FIBER BRIDGING IN GFRP COMPOSITES: MESOMECHANICAL ANALYSIS

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ABSTRACT

Computational experiments have been carried out in order to clarify the micromechanisms of damage evolution and the effect of matrix cracks on the strength of fiber reinforced composites. Computational tools for the automatic generation of 3D micromechanical models of composites and the simulation of different damage modes have been developed. The numerical testing of multifiber unit cells with matrix cracks, as well as different parameter studies were carried out. On the basis of the numerical investigations, it was concluded that the effect of the statistical variability of the fiber properties (strengths) supersedes the effect of matrix cracks on the composite strength.

1. INTRODUCTION

In connection with the development and wide utilization of brittle matrix composites (epoxy, ceramic and other matrix), the problems of the role of the matrix defects and the material toughening by crack-bridging fibers gained in importance.

The purpose of this work is to analyze the effects of damage defects and fiber bridging on the strength and damage mechanisms of fiber reinforced polymer matrix composites, using the methods of the computational mesomechanics and numerical experiments [1-6].

2. MODELLING OF MATRIX CRACKING AND FIBER BRIDGING IN FIBER REINFORCED COMPOSITES

Let us consider some models of the matrix defects in fiber reinforced composites. The classical ***fracture mechanics based model*** of matrix cracking was developed by Aveston, Cooper and Kelly [7]. (The model is often referred to as ACK). Assuming that the fibers are held in the matrix only by frictional stresses, Aveston and colleagues carried out an analysis of the energy changes in a ceramic composite due to the matrix cracking. On the basis of the energy analysis, they obtained the condition of matrix cracking in composites. Marshall, Cox and Evans [8] and Marshall and Cox [9] used the stress intensity approach to determine the matrix cracking stress in composites. The bridging fibers were represented by the traction forces connecting the fibers through the crack. Further, Marshall and Cox studied the conditions of the transitions between failure mechanisms (matrix vs. fiber failure) and the catastrophic failure and determined the fracture toughness of composites as functions of the normalized fiber strength.

Budiansky, Hutchinson and Evans [11] considered the propagation of steady state matrix cracks in composites, and generalized some results of the Aveston-Cooper-Kelly theory, including the results for the initial matrix stresses. Considering the energy balance and taking into account the frictional energy and potential energy changes due to the crack extension.

In several works, ***continuum models of a bridged matrix crack*** have been used. In these models, the effect of fibers on the crack faces is smoothed over the crack length and modeled by continuous distribution of tractions, acting on the crack faces. The relationships between the crack bridging stresses and the crack opening displacement (bridging laws) are used to describe the effect of fibers on the crack propagation. McCartney [11] used the continuum model of a bridged matrix crack, in order to derive the ACK-type matrix cracking criterion on the basis of the crack theory analysis. McCartney considered the energy balance for continuum and discrete crack models, and demonstrated that the Griffith fracture criterion is valid for the matrix cracking in the composites. Hutchinson and Jensen [12] used an axisymmetric cylinder model to analyze the fiber debonding accompanied by the frictional sliding (both constant and Coulomb friction) on the debonded surface. Considering the debonding as mode II interface fracture, Hutchinson and Jensen determined the debonding stress and the energy release rate for a steady-state debonding crack.

Using the shear lag model and the continuously distributed nonlinear springs model, Budiansky, Evans and Hutchinson [13] determined the stresses in the matrix bridged by intact and debonding fibers, and derived an equivalent crack-bridging law, which includes the effect of debonding toughness and frictional sliding.

Gonzalez-Chi and Young [14] applied the partial-debonding theory by Piggott [15] to analyze the crack bridging. In the framework of this theory (based on the shear lag model and developed for the analysis of the fiber pullout tests), the fiber/matrix interface is assumed to consist of a debonded area (where the stress changes linearly along the fiber length) and the fully bonded, elastically deforming area. Considering each fiber and surrounding matrix as a single pull-out test, Gonzalez-Chi and Young determined stresses in the fiber and on the interface. The model was compared with the experimental (Raman spectroscopy) analysis of the stress distribution in the composite.

In a series of works, the matrix cracking and its effect on the composite properties were simulated using ***micromechanical finite element models***. Zhang et al [16] studied toughening mechanisms of FRCs using a micromechanical model ("embedded reinforcement approach"), taking into account both fiber bridging and matrix cracking. They defined the cohesive law for the matrix cracking as a linearly decreasing function of the separation. For different traction-separation laws of interfaces, R-curves were obtained. Zhang and colleagues demonstrated that the strong interfaces can lead to the lower toughness of the composites. Zhang et al [17] simulated unidirectional fiber-reinforced polymers under off-axis loading, using 3D unit cell with nonlinear viscoelastic matrix and elastic fibers. In order to model the matrix cracking, smeared crack approach was used. The matrix damage growth in the form of two "narrow bands" near the interface and along the fiber direction were observed in the numerical experiments. González and LLorca [18] developed a multiscale 3D FE model of fracture in FRCs. The notched specimen from SiC fiber reinforced Ti matrix composites subject to three-point bending was considered. Three damage mechanisms, namely, plastic deformation of the matrix, brittle failure of fibers and frictional sliding on the interface were simulated. The fiber fracture was modeled by introducing interface elements randomly placed along the fibers. The interface elements used the cohesive crack model (with random strengths) to simulate fracture. The simulation results were compared with experiments (load-CMOD curve), and a good agreement between experimental and numerical results was observed.

Thus, the main approaches to the analysis of the matrix cracking in fiber reinforced composites include fracture mechanics and energy balance based models, shear lag based model, and discrete micromechanical/unit cell models. As differed from the analytical models, the discrete numerical models allow to take into account nonlinear, time dependent behavior of material components.

3. 3D FIBER BRIDGING MODEL

In this section, we investigate the effect of matrix cracks on the fiber fractures, using computational experiments. In order to produce 3D models of composites with damaged matrix, we utilize the program code "Meso3DFiber" for the automatic generation of 3D micromechanical finite element models of composites with damageable elements [1, 6]. The idea of introducing potential fracture planes (in form of damageable cohesive elements) in random sections of fibers, suggested by González and LLorca [18] was used to model the fiber cracking. Following this idea, we introduced damageable layers in several sections of fibers. The locations of the damageable layers in the fibers were determined using random number generator with the uniform distribution. A similar concept was used to simulate the interface cracking of composites. Given that surfaces of fibers can be rather rough, and the interface regions in many composites contain interphases, the interface debonding was considered not as a two-dimensional opening of two contacting plane surfaces, but rather as a three-dimensional process in a thin layer. Thus, the interface was represented as a "third (interphase) material layer" between the homogeneous fiber and matrix materials. The damage evolution in the damageable layers, placed in random sections of fibers, as well as in the matrix and interphase layers was modeled using the finite element weakening method, realised in the ABAQUS subroutine User Defined Field [3].

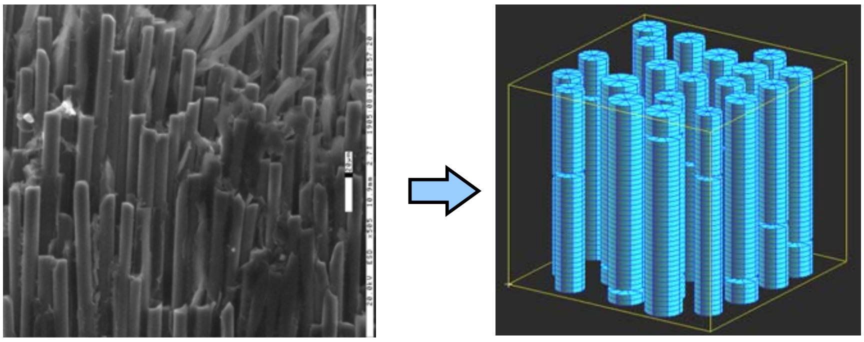

Figure 1. Micrograph of fracture surface of an unidirectional carbon fiber reinforced composite (with failed fibers) (left, courtesy of Dr. S. Goutianos, Risø) and an example of the FE models with 20 fibers, and removed layers of potential fracturing (right) (from [5, 6])

Multifiber unit cells (with 20 fibers) were generated and subject to a uniaxial tensile displacement loading, along the axis of fibers. As output results, the stress-strain curves and the damage strain curves were obtained, as well as the stress, strain, and damaged element distributions in the unit cells. The simulations were done with ABAQUS/Standard. The following properties of the phases were used in the simulations: glass fibers: elastic isotropic solids, with Young modulus EP=72 GPa, Poisson's ratio 0.26, and randomly (Weibull) distributed failure strengths [19]. The matrix properties are as follows: Young modulus 3790 MPa, Poisson's ratio 0.37, failure stress 67 MPa [20, 21, 22]. The viscoelastic properties were described by a single term Prony series, with the relaxation time 0.25 sec, and the modulus ratio g=0.125 [20, 21]. Three versions of the unit cells (with 20 fibers) were generated, containing large matrix cracks, bridged by intact fibers. The matrix cracks were oriented horizontally, normal to the fiber axis and loading vector. The lengths of the cracks were taken 0.16l (1/6 of the cell size), 0.41l (5/12 of the cell size), 0.66l (8/12 of the cell size), where L – cell size. The crack opening was taken 1/12 of the cell size. Figure 2 shows the general appearance of the cells with matrix cracks.

Figure 3 shows the maximal shear strain in the matrix with the long crack after the fiber failure. The regions of high strain level (shear bands) are seen, which connect the crack tip in the matrix with the cracks in fibers, and the fiber cracks in neighboring fibers.

Figure 4 gives the stress-strain curves and the damage (fraction of damaged elements in the damageable sections of the fibers) versus strain curves. The stiffness reduction due to the fiber cracking is more pronounced in the cells with long cracks that in the cells with short or no matrix crack (13% higher stiffness in the case of intact matrix, than in the case of the matrix with a long crack). It is of interest that the damage growth in fibers seems to be independent from the crack length in matrix. This result corresponds also to the observations of Venkateswara Rao et al. [24], who demonstrated experimentally that fiber reinforced composites are insensitive to the presence of notches under tension loading.

However, the weak influence of the matrix cracks on the fiber fracture in this case is in strong contrast to our other results obtained for the case of the constant fiber strength and ductile (aluminium) matrix, presented in [25]. In this work, a strong effect of the matrix crack length on the damage growth and the stress-strain curve of the composites was observed. In order to separate out the effect of the ductile matrix and the constant fiber strength, we carried out the simulations (similar to above) with the constant fiber strength. Figures 5 and 6 give the stress-strain curves and the damage versus strain curves for the case of constant fiber strengths. The curves for randomly distributed fiber strengths are given for comparison as well. It can be seen that the matrix cracks do influence the beginning of fiber cracking and the peak stress, if the fiber strength is constant. In the composites with constant fiber strengths, fiber fracture begins much earlier if the matrix is cracked than in the case of intact matrix. Generally, fiber cracking begins the earlier the longer crack in the matrix. The critical strain, at which the stiffness of composite is stepwise lowered, is independent on the length of the matrix cracks.

One may state that the matrix cracks have an effect somewhat similar to the statistical variability of fiber strengths: they make the material weakening during the failure process smooth and nonlinear.

The main conclusion from the above simulations is that the statistical variability of fiber strengths has stronger effect on the damage evolution in the composites, than the matrix cracks and their sizes. Thus, the variability of the fiber properties supersedes the effect of matrix cracks on the composite strength.

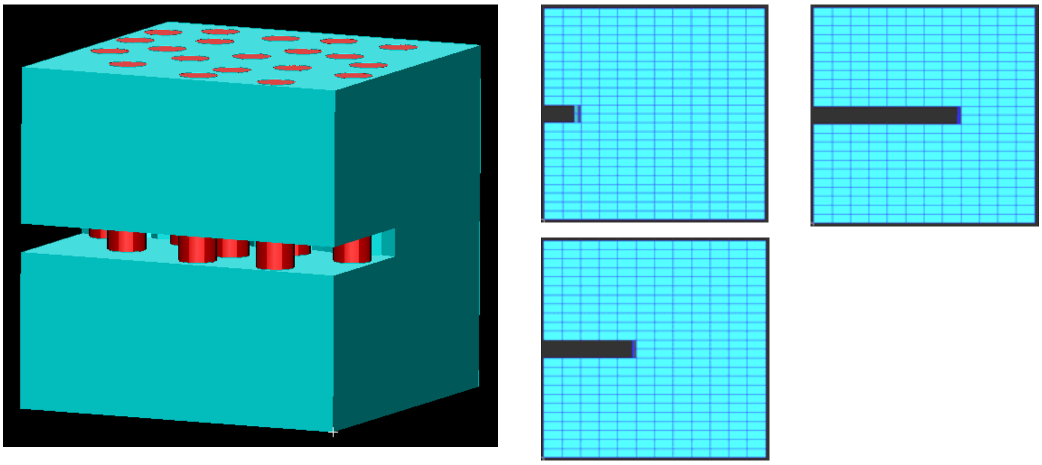

Figure 2. Unit cell with a matrix crack and bridging fibers [2, 6]

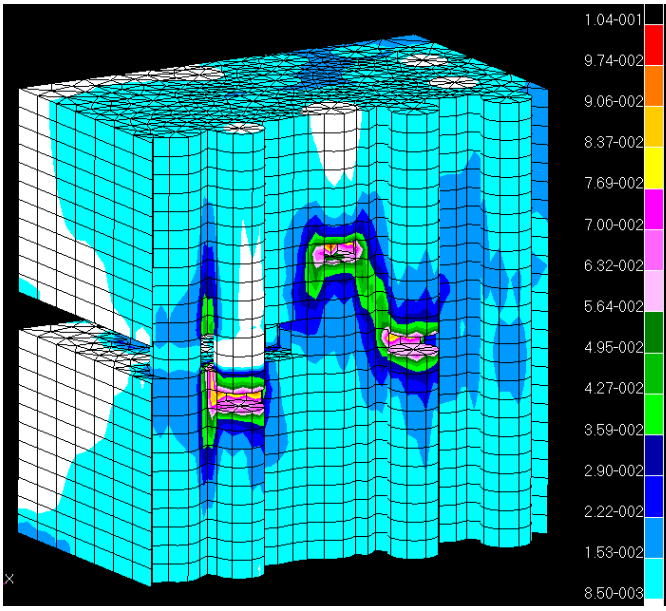

Figure 3. Maximal shear strain in the matrix after the fiber cracking

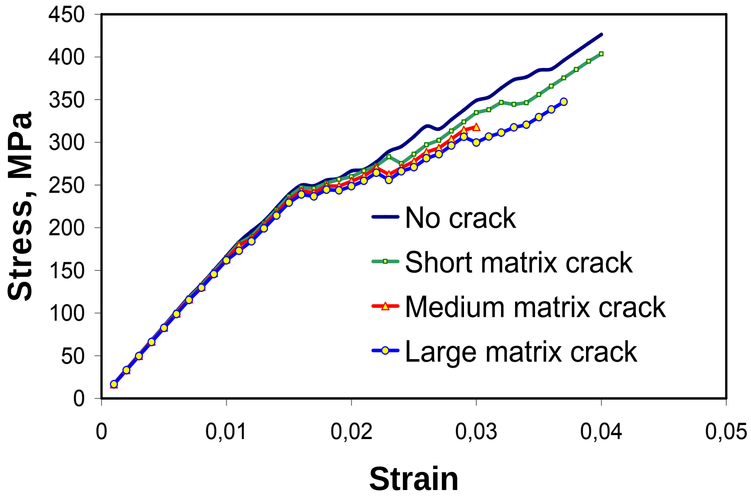

Figure 4. Stress-strain curves for the unit cells with and without the matrix cracks.

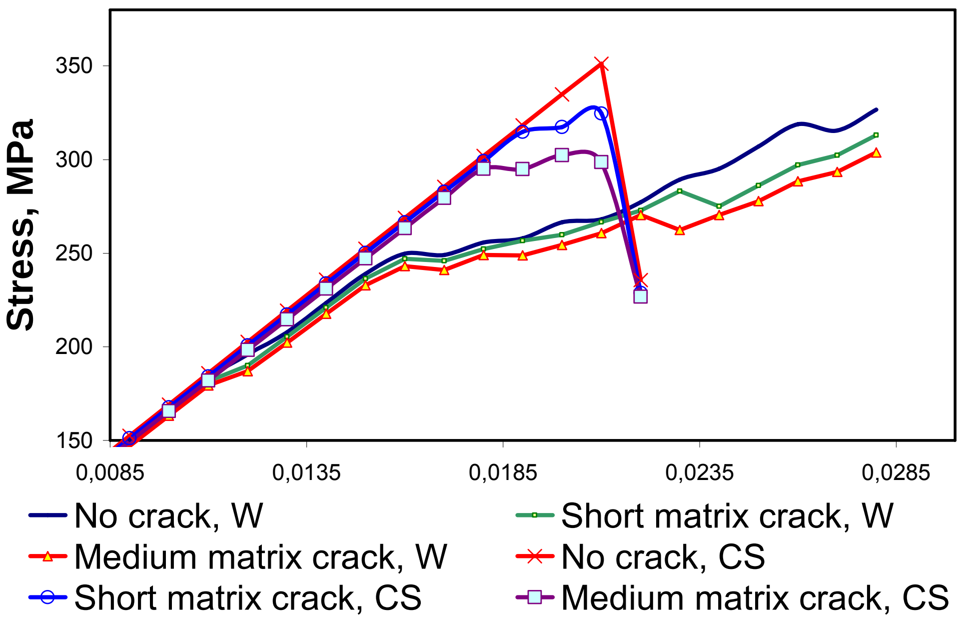

Figure 5. Stress-strain curves for the unit cells with and without the matrix cracks, with constant (CS) and randomly distributed (W-Weibull) strengths of fibers.

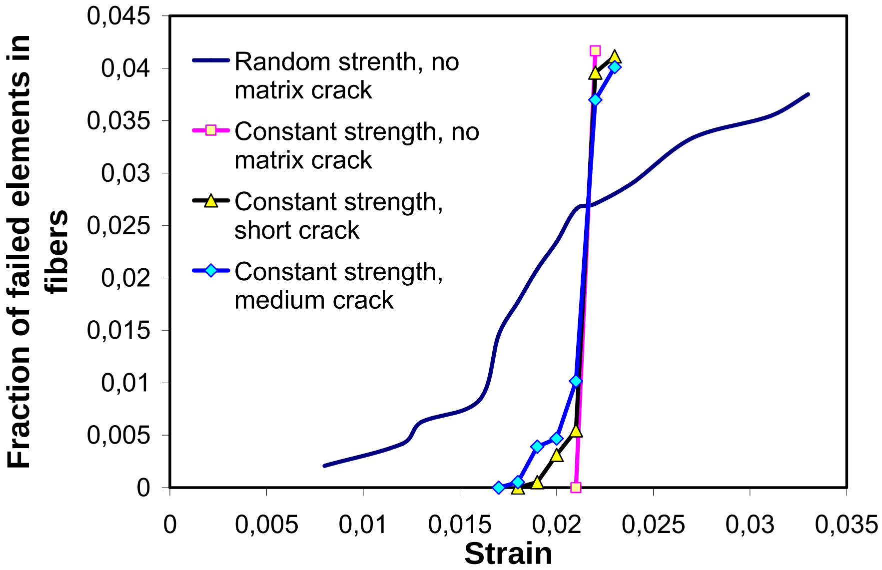

Figure 6. Damage (fraction of damaged elements in the damageable sections of the fibers) versus strain curves for the unit cells with and without the matrix cracks, with the constant strength of fibers. A curve for randomly distributed fiber strengths is given for comparison.

6. COMPETITION BETWEEN DAMAGE MODES IN COMPOSITES

In this section, the interaction between all three damage modes in composites (matrix cracks, interface damage and fiber fracture) is considered. Figure 7 shows the results of simulations: damage formation in the fibers, interface and matrix. The damage evolution begins by formation of a crack in a fiber and (in another, rather far site) in the matrix (ε=0.001). Then, the interface crack forms nearby the fiber crack, and the large matrix crack is formed (ε=0.0015). Figure 8 shows the damage-strain curves for this case.

It is of interest that in the case when all the three damage mechanisms are possible, the competition between the matrix cracking and the interface debonding is observed. In the area, where the interface is damaged, no matrix crack forms; vice versa, in the area, where the long matrix cracks is formed, the fiber cracking does not lead to the interface damage. Practically, it means that a weaker interface can prevent the matrix failure, and therefore, ensure the integrity of the material.

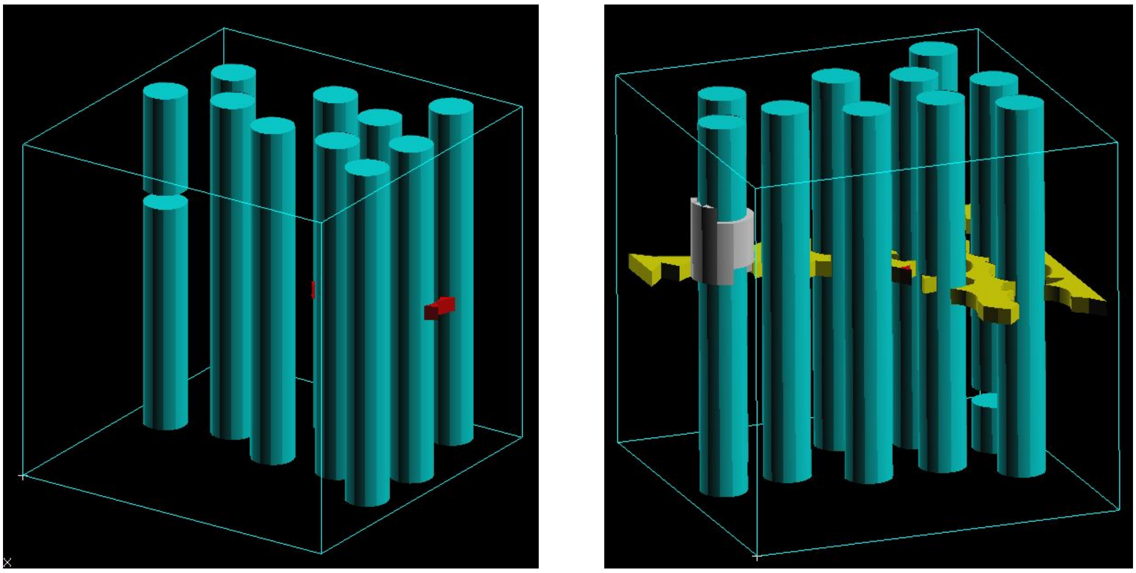

Figure 7. Competition of damage modes: (a) one failed fiber and a few microcracks in the matrix (red), ε=0.001, and (b) two fibers have failed, the interface crack is formed in the vicinity of a fiber crack and the matrix crack is formed (ε=0.0015).

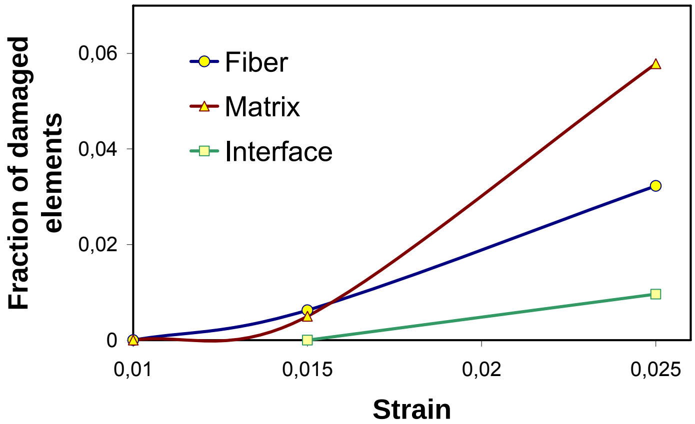

Figure 8. Damage-strain curves for the case of three acting damage mechanisms

6. CONCLUSIONS

Numerical investigations of the damage evolution in glass fiber reinforced polymer matrix composites are used to analyse the interplay of damage mechanisms (fiber, matrix, interface cracking) and the effect of local properties on the microscopic damage mechanisms. The computational investigations lead us to the conclusion, that the influence of the matrix defects on the composite strength is much weaker than the effect of the statistical variability of fiber strengths. If the fiber strength is constant, the fiber cracking begins earlier, the longer is the matrix crack. In the case of randomly distributed fiber strengths, the damage growth in fibers seems to be almost independent from the crack length in matrix, and fully controlled by the load redistribution from weak and failed to remaining fibers.

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