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# Effect of Braid Structure on Yarn Cross-Sectional Shape

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**Abstract:** The effect of braid construction parameters on yarn cross-sectional shape is presented in this paper. The location of the yarn within the braid unit cell is quantified by a compaction factor. A range of braided fabrics were produced and optically measured for actual yarn cross-sectional shape. A comparison of the theoretical and experimental values shows good correlation. Design curves can be produced with the developed model to allow selection of appropriate braid process parameter to create yarns with desired cross-sectional geometries.

**Keywords:** Braiding, Mechanics, Modeling, Elliptical yarn

## Introduction

Braided fabrics are becoming more common in industrial and composites applications, yet much remains to be understood about the fundamental geometric and mechanical response of these materials. Research in the past has presented mechanical models based on the concept of a fabric structure of repeated unit cells [1,2]. Goff introduced parameters such as crimp into the equations of braid geometry [3] and more recently differential geometry has been used by Du and Popper [4] to describe the braid structure. One missing element from the literature is a study of the changes in yarn cross-sectional geometry as a function of braid structure. Most models assume that the yarn in the braid is either round or race-track shaped, and that this shape is a known parameter prior to modeling. The work of Gowayed [5] for three dimensional braided fabrics shows that the yarn cross-section of the yarns in such a fabric go through substantial changes in cross-sectional shape depending on location within the braided unit cell.

Kawabata [6] has presented models of yarn deformation in woven fabrics as a function of axial applied tension and transverse compression, but this has not been linked to braided fabrics. Pastore [7] presented a model of yarn cross-sectional changes in a woven fabric as a result of transverse pressure applied to the yarns, but this has not been extended to braided fabrics.

It is the purpose of this paper to present experimental results on yarn cross-sectional geometry as a function of braid structure.

## Geometric Modeling of Braid

Traditionally, braid diameter and cover factor were configured through manual adjustment of machine settings until a satisfactory result was achieved. More recently, scientists have derived equations that make it easier to predict such values. A brief review of the literature relevant to both diameter and cover factor is presented below.

### Braid Diameter

Ko and Pastore [1] assume circular yarns will be inserted into the braid and approximate the yarn diameter with the equation:

$$D_y = \sqrt{\frac{4L_y}{900{,}000\phi\pi\rho}} \quad (1)$$

Where,

$L_y$: linear density of the yarn in denier
$\phi$: packing factor (volume of fiber/volume of yarn)
$\rho$: fiber volumetric density (g/cm$^3$)

When this circular yarn is introduced into the braid, it has an angle, $\alpha$, with respect to the braid axis (Figure 1). Considering the contribution of this yarn to the total perimeter of the braid, the elliptical shape of the yarn causes the apparent width ($W_y$) to be:

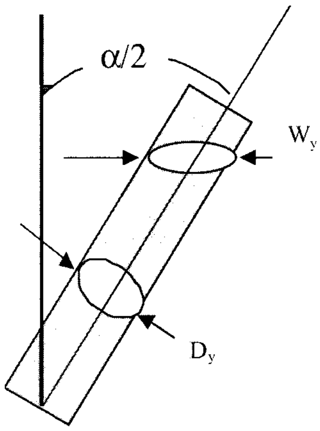


**Figure 1.** Illustration of effect of braid angle on the apparent yarn width.

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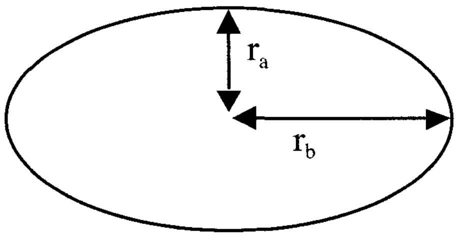


**Figure 2.** Aspect ratio in an elliptical yarn: Yarn aspect ratio is determined as $r_b/r_a$.

$$W_y = D_y/\cos(\alpha/2) \quad (2)$$

where,

$W_y$: apparent width of yarn
$D_y$: diameter of yarn
$\alpha$: angle between the two yarn systems (twice the angle between the braid axis and one yarn)

In reality, the yarns that are inserted into the braid are not circular but rather they are closer to elliptical. As a result of their non-circular nature, elliptical yarns can be described in terms of an aspect ratio, which is defined as the ratio of major radius to minor radius, as seen in Figure 2.

Using equation (1) to get the total area occupied by a yarn that is assumed to be circular, we can calculate area as

$$A = \pi D^2/4 \quad (3)$$

It is reasonable to assume that the elliptical yarn has the same area as the circular yarn. In such a case, the area of the ellipse can be approximated as

$$A = \pi r_a r_b \quad (4)$$

The geometry of the elliptical yarn can be described in terms of the aspect ratio, and can be quantified with equation (4). For example, if an aspect ratio of six is chosen, then $r_a = r_b/6$ as defined by the aspect ratio equation. Substitution into (4) will produce a value for $r_b$, which has been defined as 1/2 the width of the yarn. If this value is then doubled, an accurate value has been established for the effective yarn "diameter". This yarn diameter can then be substituted into (2) to achieve a more precise braid diameter calculation. It is also noted that simply by changing the aspect ratio of the yarn, a different braid diameter will be produced. In this sense, it is possible to pre-design braid diameter based on yarn aspect ratio and braid construction.

The braid diameter for single ply yarns can be calculated as:

$$C = \frac{\sqrt{\xi} N_c D_y}{\Xi \cos(a/2)} \quad (5)$$

where,

$C$: braid circumference

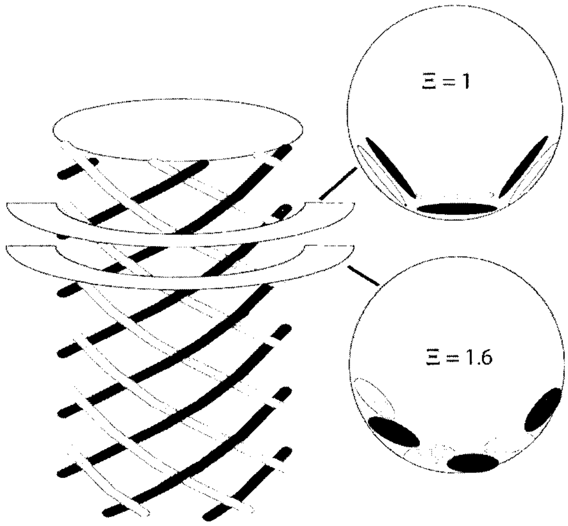


**Figure 3.** Illustration of different values of braid compaction parameter, Ξ, as a function of position of braid cross-section down the length of the braid.

$N_c$: number of carriers
$\xi$: yarn aspect ratio
$\Xi$: braid compaction factor (estimated at 1.8)
$\alpha/2$: angle of yarn orientation

When considering the yarn geometry in a braid, it becomes apparent that the cross-sectional shape of the yarn changes as a function of position down the length of the braid. The parameter $\Xi$ is introduced to quantify this. As shown in Figure 3, the yarn cross-sectional shape depends on its location with respect to the interlacings (plait) of the braid.

When the yarns completely overlap, the compaction parameter is equal to 1, and if the yarns are completely non-overlapped, the compaction factor is equal to 2. In a relatively close-packed braid, it is highly unlikely that the compaction factor will exceed 1.6. Typically braided fabrics are observed to have compaction factors ranging from 1.0 (tightest part of braid) to 1.6, depending on where along the braid length the measurement is made.

Consequently, the yarn cross-section and correspondingly the yarn aspect ratio, will vary down the length of the yarn. In experimental characterization, it is only possible to compare the measured aspect ratios to the range of expected aspect ratios which are bounded by the range of $\Xi$ used.

**Braid Cover Factor**

Zhang *et al.* [8] also explored braids and developed equations designed to determine the cover factor of the braid based on three variables: braid angle, helical length, and braid diameter. Zhang defined cover factor as the ratio of yarn-occupied area within a unit cell to the area of the unit cell. His research proved that if any two variables are specified, the third could be determined. The first case is when braid diameter is held constant. The cover factor of a braided structure is determined as:

$$K = \frac{w_y N_c}{\pi d_b \cos(\alpha/2)} - \left(\frac{w_y N_c}{2\pi d_b \cos(\alpha/2)}\right)^2 \tag{6}$$

where,
$K$: cover factor
$w_y$: width of yarn
$N_c$: number of carriers
$d_b$: braid diameter (constant)
$\alpha/2$: braid angle

It was stated that the yarn is considered as a flat strip yarn where the width is much greater than the height yet no equation to derive this value was discussed.

Experimentation has derived an accurate, reproducible method for calculating the yarn diameter that could be placed into Zhang's equation to improve accuracy. If the diameter of the braid is constant, it is possible to derive nearly the exact width of the yarn with the appropriate aspect ratio using the following.

$$2B = w_y = \pi d_b \cos(\alpha/2)/N_c \tag{7}$$

Knowing this, it is also possible to define the braid angle at jamming by determining the point where the yarns completely touch each other, as:

$$\frac{\alpha_{jam}}{2} = \cos^{-1}\left(\frac{w_y N_c}{2 d_b}\right) \tag{8}$$

## Experimental Results

Experiments were performed in an attempt to evaluate the effect of braid structure on yarn aspect ratio. A mandrel was used in the experiments to keep the braid diameter at a constant value. In this case, all diameters were one inch. A 2,900 denier para-aramid multifilament yarn was used for experimentation. A range of braid angles, number of carriers, and mandrel diameters were used to examine the effects of these parameters on yarn cross-sectional shape. After braiding, the samples were coated in an epoxy resin so that the braids could be cut in order to optically evaluate the cross section of the individual yarns. Table 1 illustrates the braid configurations produced for this study.

**Table 1.** Configuration of braids produced for experimentation

| Number of carriers | Braid angle ($\alpha/2$, deg.) | Mandrel diameter (mm) |
|---|---|---|
| 32 | 25 | 12.5 |
| 32 | 40 | 12.5 |
| 64 | 40 | 25 |
| 64 | 45 | 25 |
| 64 | 50 | 25 |
| 64 | 45 | 32 |

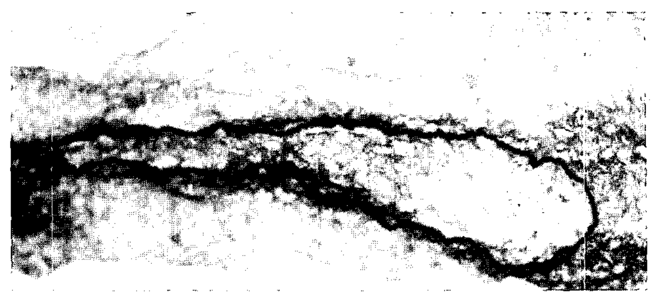

**Figure 4.** Cross-section of yarns encompassed in a braid with a known diameter (border enhanced with image analysis).

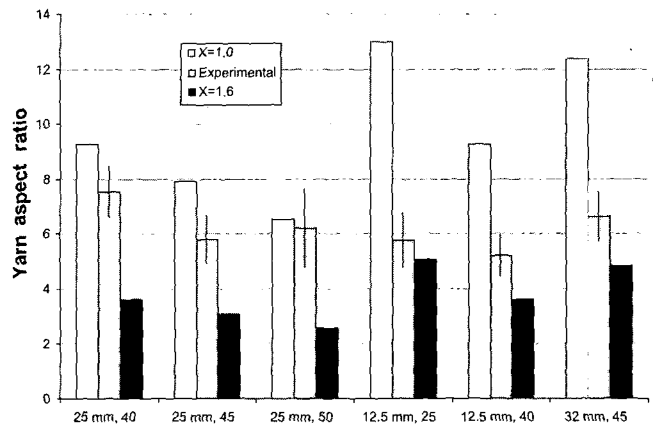


**Figure 5.** Comparison of optically measured yarn aspect ratios and theoretical values for braided fabrics.

The measured yarn cross-sectional aspect ratios were then compared to theoretical predictions to evaluate the model. Figure 4 shows a typical photomicrograph of the braid cross-section.

From microscopic measurements, the yarn aspect ratios were calculated and are presented below in Figure 5. Twenty measurements were made on each of the 6 different braids produced. In addition to the experimental values, the theoretical aspect ratios are also presented on Figure 5, with values for $\Xi = 1.0$ (upper bound) and $\Xi = 1.6$ (lower bound). It can be seen that these bounds provide good predictions of the experimental values. The lower bound of 1.6 is based on experimental results as determined by Ko *et al.* [1].

It can be seen in Figure 5 that two of the braided fabrics, the 12.5 mm, 25 ° and the 32 mm, 45 ° configurations show a much wider range of theoretical values than the experimental results reflect. The range of values comes from the variation in cross-section of the yarn as a function of length, while the experimental values are taken at some particular location. It is expected that the experimental value will fall within the theoretical range. This is due to the openness of these two braided fabrics. In both cases, the cover factor was lower than the other samples. This suggests that there are no regions which are close to jamming, thus it is rare to find a point of complete overlap, or $\Xi = 1$. It can be noted that the experimental values in these two are closer to $\Xi = 1.6$ than 1.0. This is in contrast to the first three braids presented, which were very tightly packed, and show experimental values close to the predictions with $\Xi = 1.0$.

Using the developed model, it is possible to consider the effects of various construction parameters on the yarn geometry. Figure 6 considers the effect of $\Xi$ on the yarn aspect ratio for different braid angle fabrics. As can be seen, as $\Xi$ increases,

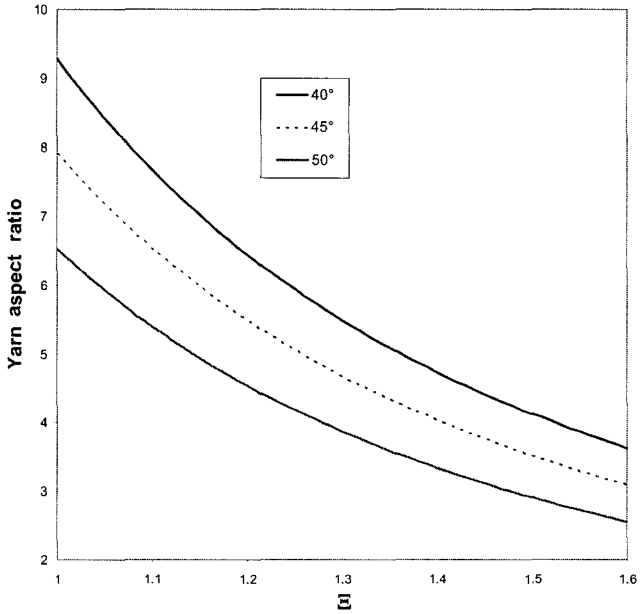


**Figure 6.** Effect of $\Xi$ on the yarn aspect ratio of braided fabrics with different braid angles ($\alpha/2$).

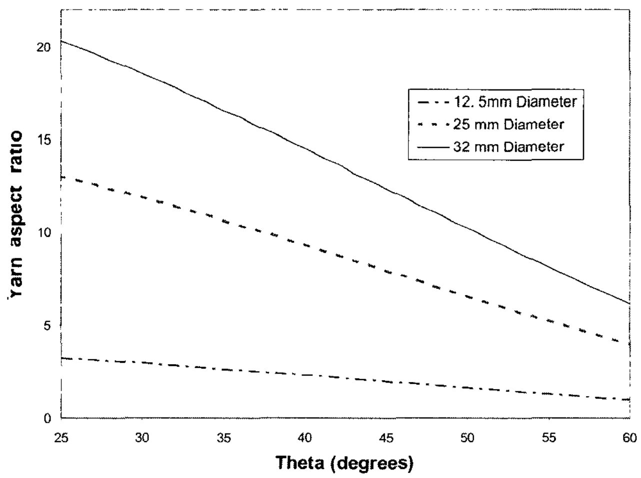


**Figure 7.** Effect of braid angle on the yarn aspect ratio of a fabric measured as $\Xi = 1.0$ for different diameter mandrels.

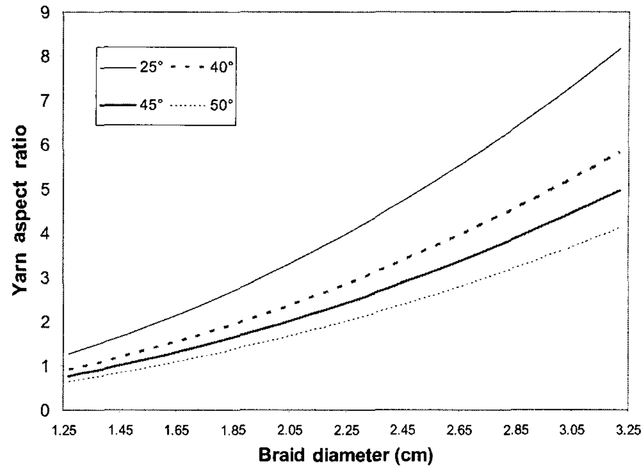


**Figure 8.** Effect of braid diameter on yarn aspect ratio for different braid angles, with $\Xi = 1.0$.

the yarn aspect ratio decreases. Recall that $\Xi = 1$ corresponds with the tightest portion of the braid, where the two yarns overlap.

In Figure 7, the effect of braid angle on yarn aspect ratio is considered. In these charts, it is assumed that the compaction factor, $\Xi$, is constant at 1.0, which assumes that all of the yarn aspect ratios are taken at the same relative position compared to the braid structure. As can be seen, increasing braid angle decreases yarn aspect ratio.

Figure 8 shows the relationship between mandrel diameter for the braid and the yarn aspect ratio. This is shown for different braid angles at a value of $\Xi = 1.0$. As braid diameter increases, yarn aspect ratio increases.

## Conclusions

Within a braided fabric, the yarn cross-sectional shape changes as a function of position. This is due to the braid structure, which periodically shifts from yarns overlapping each other at a plait, to yarns having only slight overlap between the plaits. This effect is presented in terms of a unitless parameter, $\Xi$, that corresponds to position down the length of the fabric.

A model has been developed to correlate the parameter X with yarn aspect ratio. This has been compared with experimental measurements for a range of braided fabrics. Good correlation was found between the measured results and compaction factors ranging from 1.0 to 1.6. The effects of different braid construction parameters on the yarn aspect ratio are examined.

The model presented allows for the design of specific yarn cross-sectional shapes for specific braid applications.

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