EFFECT OF UNIFORMITY OF FIBER ARRANGEMENT ON TENSILE FRACTURE BEHAVIOR OF UNIDIRECTIONAL MODEL COMPOSITES

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Keywords: *Uniformity of fiber arrangement, Tensile fracture behavior, Mesomechanics, Model composite, Monte Carlo simulation*

Abstract

In the present study, the influence of the uniformity of geometric fiber arrangement on the mesoscopic fracture behavior was analytically investigated for the unidirectional fiber-reinforced composites. A Monte Carlo simulation of the mesoscopic fracture process is performed using the modified shear-lag analysis method for polymer matrix composites and ceramic matrix composites. The overall fracture load and the mesoscopic fracture process are compared between the uniform and non-uniform fiber arrangements. Secondary, the difference in the effect of the fiber arrangement uniformity is discussed between polymer matrix composites, which have the low modulus matrix, and ceramic matrix composites, which have the high modulus matrix.

1 Introduction

The mesoscopic fracture events, such as the fiber breakage, matrix cracking and interfacial debonding, and their mechanical interactions determine the macroscopic fracture properties and morphology of the fiber-reinforced composite materials [1]. The non-uniform fiber arrangement, which is usually formed in fabrication, is suggested as one of the influential factors on the mesoscopic fracture behavior [2].

Yurgartis [3] developed the quantification method of the fiber spatial distribution using the image analysis. Milani et al. [4] developed the rough characterization method of the change in the fiber misalignment angles and their distribution during deformation for textile composites. Experimentally, Piggott [2, 5] reviewed that the fiber waviness greatly affects the macroscopic fracture properties in the unidirectional fiber reinforced composites. Friedrich [6] demonstrated that the volume fraction of voids existing at the fiber rich parts strongly affects the shear strength in the continuous glass fiber-reinforced polypropylene composites. Ramamurty et al. [7] investigated the effect of the local fiber volume fraction on the strength variability in the metal matrix composite (MMC). Analytically, Brockenbrough et al. [8] calculated the effect of the geometrical fiber arrangement on the stress distribution and matrix yielding in MMCs. Fiedler et al. [9] calculated the effect of the local fiber volume fraction on the initial matrix failure in the polymer matrix composites (PMCs) under the transverse loading. Ochiai et al. [10, 11] demonstrated that the non-uniform fiber spacing reduces the tensile strength in MMCs, using the conventional shear-lag analysis method.

The strength of the unidirectional fiber-reinforced PMCs in the fiber direction is one of the most important and fundamental data. Hence, the authors experimentally investigated the influence of the fiber arrangement uniformity on the fiber-direction tensile strength and the fracture morphology using the unidirectional fiber-reinforced model PMC composed of 20 carbon fibers and epoxy resin [12]. Since the mesoscopic fracture behavior is essential for the determination of the macroscopic fracture properties in the composite materials, it is important to describe the change in the mesoscopic fracture behavior induced by the difference in the geometrical fiber arrangement in detail.

In this study, the influence of the non-uniform fiber arrangement on the mesoscopic fracture behavior was analytically investigated for the unidirectional fiber-reinforced composites. A Monte Carlo simulation of the mesoscopic fracture process was performed using the modified shear-lag analysis method [13-16]. In order to generalize the understanding, the simulated mesoscopic fracture behaviors were compared between PMCs, which have the low modulus matrix, and ceramic matrix composites (CMCs), which have the high modulus matrix.

2 Analytical Procedure

The simulation has an advantage in the parametric study over the in-situ experiment. Thus, a Monte Carlo simulation of the mesoscopic fracture process of the unidirectional fiber-reinforced composite materials was carried out in this study. A two-dimensional calculation model was used in this study, as shown in Fig. 1. This model is composed of the small fiber-, matrix- and interface- elements. The stress redistribution induced by the initiation, propagation and accumulation of the mesoscopic fracture events was calculated under the tensile loading by means of the modified shear-lag analysis. Details of the simulation procedure are shown elsewhere [1].

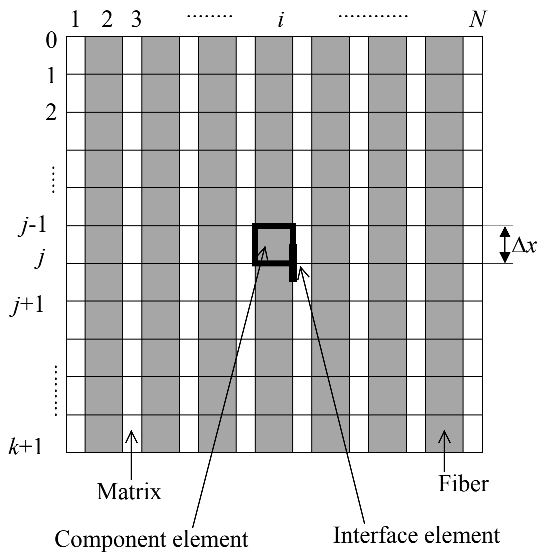


Fig. 1. Consignation of calculation model for application to the modified shear-lag analysis

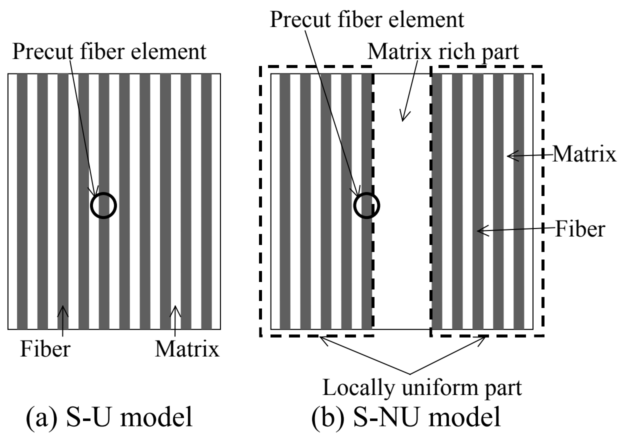


Fig. 2. Modeling for simulation of mesoscopic fracture behavior

Fig. 2 shows the simulation models for the uniform and non-uniform fiber arrangements (S-U and S-NU models, respectively). Here, S stands for "Simulation", U for "Uniform" fiber arrangement and NU for "Non-Uniform" fiber arrangement. The 10 fibers are arranged uniformly in the S-U model (Fig. 2 (a)). On the other hand, the S-NU model has one central matrix rich part, which is surrounded by the locally uniform parts composed of 5 fibers (Fig. 2 (b)). The fiber spacing in the locally uniform parts of the S-NU model was taken to be the same as that in the S-U model, in order to individualize the influence of the central matrix rich part. In this study, a two-dimensional calculation model was used for the simplification. In this case, the matrix is continuous in the real composites, whereas separated by fibers in the transverse direction in modeling. Therefore, the stress concentration induced by matrix cracking is relaxed by the stress shielding by fibers in simulation. The accentuation of the stress concentration induced by matrix cracking is necessary to avoid the relaxation of the stress concentration by the stress shielding by fibers. Hence, the width of the central matrix rich part in the S-NU model, $d_{m,n}$, was assumed to be 20 times thicker than the fiber spacing in the locally uniform parts, $d_{m,u}$.

In this study, PMCs and CMCs are subjects for simulation, in order to investigate how the effect of the fiber arrangement uniformity on the mesoscopic fracture behavior is affected by the change in the elastic modulus of matrix. The models for the uniform and non-uniform fiber arrangements in PMCs are named as the S-PU and S-PNU models, respectively. Here, P stands for "Polymer" matrix composites. In the same way, the models for the uniform and non-uniform fiber arrangements in

Table 1. Values employed for simulation

Material			PMC	CMC
Number of elments		N×(k+1)	21×32	
Number of fibers			10	
Length of element (mm)		Δx	500	
Thickness (mm)		h	4.7	
Width of element(mm)	Fiber	d_f	6.0	
	Matrix	d_m	3.0, 60(Matrix rich part)	
Tensile modulus (GPa)	Fiber	E_f	345	
	Matrix	E_m	2	200
Shear modulus (GPa)	Fiber	G_f	22	
	Matrix	G_m	0.71	71
Interfacial shear strength (MPa)		τ_c	17	
Interfacial frictional stress (MPa)		τ_f	10	
Tensile strength of matrix (MPa)		$\sigma_{0,m}$	25	2500
Weibull shape paramater	Fiber	m_f	5.8	
	Matrix	m_m	5.0	
Weibull scale paramater of fiber (GPa)		$\sigma_{0,f}$	3.45	

CMCs are named as the S-CU and S-CNU models, respectively. Here, C stands for "Ceramic" matrix composites. The model size and the mechanical properties of fiber, matrix and interface employed in this study are listed in Table 1. The distribution of fiber strength was assumed to follow the two-parameter Weibull distribution. The size effect on matrix strength was taken into account using the following formula [16].

$$\sigma_m = \sigma_{0,m} \left(d_{m,u} / d_m \right)^{1/m_m} \qquad (1)$$

Here, σ_m and d_m are the strength and the width of each matrix element, respectively, $\sigma_{0,m}$ is the strength of the matrix elements in the locally uniform parts, and m_m is the Weibull's shape parameter of matrix strength. The details for the reasons to determine these values for PMCs (S-PU and S-PNU models) are shown elsewhere [12]. For CMCs (S-CU and S-CNU models), the elastic modulus of SiC sintered body was employed as the matrix elastic modulus. This is because SiC sintered body is often used as matrix for CMCs. The matrix fracture strain in the S-CU and S-CNU models was assumed as the same as that in the S-PU and S-PNU models, in order to individualize the influence of the matrix elastic modulus. For the simplification, the initial residual stresses were neglected.

In this study, the fiber element neighboring to the matrix rich part was assumed to be broken first in the center for the non-uniform (S-PNU and S-CNU) models, in order to directly evaluate the effect of the fiber breakage on the fracture in the matrix rich part. In the actual calculation, this fiber element was precut in modeling. The same distribution of fiber strength, including the initial fiber breakage, was also used for the uniform (S-PU and S-CU) models, for comparison. Simulation for each model was carried out 10 times using different series of random values, and therefore fiber strength distribution [17].

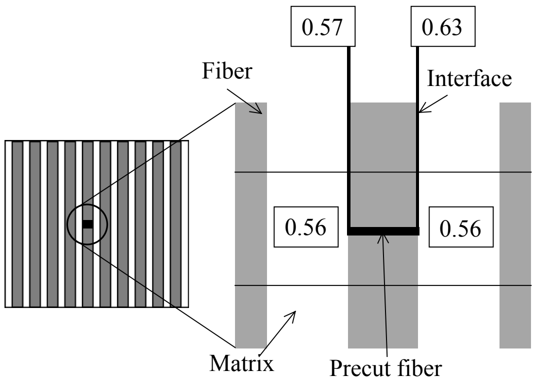


Fig. 3. Normalized stress values of matrix- and interface- elements adjacent to precut fiber element for S-PU model

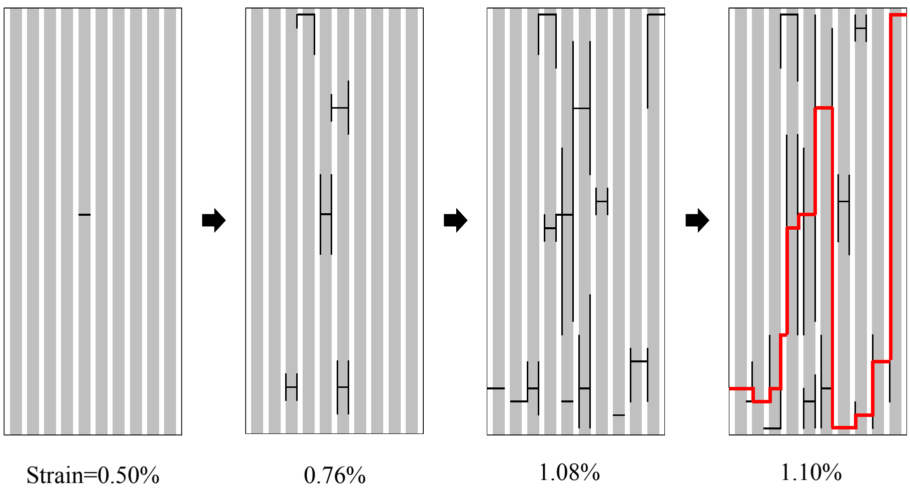


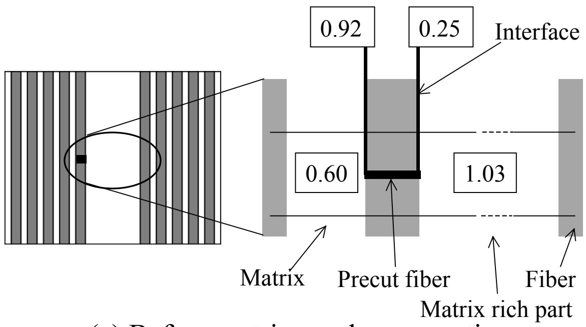
Fig. 4. Snapshots of simulated fracture process for S-PU model

3 Results and Discussion

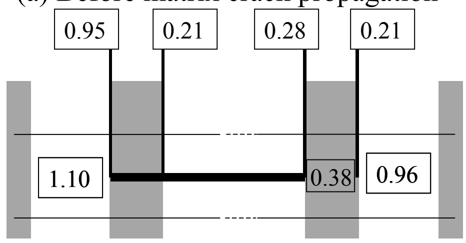
3.1 Difference in Mesoscopic Fracture Behavior of PMCs

Fig. 3 shows the calculated stresses of the matrix elements (tensile stress) and interface elements (shear stress), adjacent to the precut fiber element, at the overall strain of 0.50 % for the S-PU model. In order to make the comparison easier, the stress value of each element is normalized by the fracture strength value of each element. In this case, each element ca n be considered to be broken when the normalized stress value exceeds the critical value (1.00). Here, the normalized stress values are indicated in the square. In the S-PU model, the normalized stress values of interface elements are higher than th ose of matrix elements. This indicates the initial fiber breakage induces the interfacial debonding with priority to the matrix cracking, in the S-PU model. Fig. 4 shows the representative snapshots of the simulated fracture process for the S-PU model. Here, the red line means the overall fracture surface. Except for the initial fiber breakage, no fracture occurred up to the overall strain of 0.58 %. Then, other fiber elements broke one after another with increase in strain. Fiber breakage often led to the interfacial debonding, and the debonding length increased gradually with increase in strain. Finally, fiber breakage, matrix cracking and interfacial debonding were connected each other, resulting in the overall fracture of the composite.

Fig. 5 (a) shows the calculated normalized stress values of the matrix elements (tensile stress) and interface elements (shear stress), adjacent to the precut fiber element, at the overall strain of 0.50 % for the S-PNU model. The analysis indicated that the normalized stress value of the matrix element adjacent to the precut fiber at the matrix rich part was about twice of that in the S-PU model. This is due to the stress concentration and the size effect. This resulted in the rather low fracture strain of 0.50 % for the matrix rich part in the S-PNU model. Then, the stress redistribution was calculated with introducing the matrix crack at this matrix rich part. As a result, the normalized stress value of the opposite side matrix element exceeds the critical value, as shown in Fig. 5 (b). By repeating this procedure, the matrix crack propagated into the neighboring matrix elements successively at the same strain. Consequently, the matrix in the S-PNU model failed on the same transverse section where the fiber element had been precut.



(a) Before matrix crack propagation



(b) After matrix crack propagation

Fig. 5. Normalized stress values of matrix- and interface- elements adjacent to precut fiber element for S-PNU model

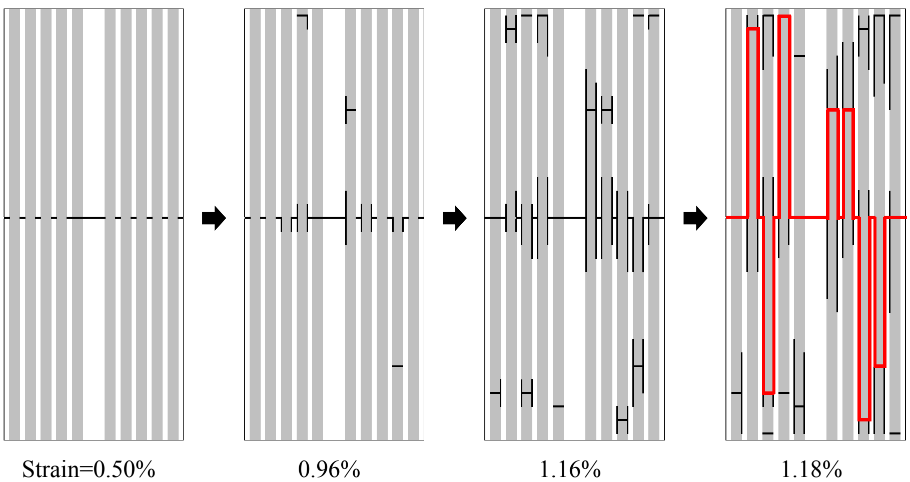


Fig. 6. Snapshots of simulated fracture process for S-PNU model

Table 2. Simulated overall fracture load

	Fracture load (N)			
	PMC		CMC	
No.	S-PU	S-PNU	S-CU	S-CNU
1	0.84	0.85	1.22	0.93
2	0.9	0.88	1.31	1.17
3	0.84	0.87	1.25	1.06
4	0.92	0.9	1.26	1.15
5	0.92	0.93	1.29	1.11
6	0.84	0.85	1.16	0.88
7	0.84	0.89	1.26	0.95
8	0.87	0.89	1.25	0.99
9	0.87	0.89	1.31	1.04
10	0.84	0.84	1.18	1.14
Ave.	0.87	0.88	1.25	1.04
S.D.	0.032	0.023	0.047	0.096
COV (%)	3.7	2.6	3.8	9.2

Fig. 6 shows the representative snapshots of the simulated fracture process for the S-PNU model. The fracture of the matrix elements was followed by the fiber breakage that occurred one after another with increase in strain. Here, the length of interfacial debonding associated with fiber breakage was about twenty elements (10 mm). This was much longer than that associated with the matrix cracking (5 elements, 2.5 mm). Finally, fiber breakage, matrix cracking and interfacial debonding were connected each other at overall section of the model. These simulated final fracture patterns of the S-PU and S-PNU models agree well with the experimentally observed fracture patterns of the unidirectional fiber-reinforced model PMCs [12].

Table 2 summarizes the simulated fracture load. The average values of the simulated fracture load were 0.87 N and 0.88 N for the S-PU and the S-PNU models, respectively. The difference in the simulated fracture load between S-PU and S-PNU models was within the scatter. The standard deviation of the fracture load for the S-PNU model, 0.023 N, was lower than that for the S-PU model, 0.032 N. These tendencies are also corresponding to those of the experimental results, where the non-uniform fiber arrangement does not affect the average value of the fracture load and reduces the standard deviation of the fracture load in the fiber-reinforced model PMCs [12].

Thus, the results of a Monte Carlo simulation indicate that the non-uniform fiber arrangement enhances the fiber-breakage growth towards the matrix rich part on the same cross section. However, the fracture load is insensitive to the fiber arrangement uniformity. This is caused by the extremely high ratio of elastic modulus and strength of fiber to those of polymer matrix. Since matrix carried almost no load, the matrix cracking did not cause the stress concentration enough to cause the fiber breakage. As a result, the difference in matrix cracking was not reflected in the overall fracture load of the composites.

3.2 Comparison between PMCs and CMCs on Fracture Behavior

Figs. 7 and 8 show the calculated normalized stress values of the matrix elements (tensile stress) and interface elements (shear stress), adjacent to the precut fiber element, at the overall strain of 0.50 % for the S-CU and S-CNU models. Similarly to the case of PMCs, the stress concentration at the matrix rich part in the S-CNU model resulted the matrix failure on the same transverse section where the fiber element had been precut.

Figs. 9 and 10 compare the difference in the simulated fracture process between the S-CU and S-CNU models. In the S-CU model, the fiber elements were broken independently. Consequently, the interfacial debonding and matrix cracking were induced by the fiber breakage. Finally, the accumulation of these mesoscopic fracture events resulted the overall fracture. On the other hand, the almost all fiber was broken on the transverse section close to the section where the matrix crack was initiated by the precut fiber element, in the S-CNU model. Table 2 also summarizes the simulated fracture load for the S-CU and S-CNU models. The average value of the simulated fracture load in the S-CNU model (1.00 N) was lower than that in the S-CU model (1.15 N).

In the case of CMCs, matrix carries higher load because of its high elastic modulus. Therefore, the redistributed stresses in the surrounding elements by the matrix crack for CMCs are higher than those for PMCs. In the S-CU model, the fiber elements were broken independently, because the stress concentration induced by the matrix cracking was not high. In the S-CNU model, the matrix rich part was first broken, and consequently the propagation of the matrix crack induced the breakage of weak fiber elements, which existed close to the matrix cracking section. This results the low overall fracture load in the S-CNU model.

In conclusion, the non-uniform fiber arrangement changes the mesoscopic fracture process, nevertheless does not affect the overall fracture load, in PMCs. On the other hand, the overall fracture property of CMCs is sensitive to the fiber arrangement uniformity. This means PMCs have the smart structure and CMCs need the precise control of the fiber arrangement.

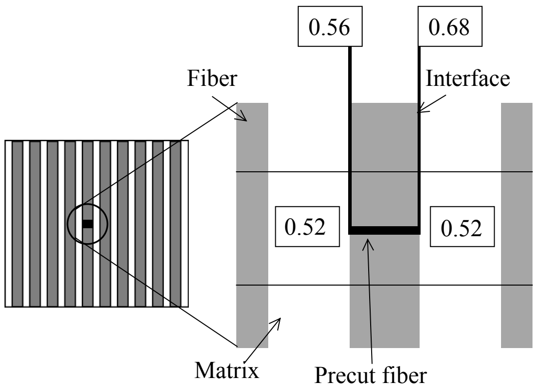


Fig. 7. Normalized stress values of matrix- and interface- elements adjacent to precut fiber element for S-CU model

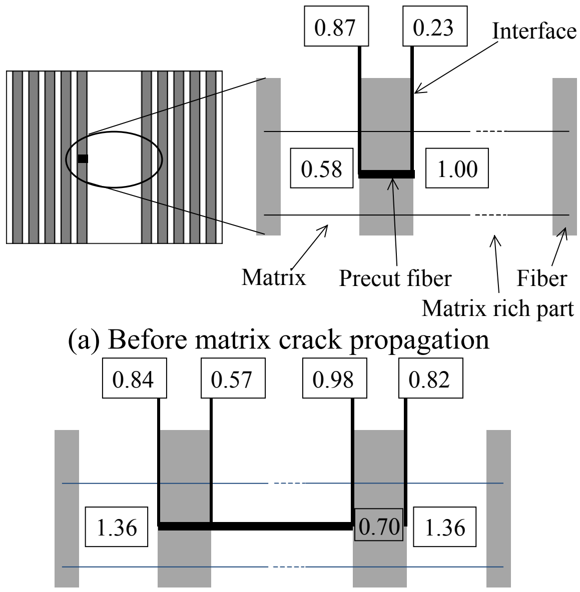


Fig. 8. Normalized stress values of matrix- and interface- elements adjacent to precut fiber element for S-CNU model

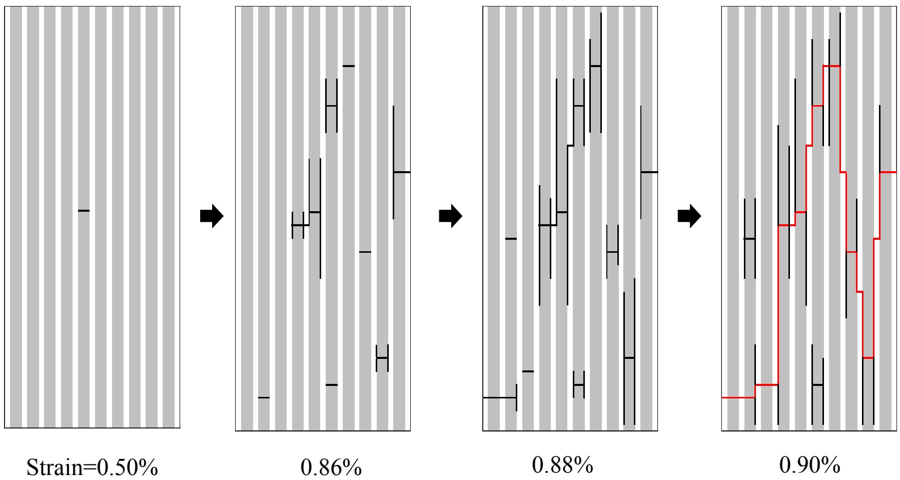


Fig. 9. Snapshots of simulated fracture process for S-CU model

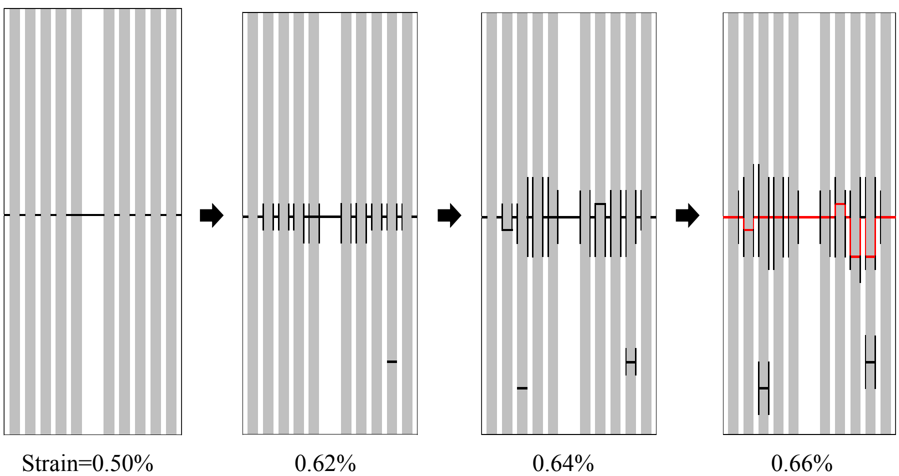


Fig. 10. Snapshots of simulated fracture process for S-CNU model

4 Conclusions

In this study, the influence of the non-uniform fiber arrangement on the mesoscopic fracture behavior was investigated analytically for the unidirectional fiber-reinforced composites. The results are summarized as follows.

(1) Although the difference in the overall fracture load is insensitive to the fiber arrangement uniformity, the order of mesoscopic fracture process is different between the models with the uniform and non-uniform fiber arrangements, in PMCs.

(2) The simulation indicates that the non-uniform fiber arrangement enhances the fiber-crack growth towards the matrix rich part on the same cross section.

(3) In CMCs, the overall fracture load is sensitive to the fiber arrangement uniformity. This indicates the fabrication of CMCs needs the precise fiber arrangement control.

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