Numerical Modeling of the Dynamic Tensile Behavior of Irregular Fibers

Wendy W. He, Xungai Wang

School of Engineering and Technology, Deakin University, Geelong VIC 3217, Australia

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ABSTRACT: Most fibers are irregular and are often subjected to rapid straining during mechanical processing and end-use applications. In this article, the effect of fiber dimensional irregularities on the dynamic tensile behavior of irregular fibers was examined using the finite-element method (FEM). Fiber dimensional irregularities are simulated with sine waves of different magnitude (10, 30, and 50% level of diameter variation). The tensile behavior of irregular fibers was examined at different strain rates (333, 3333, and 30,000%/s). The breaking load and breaking extension of irregular fibers at different strain rates were then calculated from the finite-element model. The results indicate that strain rate has a significant effect on the dynamic tensile behavior of an irregular fiber, and that the position of the thinnest segment along the fiber significantly affects the simulation results. Under dynamic conditions, an irregular fiber does not necessarily break at the thinnest segment, which is different from the quasi-static results. © 2004 Wiley Periodicals, Inc. J Appl Polym Sci 91: 2855–2861, 2004

Key words: fibers; finite-element method (FEM); dynamic tensile behavior; stress; strain

INTRODUCTION

Fibers, yarns, and even some fabrics are often subjected to a high rate of straining during processing and applications. For instance, in a regular passenger-car tire traveling at 50 miles per hour, the cords are strained at a rate approaching 1000%/s, and the threads during a stitching operation are also applied at a high-impact velocity of 10 m/s.[1] In processes such as high-speed carding, the individual fibers are also impacted at speeds exceeding 10 m/s. The impact velocity for ballistic fabrics is much higher still. Therefore, study of the tensile behavior of textile materials under dynamic conditions is important.

Some studies have reported the tensile properties of textile materials at different strain rates. Meredith[2] measured the stress–strain relationships of rayon, silk, and nylon yarns for several strain rates from 0.001 to 1000%/s, respectively. He found that with increasing rate of straining, the strength increased for all the yarns and the breaking extension increased for rayon and silk yarns but decreased for nylon at a higher strain rate. He also confirmed that the effect of strain rate on breaking extension was much smaller than its effect on strength. Holden[3] used a modified experimental apparatus to increase the strain rate to 66,000%/s and obtained the data of breaking stress and breaking stain of different continuous-filament yarns. Hall[4–6] examined the stress–strain curves of different fibers and yarns at strain rates between 0.01 and 33,000%/s and reported that the breaking stress was high, although the breaking strain might be low or high with increasing the strain rate depending on the materials tested, which is consistent with the results obtained by Smith et al.[7] In recent years, there has been increasing interest in the tensile behavior of fiber-reinforced composites at different strain rates. Wang and Xia[8] established the relationships of the glass fiber strength and six different strain rates using bimodal Weibull distribution. Mano and Viana[9] and Wang et al.[10] carried out the tensile stress–strain experiments in a glass fiber–reinforced polyamide-6 composite at different strain rates and Gilat et al.[11] also examined a carbon/epoxy composite in this aspect. They all reported similar results, that is, the strength of composite significantly increased with increasing strain rate, but the extension would decrease slightly except for the ±45° laminate composite.[11] A modified Weibull distribution was also developed for fibers with dimensional irregularities along the fiber length.[12] However, little is available in the research literature on the effect of fiber diameter irregularities on the dynamic tensile properties of irregular single fibers.

We applied the finite-element method (FEM) to investigate the quasi-static tensile behavior of fibers with dimensional irregularities.[13,14] In this study, we used this technique with the ABAQUS (Version 6.3)[15,16] software package to simulate dimensional ir-

Correspondence to: X. Wang (xwang@deakin.edu.au).

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regularities of single fibers and analyze their tensile behavior at high straining rates.

FINITE-ELEMENT MODEL

Assumptions of fiber specimen

In this study, we ignored any internal structure variability of the fiber specimen and considered only the fiber dimensional irregularity along the fiber length. We also assumed that the fiber cross section is circular and the fiber is axisymmetric, so that fiber diameter variation can represent its dimensional irregularity. The different fiber diameter variations followed the sine wave pattern in all the simulations below. The material was strain rate dependent and its tensile behavior (stress–strain curves) is given by Lyons[1] in Figure 1. In the simulation, the data of static curve are used for ABAQUS input, and the rate-dependent curves are then expressed in terms of the static relation. Relevant parameters concerning the fiber specimen are listed in Table I.

Description of the finite-element model

Nonlinear finite-element analysis was used in this study. We modeled the fiber specimen as a three-dimensional (3D) solid structure using C3D8R elements. The shape of elements in the model was cuboid. There were eight nodes on each element, one on each corner of the cube. In the analysis, one end (left) of the fiber specimen was fixed and the other end (right) was extended along the fiber length at different stain rates until the fiber specimen reached the maximum tensile stress (true stress at break at the corresponding strain rate) and breaks. Figure 2 gives an example of the finite-element mesh of the fiber specimen.

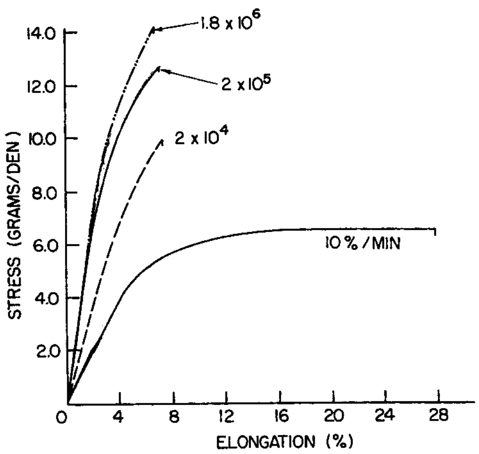

Figure 1 Stress–strain curves of polyethylene fibers at various strain rates.

TABLE I
Parameters of the Fiber Specimen

Property	Value
Young's modulus (MPa)	8160
Poisson's ratio	0.35
Density (g/cm^3)	0.95
Static true stress at break (MPa)	697
Strain rate dependency	
Yield stress ratio	3.0
Equivalent plastic strain rate	300
Specimen diameter (μm)	20
Specimen length (mm)	0.5

Determination of the number of elements or mesh density

It is important that an adequate mesh is used to ensure that the results from the ABAQUS simulation are accurate. Coarse meshes can yield inaccurate results and very fine meshes require more computing time. It is therefore necessary to determine the appropriate number of elements (mesh density) needed for a particular problem.

Here we performed a mesh convergence study using information given in the previous sections. The fiber specimen was analyzed with different mesh densities and we considered the influence of the number of elements on the fiber breaking load at a strain rate of 30,000%/s. The results from the model are depicted in Figure 3, which shows that the variation of breaking load is less than 0.1% when the number of elements is greater than 7040/0.5 mm. In other words, the simulation model at this mesh density will produce an accurate solution. Therefore, we chose a mesh density of 7040/0.5 mm of fiber specimen for all simulations; the models were meshed by dividing them into 44 elements in cross-sectional area [see Fig. 2(c)] and a total of 160 layers along the fiber specimen length (0.5 mm) [see Fig. 2(a) and (b)].

RESULTS AND DISCUSSION

Verification of the finite-element model

To investigate the effect of fiber nonuniformity on fiber dynamic tensile behavior, we need to know the tensile behavior of the fiber without any structural and dimensional irregularities at a range of different strain rates. Here, we chose a group of stress–stress curves obtained at different strain rates for the polyethylene fiber.[1] In the model, we simulated only three different strain rates: 2×10^4%/min (333%/s), 2×10^5%/min (3333%/s), and 1.8×10^6%/min (30,000%/s).[1] In addition, 10%/min (0.167%/s) is regarded as quasi-static rate (<3.3%/s) and the data from its stress–strain curve are supplied to define the characteristics of ma-

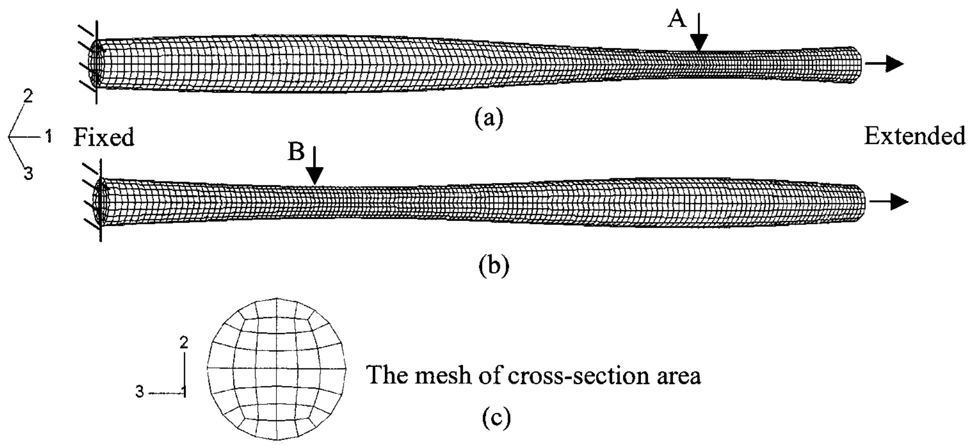

Figure 2 3D finite-element mesh used for analyzing the dynamic fiber tensile behavior.

terial in ABAQUS. A comparison between the results obtained from experiments[1] and those from the FE model is shown in Figure 4. We found a similar trend in both breaking load and breaking extension between the experimental and modeling results, with a relatively small discrepancy. This discrepancy may be attributed to the assumption that the cross section is circular and uniform along the fiber length, which may not be strictly the case for the polyethylene fibers used in the previous experiments.[1] Nevertheless, the agreement between the two sets of data is good, and the FE model can be acceptable for the simulation work that follows.

Effect of level of variation on fiber dynamic tensile properties

We simulated two different cases here: Case 1 and Case 2 in Table II. Case 1 represents a uniform fiber specimen with a diameter of 20 μm and a length of 0.5 mm (a short specimen length was used to save computation time). Case 2 simulates the irregular fiber with the same average diameter and length but with 10, 30, and 50% levels of diameter variation, respectively, which are represented by a complete sine wave, and the thinnest segment (A) along the fiber is near the right end (the end of force application) in each fiber specimen [Fig. 2(a), 30% level of variation only]. In the simulation model, we also applied a strain rate of 333, 3333, and 30,000%/s to these fiber specimens, respectively. Table II lists the results from the FE model.

The results indicate that for a fixed strain rate, an increase in the level of diameter variation leads to a reduction in the breaking load and breaking extension. Because the minimum fiber segment is close to the end of force application along the fiber, the maximum stress propagates to or near the thinnest seg-

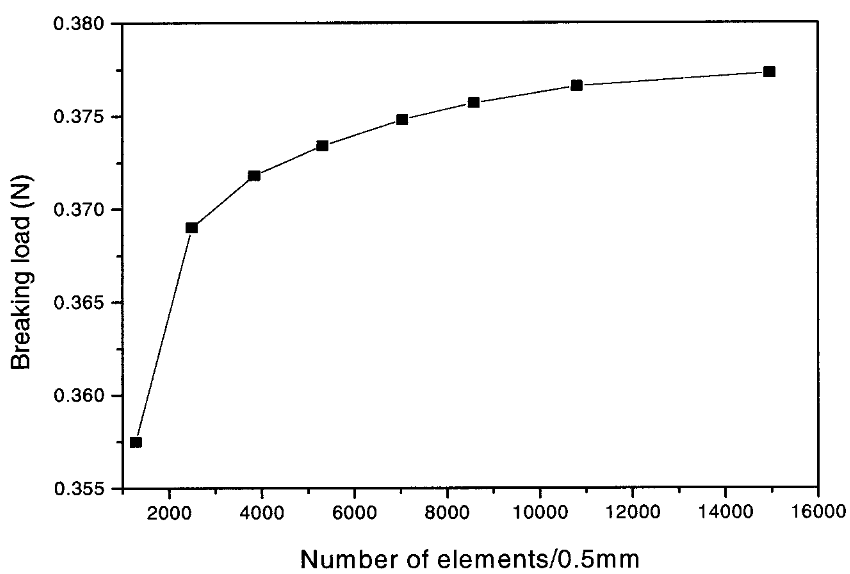

Figure 3 Breaking load versus number of elements (strain rate of 30,000%/s).

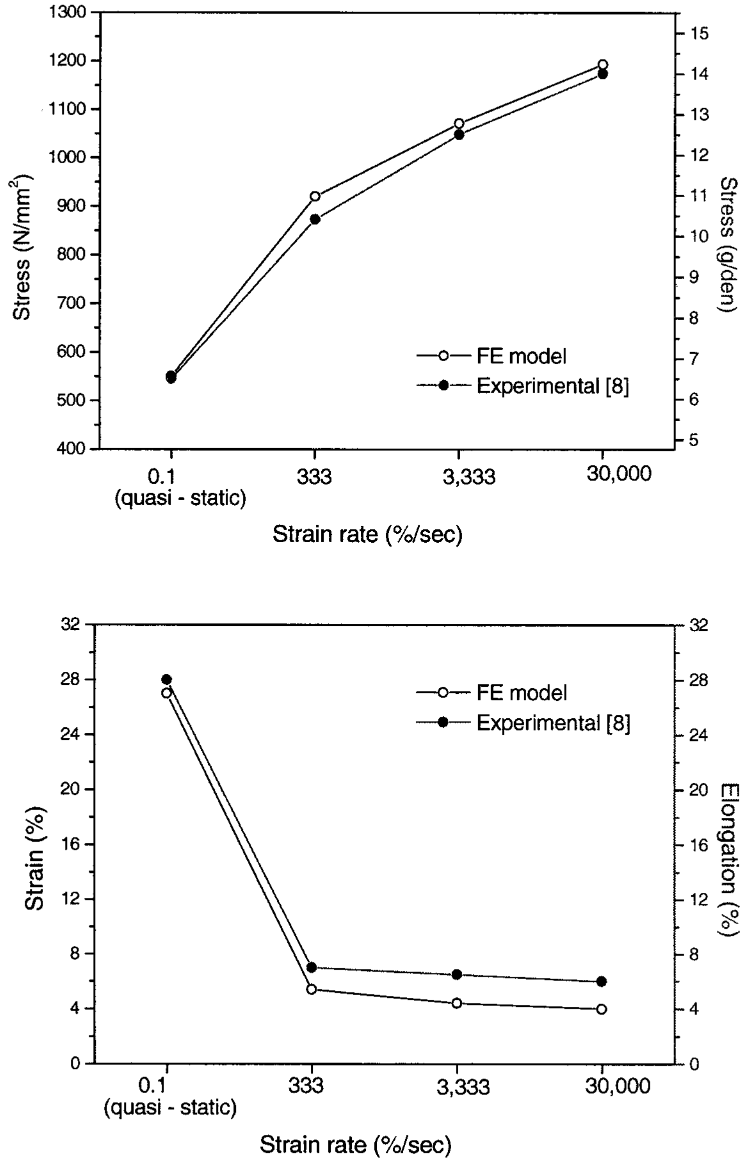

Figure 4 Comparison of the simulation results from the FE model and experimental results obtained by Lyons under quasi-static condition and at three different strain rates.

ment of the fiber during fiber extension. A graphical depiction of stress distribution of these cases is illustrated in Figure 5. As the level of irregularity increases, the minimum fiber diameter decreases, and thus the fiber weakens. Figure 6 shows the load–extension curves of fiber specimens with different levels of diameter variation extended at a strain rate of 3333%/s. The results are also consistent with early experimental results[17] and our quasi-static modeling results.[13,14] However, when the strain rate increased, there was a significant increase in the breaking load and a slight decrease in the breaking extension of the fiber for three different levels of variation. This is consistent with the experimental results obtained in previous studies.[2,9] The load–extension curves of fiber specimens with 30% level of diameter variation at different strain rates are given in Figure 7.

Effect of position of the thin segment on fiber dynamic tensile properties

As indicated in Table II, we simulated three different cases (Case 3, Case 4, and Case 5). Their simulation conditions are the same as those of Case 2, but the thinnest segment (B) along the fiber is away from the right end (the end of force application) in each case [Fig. 2(b), 30% level of variation only]. In the model, we applied strain rates of 333 and 30,000%/s to the fiber specimens. The simulation results from the FE model are listed in Table II.

TABLE II
Data for Fiber Specimen with Different Diameter Variations at Different Strain Rates

	Simulation conditions			Simulation results	
Simulation case	Position of the thinnest segment	Level of variation (%)	Strain rate (%/s)	Breaking load (g)	Breaking extension (%)
Case 1	—	0 (uniform)		30.27	5.30
				34.33	4.34
				38.23	3.97
Case 2	A	10	333	21.94	3.69
				32.76	3.50
				36.76	3.36
		30	3,333	17.74	3.42
				28.73	3.30
				33.08	3.24
		50	30,000	14.64	3.11
				18.05	3.03
				21.76	2.90
Case 3	B	10	333	30.64	3.49
				38.89	3.26
Case 4		30	30,000	31.75	3.20
				40.28	2.93
Case 5		50		33.43	2.77
				41.45	2.65

When the fiber was extended, we found that its breaking load increased and its breaking extension decreased with increasing strain rate for a given level of diameter variation. However, for a given strain rate, the higher the level of diameter variation, the higher the breaking load and the lower the breaking extension. For a dynamic tensile behavior analysis, we should consider the stress propagation along the fiber specimen. Figure 8 shows the propagation of stress in the fiber at successive extensions during the simulation for Case 4 at the strain rate of 333%/s. We observe

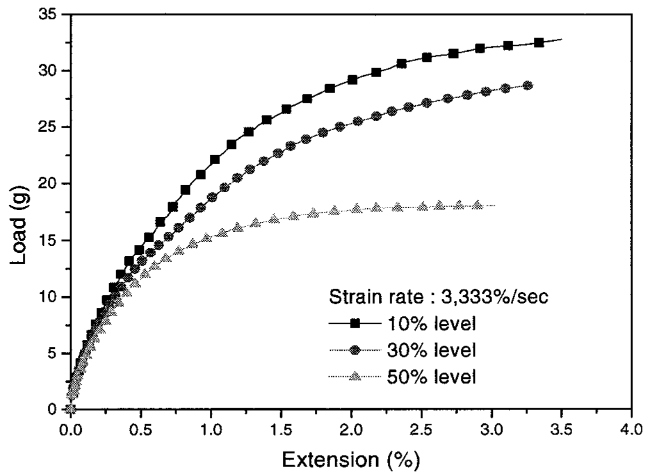

Figure 6 Load–extension curves for fiber specimen with different levels of diameter variation (strain rate of 3333%/s).

that the maximum stress in fiber specimen does not propagate to the thinnest segment along the fiber when the fiber is extended but concentrates on the relatively coarse end. As the level of diameter variation increases, the maximum fiber diameter increases (for a given average fiber diameter) and the fiber will be able to sustain increased load. This leads to increased fiber breaking load and reduced fiber breaking extension. In fact the breaking load is even higher than that of the uniform fiber at the same strain rate (Cases 3, 4, 5, and Case 1 in Table II). In other words, the significant result here is that the breakage of fiber does not always occur at the thinnest segment along the fiber under dynamic tensile conditions, which is obviously different from the static analysis. It is worth noting that the effect of position of the thinnest segment on the fiber dynamic tensile behavior is more marked at a higher level of diameter variation than

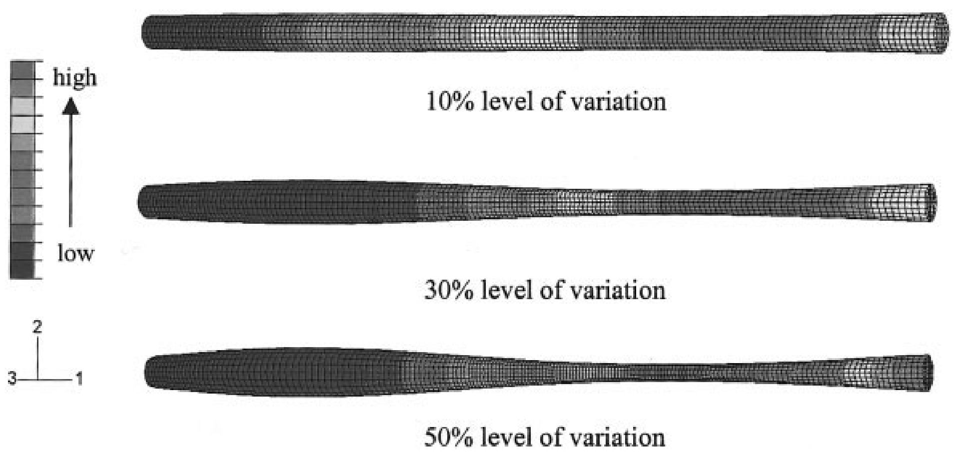

Figure 5 Graphical depiction of stress distribution of Case 2 at the strain rate of 3333%/s.

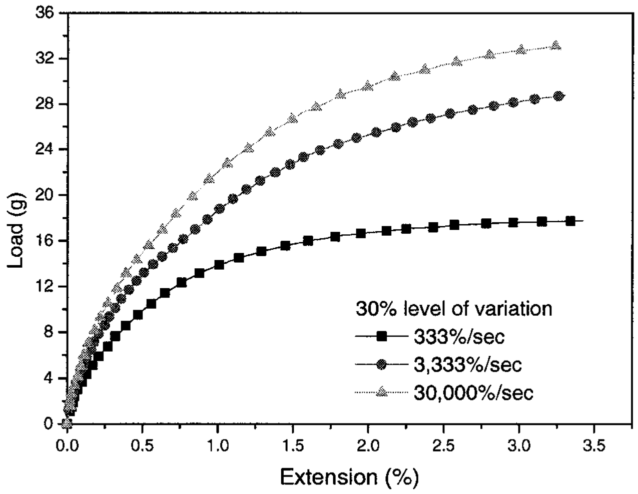

Figure 7 Load–extension curves for fiber specimen at different strain rates (30% levels of diameter variation used).

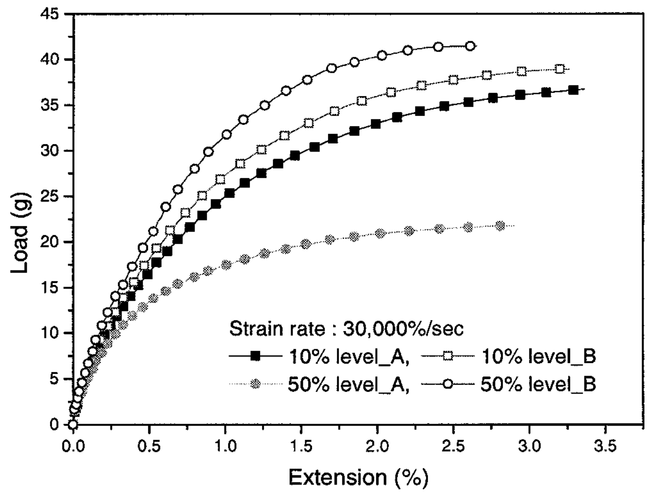

Figure 9 Load–extension curves for fiber with different diameter variation and position of the thinnest segment at the strain rate of 30,000%/s.

that at a lower level of diameter variation, which is shown in Figure 9.

CONCLUSIONS

A three-dimensional (3D) finite-element model was used to investigate the dynamic tensile behavior of fiber specimens with simulated dimensional irregularities. The following conclusions can be drawn from this study:

- The level of diameter variations significantly influences the dynamic tensile behavior of the fiber. As the level of variation increases, the breaking load and breaking extension decrease at different strain rates. At a fixed level of diameter variation, the higher the strain rate, the higher the breaking load, but the lower the breaking extension.
- For a dynamic tensile behavior analysis, the propagation of stress wave in the fiber specimen is important and the fiber does not necessarily break at its thinnest segment. The position or distribution of the thinnest fiber segment along the fiber length has a significant influence on the dynamic tensile behavior of the fiber. When the thinnest segment along the fiber is far away from the end of force application, the fiber specimen has a high

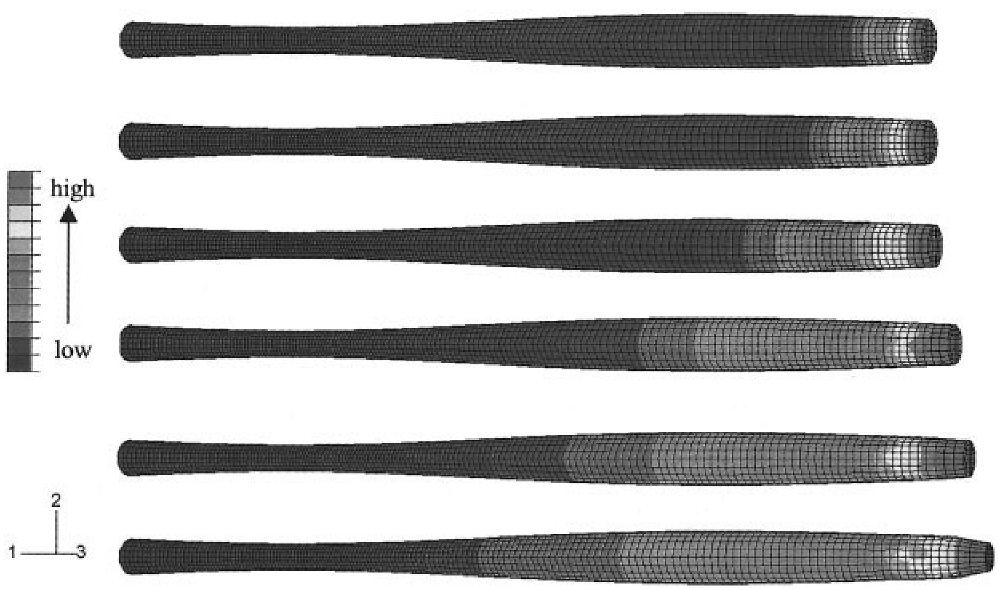

Figure 8 Contours of the stress in a fiber during successive extensions for Case 4 at the strain rate of 333%/s.

breaking load and a low breaking extension, and the breaking load of such an irregular fiber is even higher than that of a uniform fiber under the same simulation conditions. This is an important difference from the results obtained under quasi-static conditions.

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