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MODELING OF EUCLIDEAN BRAIDED FIBER ARCHITECTURES TO OPTIMIZE COMPOSITE PROPERTIES

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ABSTRACT

Three-dimensional braided fiber reinforcements are a very effective toughening mechanism for composite materials. The integral yarn path inherent to this fiber architecture allows for effective multidirectional dispersion of strain energy and negates delamination problems. In this paper a geometric model of Euclidean braid fiber architectures is presented. This information is used to determine the degree of geometric isotropy in the braids. This information, when combined with candidate material properties, can be used to quickly generate an estimate of the available load-carrying capacity of Euclidean braids at any arbitrary angle.

INTRODUCTION

Three-dimensional braided fiber architectures generate thick fabrics with yarns traveling diagonally through the fabric thickness. The outstanding performance features of these braids are high damage tolerance and delamination resistance. The mechanical properties of these materials are documented in previous works [1, 2].

Correlations between braid fiber architecture and resultant mechanical properties have been made [2]. Further efforts have been made to develop a processing science model of Euclidean braid fiber architectures [3]. The processing model incorporates yarn geometry and other fabrication variables in a geometric cross-sectional slice model. The processing model correlates fabric design inputs parameters with a geometric model in order to more accurately determine the resultant yarn orientations and fabric dimensions.

This paper presents a unit cell model of Euclidean braids in the close-packed condition. The dependence of fiber volume fraction on braid angle is formulated. A geometric isotropy model [4] is applied to the unit cell model. This application generates plots of the distribution of effective fibrous reinforcement in Euclidean braids. These plots provide a quick and effective guideline for selecting the proper braid angle for a specific application.

FABRIC FORMATION PROCESS

Braids are formed by the intertwining of yarns. This intertwining is accomplished by the crossing of yarns on individual yarn carriers. Three-dimensional Euclidean braids are formed in a four-step braiding sequence. In step one columns of yarn carriers are moved up and down relative to each other. In step two tracks of yarn carriers are moved back and forth relative to each other. In step three columns of yarn carriers are moved up and down relative to each other. In step four tracks of yarn carriers are moved back and forth relative to each other. The correspondence between track and column loom movements and yarn movements in forming a fabric are shown in Figure 1.

FOOTNOTES:
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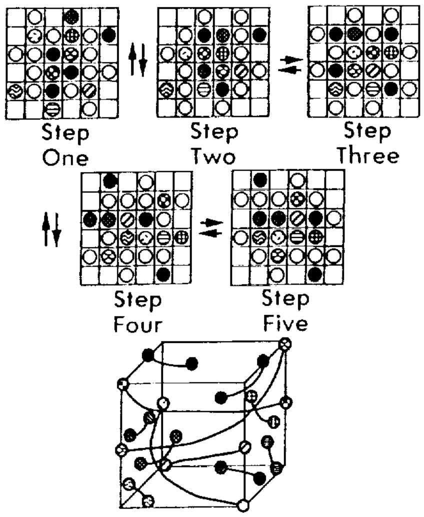

Figure 1. Track/column loom motion used to form an Euclidean braid and the initial unit cell produced by this process

After each set of track and column movements, the yarns are compacted. In this process body diagonal yarn pairs resulting from a track/column movement are compacted against body diagonal pairs arising from the previous track/column motion. The compacting motion intertwines the yarns.

The yarns transverse through the thickness of the fabric in a zig-zag motion as the braiding sequence is repeated. Figures 2 and 3 project the resultant yarn paths into the loom plane for rectangular and circular looms. The three dimensional path of one yarn in a Euclidean braid is depicted in Figure 4. In this figure a discrete lattice is used to locate the yarn in the braid. The presence of this lattice has generated the nomenclature, Euclidean braiding, to describe the track/column braiding process.

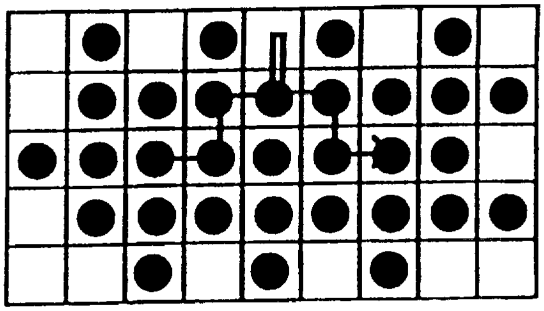

Figure 2. Yarn path projected onto the braiding plane of a rectangular loom [3]

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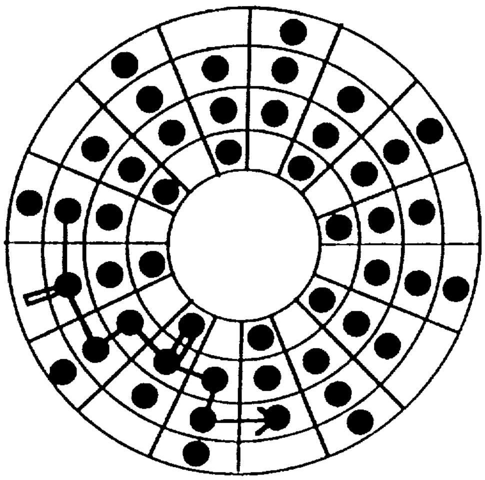

Figure 3. Yarn path projected onto the braiding plane in a circular loom [3]

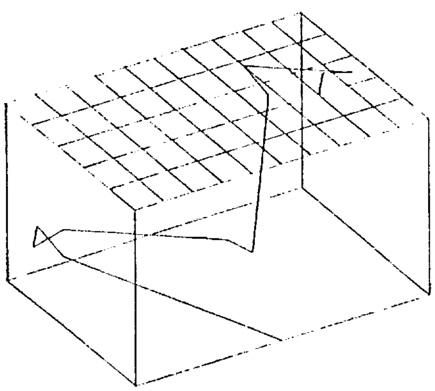

Figure 4. Isolated path of a single yarn in a 3D braided fabric [3]

UNIT CELL MODEL

This model describes the unit cell of a three-dimensional braid when the yarns are close-packed in the xy fabric formation plane. Several simplifying yarn geometry assumptions are made for this model. The yarns are assumed to be incompressible, identical, and circular in cross-section.

The loom and compaction motions involved in the Euclidean braid fabric formation process cause the diagonal movement of the yarns in space. The path of these yarns through a unit volume element is shown in Figure 5. The volume is tetragonal since the yarns possess a circular cross-section and the yarn carriers on the loom are equally spaced in the x and y directions.

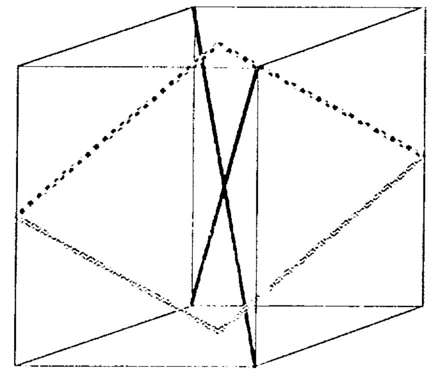

Figure 5. A schematic of yarn paths in an Euclidean braid

Figure 6 is a schematic of through-thickness cross-sections of an Euclidean braid. These cross-sections correspond to the xy planes of the unit cell. The yarns appear elliptical due to the braiding angle. The squares superimposed on the yarns represent the unit cell boundaries in the xy planes. The length of the cell in the x direction is a. The length of the cell in the y direction is b. The unfilled yarns pass through the fringes of the unit cell. The yarns progress through the unit cell as a result of the loom motions. For example, as the columns move, the shaded yarn in the lower left-hand corner of the bottom cell plane zigs halfway up the b length. The subsequent track movement zag and compaction place the shaded yarn in the central region of the unit cell.

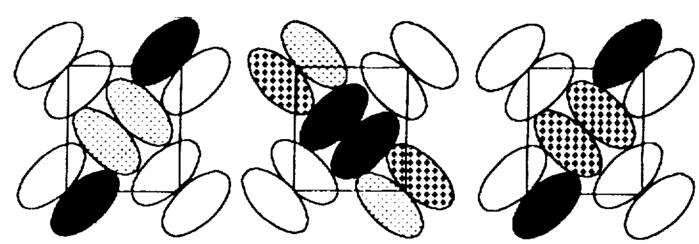

Figure 6. Close-packed through-thickness planes of an Euclidean braid

The lengths of the a and b parameters are equivalent. These lengths are a function of the braid angle and the yarn diameter. Figure 7 defines the braid angle as it appears in the unit cell. The length of the a and b parameters can be defined as:

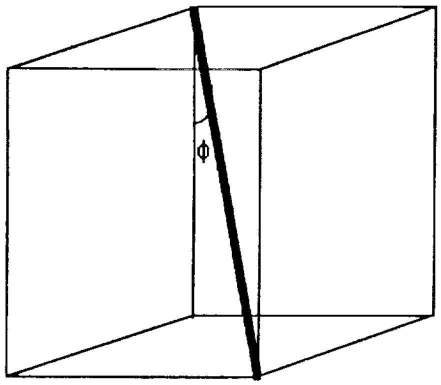

Figure 7. The relationship of the braid angle to the unit cell

$$a = b = (D/\sin\phi) + 2D)/SQRT(2) \qquad (1)$$

The height of the unit cell is measured by the parameter c. The length of c can be defined as:

$$c = a\ SQRT(2)/\tan\phi \qquad (2)$$

Since there must be enough room in the unit cell for yarns to form the V-shaped and X-shaped cross-overs in the cell, there exists a minimum value for c. This minimum can be defined as:

$$c_{min} = 2D/\sin\phi \qquad (3)$$

The volume of the unit cell is the product of these three lengths.

The unit cell contains the six yarns depicted in Figure 5. The sum of the lengths of all these yarns is equivalent to four times the body diagonal length. The volume of yarn in the unit cell is equal to the yarn length times the yarn cross-sectional area. This relationship can be expressed as:

$$V_y = \pi D^2 \sqrt{2a^2 + c^2} \qquad (4)$$

The fiber volume fraction in the unit cell is equal to the yarn volume divided by the unit cell volume times the yarn packing factor. The yarn packing factor accounts for interstitial space within the yarn bundle. The value used for this work is 74%. The value results from experimental work performed by C. Pastore at NASA Langley.

MODELING THE EFFECT OF FABRICATION VARIABLES

Since the yarns are close-packed in this model, the fiber volume fraction is solely a function of the braid angle. The effect of varying this angle is plotted in Figure 8. Fiber volume fraction increases with braid angle. The maximum braid angle, 52°, yields a fiber volume fraction of 0.79. The maximum angle corresponds with a minimum in the value of c.

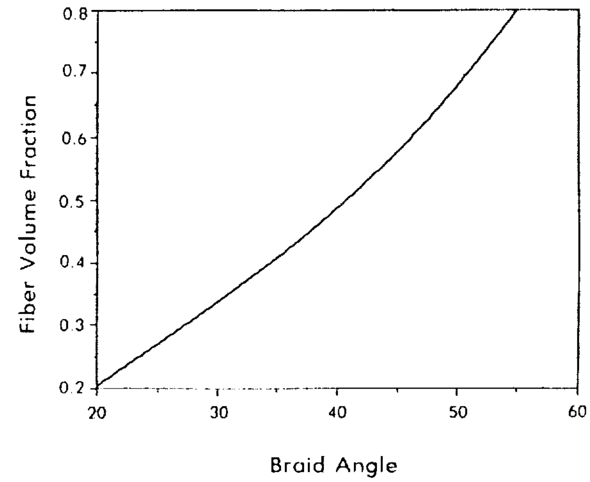

Figure 8. The effect of varying braid angle on fiber volume fraction

DISTRIBUTION OF FIBROUS REINFORCEMENT

A fiber architecture possesses geometric isotropy if the variation in effective fiber volume fraction directly contributing to a loading direction is constant for any angle. The effective fiber volume fraction of a fabric is defined as the fraction of fibers aligned in the proper direction in order for the applied load to be transferred to the fibers. For this model of geometric isotropy the load bearing capacity of a fiber in the transverse direction is assumed to be zero. This capacity is assumed to be one in the longitudinal direction. These assumptions can be applied since the load bearing capacity of a yarn in the transverse direction is many orders of magnitude lower than that in the longitudinal direction.

The unit cell is composed of six yarns which transverse the cell in four distinct yarn orientations. These yarn orientations are orthogonal to each other. The yarn orientations are translated to correspond with 0, 90, 180, and 270 degrees.

The distribution of fibrous reinforcement is described by plotting the effective fiber volume fraction at an arbitrary angle in the xy, xz, and yz planes. The braid angle is projected onto a given plane. Then the effective fiber volume is calculated for any angle in this plane. The fibrous reinforcement distribution function in the xy plane is:

$$V(\vartheta) = 0.25V_f \sin\phi\ (|\cos(\vartheta)| + |\sin(\vartheta)|) \qquad (5)$$

The fibrous reinforcement distribution function in the xz and yz planes is:

$$V(\vartheta) = 0.25V_f \cos\phi\ (|\cos(\vartheta)| + |\sin(\vartheta)|) \qquad (6)$$

Figure 9 plots fibrous reinforcement distributions in the xy plane for two different braid angles. The xy fabric formation plane corresponds with the through-thickness direction in the finished fabric. Minima in the plot occur at the principal yarn orientation directions. In these directions the other orthogonal yarn pair contributes nothing. Maxima occur 45° from the minima. At this location all yarns are contributing to load-carrying ability. The effective load-carrying ability varies 33% as a function of the arbitrary angle.

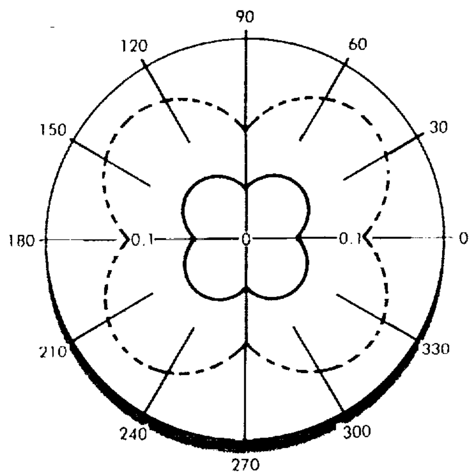

Figure 9. The distribution of fibrous reinforcement in the through-thickness plane

Figure 10 plots fibrous reinforcement distributions in three orthogonal fabric planes for 52° braid angle. Euclidean braid fiber architectures with this maximum braid angle possess the highest amount of through-thickness load carrying ability. As the angle decreases, overall fiber volume decreases and the portion of the fiber volume contributing to through-thickness load-carrying ability decreases.

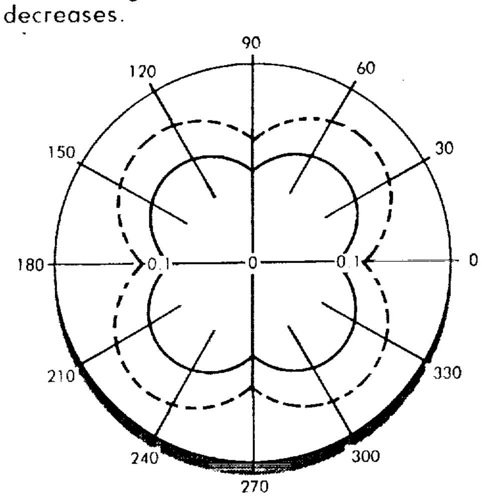

Figure 10. Fibrous reinforcement distribution in the three fabric planes of an Euclidean braid

SUMMARY

Euclidean braid fiber architectures do possess a close-packed fiber plane. With the close-packed condition, fiber volume fraction is solely a function of the braid angle. The fiber volume fraction increases with the braid angle.

The fibrous reinforcement distributions for Euclidean braids closest approach isotropic conditions when the load-carrying ability in each plane is equivalent. Within a plane the fibrous reinforcement distribution is similar to a four-leaf clover. Maxima and minima differences correspond with a 33% difference in load-carrying ability. Due to the degree of isotropy present, no arbitrary angle contributes a large percentage of reinforcement.

In general, geometric isotropy plots are a useful means to determine which fiber architecture is most suited for the desired loading conditions for a particular application.

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