INVITED REVIEW PAPER

MECHANICAL PROPERTIES OF IRREGULAR FIBERS

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Abstract Irregularities are inherent to virtually all fibers, including the conventional textile fibers, the high-performance brittle fibers and newly developed nano-fibers. These irregularities can fall into two main categories: dimensional or geometrical irregularity (external) and structural irregularity (internal). For natural fibers such as wool, diameter variation along fiber length is a typical example of fiber dimensional or geometrical irregularity, while the presence of flaws and defects within a fiber signifies structural irregularity. The irregularities of fibers are bound to have major impact on the mechanical behavior of fibers. In recent years, there has been a growing awareness of the importance of this particular fiber attribute – fiber irregularity, particularly the within-fiber diameter variation. Instruments have been developed to accurately measure fiber diameter variations. In addition, with the development of computing technology, numerical modeling technique has been applied to examine the impact of fiber irregularity on fiber mechanical properties. This paper reviews research progress in the area of fiber geometrical irregularity and its effect on important fiber mechanical properties.

Key Words Fiber Irregularity, Tensile Behavior, Flexural Buckling Behavior, Combined Tensile and Torsional Behavior, Modified Weibull Distribution, Finite Element Model

چکیده در تمام الیافها و از جمله الیافهای پارچه معمولی، الیافهای ترد پرکار و الیافهای جدیداً ساخته شده نانو بی‌نظمی وجود دارد. این نقایص دو دسته هستند: بی‌نظمی ابعادی یا هندسی (خارجی) و بی‌نظمی ساختاری (داخلی). نمونهٔ متداول بی‌نظمی ابعادی یا هندسی، تغییر قطر در امتداد طول در الیافهای طبیعی مانند پشم و نمونهٔ بی‌نظمی ساختاری، ترک یا نقص در داخل الیاف است. این بی نظمیها می‌بایست تاثیر عمده‌ای بر رفتار الیاف داشته باشند. بطوریکه رشد آگاهی در بازهٔ اهمیت آنها بویژه در درون قطر الیاف و توسعهٔ تجهیزات اندازه گیری دقیق برای تعیین تغییر قطر الیاف در سالهای اخیر را سبب شده است. بعلاوه با توسعه فن آوری محاسباتی، روشهای مدلسازی عددی برای آزمایش تأثیر بی‌نظمی بر خواص مکانیکی الیاف در سالهای اخیر بکار گرفته شده است. این مقاله به مرور پیشرفت تحقیقات در زمینهٔ بی‌نظمی هندسی و تأثیر آن بر خواص مکانیکی الیاف می پردازد.

1. INTRODUCTION

The geometry of most fibers varies both between fibers and within a fiber. Normally, manufactured fibers may be formed with little variation in cross-sectional area along fiber length and even between fibers by means of well-controlled process conditions. For example, the relative standard deviations of diameter of an alumina fiber (FP) and alumina-zirconia fiber (PRD) are 3.0% and 2.8%, respectively [1]. The natural fibers are affected by growth factors, e.g., the nutrition, climate and environmental conditions etc. Their cross-sectional areas vary greatly from fiber to fiber as well as along the fiber length. The typical profiles of single fiber diameter variation are shown in Figure 1 [2] and the between-fiber diameter distribution of a wool sample is given in Figure 2 [3].

The dimensional variation for natural fibers, particularly for wool fibers, is generally more than that for manufactured fibers [4,5]. Therefore, research literature on fiber dimensional irregularity

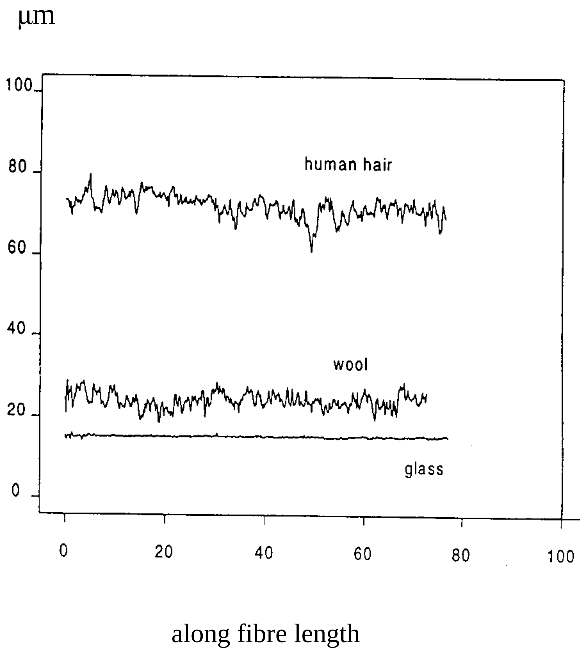
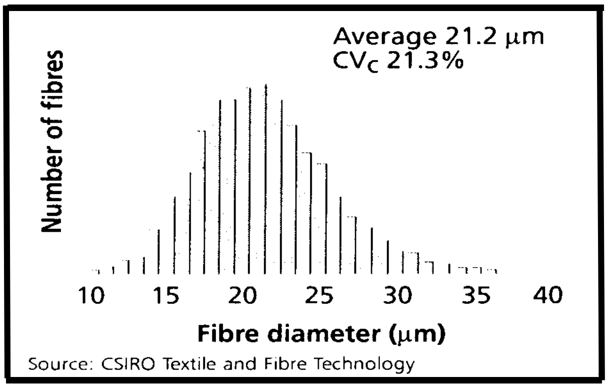


Figure 1. Typical fiber profiles [2].



Source: CSIRO Textile and Fibre Technology

Figure 2. Diameter distribution of wool sample [3].

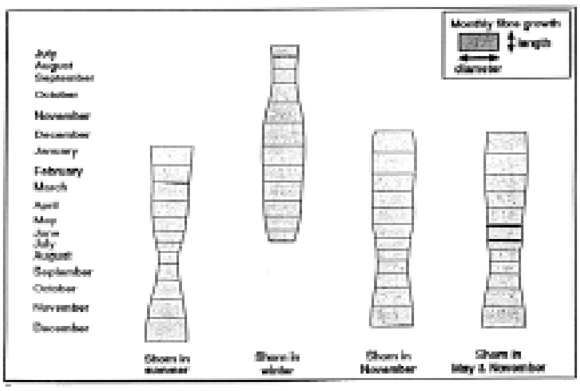
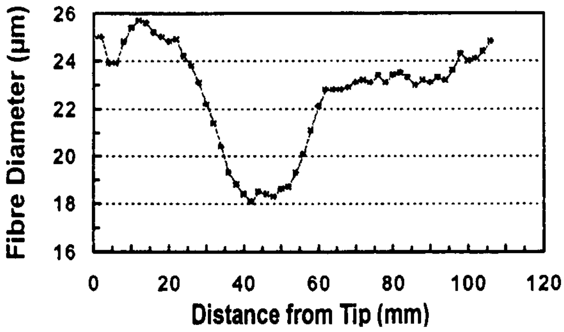
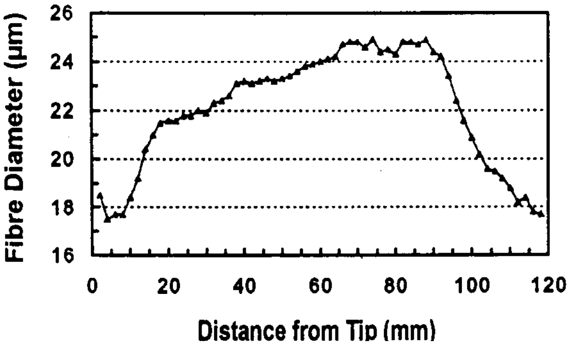


Figure 3. Seasonal variation in length and diameter (Source: NZWB, Wool Grower Handbook).



(a) August Shorn



(b) February

Figure 4. Diameter profiles of staple from August and February shorn sheep run in South-west WA [10].

is largely concerned with wool fibers.

Wool fibers are non-uniform both between fibers and within a fiber as wool growth is largely affected by breeding, nutrition, environment, physiology and other factors [6,7,8,9,10]. Buerden and Bosman [11] examined the thickness, or, ‘diameter’ of three different sections along the Merino wool staple and found that the diameter was variable from the top, middle to base (bottom) in the staple due to changes in the conditions of growth of the Merino fleece. Nichols [12] also confirmed this result, and he further reported that there was greater variation in the middle section of the staple than in the tip and base sections. The seasonal variation in diameter of a wool fiber using a stylized wool fiber cross-section, with growth depicted from top to bottom is illustrated in Figure 3 [13]. This pattern shows that the diameter of fiber varies along the fiber length. The thinner (tender) position also differs in the fiber depending on the time of shearing the sheep, as illustrated in Figure 4 [10].

Measurements of between-fiber diameter variations are now routinely carried out using instruments such as OFDA (Optical Fiber Diameter Analyzer) [14,15,16] and Sirolan-Laserscan [17,18]. The development of the single fiber analyzer or SIFAN [19,20] and a single fiber profile meter [2] has simplified the measurement of diameter variations within or along single fibers. The SIFAN instrument can also test the tensile behavior of the same single fiber, which provides an effective tool for studying the relationship between diameter variation of a single fiber and its tensile behavior.

Apart from the dimensional variation of wool fibers, the variation of manufactured fibers should not be ignored even though it is much lower than that of wool fibers. Recent studies of carbon and glass fibers have shown that the long fragments of these fibers are characterized by fluctuations of cross-sectional area along their length, which also affects their tensile property [21].

2. FIBER DIAMTER VARIATION AND ITS EFFECT ON FIBER TENTILE PROPERTIES

The effect on fiber tensile properties of fiber irregularities has long been recognized, as entailed in the truism that the strength of a chain is that of its weakest link [22]. Banky and Slen [23] conducted experiments on irregular wool fibers, and reported large difference in the amount of extension experienced by segments of the same fiber, with the thinner segments extending more than the thicker segments. Kenny and Chaikin [24] studied the subject of fiber irregularity or non-uniformity analytically. They examined the stress-strain-time relationships of non-uniform textile materials, and demonstrated the profound effects of fiber dimensional non-uniformity on fiber stress-strain behavior. For example, they revealed that a typical keratin fiber with a 16% coefficient of variation (CV) in cross section extended 60% more than a uniform fiber with the same average cross-sectional area, subjected to a particular load. Collins and Chaikin [25-29] conducted further study in this area. They used an analytical approach to examine the effect of non-uniformity on the tensile properties of non-uniform fibers of special geometries such as a cone. Recent research has focused on how fiber diameter variations affect fiber breaking load and strain, as discussed below.

2.1 Variations in Fiber Diameter and Breaking Load

Previous research has shown that the diameter of wool generally follows a log-normal distribution [30,31,32] and that fiber breaking load is approximately a function of the square of fiber diameter [33,34]. Based on these findings, Wang and Wang [35] have derived the following formula (Equation 1) relating the coefficient of variation of wool fiber diameter (CV_{FD}) to that of wool fiber breaking load (CV_{BF}):

$$CV_F = \sqrt{[1+(CV_{FD})^2]^4 - 1} \qquad (1)$$

This relationship has been verified for a large sample size. When the sample size is small, Wang [36] has shown that the following equations should be used instead:

$$CV_{BF} = \sqrt{[1+(CV_{mFD})^2]^4 - 1} \qquad (2)$$

Or simply,

$$CV_{BF} \approx 2CV_{mFD} \qquad (3)$$

Where CV_{mFD} is the coefficient of variation of minimum fiber diameters.

These equations were derived statistically based on a linear relationship between the fiber breaking force and the square of fiber minimum diameter (D_{min}^2). They have been verified for scoured wool [36] and other animal fibers [37], and later for processed wool fibers also [38]. These results demonstrate the direct connection between the variations in fiber geometry and in fiber tensile properties.

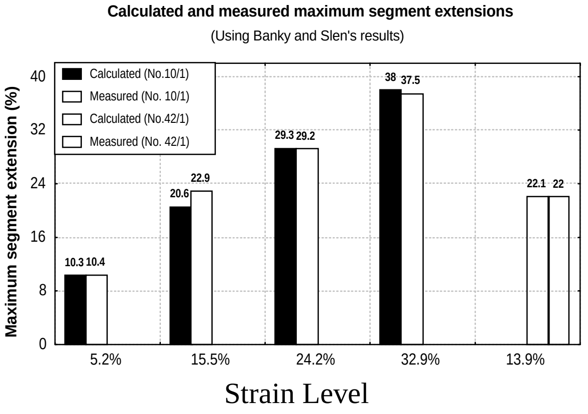


Figure 5. The calculated fiber extensions compared with the measured values.

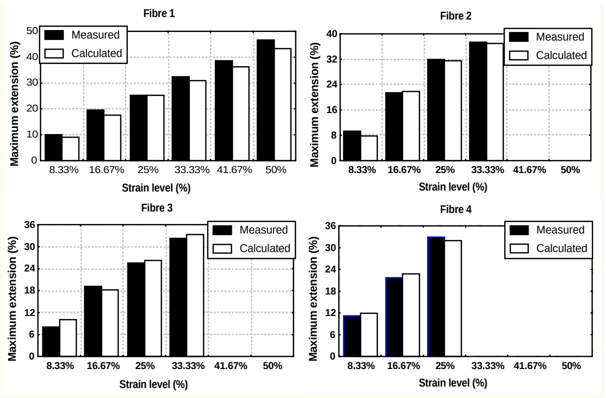


Figure 6. The calculated and measured maximum segment extensions for merino wool.

2.2 Variation in Fiber Diameter and Tensile Strain

For geometrically irregular fibers, the strain experienced by different segments of the same fiber under extension is different, with the thinnest segment experiencing the maximum strain. Zhang and Wang [39] have recently established an empirical relationship between the maximum strain, the average strain and the along-fiber diameter variation, as indicated in Equation 4 below.

$$e_{max} = e_{ave} + CV_{Da} \qquad (4)$$

where e_{max} is the maximum strain, e_{ave} is the average strain as obtained from a tensile test, and CV_{Da} is the along-fiber diameter variation. It should be noted that while the maximum strain will govern the tensile failure of a fiber, it is the average strain that can be measured in a normal tensile test.

This empirical relationship has been verified by experimental results from Banky and Slen [23], as indicated in Figure 5.

Our further experimental results with different fibers also confirm this relationship, as indicated in Figure 6 [39].

3. MODIFIED WEIBULL DISTRIBUTION FOR IRREGULAR FIBERS

Based on the weakest-link theory, Weibull [40] proposed a simple distribution of material strength x:

$$P = 1 - \exp[-n(\frac{x}{x_0})^m] = 1\text{-}\exp[-\frac{V}{V_0}(\frac{x}{x_0})^m] \qquad (5)$$

Where P is the failure probability of a long fiber connected by n independent segments, x is generally the strength, V is the fiber volume, V_0 is the volume of a unit link or a segment, m is Weibull modulus and x_0 is scale parameter.

From this simple Weibull distribution, the average and CV value of x can be obtained:

$$\bar{x} = x_0(\frac{V}{V_0})^{-1/m}\Gamma[1+(1/m)] \qquad (6)$$

$$CV = \frac{\{\Gamma[1+2/m] - \Gamma^2[1+(1+m)]\}^{1/2}}{\Gamma[1+(1/m)]} \qquad (7)$$

The CV of the variable x is determined by Weibull modulus only.

From the conventional Weibull distribution (Equation 5), for constant fiber diameter, the average value of the variable x at gauge length L_2 can be calculated from that at gauge length L_1:

$$\overline{x_2} = \overline{x_1}\left(\frac{L_2}{L_1}\right)^{-1/m} \qquad (8)$$

Where x_1 and x_2 are the fiber strengths at gauge

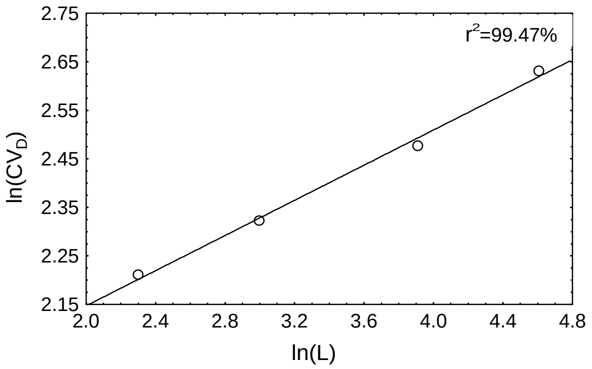


Figure 7. Change of within-fiber diameter variation with the gauge length.

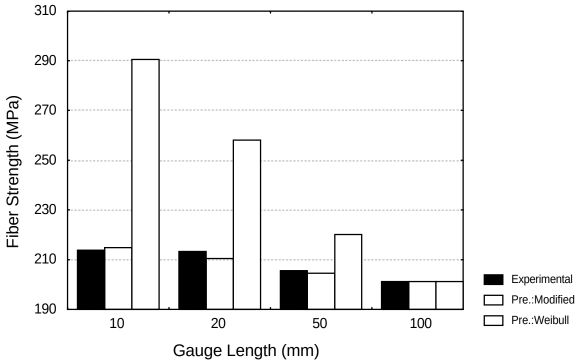


Figure 8. A comparison between the experimental and the predicted values of average fiber strength (results at 100 mm gauge length were used for the predicted results at other gauge lengths).

length L_1 and gauge length L_2 respectively.

The gauge length effect predicted by this formula deviates significantly from the actual value [1,41,42]. This is not surprising considering that most fibers have within-fiber geometrical irregularity and this feature would have considerable impact on the fiber tensile behavior as indicated in the previous sections.

For irregular fibers such as wool, it has been shown that the within-fiber diameter variation changes (CV_D) with the fiber length (gauge length L, mm), as indicated in Figure 7 [43].

Since the within-fiber diameter variation is the exponential function of the gauge length, it should not be ignored in predicting the gauge length effect. A parameter λ has been introduced in Equations 5 and 8 to take into consideration of within-fiber geometrical irregularities.

$$P = 1 - \exp[-(\frac{V}{V_0})^{\lambda}(\frac{x}{x_0})^{m}] \quad (9)$$

$$\overline{x_2} = \overline{x_1}\left(\frac{L_2}{L_1}\right)^{-\lambda/m} \quad (10)$$

Where λ is the exponential parameter of the change of within-fiber diameter variation with the gauge length. For instance, the following relationship exists for Figure 7:

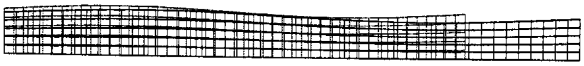
$\ln(CV_D) = 18.14 \times 10^{-2} \ln(L) + 1.78 + \varepsilon$
(ε is a random error)

So $\lambda = 18.14 \times 10^{-2}$ for the wool fiber examined.

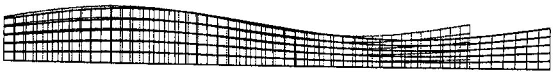
Therefore, the modified Weibull distribution (Equation 9) has not only considered the diameter variation between the fibers ($V = \frac{1}{4}\pi D^2 L$, ignoring the slight ellipticity of wool fiber cross section), but also the within-fiber diameter variation (λ). This modified Weibull distribution has been verified to be able to predict the gauge length effect for irregular fibers much more accurately than the conventional Weibull distribution, as indicated in Figure 8 [43].

4. NUMERICAL MODELING OF FIBER DIMENSIONAL IRREGULARITY

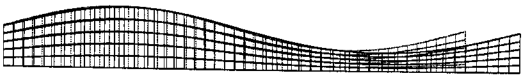
In order to evaluate the effect of different irregularities on fiber mechanical behavior, numerical modeling technique has been used to simulate different fiber irregularities and predict the mechanical behavior of the fibers [44-47]. With the numerical modeling, the various features of fiber irregularity, such as the magnitude and frequency of within-fiber diameter variation, can be isolated to examine their effects on fiber mechanical behavior individually. The mechanical properties examined so far include tensile properties, flexural buckling behavior, and fiber behavior under combined tensile and torsional loading.



10% variation



30% variation



50% variation

Figure 9. Graphical representation of the un-deformed and deformed specimens at different levels of irregularity.

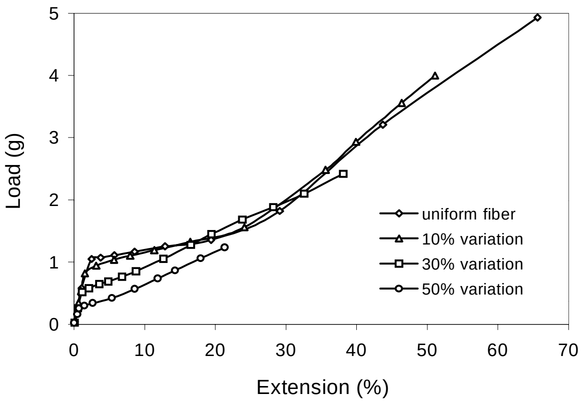


Figure 10. Load – extension curves for fibers with different levels of diameter variation.

4.1 Tensile Behavior of Irregular Fibers The fiber dimensional irregularities have been simulated with sine waves of different lever (magnitude) and frequency using 2D finite element model. Figure 9 shows the simulated fiber with three different levels of diameter variation [44].

As indicated in Figure 10, the fiber irregular level has a marked effect on the shape of the load-extension curve - the yield load and yield extension decrease, the yield slope increases, and the turnover point from the yield to the post-yield regions becomes less distinct with increased dimensional irregularity. An increase in the level of diameter variation leads to a large reduction in the breaking load and breaking extension, which is consistent with experimental results obtained by Zhang and Wang [39]. However, the frequency of diameter variation affects the fiber tensile properties less than the level of diameter variation.

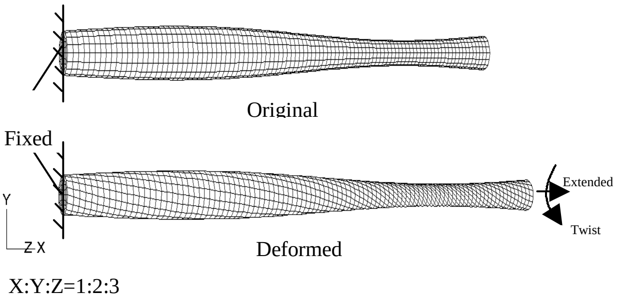


Figure 11. An irregular fiber under combined tensile and torsional loading.

4.2 Combined Tensile and Torsional Behavior of Irregular Fibers Actually, fibers are not subjected only to pure tension during the processing and end-use. It happens frequently that two or more types of loads are applied simultaneously to the fibers. An obvious example is the ring spinning process, in which fibers in the spinning triangle are twisted under tension. In this case, the fibers can generally only be regarded as being subjected to a combined load case of tensile loading in conjunction with a restrained torque [48]. However, most of previous works were focused on study of one load only, for example, pure tensile and pure torsion [49, 50, 51], etc. Only a few papers were published on the combined torsional and tensile properties of fibers. For example, Dent and Hearle [52] examined the tenacity and breaking extension of different kinds of fibers and reported that the tenacity and the extension at break decreased with the increase of twist. They also found that the twist would markedly affect the shape of the load-elongation curve, increasing the twist led to decreasing the initial modulus and smoothing the inflexion at the yield point. However, little attention has been paid to the combined loading of single irregular fibers

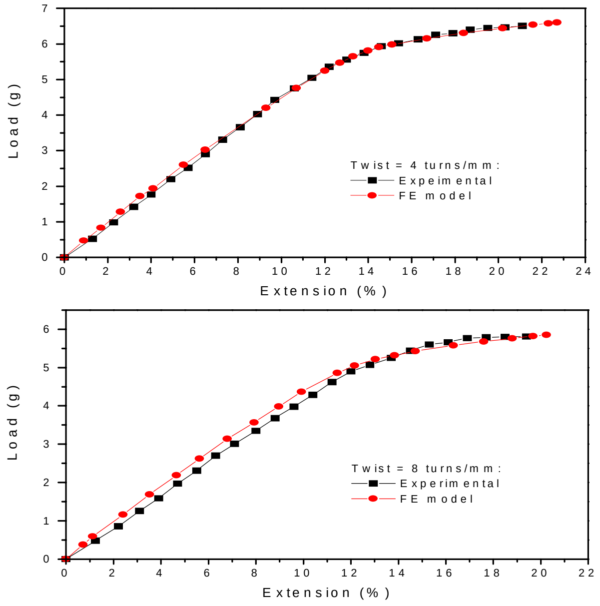


Figure 12. Comparison of the FE model and experimental results for polyester fiber.

until recently. Figure 11 shows a 3D fiber model with dimensional irregularity under combined tensile and torsional stress [47].

The model predictions have been verified by experimental results obtained from stretching polyester fibers with different twist levels, as illustrated in Figure 12.

Figure 13 shows the simulation results for fibers with different level (10% and 30%) and frequency (1 and 5 sine waves) of diameter variations, tested under combined tensile and torsional stresses. Increasing the level of diameter variation reduces the breaking load and breaking extension of fiber specimens, and a higher torsional stress (more twists) in the fiber leads to a lower fiber breaking load and breaking extension. However, 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. Beyond this twist limit, increasing the frequency of diameter variation will reduce the fiber breaking load and extension.

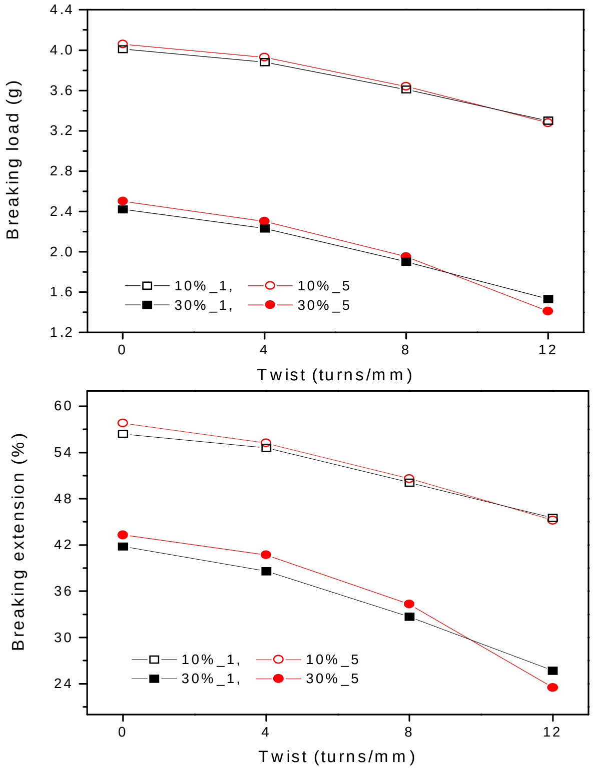


Figure 13. The breaking load and extension of the fiber specimen with different diameter variations.

4.3 Flexural Buckling Behavior of Irregular Fibers

Fiber flexural buckling behavior is one of the important mechanical properties. Research over the past several years has shown that the buckling behavior of fibers is associated with fabric-evoked prickle and affects the cloth comfort and even aesthetics. Naylor [53] and Veitch and Naylor [54] applied the buckling theory of thin rods to uniform fibers and proposed that the critical buckling load is proportional to d^4/l^2 (d is fiber diameter and l is fiber length). Some studies of prickle from knitwear have shown that the buckling load of protruding fiber ends can be decided by different parameters, *e. g.* the coarse edge values of fiber ends [55], the mean diameter of fibers [3,56-58], coefficient of variation of fiber diameter (CV %) [59] and the shape of fiber ends [60]. These studies have highlighted the importance of fiber

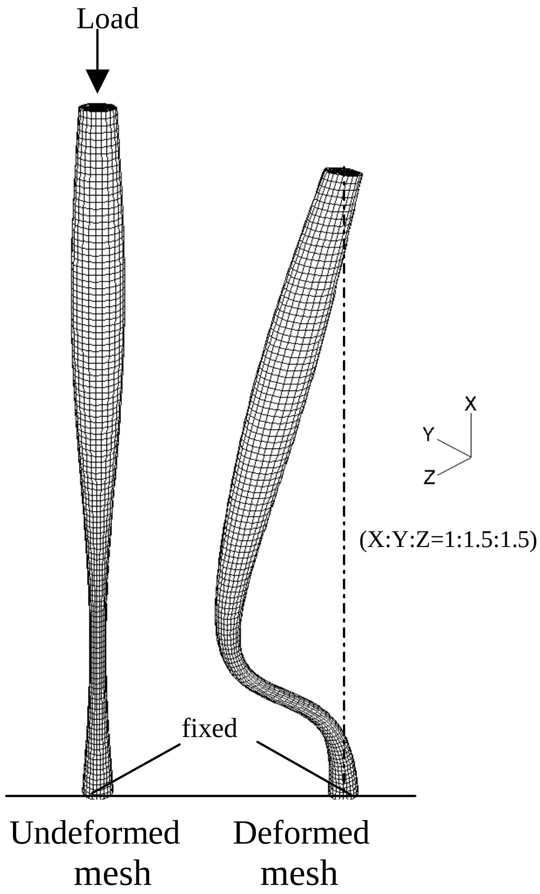


Figure 14. Three dimensional finite element meshes used for analyzing fiber-buckling behavior.

diameter profile along fiber length. Recently, the effect of dimensional variation of a single fiber on its buckling behavior was examined using a 3D finite element model [46]. An example showing the simulated buckling of irregular fibers is given in Figure 14. The critical buckling loads of different simulated fibers can be calculated from the FE model.

The results show that the diameter variations significantly influence the buckling behavior of irregular fibers. The calculated effective length (L_e, see Figure 15) and the average diameter ($\bar{d}$) within the effective length of an irregular fiber are the key factors influencing the critical buckling load of the fiber. The buckling behavior of fibers is also related to the shape of the fiber specimen and fibers with a thinner tip buckle more easily than fibers with a coarser tip under the simulated conditions, which agrees with earlier findings [60].

5. CONCLUSION

This paper has reported the research findings concerning the effect of fiber irregularities on fiber mechanical properties. The focus has been on fiber geometrical non-uniformities rather than structural defects. It has highlighted the significant effect fiber geometrical irregularities have on fiber mechanical behavior, including tensile and flexural behaviors. The results reported in this paper have largely been derived from quasi-static tests and simulations. In the future, this work should be extended to cover the dynamic behavior of irregular fibers, with both geometrical and structural non-uniformities.

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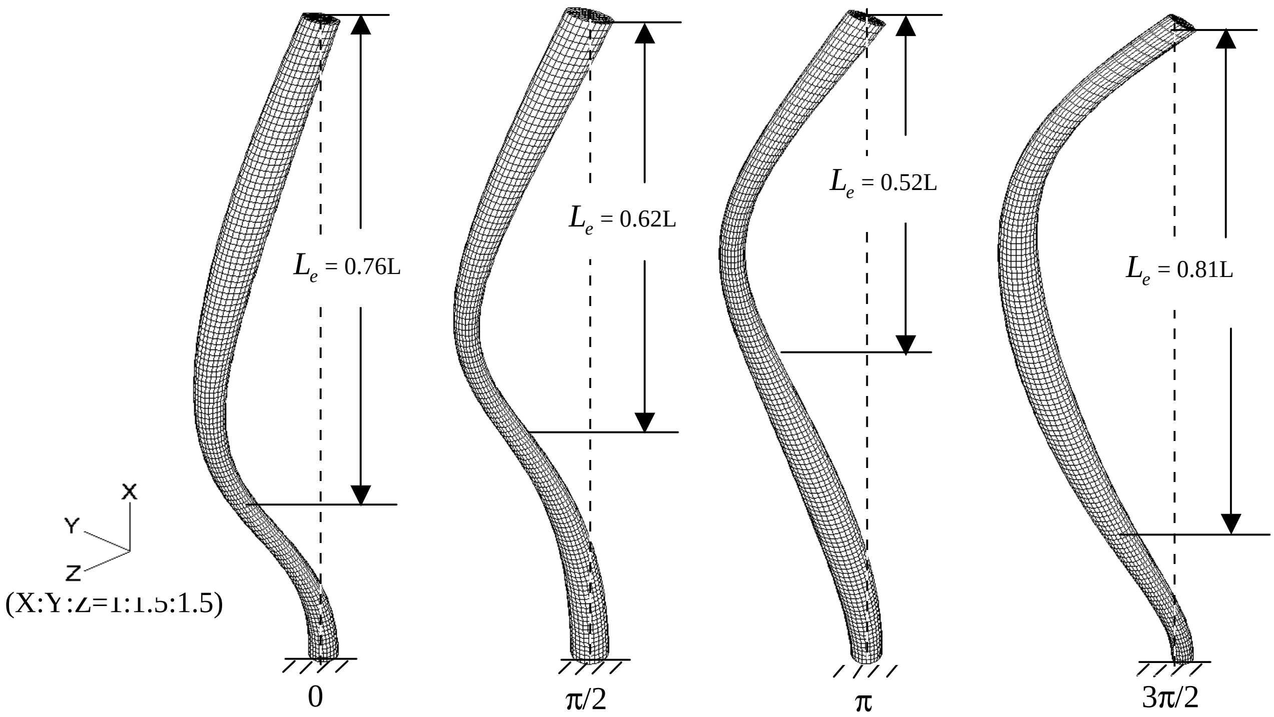

Figure 15. Buckled specimens with different position of the thin segment on fiber (30% diameter variation used).

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