THE EFFECT OF VOIDS ON TRANSVERSE CRACKING IN COMPOSITE LAMINATES AS REVEALED BY COMBINED COMPUTATIONAL ANALYSIS AT THE MICRO- AND MESO-LEVELS

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ABSTRACT

An extensive amount of experimental research on voids and their effects on mechanical properties of composite materials has been performed over the years. However, fewer studies have tried to investigate these effects through computational modeling. The scale issue is one of the reasons. Intra-laminar voids are defects that have microscopic features and interact with other micro-heterogeneities like fibers, and at the same time they influence the behavior of composites at the ply and laminate levels (referred here as the meso-level). Prediction of their effects on statistically-controlled properties, such as transverse cracking, requires a multiscale modeling approach. In the present study, a methodology is proposed, in which the micro-scale effect of voids on transverse strength of fiber-reinforced composites is evaluated through computational micromechanics. The results are then transferred to a ply-level model as input parameters to investigate the influence of voids on transverse cracking of a cross-ply composite laminate. Through this methodology, the influence of void size on the evolution of crack density in function of the applied strain can be modeled in a macro-level specimen at a manageable computational cost. The results show strong influence of voids on transverse cracking. They also reveal that the developed two-level methodology is a promising technique to evaluate this influence.

1 INTRODUCTION

Voids are a very common type of manufacturing defects in fiber-reinforced polymer composites. Being formed from entrapped air or matrix volatiles, they are inevitable in different manufacturing techniques such as liquid composite molding and (out-of-)autoclave processing. They have a large influence on mechanical properties of fiber-reinforced composites, especially on those that are matrix dominated. For example, they can reduce inter-laminar shear [1, 2], transverse tensile [3, 4], longitudinal compressive [1, 5], and flexural strength [6]. Voids can also influence transverse cracking in composite laminates. This damage mechanism, though does not directly control the final failure of the laminate, can cause delamination, which is a mechanism proceeding the final failure.

The research on effect of voids on transverse cracking concludes that voids can control the initiation of transverse cracks, but the saturation crack density has a small dependence on voids [7-10]. However, these studies either focus only on local or global effect of voids, while voids are micro-scale features that simultaneously influence the behavior at the ply and laminate levels. Therefore, prediction of their effect on statistically-controlled properties, such as transverse cracking, needs a multi-scale framework. Recently, full-scale numerical modeling [11] and multi-scale statistical prediction [12] of transverse cracking (in the absence of voids) are investigated. In the current study, a methodology, which combines computational analyses at the micro- and meso-levels is established. This methodology allows investigating the effect of intra-laminar voids on the process of transverse cracking in cross-ply laminates.

2 MODELING METHODOLOGY

A micro-level Representative Defective Volume (RDV) of a unidirectional ply is created. It includes randomly distributed fibers in a homogenous matrix and a void. The degradation of the properties of the *RDV* caused by the void is calculated using finite element modeling. This model accounts for plasticity and pressure-dependent damage in the matrix. The homogenized degraded properties are then transferred to a 3D meso-level model of a cross-ply composite laminate, where they are used as input parameters for 'weakened' regions, where voids are located. The weakened regions are distributed in the transverse ply with a random distribution algorithm. Applying deformation to the meso-level model, a 3D representation of the onset, development, and saturation of transverse cracks, affected by voids, are predicted via eXtended Finite Element Method (XFEM).

2.1 Micro-scale modeling

3D Micro-scale finite element models of unidirectional plies are created with a random distribution of fibers inside a homogenous matrix. The fiber random distribution is based on the algorithm developed in [13]. Fibers are assumed to be transversely isotropic with the properties presented in Table 1. An elasto-plastic damage model is prescribed to the matrix. The details of the model as well as the specific quantitative matrix behavior can be found in [14, 15]. The input properties for the matrix are presented in Table 1. The properties are carbon fibers are taken from [11] and also listed in Table 1. Three micro-models are built: one reference (*RVE*) and two with voids of different sizes, i.e. 30 and 60 µm (*RDV-S* and *RDV-L*). Voids are created in the center of each model with almost zero stiffness, assuming the void is cylindrical and along the fibers. The size of each model is chosen such that the stress concentration caused by the void becomes negligible at the model boundaries. The model dimension in the fiber direction is very small (0.15 × fiber radius). Transverse horizontal tension is applied to each model with symmetric boundary conditions in the other two directions. Due to the symmetry, only half of the models are created, as shown in Fig. 1.

Epoxy matrix	Elastic modulus (GPa)	Poisson's ratio	Plastic Poisson's ratio	Tensile strength (MPa)	Fracture toughness (N/mm)
	3.9	0.39	0.3	93	0.09
Carbon fiber	Long. elastic modulus (GPa)	Trans. elastic modulus (GPa)	in-plane Poisson's ratio	out-of-plane Poisson's ratio	in-plane shear modulus (GPa)
	232.00	13.00	0.30	0.46	11.30

Table 1: Constituents input properties for the micro-models.

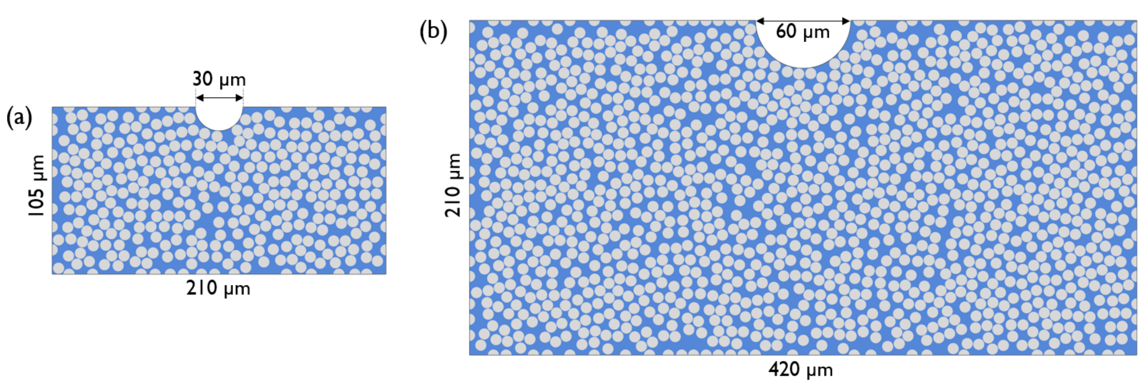

Figure 1: Micro-models with a (a) 30-µm and (b) 60-µm void.

2.2 Meso-scale modeling

3D meso-scale models of a [0,90,0] laminate (Fig 2a) are created to evaluate the effect of voids on the evolution of crack density. Each ply has a thickness of 0.2 mm, length of 20 mm and width of 20 mm. The mesh in each ply has 3 elements through the thickness, 100 elements in the width direction and 300 elements in the length direction (Fig 2b). Three models are created "*Meso-S*", "*Meso-L*" and "*Meso-Ref*", where *S* stands for small voids of 30 μm in diameter and *L* for large voids of 60 μm. The void content is fixed to 1.6% in these models. *Meso-Ref* is a reference model without voids for comparison. Each model is subjected to longitudinal tensile displacement equivalent to ~0.9% of strain. The illustration of *Meso-L* model can be found in Figure 2.

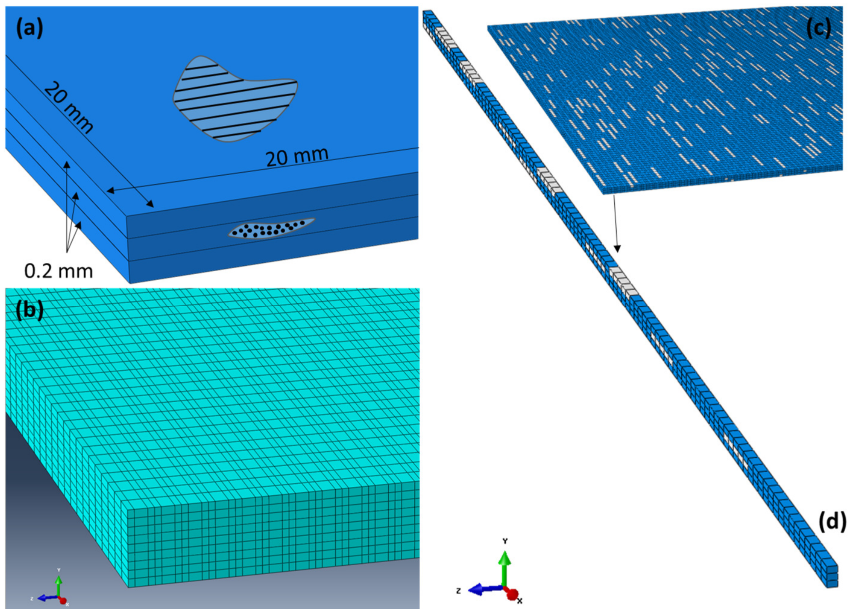

Figure 2: The meso-scale model: (a) geometry, (b) mesh, (c) grey elements with voidy material in the *Meso-L* model and (d) a zoom in view on the enriched region with voids where crack is allowed.

XFEM is utilized to model the formation and propagation of cracks in the transverse ply. In all models, a crack is allowed in 100 evenly spaced regions called enrichments or enriched regions. A linear cohesive law is specified in these regions with a maximum stress initiation criterion and a mode-independent energy-based damage evolution criterion. The transverse strength is assumed to follow normal distribution with a standard deviation of 15%. The strength of each enrichment is calculated through multiplying the input strength by a factor, which is obtained from the normal distribution around 1.

The elastic properties, except transverse stiffness, obtained from the micro-scale model without voids, i.e. *RVE*, are assigned for all meso-models. The transverse stiffness of the *Meso-Ref*, *Meso-S*, and *Meso-L* are calculated respectively from the *RVE*, *RDV-S*, and *RDV-L*. The transverse strength resulted from the *RVE* is assigned for the regions without voids in all meso-models. The strength of the voidy elements (colored grey in Fig 2c and d) in *Meso-S* and *Meso-L* is reduced to that obtained from the *RDV-S* and *RDV-L*, respectively (explained in Section 4). Ply properties, obtained from the micro-models and used in the meso-models, are listed in Table 2.

	E_1 (GPa)	$E_2 = E_3$ (GPa)	$G_{12} = G_{13}$ (GPa)	G_{23} (GPa)	$\nu_{12} = \nu_{13}$	ν_{23}	σ^s (MPa)	σ^s_{voidy} (MPa)	G_{IC} (N/mm)
Meso-Ref		8.04						-	0.15
Meso-S	134	7.74	4.15	2.6	0.34	0.54	64.24	43.32	0.09
Meso-L		7.71						16.68	0.09

Table 2: Ply properties in the meso-scale models, where 1: fiber direction, E: elastic modulus, G: shear modulus, ν: Poisson's ratio, σ^s: strength of the non-voidy material before the distribution, σ^s_{voidy}: strength of the voidy material, and G_{IC}: fracture toughness.

4 RESULTS AND DISCUSSION

The micro-scale modeling results show that the presence of the void reduces the transverse stiffness of the composite. The transverse strength, which is calculated as the maximum stress in the homogenized transverse stress-strain curve, is also decreased by the presence of voids, as can be observed in Table 2. Transverse cracks start from voids, in models with voids, i.e. *RDV-S* and *RDV-L*. The failure of the micro-models is represented in Fig. 3. The transverse stiffness and strength of the *RVE* is used as the input data for the reference meso-model. The same is done for the RDVs and the meso-models with voids. It needs to be noted that the transverse strength is calculated over a region, which has the size of an element of the meso-model, i.e. $100 \times 70\ \mu m^2$.

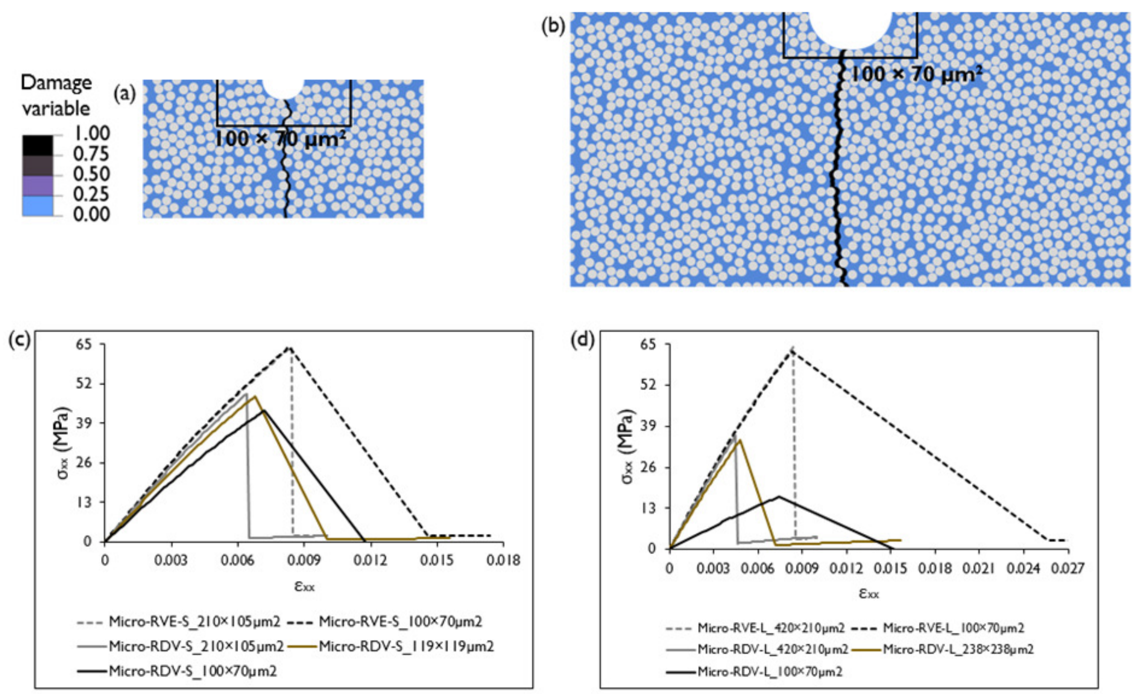

Figure 3: Computationally predicted matrix damage under transverse tension in the (a) small and (b) large micro-scale models; (c), (d) their homogenized stress-strain curves.

The meso-model predicts the density of fully-opened cracks in function of the applied strain. A crack is treated as fully-opened when 50% of all elements are opened (become traction free according to the cohesive law) in the enriched region. The results show that voids have an effect on the cracking process inside the transverse ply (Figure 4). More specifically, the presence of voids decreases the strain at which cracks appear and changes the character of their accumulation. At the same time, the size of the voids does not seem to affect their evolution as far as the total void content is low and the same.

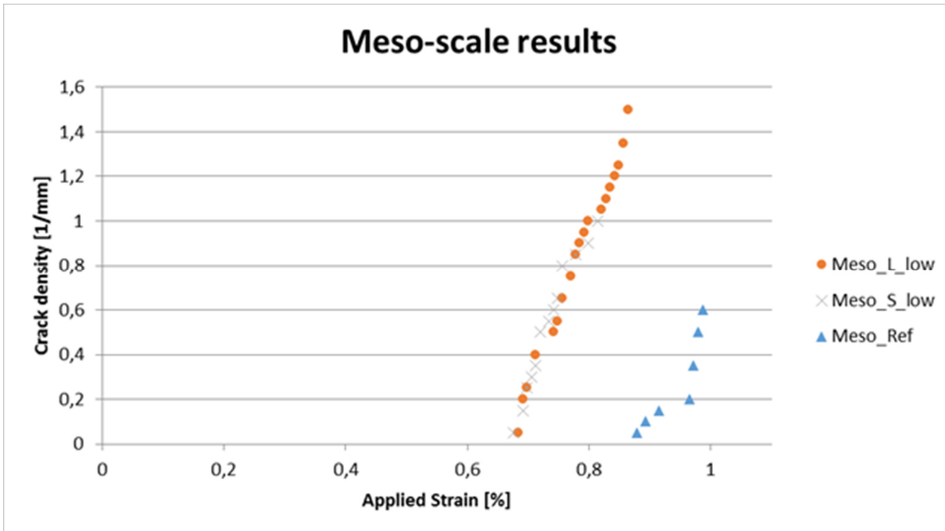

Figure 4: Crack density obtained from meso-scale models with and without voids.

9 CONCLUSIONS

A multi-scale methodology for prediction of the effect of intra-laminar voids on transverse cracking in cross-ply laminates is developed. The effect of voids on micro-scale transverse failure of unidirectional composites is evaluated through computational micromechanics, where an elasto-plastic damage model is considered for the matrix. Failure initiation from the void and reduction in transverse stiffness and strength are the results of modeling at the micro-scale. The transverse properties are imported to a meso-scale model as the input parameters. The meso-model, utilizing XFEM, can reveal the effect of randomly distributed regions with voids and reduced properties on evolution of crack density. The results show sensitivity of transverse cracking to intra-laminar voids.

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