MESO-MECHANICAL PERFORMANCE OF UNIDIRECTIONAL FIBER COMPOSITES WITH MATRIX SHEAR BAND EFFECT

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1 Introduction

The stress concentration phenomenon plays an important role in determining the failure behavior of composites. A number of researchers have studied the phenomenon experimentally, theoretically and numerically [1~17]. Matrix plays a significant role in controlling the stress concentration as the variety of matrix mechanical properties changes the way in which the load is transferred from the broken fiber to its neighbors and the subsequent stress is redistributed after the initial fiber failure. The importance of the matrix plasticity was also indicated in the experiment reports [1, 2, 16], after which considerable attentions have been paid to the matrix plasticity for recent years by experimental approaches [17]. However, the post-yield softening behavior, which is a characteristic of glassy polymer, was ignored or overlooked in previous theoretical and numerical researches on fibrous polymeric composites, although lots of authors have been contributing to relevant experimental researches on straight glassy polymers [18]. The theoretical models predicting stress redistribution either failed to include material properties [7], or were proposed for elastic/elasto-plastic matrices [8~10]. When it comes to the former numerical simulations of long-fiber-reinforced PMC system [11~15], the softening effect was often eliminated as a result of being limited to the correlative researches on proper constitutive models and computing techniques.

Now it's time to reconsider the neglect of this important matrix property. Due to the intrinsic character of immediate softening after yield and progressive hardening, glassy polymers are inclined to strain localization, including necking or shear banding, which is often triggered by material imperfections [19, 20]. That naturally drives us to ask, what is the meso-scale deformation behavior of the matrix material around the fiber break? Could there be certain kinds of strain localization phenomena exhibiting? After all, the matrix micro/macro cracks caused by fiber breaks can be obviously considered as material imperfections. If the answer is yes, which kind should it be, and how will it perturb the stress distribution in the adjacent fibers? On the other hand, we and previous authors [21, 22] have indeed observed the phenomenon of localized deformation: shear bands emanating from the matrix crack tip (see Fig. 2a here and Fig. 4 in [21]). But, again, we didn't know the origin and their influence on stress redistribution in the adjacent fibers [21, 22].

The purpose of this study is to figure out whether there is a correlation between the shear band phenomenon and the post-yield softening character of polymer matrix, and to gain a comprehensive understanding of the influence of matrix softening on the stress state of the unbroken fibers and on the composite fracture modes.

2 Mesoscopic Mechanical Modelling

2.1 Geometric Model

The commercial software ABAQUS was used to generate a 2D mechanical model (shown in Fig. 1) representative for a unidirectional fiber reinforced composite with a fiber breakage. For the entire model, the length (*x*-direction) was 15*d*, where *d* denotes the fiber diameter (10 μm). An area of equivalent composite part was introduced, for the purpose of accounting for the influence of the rest of the surrounding composite. To examine the effect of matrix softening under different inter-fiber spacings, seven fiber-fiber distances were modeled, namely, from 1*d* to 7*d* in increments of 1*d*.

2.2 Boundary Conditions and Loads

To meet the symmetry, the nodes at $y = 0$ were constrained in the *y*-direction. A "pre-break" was introduced by applying no constraints to the nodes at the broken end of the center fiber and the crack zone in matrix, while *x*-direction displacement of the rest nodes at $x = 0$ was equal to zero owing to symmetry. The load was applied by the displacement method: an *x*-direction displacement was imposed at the far end of the model which was equivalent to a total strain of 5% with respect to the longitudinal length.

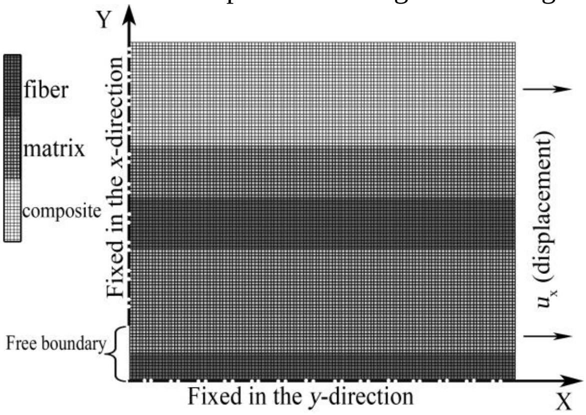

Fig.1. Finite element mesh and boundary condition.

2.3 Constitutive Models

We followed the modified BPA model given by Wu and Giessen [19], to take into account the large strain visco-plastic softening and rehardening behavior of polymer matrix. It decomposes the rate of matrix deformation into elastic and plastic parts: $\boldsymbol{D}=\boldsymbol{D}^{e}+\boldsymbol{D}^{p}$, while the latter item $\boldsymbol{D}^{p}$

$$\boldsymbol{D}^{p}=\frac{\dot{\gamma}^{p}}{\sqrt{2}\tau}\bar{\boldsymbol{\sigma}}' \quad (1)$$

is specified in terms of deviatoric part $\bar{\boldsymbol{\sigma}}'$ of the driving stress $\bar{\boldsymbol{\sigma}}$. We can obtain $\bar{\boldsymbol{\sigma}}$ by $\bar{\boldsymbol{\sigma}}=\boldsymbol{\sigma}-\boldsymbol{b}$, where $\boldsymbol{b}$ denotes the back stress tensor, which describes the orientational hardening of the material due to the severe molecular network stretch. τ denotes the equivalent shear stress.

The equivalent plastic shear strain rate is given by

$$\dot{\gamma}^{p}=\dot{\gamma}_{0}\exp[-\frac{A\tilde{s}}{T}(1-(\frac{\tau}{\tilde{s}})^{5/6})] \quad (2)$$

where $\dot{\gamma}_0$ and A are material parameters, and T is the absolute temperature. The shear resistance $\tilde{s}$ is assumed to evolve with plastic strain via

$$\tilde{s}(\gamma^{p})=s_{s}+(s_{0}-s_{s})\exp(-h\gamma^{p})+\alpha p \quad (3)$$

from an initial value s_0 to a saturation value s_s in order to model the intrinsic softening following the pronounced yield point, while α and h are additional material parameters.

3 Results and Discussion

3.1 Deformation Pattern

Without loss of generality, we studied the deformation pattern of the composite with an inter-fiber spacing of 2d firstly. The deformation pattern of the composite visualized by the distribution of the maximum in-plane principal logarithmic strain is shown in Fig. 2b, from which it can be easily seen that two pairs of intensely deformed zones have formed in the matrix, approximately 45° starting from the matrix crack tip. The shape, location and orientation of these narrow zones agree well with that of the shear bands observed in our experiments (shown in Fig. 2a).

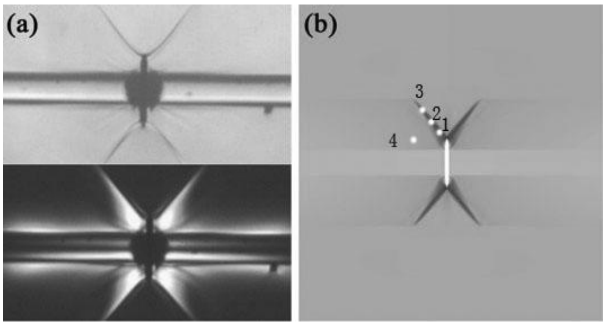

Fig. 2. Comparison between the simulated results and experimental observation. (a) optical micrograph (upside) and polarized optical micrograph (underside) of shear bands captured in our epoxy/glass fiber composite tensile test; (b) the maximum in-plane logarithmic strain contour.

3.2 Property of Shear Bands

We proceed by taking a closer look at these shear bands in present study. Fig. 3 shows the stress-time and accumulative plastic strain evolution curves of typical four material points (labeled in Fig. 2b). When reaching the yield point, the three material points on the shear band undergo a stress decrease, followed by progressive rehardening as time goes by. The nearer the material point to the crack tip, the earlier the stress begins to drop. Meanwhile, Fig. 3 illustrates that, for the materials on the shear bands, the accumulative plastic strain begins to dramatical-ly increase almost simultaneously with its arrival at the yield point, as a result of the local strain instability (resulting from the strain softening after yield). On the contrary, the materials outside the shear bands are not subjected to any strain softening, nor does the value of plastic strain obtain any increase, as illustrated by the curves of material point 4. This contrast indicates that, the material plastic flow initiated by the post-yield softening and the severe stress concentration around matrix crack tip can propagate approximately 45° with tensile direction, resulting in the localized deformation on its covered area. Besides, the progressive hardening prevents the sharpness of these severely deformed zones from loss, finally leading to the formation of the shear bands. To summarize, the intrinsic softening behavior of matrix is a prerequisite for the initiation and promotion of shear bands.

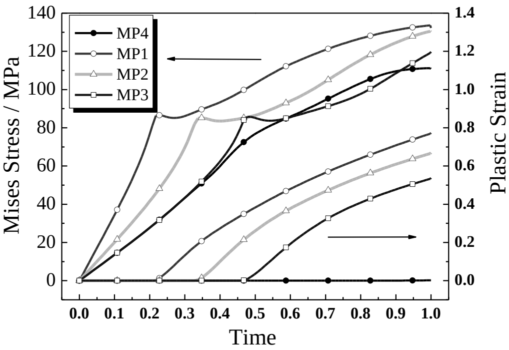

Fig. 3. Mises stress-time and accumulated plastic shear strain-time relationships for typical four Material Points (MP for short in the legend) in the composite. Note that the time represents the normalized solving process, instead of the real time.

3.3 Effect of Shear Band on Stress Redistribution

Through comparative studies [23~28], we conclude that the post-yield softening character determines the development of the shear band, which can further disturb the stress state of the adjacent fibers by inducing additional stress concentration when its front end reaches the adjacent fibers.

The distributions of stress concentration factors (SCF) in the adjacent fibers for various composite models with different inter-fiber spacings are shown in Fig. 4. The overstress zone in the adjacent fiber becomes like a plateau in case of shear band existing, as a result of the stress concentration caused by shear bands.

Here the region with SCF larger than 1.05 can be regarded as the potential fracture zone (PFZ), while the positions with SCF smaller than 1.05 imply the absence of subsequent failure. The lengths of the PFZs on the adjacent fibers for various composite models are illustrated in Fig. 5. For the small inter-fiber spacing, there is a narrower zone that undergoes much higher stress concentration. Compared with a “hard and tough” matrix, the “soft and tough” matrix is extremely inclined to constrain the subsequent breakages on the adjacent intact fibers within a narrower zone. So a higher probability of “cluster fracture” in composites with stronger post-yield softening matrix could be expected.

4 Conclusion

The intrinsic character of “post-yield softening” in glassy polymer makes it possible to promote shear bands emanating from matrix crack tips, which cannot be displayed in simulations using linear elastic or elasto-plastic models for matrices. The overstress zone in the adjacent fiber becomes like a plateau in case of shear band existing, as a result of the stress concentration caused by shear bands.

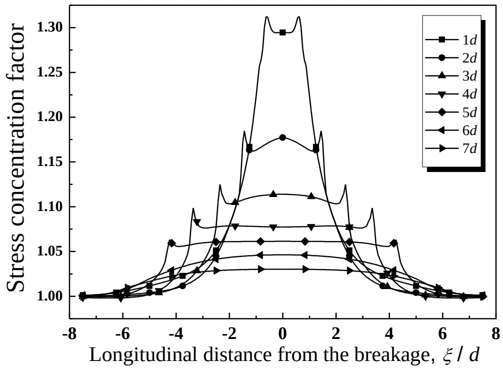

Fig. 4. Distribution of stress concentration factors.

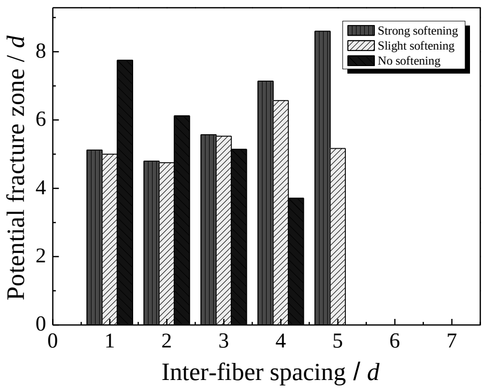

Fig. 5. Length of potential fracture zones.

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