lacks accuracy in the observation that different experimental setups that describe the same mode of fracture provide different values for the fracture energy as has been observed for the two different mode II setups of the end-notched flexure (ENF) test and the transverse crack tensile (TCT) test.

To gain more insight in the dissipative processes that constitute the fracture energy, it is relevant to zoom in to the microscale, where processes as fiber/matrix debonding, matrix microcracking and matrix plasticity can be explicitly accounted for. Micromechanical models have been proposed in literature to predict the nonlinear response up to failure of composite materials. The idea is that a representative volume element (RVE) can be subjected to a fundamental loading scenario to compute the homogenized stress/strain response. However, in fracture tests, the local strain history that is seen is not as simple as in fundamental loading scenarios like simple tension or pure shear. The strain path that a macroscopic material point near the crack plane follows in a fracture test is not monotonic. The nonlinear interaction between

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neighboring material points in and around the fracture process zone makes it impossible to know the strain path at any point before solving the full macroscale problem. Therefore, in order to use a micromodel for describing the material response in a fracture test, a fully coupled approach is needed. This can be achieved either by explicitly modeling the microstructure in (part of) the macroscopic domain with an embedded model in a direct numerical simulation (DNS), or by coupling an RVE simulation to every macroscopic integration point using computational homogenization (or FE^2).

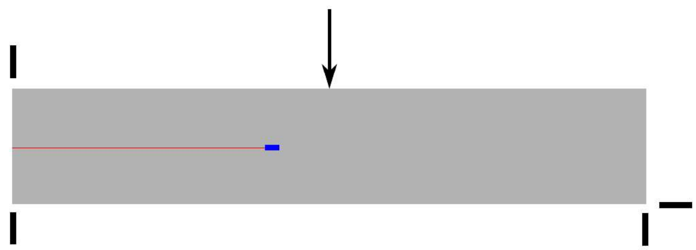

Figure 1. Geometry and boundary conditions. The red line indicates the notch, the blue line shows a region in which the nonlinear response is modeled, either with DNS or with FE^2. Figure not to scale.

With FE^2 no assumptions on the constitutive response of the homogenized material are needed—the micromodel replaces the macroscopic constitutive model. The strain from the macroscale is translated to microscale boundary conditions, after which the micromodel is solved and averaged stresses are passed back to the macromodel. When localization takes place, the standard homogenization approach in which the micromodel is used to compute macroscopic stress from macroscopic strain breaks down because the averaged response becomes pathologically dependent on the size of the micromodel. However, it is possible to repair this by using a discontinuous approach on the macroscale, such that the micromodel is used to provide a traction separation relation. The size of the micromodel can then be included in the scale transition to recover RVE-size independence in the macroscopic response.

In this work, FE^2 for crack growth is applied to the study of energy dissipation for a delamination crack. To establish the suitability of the framework for describing crack growth in an elasto-plastic medium under mode II conditions comparison with DNS is performed. Because DNS of an actual fiber/matrix composite for the case where the crack grows in direction parallel to the fibers is not computationally feasible, a simplified layered microstructure is devised with alternating thin layers of elastic and elasto/plastic material and with the possibility of debonding along the interface between the layers. Mode II crack growth in the layered material is investigated with DNS as well as with FE^2 and results are compared. The influence of plasticity on the total energy dissipation per unit crack length is assessed for the ENF setup.

2. Methods

In this paper, we show results for an ENF test. Like in most delamination tests, the ENF operates on unidirectional laminates. On the macroscale, the test can be simulated quite accurately in two dimensions. However, when considering a microstructure of fiber-reinforced composite material, a three-dimensional micromodel is needed, because the plane in which the

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microstructural geometry can be described (the transverse plane) is perpendicular to the plane in which the macroscopic geometry and boundary conditions can be described. Under the assumption that fibers are straight and perfectly aligned, a three-dimensional RVE can be obtained by extruding a two-dimensional RVE with random fiber direction to a single element in fiber direction. Such thin-slice RVE can be used in FE^2 and capture the interaction between longitudinal shear and stress in fiber direction [1]. Notably, the slice itself does not experience crack growth. However, in line with the concept of separation of scales, a series of thin slice RVEs representing different stages of material degradation can be representative for the fracture process zone.

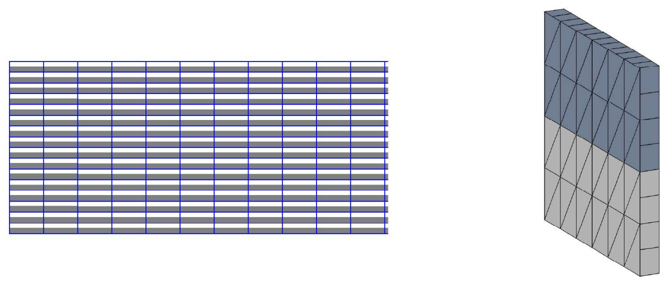

Figure 2. Region with layered microstructure for DNS (left) and bimaterial RVE used for FE^2 (right)

In order to validate the FE^2 approach with a thin slice RVE for mode II crack growth through a comparison with DNS is made. It is computationally not feasible to run a DNS through an embedded model of fiber-reinforced material. Therefore a simplified microstructure is considered in this paper. A layered microstructure is modeled with alternating stiff elastic layers and softer elasto/plastic layers. For this microstructure, a two-dimensional DNS can be performed and a representative micromodel can be constructed of two materials. The RVE response for this simple micromodel will be independent of the RVE dimensions, just as it is at least in statistical sense for the more realistic heterogeneous RVE [2].

In mode II crack growth, there is a thin layer of material around the crack in which crack growth is accompanied by significant plastic deformations. In a homogenized model, and therefore also on the macroscale in FE^2, a sufficiently refined mesh is needed to capture this accurately [3]. Furthermore, the FE^2 model relies on the principle of separation of scales, meaning that every macroscopic integration point represents a region with uniform deformation apart from a microscopic fluctuation that can be modeled as periodic. For agreement between DNS and FE^2 sufficiently thin layers in the DNS and a sufficiently refined mesh in the FE^2 are required. Therefore, a twofold convergence study is performed on these two aspects. The results are compared in terms of global force-displacement response and predicted plastic energy dissipation.

For the elasto/plastic 'matrix'-material, we use Melro's model developed for pressure dependent plasticity in polymers [4, 1]. The 'fibers' are modeled as isotropic linear elastic. For matrix microcracking and fiber/matrix debonding, interelement cohesive elements are inserted on the fly based on a stress-based criterion [5, 6].

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For computational homogenization we use framework by Ke and Van der Meer [2]. In this approach, localization is detected by analysis of the sign of the determinant of the acoustic tensor. Prior to localization, standard first order homogenization is applied, where strain is imposed on the micromodel with periodic boundary conditions and stress is defined as the average of the microscale stress over the RVE domain. Upon detection of localization in an RVE, a discontinuity is inserted through the corresponding macroscale element, using the phantom node version of XFEM. The softening RVE with its history variables is then cloned to be used in the integration points along the discontinuity. To define the boundary conditions for the RVEs corresponding to these integration points, an equivalent strain is computed that is composed of the bulk strain in the material right next to the crack and a regularized strain measure related to the magnitude of the displacement jump. The relation between the displacement jump and the equivalent strain accounts for the size of the RVE to remove pathological RVE size dependence in the homogenized response. To compute the macroscale cohesive traction from the RVE response, macroscale stresses obtained through the standard averaging procedure are multiplied with the normal to the discontinuity.

3. Results

Two different ENF simulations are performed in which a short thin region is defined over which the microstructure is modeled, either with FE^2 or with an embedded model, see Fig. 1. Figure 2 shows the layered microstructure modeled in the DNS and the thin slice RVE used for FE^2. Load-displacement results are shown in Figure 3 where for the DNS the layer thickness is progressively reduced and for FE^2 the macroscale mesh is refined by changing the number of element layers in the refined region. Because only a short region of crack growth is modeled, the load-displacement graphs start to increase very soon after a small drop. However, the refined region is of sufficient length to get stable crack growth, meaning that the position of the small load drop is governed by the effective fracture energy consisting of a cohesive contribution and a plastic contribution. For both refinement studies, the results tend to converge to a unique one. However, although not far apart, they do not converge to exactly the same results.

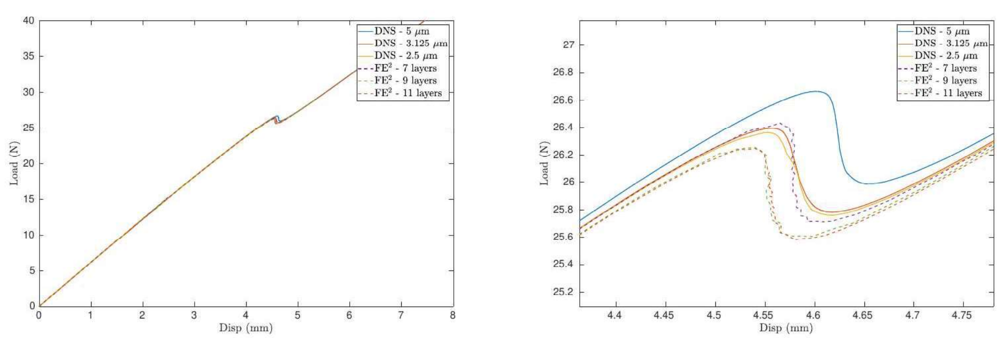

Figure 3. Load-displacement response in DNS with different layer thicknesses and in FE^2 with different macroscale element sizes

In Figure 4, the evolution of plastic energy dissipation across the height of the refined region is visualized. For this figure, a single column of integration points across the height of the refined domain is selected and dissipation for each integration point is plotted for each time step.

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Results from both simulations show a similar profile with localized plastic deformation adjacent to the crack and a wider region of diffuse plasticity. It is evident from these results that a fine discretization of layers in the DNS is needed to get a response that can be homogenized and that a fine mesh in the FE^2 is needed to capture this homogenized response accurately.

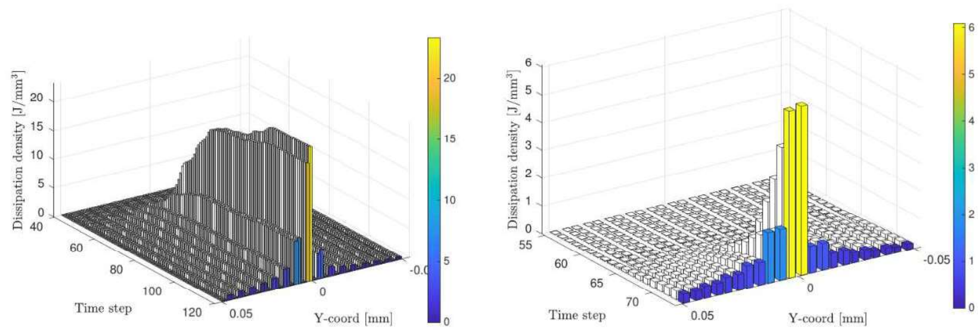

Figure 4. Evolution of dissipation across the height of the refined region as the crack passes: DNS vs FE^2

There remains a significant difference between the results from the two models. A difference can be expected from the fact that in the DNS results the two phases are separately present while in the FE^2 results the averaged dissipation from the complete micromodel is shown. However, dividing the peak values from the DNS by a factor of two to perform the averaging still does not lead to a perfect match with the FE^2 results. A more detailed investigation of the local stress and strain history may shed light on the cause for this difference.

4. Conclusions

A multiscale framework for modeling mode II delamination in unidirectional composites has been developed. In this paper, it is shown through comparison with DNS on a material with simplified microstructure that the FE^2 framework can capture plastic energy dissipation around a growing crack with reasonable accuracy. The multiscale model response is independent from the RVE size as shown in earlier work [2], and here it is also shown that the model response is independent on the macroscale element size although much refinement is needed to obtain an objective response. The need for extreme refinement exacerbates the need for acceleration techniques to speed up microscale simulations for instance with the approach presented elsewhere in this conference [7].

Acknowledgement

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