Modeling the Tensile Behavior of Fiber Bundles with Irregular Constituent Fibers

Wendy W. He, Xungai Wang

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

Received 11 November 2003; accepted 29 March 2004
DOI 10.1002/app.20852

ABSTRACT: In this article, the effect of fiber dimensional irregularities on the tensile behavior of fiber bundles is modeled with the finite element method. The fiber dimensional irregularities are simulated with sine waves of different magnitudes. The specific-stress/strain curves of fiber bundles and their constituent single fibers are obtained and compared. The results indicate that fiber diameter irregularity along the fiber length has a significant effect on the tensile behavior of fiber bundles. For a bundle of uniform fibers of different diameters, all the constituent fibers will break simultaneously, regardless of the fiber diameter. Similarly, if fibers within a bundle have the same pattern and level of diameter irregularity along the fiber length, the fibers will break at the same time, also regardless of the difference in the average diameter of each fiber. In these cases, the specific-stress/strain curve for the bundle overlaps with that of the constituent fibers. When a fiber bundle consists of single fibers with different levels of diameter irregularities, the specific-stress/strain and load–elongation curves of the fiber bundle have a stepped or ladder shape. The fiber with the highest irregularity breaks first, even when the thinnest section of the fiber is still coarser than the diameter of a very thin but uniform fiber in the bundle. This study suggests that fiber diameter irregularity along the fiber length is a more important factor than the fiber diameter itself in determining the tensile behavior of a fiber bundle consisting of irregular fibers. © 2004 Wiley Periodicals, Inc. J Appl Polym Sci 93: 2664–2668, 2004

Key words: fibers; modeling; strain; stress

INTRODUCTION

The tensile properties are the most important characteristic of textile fibers, affecting the yarn strength and spinning performance and the properties of the final product. Much work has been done to study the tensile behavior of single fibers.[1–8] However, the single-fiber test method is extremely laborious and time-consuming, and the data collection is also tedious. Therefore, instead of many single fibers being tested, the measurement of fiber bundles has been used, particularly for natural fibers such as wool and cotton.

The relationships between the tensile properties of single fibers and their behavior in fiber bundles have been investigated by many researchers. Peirce[9] first proposed an ideal bundle consisting of straight and parallel fibers of equal length, and he then gave a mathematical formula for the bundle load. Further theoretical studies and experimental works on straight-fiber bundles have been reported. Nachane and Krishna Iyer[10] made a generalization of Peirce's theory, which was verified by his experiments. Dhavan et al.[11] derived a mathematical model to predict the strength properties of single cotton fibers on the basis of bundle load–elongation curves. Similar research was also done by Sasser.[12] Virgin and Wakeham[13] conducted experiments on the tensile properties of single fibers and bundles of cotton and found that the single-fiber breaking tenacity and breaking elongation were well correlated with the breaking tenacity and breaking elongation of the bundles, respectively, and the correlations were better at longer gauge lengths. These results agreed with the experimental results obtained by Rebenfeld.[14] Work has continued in this area in recent years. For example, Yang et al.[15] measured wool-fiber bundles and reported that the tensile properties of the fiber bundles were positively correlated with the mean fiber diameter. The same result was obtained by Yu et al.[16] with a multiple regression method. Wang and Wang[17] proposed a method of obtaining the average single-fiber strength from actual and ideal bundle strength profiles. Moreover, Yu et al.[18] analyzed the tensile curves of wool-fiber bundles schematically and theoretically and indicated that the specific work before or after the peak point and their ratio in the stress–strain curve of bundles were important for predicting single-fiber properties.

Little has been reported in the literature on how single-fiber dimensional variations affect the tensile behavior of a fiber bundle. We have used the finite element model (FEM), via the ABAQUS software package, to simulate the dimensional variations of

---

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

Journal of Applied Polymer Science, Vol. 93, 2664–2668 (2004)

TABLE I
Parameters of the Fiber Specimen

Property	Value
Young's modulus (MPa)	8160
Density (g/cm^3)	0.95
Poisson's ratio	0.35
Specimen diameter (μm)	Varied
Specimen length (mm)	0.5

single fibers and analyze the tensile behavior of fiber bundles with irregular constituent fibers.

FEM

Assumptions for the fiber specimen

The variability of the fiber internal structure is ignored here; only the dimensional irregularity of single fibers is considered in this article. We also assume that the fiber cross section is circular along the fiber length and that the fiber is axisymmetric, so that the variation of the fiber diameter can represent its dimensional irregularity. The different variations of the fiber diameter follow a sine wave pattern in all the simulations. The material is polyethylene fiber,[19] and the data from its stress–strain curve (quasistatic rate = 10%/min) are supplied to define the material properties in ABAQUS. Relevant parameters for the fiber specimen in all the following cases are listed in Table I.

Description of FEM

A nonlinear, three-dimensional (3D) finite element analysis with the finite element method via the ABAQUS software package was used to obtain the tensile property relations of fiber bundles. The fiber bundle model is shown in Figure 1, and it consists of four parallel single fibers of the same length (0.5 mm) but different diameters. There is a 5-μm interval between the fiber specimens, so the interaction between the fibers is ignored. This can be regarded as an ideal fiber bundle. In the model, a fine mesh is used, and the mesh density ranges from 17,200 to 18,200/0.5 mm for different simulation cases. The elements are eight-node quadratic, reduced-integration, continuum (solid) elements (C3D8R in ABAQUS). In the analysis, one end (left) of the fiber bundle is fixed, and the other end (right) is extended along the fiber axis direction, as illustrated in Figure 1.

RESULTS AND DISCUSSION

Fiber bundles consisting of uniform fibers and fibers with the same level of diameter variation

As indicated in Table II, we have simulated two different cases. Case 1 represents a fiber bundle, which consists of four uniform single fibers (0.5 mm long) with different diameters. Case 2 simulates a fiber bundle consisting of four irregular single fibers. Each single fiber has a 30% level of diameter variation, which is represented by a complete sine wave. The mean diameter of each single fiber is different.

The simulation results are listed in Table II, and the load–elongation curves and specific-stress/strain curves for both cases are illustrated in Figures 2 and 3, respectively. For case 1, we find that four single fibers in the fiber bundle break together, although they have different fiber diameters. The larger diameter fiber can withstand a higher load [Fig. 2 (a)], and the breaking load of the fiber bundle is equal to the sum of the breaking loads of the single fibers. In addition, the specific-stress/strain curves of each single fiber and fiber bundle overlap [Fig. 2 (b)]. Of course, the specific stress and strain at the maximum load are the same as they are at the breaking point (Table II, case 1). For case 2, the same situation can be observed from the simulation results [Fig. 3(a,b) and Table II, case 2]. However, in case 2, because of the fiber diameter variation, the specific stress, strain, and specific work of rupture at break are all lower than those of case 1; the shape of the specific-stress/strain curves is changed also. The fiber bundle with irregular single fibers is easier to break than a fiber bundle consisting of uniform fibers. This is similar to results obtained from previous simulation and experimental results for single fibers under the examined conditions.[8,20,21] The tensile properties of fiber bundles depend on the ten-

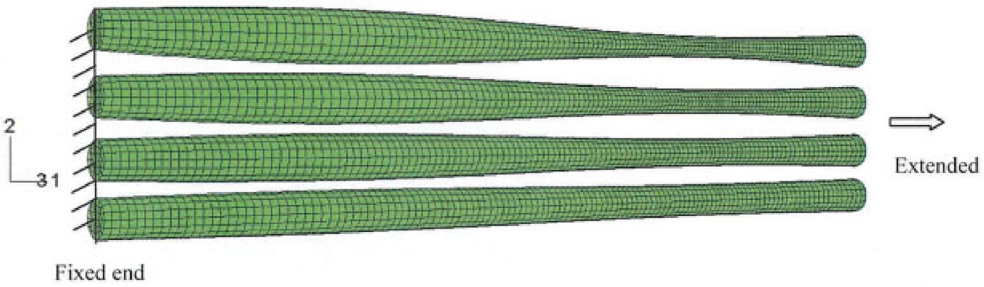


Figure 1 FEM of a fiber bundle.

TABLE II
Simulation Conditions and Data for Fiber Bundles in Different Cases

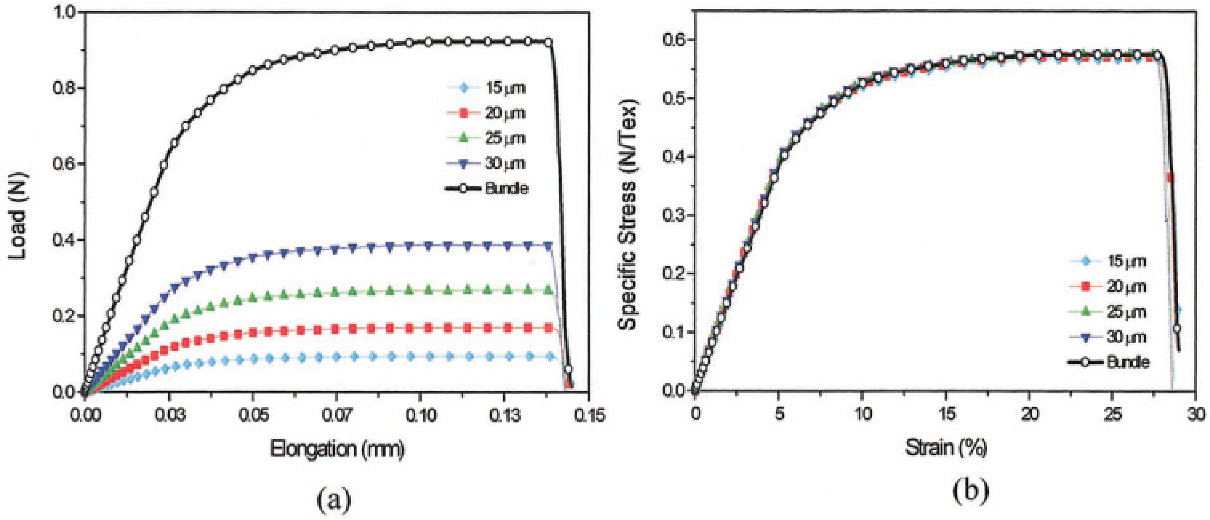
	Simulation conditions: Single fibers in bundles		Simulation results				
	Mean diameter (μm)	Level of variation (%)	Specific stress at the maximum load (N/tex)	Strain at the maximum load (%)	Specific stress at break (N/tex)	Strain at break (%)	Specific work of rupture (kJ/g)
Case 1	15	0 (uniform)	0.576	27.10	0.576	27.10	12.94
	20						
	25						
	30						
Case 2	15	30	0.286	6.13	0.286	6.13	1.15
	20						
	25						
	30						
Case 3	20	0	0.316	5.03	0.220	27.10	5.69
	20	20					
	10	0					
	20	40					
Case 4	20	10	0.295	5.05	0.117	10.04	1.74
		20					
		30					
		40					

sile properties of single fibers, which are affected by geometric variations.

Fiber bundles consisting of single fibers with different levels of diameter variation

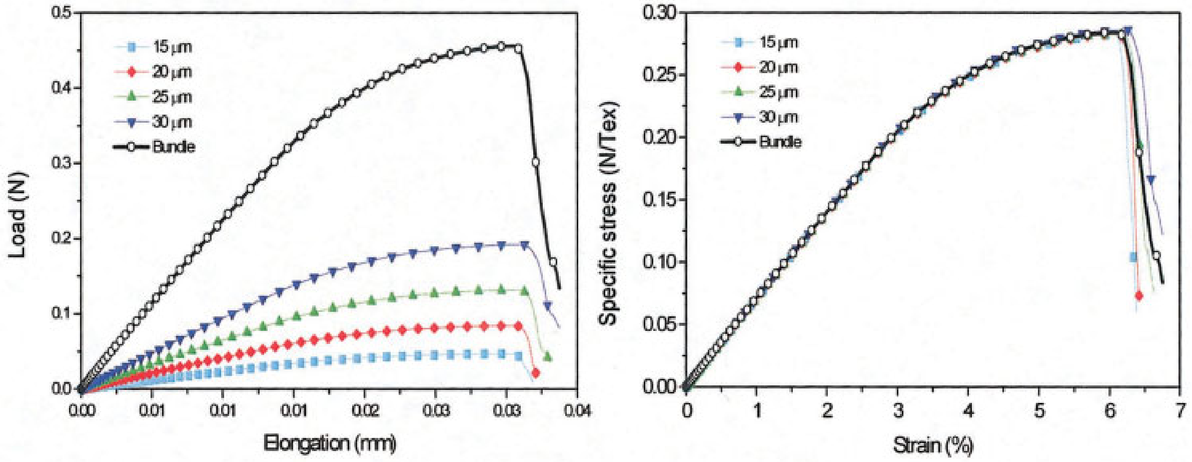
We have simulated two other cases. Case 3 represents a fiber bundle consisting of two uniform single fibers with diameters of 10 and 20 μm, respectively, and two irregular single fibers with the same mean diameter of 20 μm but with 20 and 40% levels of diameter variation. Case 4 represents a fiber bundle with four single fibers. They all have the same mean diameter (20 μm) but different levels of diameter variation (Table II, case 4). The variation of the diameter of each single fiber follows the sine wave pattern in both cases.

Figures 4 and 5 show the load–elongation curves and specific-stress/strain curves for cases 3 and 4, respectively. The simulation results for both cases are



(a) (b)

Figure 2 Tensile curves for a fiber bundle and single fibers in case 1: (a) load–elongation curves and (b) specific-stress/strain curves.



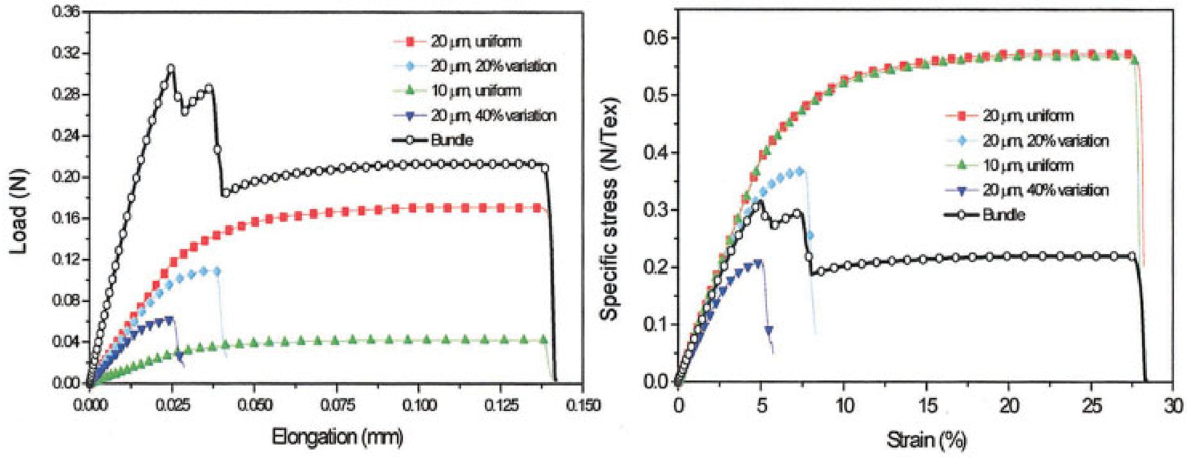
(a) (b)

Figure 3 Tensile curves for a fiber bundle and single fibers in case 2: (a) load–elongation curves and (b) specific-stress/strain curves.

also reported in Table II. When a fiber bundle consisting of irregular single fibers is extended, the breakage of the constituent fibers is not simultaneous. The fibers with the highest level of diameter variation break first, and then the load is shared between the remaining fibers; consequently, the load on each fiber is greater, and this leads to further fiber breakage until the whole fiber bundle breaks. Therefore, the load–elongation curves or specific-stress/strain curves of the fiber bundle have a ladder shape, and the breaking point of each single fiber can be distinguished from the tensile curves (see Figs. 4 and 5). This is consistent with the experimental results obtained by Ahumada et al.[22] In case 3, even though the uniform fiber is thinner than the minimum diameter of the nonuniform fiber, the nonuniform fiber breaks before the thin uniform one; this highlights the importance of fiber diameter irregularity. Figure 6 gives the contours of the Mises stress at different fiber extensions during the simulation. The diameter variation along the fiber is a more important factor than the average fiber diameter for determining the tensile behavior of a fiber bundle. Furthermore, we find that, in both cases, the strain at the maximum load and the strain at break are equivalent to the breaking strain of the single fibers with the highest and lowest levels of variation in the fiber bundle, respectively (see Table II, cases 3 and 4). In case 3, because the fiber bundle contains two uniform fibers, its strain at break reaches the breaking strain of the uniform fibers, and this leads to a higher specific work of rupture than that of case 4.

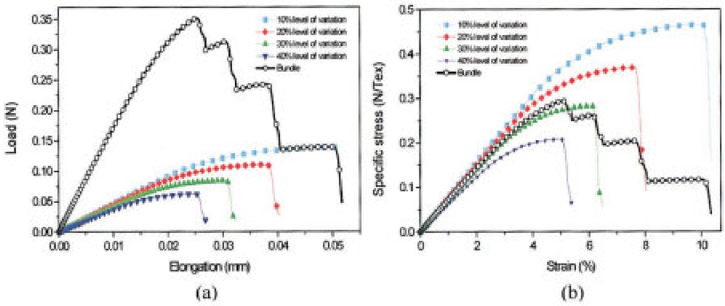
CONCLUSIONS

We have used a 3D FEM to investigate the tensile behavior of fiber bundles consisting of single fibers



(a) (b)

Figure 4 Tensile curves for a fiber bundle and single fibers in case 3: (a) load–elongation curves and (b) specific-stress/strain curves.



(a) (b)

Figure 5 Tensile curves for a fiber bundle and single fibers in case 4: (a) load–elongation curves and (b) specific-stress/strain curves.

with simulated dimensional irregularities and have drawn the following conclusions from this study.

The variation in the fiber diameter significantly influences the tensile behavior of the fiber bundle. For a bundle of uniform fibers, all the constituent fibers will break simultaneously, regardless of the diameter of the fibers. Similarly, if the fibers within a bundle have the same pattern and level of diameter variation along the fiber length, the fibers will break at the same time, also regardless of the difference in the average diameter of each fiber. In these cases, the specific-stress/strain curve for the bundle overlaps with that of the constituent fibers.

When the fiber bundle consists of single fibers with different levels of diameter variation, the stress–strain curves and load–elongation curves of the fiber bundle exhibit a ladder or stepped shape. The fiber with the highest irregularity breaks first, even when the thinnest section of the irregular fiber is coarser than the diameter of a very thin uniform fiber. This study suggests that the variation in the fiber diameter along the fiber length is a more important factor than the fiber diameter itself in determining the tensile behavior of a fiber bundle.

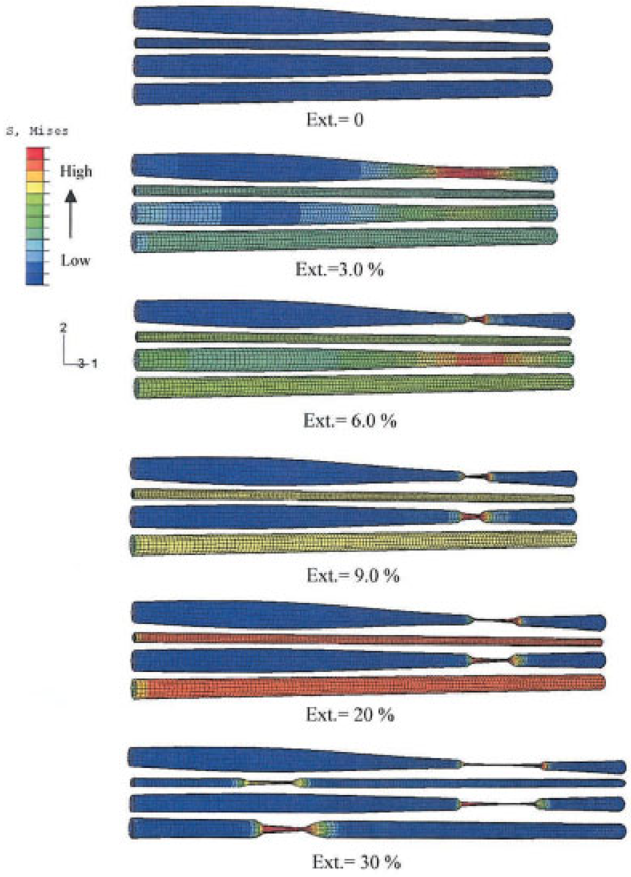


Figure 6 Contours of the Mises stress in fiber bundles during the simulation (case 3).

References

1. Meredith, R. J Text Inst T 1945, 36, 107.
2. Collins, J. D.; Chaikin, M. Text Res J 1965, 35, 679.
3. Collins, J. D.; Chaikin, M. Text Res J 1969, 39, 121.
4. Smuts, S.; Hunter, L.; Rensburg, H. L. J. V. Some Typical Single Fibre Tensile Properties for Wools Produced in South Africa; South African Wool and Textile Research Institute Technical Report 482; South African Wool and Textile Research Institute: Port Elizabeth, South Africa, 1981.
5. Smuts, S.; Hunter, L.; Rensburg, H. L. J. V. The Effect of Fibre Diameter and Crimp on Some Single Fibre Tensile Properties of Wool; SAWTRI Technical Report 485; SAWTRI: 1981.
6. Wang, X.; Chang, L.; Wang, L. J. J Text Inst 1999, 90, 456.
7. Wang, X. Text Res J 2000, 70, 191.
8. Zhang, Y. P.; Wang, X. Wool Technol Sheep Breed 2000, 48, 303.
9. Peirce, F. T. J Text Inst T 1926, 17, 355.
10. Nachane, R. P.; Krishna Iyer, K. R. Text Res J 1980, 50, 639.
11. Dhavan, K.; Bhatt, H. H.; Radhakrishnan, T. Text Res J 1984, 54, 549.
12. Sasser, P. E. Text Res J 1991, 61, 681.
13. Virgin, W. P.; Wakeham, H. Text Res J 1956, 26, 177.
14. Rebenfeld, L. Text Res J 1958, 28, 585.
15. Yang, S.; Blenman, G.; Lamb, P. R. Proc Asian Text Conf 1995, 1, 153.
16. Yu, W.; Postle, R.; Yang, S.; Yan, H. Proc China Int Wool Text Conf 1998, 2, 742.
17. Wang, L.; Wang, X. Text Res J 2000, 70, 98.
18. Yu, W.; Postle, R.; Yan, H. Proc China Int Wool Text Conf 2002, 3, 403.
19. Lyons, W. J. Impact Phenomena in Textiles; MIT Press: Cambridge, MA, 1963; Chapter 6.
20. He, W.; Zhang, S.; Wang, X. Text Res J 2001, 71, 556.
21. He, W.; Wang, X.; Zhang, S. Text Res J 2001, 71, 939.
22. Ahumada, O.; Cocca, M.; D'Orazio, L.; Gentile, G.; Martuscelli, E. Text Res J, to appear.