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The Combined Tensile and Torsional Behavior of Irregular Fibers

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Abstract: Most fibers are irregular, and they are often subjected to combined loading conditions during processing and end-use. In this paper, polyester and wool fibers under the combined tensile and torsional loads have been studied for the first time, using the finite element method (FEM). The dimensional irregularities of these fibers are simulated with sine waves of different magnitude and frequency. The breaking load and breaking extension of the fibers at different twist or torsion levels are then calculated from the finite element model. The results indicate that twist and level of fiber irregularity have a major impact on the mechanical properties of the fiber and the effect of the frequency of irregularity is relatively small.

Keywords: Fiber irregularity, Finite element method, Twist level, Breaking load and extension, Polyester, Wool

Introduction

While the tensile behavior of fibrous materials has been studied extensively by many researchers, little has been reported on the behavior of irregular fibers under combined tensile and torsional loading. Some papers[6,11-13] reported the pure torsional behavior of fibers and most of them were focused on measuring the torsional rigidity of single fibers and the experimental methods. Other papers investigated the torque-twist relationships of fibers. For example, Morton and Permanyer[9] examined the torque-twist relationships in single rayon filaments and obtained their torque-twist curves. They indicated that the shape of the curves was similar to its load-elongation plots. Mitchell and Feughelman [7] conducted experiments on the torsional properties of single wool fiber in water at a constant rate of straining, and reported that the inverse torque and inverse twist for a single wool fiber had a linear relationship. Further, Feughelman and Mitchell[2] examined the torque-twist relationship on single wool fibers in water over the temperature range 7°C to 44°C and they found that the torsional modulus of a fiber decreased with increasing temperature, and the shape of the torque-twist curves showed no difference. All of these works were concerned with the torsional property of fibers only. In 1960, Dent and Hearle[1] carried out the experimental on the combined torsional and tensile properties of single fibers and examined the tenacity, breaking extension and modulus of single fibers under the both constant-tension and constant-length twisting. They found that the initial modulus decreased for all fibers except nylon and cotton. And they also reported that the tenacity and the extension at break decreased with the increase of twist and all fibers responded in a similar manner. Recently, study in this area has been concerned with the torsional behavior of yarns[14,15], even fabrics[8]. However, little has been published on the effect of the level and frequency of single fiber diameter irregularities on the combined tensile and torsional properties of fibers.

We have applied the finite element method (FEM) to investigate the tensile behavior and buckling behavior of fibers with dimensional irregularities[3-5]. In this paper, we use this technique with ABAQUS software package to simulate dimensional irregularities of fibers and analyze their behavior under combined tensile and torsional loading.

Finite-elemnet Model

Assumptions of Fiber Specimen

The fiber internal structure variability is ignored here, only dimensional irregularity of fiber specimens is considered in this paper. We also assume that the fiber cross-section is circular along fiber length and the fiber is axisymmetric, so that fiber diameter variation can represent its dimensional irregularity. The different fiber diameter variations follow the sine wave pattern in all the simulations below. Relevant parameters concerning the fiber specimen in all following cases are listed in Table 1.

In order to investigate the effect of fiber non-uniformity on fiber tensile behaviour, we need to know the tensile behaviour of the fiber without any structural and dimensional irregularities. Therefore, for the wool fiber, a tensile behaviour similar to uniform pen-grown Corriedale wool (Collins 1964) is chosen for the modeling, as we did in a previous study[4]. For the relatively uniform polyester fiber, the tensile behavior used for the modelling is obtained from the tensile test.

Table 1. The parameters for FE model in combined loads analysis

Properties	Value	
	Polyester	Wool[4]
Young's modulus E (MPa)	5500*	1700
Poisson's ratio γ	0.35	0.35
Specimen average diameter d (μm)	10.8*	20
Specimen length L (mm)	0.5	0.5

*Obtained from experiment.

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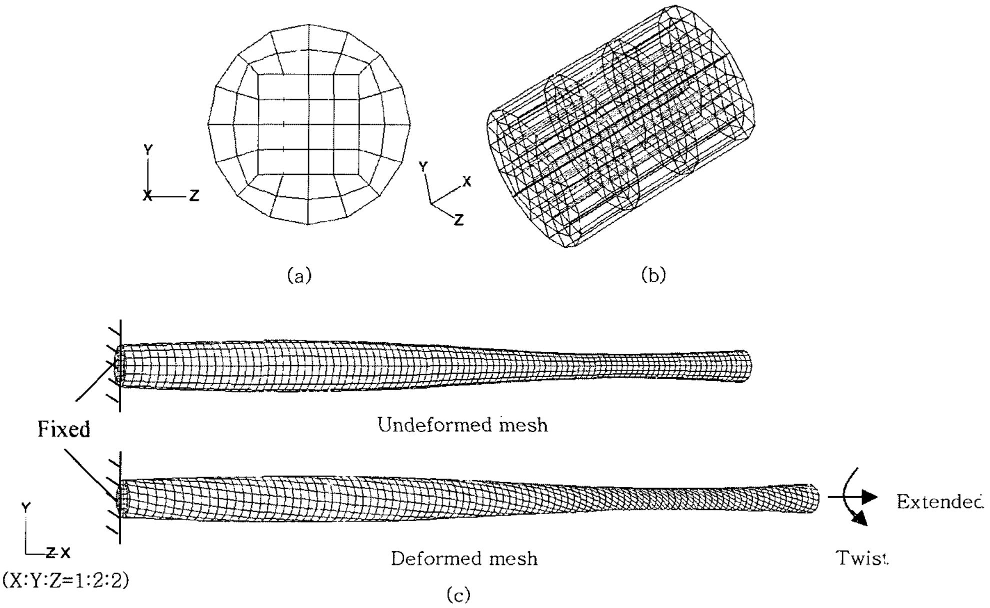


Figure 1. 3-D finite element mesh used for analyzing combined fiber tensile and torsional behavior.

Description of Finite Element Model (FEM)

We used three-dimensional finite element models for this simulation as the deformation of fiber specimen is not asymmetric in the analysis. The finite-element models are meshed by dividing them into 48 elements in cross-section area (see Figure 1(a)) and a total of 100 layers along the fiber specimen length (0.5 mm) (see Figure 1(b), only three layers are shown). So we used the mesh density of 9600 elements per mm of fiber specimen in the simulation model. The shape of elements is cuboid. There are eight nodes on each element, one on each corner of the cube. In the analysis, one end (left) of the fiber specimen is fixed, the other end (right) is extended along the fiber length and twisted around the axis of the fiber simultaneously to give the fiber combined tensile and torsional loading. Figure 1(c) gives an example of the original mesh and the deformed mesh of the fiber specimen.

Experimental

Materials

Short-staple polyester fibers were used in the test. The samples were conditioned under conditions of 65% ± 2% r.h. and 20°C ± 2°C for at least 24 hours. The tests are carried out under these conditions.

Method

Two experiments are performed here. A Single Fiber Analyser (SIFAN)[10] is used for both experiments. This tensile tester can also measure the diameter of a single fiber along its length. The parameters used in the testing are:

- Pre-tension: 0.1 cN
- Diameter scanning: every 10 μm interval along the fiber length
- Extension rate: 30 mm/min
- Gauge length: 15 mm (for measuring the fiber diameter)
  10 mm (for measuring the tensile properties)

Firstly, we measured the polyester fiber diameter along the fiber length. The diameter profile of a polyester fiber over a 0.5 mm length is illustrated in Figure 2. The mean diameter, standard deviation and coefficient of variation of diameter are 10.8 μm, 0.37 μm and 3.5%, respectively, indicating a low variation in diameter along the fiber length. We regarded this polyester fiber as a uniform fiber for further testing and FE modeling. And then, we used this instrument to measure the

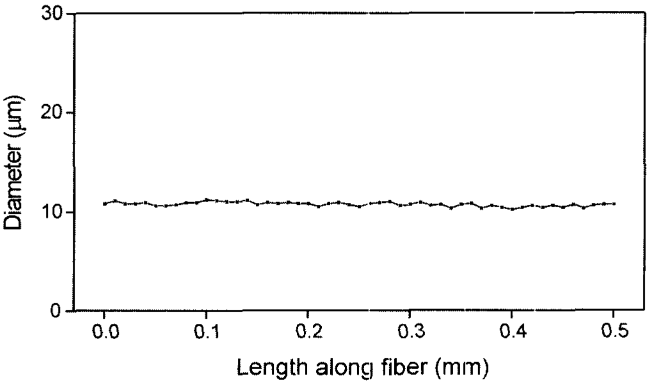


Figure 2. The diameter profile of a polyester fiber with a 0.5 mm length measured by the SIFAN instrument.

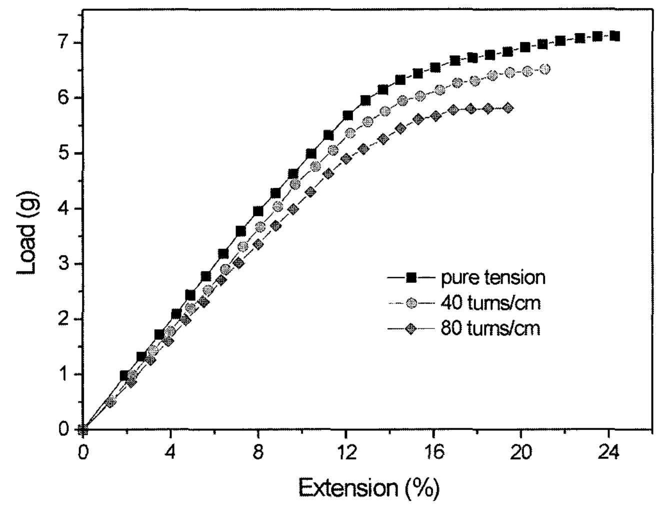


Figure 3. Experimental load-extension curves obtained from fibers at different twist levels.

fiber tensile properties under the conditions of pure tension, 4 turns per mm twist, 8 turns per mm twist, respectively. The load-extension curves are plotted in Figure 3.

Results and Discussion

Verification of the FE Model with Experimental Results

A comparison between the results obtained from experiments and those from FE model is shown in Figure 4. We found that the discrepancy in load-extension curves between the empirical and modeling results is very small. This small discrepancy may be due to the different ways of twisting the fiber. In the experiment, the polyester fiber was twisted first, then stretched to break with the SIFAN instrument. But in the FE simulation, the fiber specimen is applied a torque under a gradually increasing twist during the stretching, resulting in a slight increase in initial modulus, breaking load and breaking extension (Figure 4).

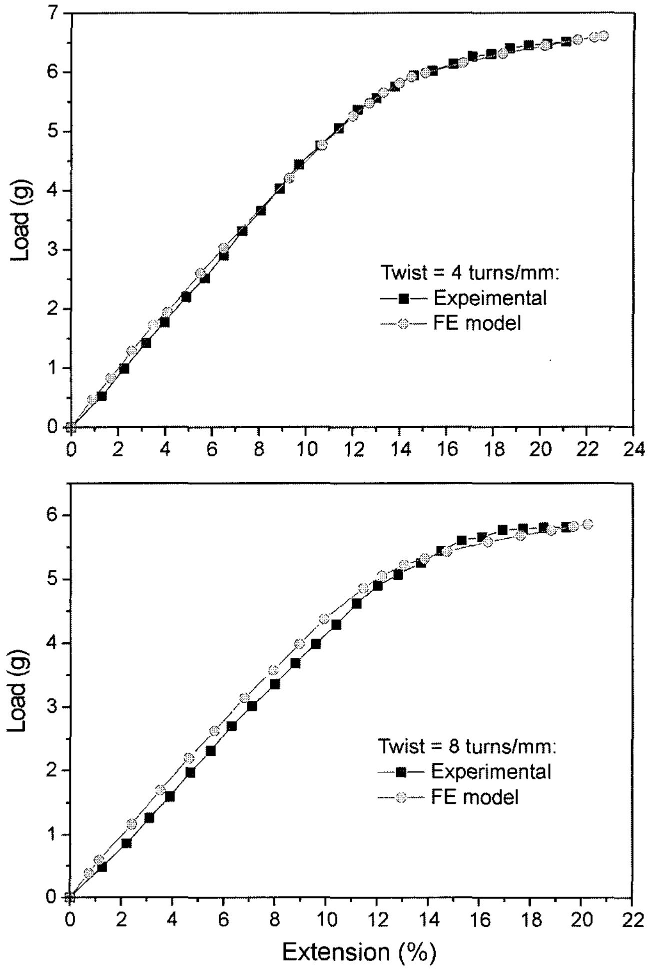
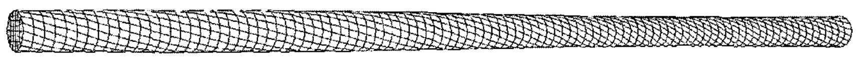
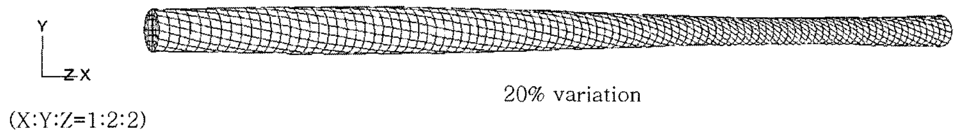


Figure 4. Comparison of the FE model and experimental results for polyester fiber at twist levels of 4 and 8 turns/mm.

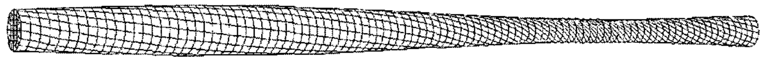
Nevertheless, the agreement between the two sets of data is quite good, and the FE model is therefore acceptable for the simulation work that follows.



10% variation



20% variation



30% variation

Figure 5. Graphical representation of deformed specimens with different levels of variation at the twist of 8 turns/mm (Case 2).

Table 2. Data for polyester fiber with different diameter variations at different twist levels

Different variation in the simulation	Simulation conditions				Results of simulation	
	Mean diameter (μm)	Level of variation (%) (diameter range)	Frequency of variation	Twist (turns/mm)	Breaking load (g)	Breaking extension (%)
(I) Level						
Case 1	10.8	0 (uniform)	1	0 (pure tension) 4 8	6.96	24.61
					6.60	22.70
					5.85	20.24
Case 2		10 (9.72-11.88 μm)			5.66	15.25
					4.87	12.90
					3.21	9.10
		20 (8.64-12.96 μm)			4.46	11.95
					3.50	9.25
					2.28	6.80
		30 (7.56-14.04 μm)			3.41	9.70
					2.42	6.85
					1.69	5.40
(II) Frequency						
Case 3	10.8	10	5	0 (pure tension) 4 8	5.71	15.45
					5.00	13.55
					3.06	8.70
Case 4		30			3.52	10.30
					2.61	7.55
					1.30	4.82

Table 3. Data for wool fiber with different diameter variations at different twist levels

Different variation in the simulation	Simulation conditions				Results of simulation	
	Mean diameter (μm)	Level of variation (%) (diameter range)	Frequency of variation	Twist (turns/mm)	Breaking load (g)	Breaking extension (%)
(I) Level						
Case 5	20	0 (uniform)	1	0 (pure tension) 4 8 12* (* Used for 10% and 30% levels of variation)	4.92	56.0
					4.86	53.8
					4.73	50.8
Case 6		10 (18-22 μm)			4.01	56.4
					3.88	54.6
					3.61	50.1
					3.30	45.5
		20 (16-24 μm)			3.15	48.5
					3.00	46.1
					2.69	41.2
		30 (14-26 μm)			2.42	41.8
					2.23	38.6
					1.90	32.7
					1.53	25.7
(II) Frequency						
Case 7	20	10	5	0 (pure tension) 4 8 12	4.06	57.8
					3.93	55.2
					3.64	50.6
					3.28	45.2
Case 8		30			2.50	43.3
					2.30	40.7
					1.95	34.3
					1.41	23.5

Effect of the Level of Diameter Variation on the Combined Fiber Tensile and Torsional Behavior

As indicated in Table 2(I) and Table 3(I), we simulated polyester and wool fibers with different levels of variation. Case 1 represents a uniform polyester fiber specimen with a diameter of 10.8 μm and a length of 0.5 mm and Case 2 simulates the irregular polyester fiber with the same average diameter and length but with 10%, 20%, and 30% levels of diameter variation, respectively (Figure 5). For the wool fiber (see Cases 5 and 6), only the mean diameter of fiber is changed to 20.0 μm and all other simulation conditions are kept the same as the polyester fiber. Table 2(I) and Table 3(I) list the results from the FE model. Figures 6 and 7 also give the effect of level of diameter variation on fiber breaking load and extension at different twist levels for polyester and wool fibers, respectively. The results indicate that with increased level of diameter variation of either polyester or wool fiber, the breaking load and breaking extension decrease markedly. And the higher the applied twist, the lower the breaking load and breaking extension, which is consistent with the experimental results obtained by Dent and Hearle[1]. This can also be explained by the fact that as the level of irregularity increases, the minimum fiber diameter decreases; while as the twist increases, torsional stress concentrates at the thinnest segment of fiber specimen, the fiber weakens as a consequence. Moreover, comparing Figure 6 and Figure 7, we found that there was a near linear reduction in breaking load and breaking extension of wool fiber at different twist levels (Figure 7). But for polyester fiber, the reduction in the breaking extension and breaking load at twist of 8 turns/mm is large from 0 (uniform) to 10% level of variation, and further increasing the level of diameter variation from 10% to 30% led to a relatively small reduction in fiber breaking load and extension (Figure 6). This might be due to that the polyester and wool fibers have different inherent tensile properties. In general, the polyester fiber shows a higher initial modulus, a higher breaking load and a lower breaking strain than the wool fiber.

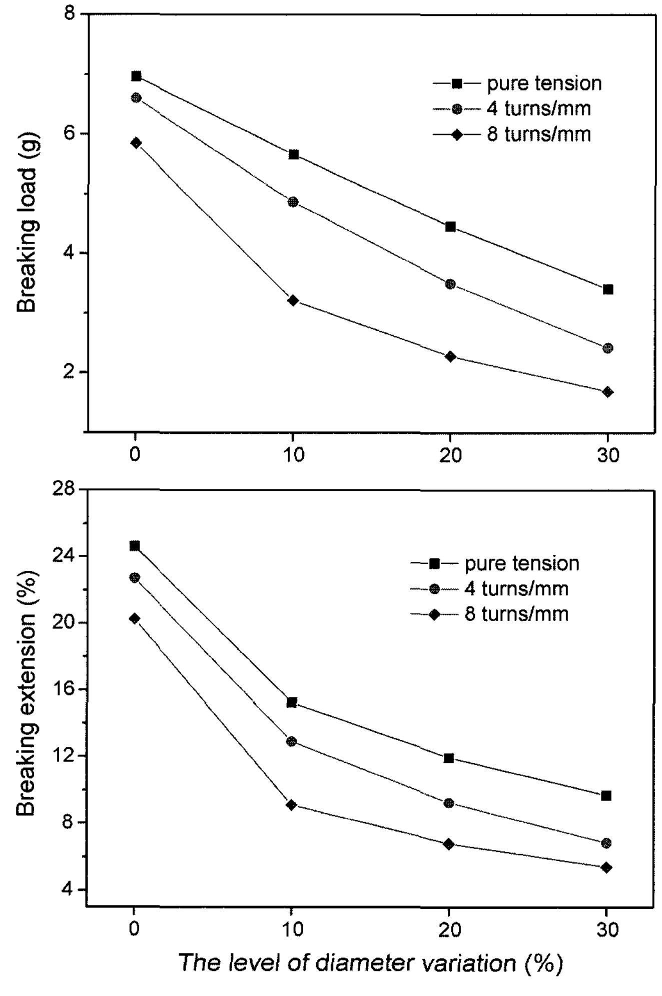


Figure 6. The effect of level of diameter variation on breaking load and breaking extension for polyester fiber at different twist.

Effect of Frequency of Variation on the Combined Fiber Tensile and Torsional Behavior

The polyester fiber simulated here (Table 2(II)) has an average diameter of 10.8 μm and a length of 0.5 mm, and the

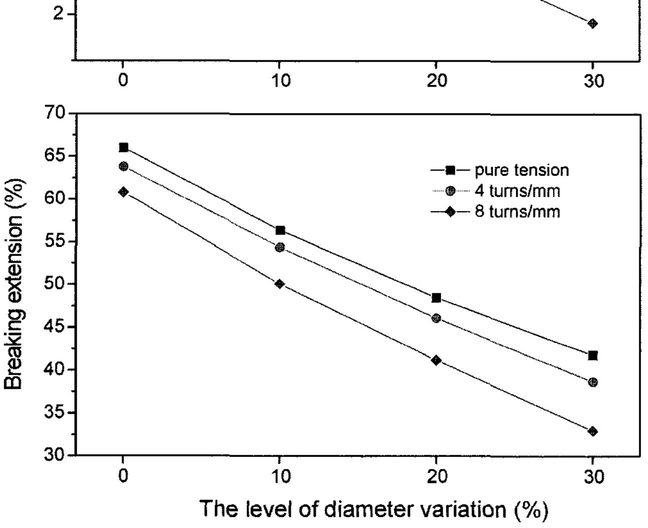


Figure 7. The effect of level of diameter variation on breaking load and breaking extension for wool fiber at different twist.

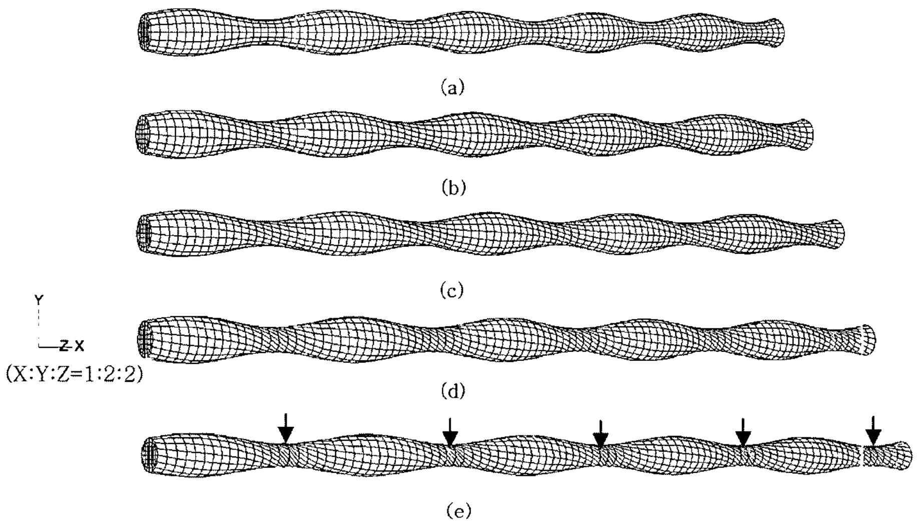


Figure 8. A plot of the finite element mesh for the frequency of variation during the simulation (Case 4, twist of 8 turns/mm used); (a) Undeformed mesh, (b)~(e) Deformed mesh at successive steps.

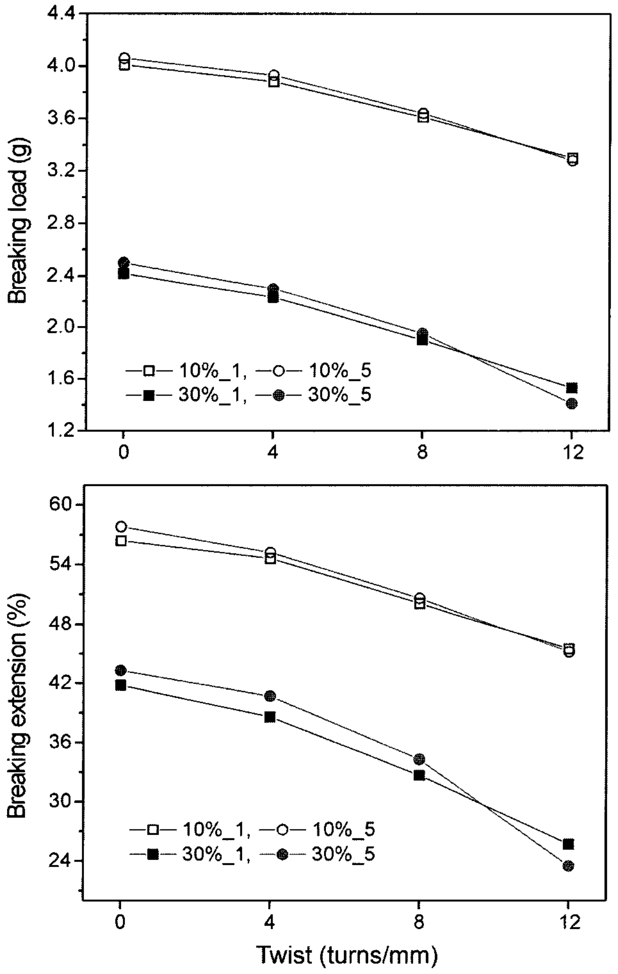


Figure 9. The breaking load and extension of wool fiber with different frequency of diameter variation at different twist.

wool fiber is simulated with an average diameter of 20 μm and its length is also 0.5 mm (Table 3(II)). We use the 10% and 30% levels of diameter variation for both fibers here. To predict the effect of the frequency of irregularity on the combined fiber tensile and torsional properties, we added 1 and 5 sine waves into these two fibers, respectively. In the simulation model, we applied a twist of 4 and 8 turns/mm to polyester fiber and 4, 8 and 12 turns/mm to wool fiber. Figure 8 shows the successive plots during the simulation at the twist of 8 turns/mm for case 4. Table 2(II) and Table 3(II) list the simulation results. The simulation results for the wool fiber are shown in Figure 9. It is worth noting that at a given level of variation, a higher frequency of variation is better for fiber breaking load and extension up to a certain twist level, beyond which the increased frequency leads to reduced fiber breaking load and extension. A similar trend can be observed from the simulation results for polyester fiber (Table 2(II)). As the frequency of diameter variation increases, an increased number of thin fiber segments could share the axial and torsional stresses when a low twist is applied to fiber specimen during the stretching, which led to the increased breaking load and breaking extension. This is also consistent with the previous study simulating the pure tensile behavior of irregular fibers[4]. But when the fiber specimen is subjected to a high twist, more twists are distributed to these thin segments (see Figure 8(e)). This leads to concentration of excessive torsional stress in the thin segments, resulting in a reduction in the fiber breaking load and breaking extension.

Conclusions

A three dimensional finite-element model has been utilized to investigate the combined tensile and torsional behavior of polyester and wool fibers with simulated dimensional irregularities. The following conclusions can be drawn from this study:

The level of diameter variation significantly influences the breaking load and breaking extension of fiber specimens under torsional stress. As the level of variation increases, the breaking load and breaking extension of fibers decrease, and a higher torsional stress in the fiber leads to a lower fiber breaking load and breaking extension. But the decreasing patten differs for different fiber types.

The frequency of diameter variation has a relatively small effect on fiber tensile behavior under the conditions examined. At a given level of diameter variation, a higher frequency of variation helps fiber breaking load and extension up to a certain limit of twist or torsional stress in the fiber. Beyond this twist limit, increasing the frequency of diameter variation will reduce the fiber breaking load and extension.

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