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A methodology for Cartesian braiding of three-dimensional shapes and special structures

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Cartesian three-dimensional braiding as a method of preforming has been investigated. The design of complex and unusual 3-D braids was studied in three parts. These are the grouping of yarns, the fabrication of braids with a complex cross-section, and braids with surrogate material (replacing fibrous tows) added or removed. The grouping of yarns to potentially form hybrid composites was studied via an iterative simulation of the braiding process. Through further analysis of the braid cycles which produce specific yarn grouping, it was found that isolation/insertion rows and columns may be used to quarantine yarns within desired areas of preform cross-section and improve interlacing of the braided structure. In this study, the design of braided composite cross-sectional shape is accomplished through adaptation of the Universal Method. A computer algorithm has been developed which allows the desired cross-sectional shape to be specified and a braid plan for its fabrication automatically determined. A number of 3-D braids, the result of variations or extensions to Cartesian braiding, are also presented. These have been classified as those with axial and transverse yarn insertion, structures with voids, and fillers and fasteners. Braiding equipment has been developed to braid the designed structures. The machines have been used to fabricate four-step braids with transverse, fastener, and filler insertion, special hybrid structures from multiple row and column displacement and multi-step cycles, and uniquely shaped structures with constant and varying cross-sections along their lengths.

1. Introduction

The design and fabrication of preforms for advanced composites has gained considerable attention in light of the recent advancements in textile preforming techniques. It is within this realm of preforming technology that the full advantage of the knowledge of process-structure-property relations may be realized [1]. The fabrication process of these preforms directly determines composite micro-structure and resulting mechanical properties. Textile preforms may be loosely classified into two-dimensional (2-D) and three-dimensional (3-D) structures, depending on the degree of reinforcement between layers. These textile structures may be either stitched, knitted, woven, braided, or a combination of two or more forming methods. In general, the weaving process incorporates a large number of stationary yarns (warp) with a single (or very few) inter-twinning yarn(s) to form the desired fabric. It is believed to be highly advantageous, from a time and cost perspective, to limit the number of yarn packages (carriers) which must be transferred during fabric processing. From this vantage point, weaving appears to be quite attractive. However, current weaving technology is extremely limited in the architecture (yarn bias orientation) and shape of the structures which may be formed. As an alternative, a generic braiding process incorporates the transfer of a large number of yarn packages (carriers) with a moderate number of fixed (axial) yarns. What is lost, mainly due to process set-up time and cost, is believed to be amply compensated for in the range of available architectures, structural shapes, and resulting mechanical properties.

1.1. Three-dimensional braiding

Three-dimensional braids are formed on two basic types of machines. These are the horngear and Cartesian machines which differ only in their method of yarn carrier displacement. While the horngear type machines offer improved braid speed over the Cartesian

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machines, the Cartesian machines offer compact machine size, comparatively low development cost, and braid architectural versatility.

Horngear machines with square or circular arrangement are employed in the fabrication of solid braids. Present-day machines are commonly limited to 16 axial/52 yarn carriers (mainly due to the yarn carrier mechanism employed) and therefore limited size and shape of preform. The micro-geometry of braid is also restricted. The braider yarns in a solid braid structure form inter-twined helical paths throughout the structure, an inherent characteristic in conventional 3-D braids.

To allow for more flexibility in preform size, shape, and micro-structure, new braiding processes have been introduced. These include AYPEX [2], interlock twiner [3, 4], 2-step [5], 3-D Solid [6], and Cartesian [7] which is additionally referred to as 4-step or track and column in the literature. An excellent assessment of textile preforming methods has been conducted by Chou *et al.* [8]. Additionally, while patent references to textile performing methods and machines, especially 3-D braiding related, are too numerous to list, a recent review of textile processes and related analysis work has been conducted by Chou *et al.* [9]. Of all the 3-D braiding processes, the 3-D solid and Cartesian methods represent the apex of braiding technology. Since they differ mainly in approach to yarn carrier displacement (horngear vs. row and column), we need only to understand a single process in order to understand the architectures and structures which may be formed.

1.2. Cartesian braiding process

The basic Cartesian braiding process involves four distinct Cartesian motions of groups of yarns termed rows and columns. For a given step, alternate rows (or columns) are shifted a prescribed distance relative to each other. The next step involves the alternate shifting of the columns (or rows) a prescribed distance. The third and fourth steps are simply the reverse shifting sequence of the first and second steps, respectively. A complete set of four steps is called a machine cycle (Fig. 1). It should be noted that after one machine cycle the rows and columns have returned to their original positions. The braid pattern shown is of the 1×1 variety, so called because the relation between the shifting distance of rows and columns is one-to-one. Braid patterns involving multiple steps are possible but they require different machine bed configurations and specialized machines. This unique "multi-step" braiding technique is what renders Cartesian braiding a versatile process. Row and column braiders of the type depicted in Fig. 1 may be used to fabricate preforms of rectangular cross-section such as T-beam, I-beam, and box beam if each column and row may be independently displaced. Cartesian braided composites offer excellent shear resistance and quasi-isotropic elastic behavior due to their symmetric, intertwined structure. However, the lack of unidirectional reinforcement results in low stiffness and strength, and high Poisson effect. To help eliminate this, some advanced machines allow stationary axial yarns to be fed into the structure during fabrication.

If one allows for multiple steps in a machine cycle, independent displacement of rows and columns, and non-braider yarn insertion, the Cartesian braiding process is capable of producing a variety of yarn architectures, hybrids, and structural shapes. The relationship between the Cartesian braiding process and the resulting braid architecture establishes a method of tailored fiber placement. The importance of this to the design of fibrous composites comes to light when one considers hybrid composites, composites with complex cross-sectional shapes, and textile composites with surrogate material added or removed. A tried-and-true approach to the fabrication of these unique materials is required to fully exploit the advantages of 3-D "multi-step" braiding.

2. Selectively grouped hybrid structures

The recent development of three-dimensional, multistep braided composites has given birth to other exciting design possibilities. One of these design approaches is the grouping of yarns at a desired location in order to form a hybrid composite (see Glossary below). In a hybrid composite, two or more types of fibrous (or surrogate) material may be employed at the preforming stage of fabrication in order to further benefit from the combined properties. For example, the stiffness or electrical properties of carbon fiber may be desired at select locations of a given component, but not required at other locations where less expensive material may be called for. Hybrid design was studied via a simulation of the multi-step, Cartesian braiding process. It was found that an iteration procedure is first required to insure the desired yarn grouping is achieved. After further study, some general rules governing the braiding of hybrid

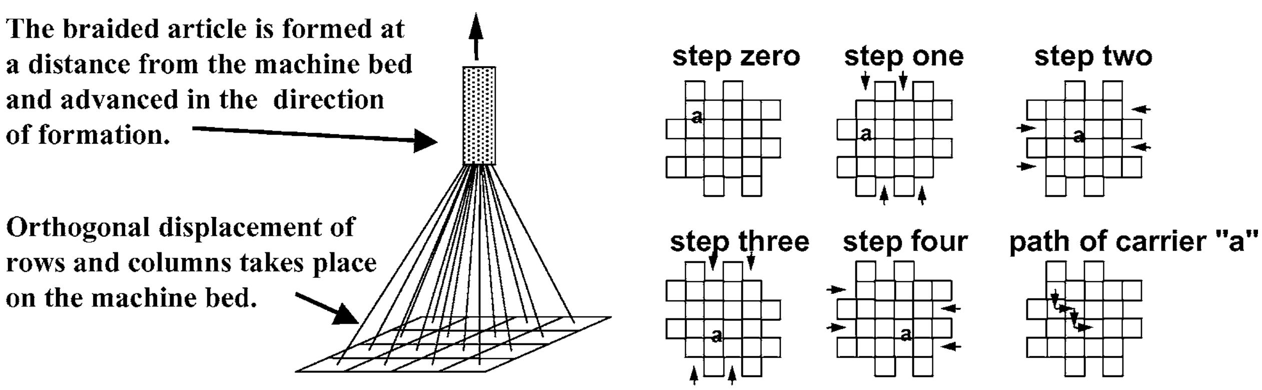


Figure 1 The Cartesian braiding process.

composites were discovered. Both the iteration procedure and the fundamental rules are discussed below.

2.1. Computer algorithm

Yarn groups are sets of yarn tows which travel the same path. A four-step braiding process will yield either one, two, or more yarn groups depending on factors such as the even/odd number of rows and columns [10] (this phenomena is akin to the "harmonic" patterns of a billiard ball bouncing about a pool table [11]). In addition, these groups will always form in a symmetrically distributed pattern and contain the same number of yarns. However, a multi-step braiding process may have multiple yarn groups and a varying number of yarns per group. As will be seen shortly, different braiding schemes will yield different distributions of yarn groups. This phenomenon has a direct application to hybrid composites where high performance yarns such as carbon may be placed only where needed.

Suppose that individual control of each row or column displacement is possible (up to three units) and any number of steps may be specified in a given braid cycle. To exemplify this idea, consider the braid cycle depicted in Fig. 2. The cycle consists of eight steps with a one-unit displacement for each step. For simplicity, a square base array of 4×4 is used. To start, the idealized architecture, shown as a "stick figure", is unique to this braid cycle. The relationship between braid cycle and fiber architecture, an interesting study by itself, is discussed in detail by Kostar [10]. Regarding the phenomena of yarn grouping, notice the number and location of the yarn groups. Groups "a" and "d" tend to occupy the corner locations while groups "b" and "c" the sides and interior. For reasons of clarity, the "mean paths" of the yarn-ends in question are shown in Fig. 2. It is readily apparent that knowledge of the relationship between the braid cycle and this grouping phenomenon would open the door to the design of hybrid composites.

As will be seen in the next section, preforms of a variety of cross-sections may be fabricated through a suitable use of rectangles. As a result of this, attention will focus on the design of hybrids (or grouping of yarns) within a rectangular domain. In addition, due to the extremely large number of braiding sequences yielding the defined grouping of yarns, an analytical solution to this problem is not plausible. Instead, one is forced to limit the approach to one of simulation. A simulation, for similar reasons, focused on multiple displacement (3×3) braid cycles comprised of four steps.

The simulation approach has its disadvantages. However, it is a pragmatic means to determine unique braid cycles yielding the desired grouping of yarns. The idea is simply to iterate through all possible row and column shifting sequences, in an intelligent fashion, until the appropriate braid cycle is found. Additionally, through this approach, knowledge is acquired which allows for the development of fundamental rules.

First, the user inputs the effective yarn diameter (d), the braid pitch length (h), and the target macro-dimensions of the preform (see Glossary). Using established geometric models for the packing of the yarns within the preform cross-section [10], the size of the base array ($m \times n$) is calculated. It should be reiterated here that m and n represent the number of rows and columns utilized in the base array of the machine bed,

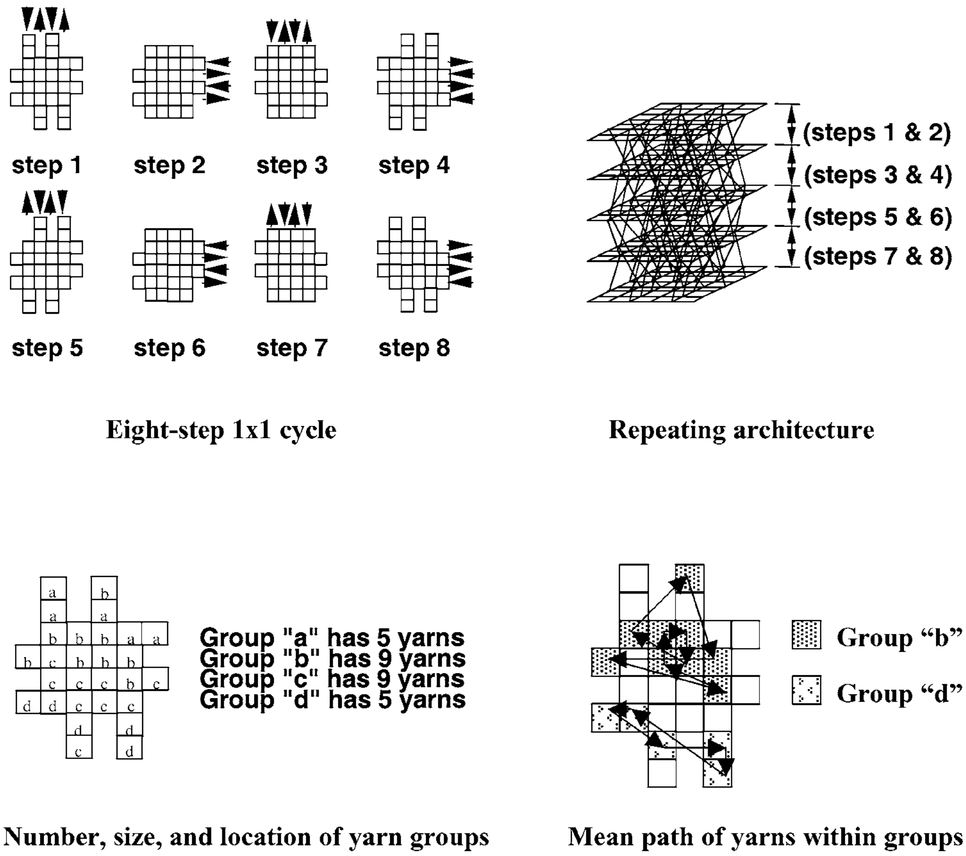


Figure 2 Eight-step 1×1 braid cycle and yarn groups.

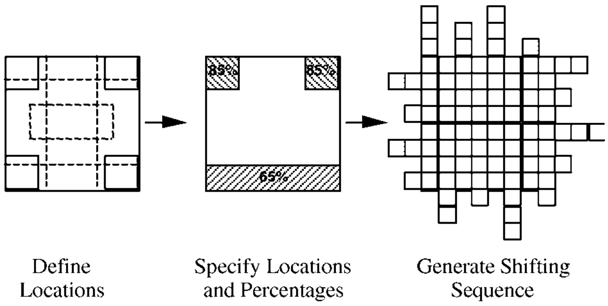


Figure 3 Approach to the design of a hybrid composite.

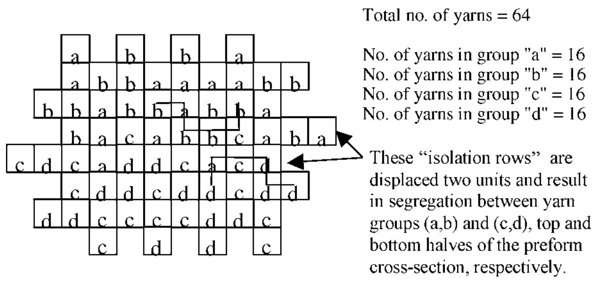


Figure 4 Concept of isolation rows.

respectively. Sides, corners, and interior are then defined and the specific desired grouping locations are identified. The percentage of yarns starting in these identified locations is also specified and the iterations are begun. Fig. 3 exemplifies this procedure. For a given perform cross-section (shown as a square in the Figure), the user first defines locations of the cross-section as corners, sides, center, etc... Next, specific areas of the preform cross-section of interest are identified (for example, a side and two corners in Fig. 3). The user then specifies the percent of the yarns to remain within these special cross-sectional areas (for example, 65% of the yarns in the specified side of the perform cross-section of Fig. 3 are required to remain within the side area). A shifting sequence is then found which yields a minimum of these percentages at the desired locations. If the resulting braid architecture, as seen through the simulation software (i.e., color coordinated to display distribution of yarn groups), is not satisfactory (i.e., the designer does not believe the orientation and distribution of fibers in the resulting structure will yield the desired mechanical properties), the iterations may be continued.

2.2. General rules

There exists certain procedures which result in higher grouping percentages at the desired locations. By overdefining the size of the grouping location, one may specify a higher percentage of yarns to remain. The larger area will allow yarns to migrate a short distance beyond the borders of the specified true grouping area. This yields a higher percentage of yarns in the group in a shorter computation time. Secondly, once a shifting sequence is found which produces the desired grouping, it is always advantageous to continue the iterations. The next few iterations will usually yield similar or increased grouping percentages in the specified areas with the possibility of unique global grouping occurring.

2.2.1. Isolation rows and columns

Consider the simplified shifting sequence shown in Fig. 4. Here, the introduction of two rows, each displaced two units of displacement, results in a well-defined, two-half yarn grouping. It can be seen that groups (a,b) and (c,d) almost exclusively occupy the top and bottom sides of the perform cross-section, respectively. By following the paths of two representative yarns, we see why this is so. The yarns are effectively forced to migrate back to their starting regions. It has to do with the re-directing of yarn paths entering the mid-cross-section area. The analogy of the pool ball on the frictionless table may only be loosely applied [11]. The introduction of the isolation rows effectively forms a "bank" in the middle of the table where the yarn elements (balls) are "bounced back" to their starting regions.

2.2.2. Insertion rows and columns

Keep in mind, the above approach does not guarantee proper interlacing across the location border. A possible solution to this is the introduction of a "stitcher" yarn by way of an "insertion" column (Fig. 5). The addition of an "insertion column" maintains a unique two-half yarn grouping (a,c), but introduces a yarn group (b) which migrates between groups or sides. The effect of this insertion column is to locally disrupt migration blockage and to allow the stitcher yarn to penetrate the grouping location. Keep in mind that the words "row" and "column" in the above may be interchanged. While this does allow for improved interlacing, some sacrifice is made to the desired yarn grouping. It is seen that a combination of isolation rows/columns and insertion rows/columns may allow any desired yarn grouping to occur. By applying this fundamental rule, it should be possible to isolate any defined location within the braid cross-section and employ insertion rows/columns where needed.

2.3. Hybrid fabrication

As previously stated, the grouping of yarns at preform side is a fundamental issue. After neglecting the fairly poor interlacing obtained from lack of "stitcher" yarns, single side and double side groupings within the preform cross-section may be easily obtained. Fig. 6a and b show these resulting side groupings for the hybrid machine cycle depicted. The microstructure of hybrid composites formed in this way will be examined in detail in a subsequent paper. Although unable to be fabricated on the available equipment, a suitable use of isolation rows and columns may be used to obtain a desired

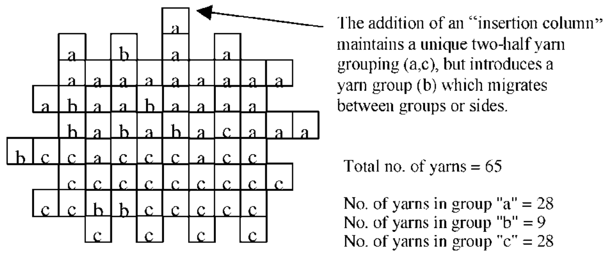


Figure 5 Concept of insertion column to produce stitcher yarns.

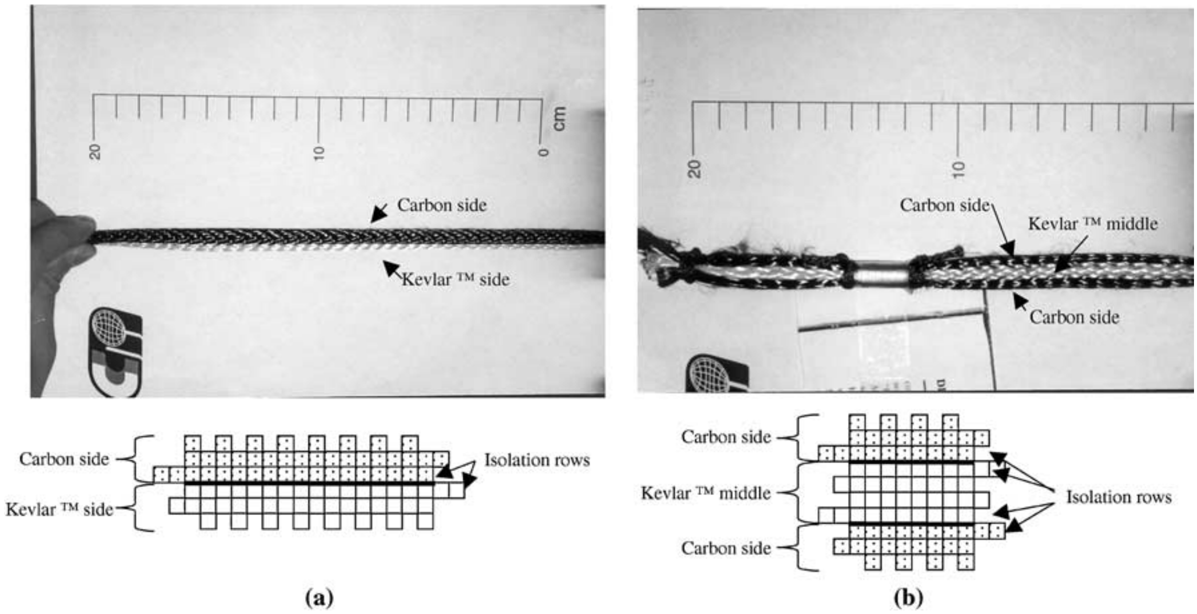


Figure 6 Examples of side grouping. (a) Single side group and (b) double side group.

grouping in a corner of preform cross-section. Finally, by isolating all four sides of preform cross-section, we effectively isolate the interior of the braid.

3. Shapes

In this study, the design of composite cross-sectional shape is accomplished through adaptation of the Universal Method (UM) of braiding [12]. Frontier work on the braiding of complex shapes is, unfortunately, limited but a few pioneers have presented their approaches [13–15]. The basic concept behind the UM is to cut the complex cross-section of the preform into finite rectangular elements and then to braid these elements in groups. Since any shape may be estimated through a suitable number of rectangular elements, the UM provides a plausible means to determine an appropriate braid plan. A computer algorithm has been developed which allows for the user to draw (point and click) a complex cross-section. A set of rectangular braiding elements are then generated within the desired shape. Similar groups of these elements are identified for successive steps in the braid cycle and, hence, the entire braid plan is revealed. Additionally, yarns may be added to or removed from the braiding process in order to vary the cross-section along the length of the braid. A number of preforms with complex shape are designed and braided as example.

3.1. Universal method and algorithm

The Universal Method (UM) utilizes only one braiding pattern for a preform. The basic concept is to subdivide the complex cross-section of the preform into finite rectangular elements and then braid these elements in groups. The determination of a braiding sequence which will produce a desired shape follows five basic gradations. These five gradations are exemplified in Fig. 7. In the first gradation, the shape is defined by a series of line segments, drawn via a “point and click” interface. Here, the computer screen displays an X-Y grid with a blinking cross-hair at the current grid

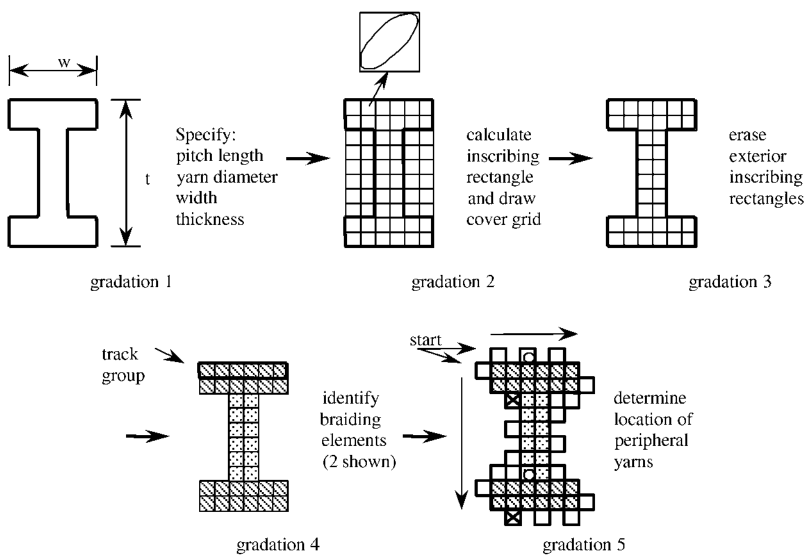


Figure 7 Five gradations involved in the design of a complex shape.

coordinates. Further, current grid coordinates are displayed numerically and graphically on the axes by movable tick marks. Once the final side of the polygon is drawn, dimension arrows appear so that the user may specify the macro-dimensions of the cross-section. All other dimensions are relative to these macro-dimensions as the cross-section has been drawn to scale. The pitch length (a control parameter in perform processing which determines mean fiber angle) and effective yarn diameter are then specified. Keep in mind that a shape with a curvilinear surface must be estimated by a series of line segments.

In gradation two, the relative dimensions of the yarn inscribing rectangle are calculated [9] and the macro-dimensioned area is appropriately filled in. It should be noted that the inscribing rectangles represent the area occupied by individual yarns to be braided into the structure at the specified pitch length. The third gradation entails the determination of which inscribing rectangles (yarns) are inside the polygon and which outside. To accomplish this, the center point of each inscribing rectangle is checked by way of a suitable computer subroutine [16]. In this subroutine, a line segment is constructed between the center point of each inscribing rectangle and a point randomly generated outside the polygon. If the line segment intersects the polygon boundary an odd number of times, the center point is considered to be inside the polygon. Conversely, an even number of intersections indicates the center point is outside the polygon. Center points lying on the boundary are considered outside. Of course, care must be taken when generating the intersecting line segment. It must not be near vertical or near the slope of a polygon boundary. If a center point is outside the polygon, the inscribing rectangle is considered to be outside and the graphical display is upgraded accordingly. That is to say, only inscribing rectangles (yarns) that are inside the cross-sectional shape are retained, where exterior ones are erased.

The identification of rectangular braiding elements in gradation four involves the values of the left most and right most points of a particular row group (Fig. 7). A row group is a continuous series of yarn elements along an individual row (remember we are dealing with row and column or Cartesian braiding). Each successive row group which has equal left most and right most center point values is considered to belong to the same braiding element. In actuality, these center point values correspond to columns, utilized to define the left most and right most extremes of the rectangular braiding elements. Braiding elements are then seen as rectangular "slabs" which will be braided during the same four steps of the entire cycle. Regardless of its position in the cross-section, if a braiding element's left/right most columns are the same as others, they may be braided during the same four steps of the entire braid cycle. In other words, independent braid elements (or rectangular sub-elements of the total cross-section) which share common rows but do not share common columns with other braid elements may be braided simultaneously (where the words "row" and "column" are interchangeable). It should be noted that the sequence of braiding each braid element affects the fiber architecture of the final braid product. Each of the independent braiding elements (ones to be braided simultaneously) is then given a unique color to graphically identify them. The total number of different colors represents the number of four-step cycles in a complete machine cycle. For example, the presence of the two braiding elements in Fig. 7 suggests that 2×4 (steps) = 8 (steps) will be required to braid the I-beam (i.e., the flanges are braided and then the web).

The final gradation is the determination of the peripheral yarn locations. Since each of the braid elements will be braided by a four-step 1×1 pattern, this is simply a question of graphically generating the peripheral yarns in an alternating fashion. The peripheral yarns for each column are generated first. Starting with the left and top most inscribing rectangle, the first column peripheral yarn is graphically displayed. Successive peripheral yarns are then graphically displayed, in an alternating fashion, on all opposite sides. For example, the second column of Fig. 7 (gradation 5) has two peripheral yarns (marked with an $\times$) for each of the two flanges. Additionally, only one peripheral yarn is generated for the third column but an internal yarn element (marked with an o) is seen to act as a peripheral yarn for the bottom flange. This "sharing of yarns" between braiding elements is what allows them to be interlaced. Finally, the row peripheral yarns are generated in a similar fashion.

3.1.1. Rectangular

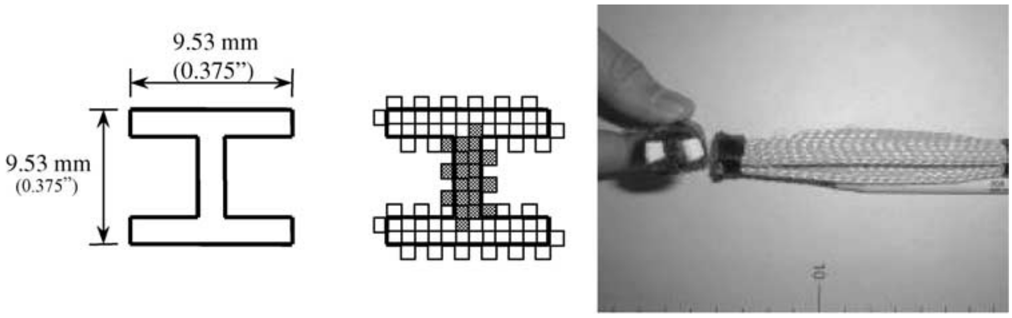
As testimony to the applicability of this approach, consider the following desired shapes. Keep in mind that, due to the limited size of the available braiding equipment, fairly small cross-sections are specified. The material used in the fabrication of each braided structure (unless otherwise specified) is Kevlar 49^{TM} with an effective yarn diameter of 0.752 mm (0.0296 in.) and a specified pitch length of 3.8 mm (0.15 in.).

An I-beam with a flange width of 9.53 mm (0.375 in.) and a total height of 9.53 mm (0.375 in.) was drawn and specified first. The I-beam, as expected, may be braided using only two braid elements which yields a total of eight steps for one complete cycle. Fig. 8a and b show both the determined braid plan and the resulting braided structure. Through shading, Fig. 8a shows the two braid elements which are fabricated in each subsequent four steps of the complete cycle.

3.1.2. Irregular and axi-symmetric

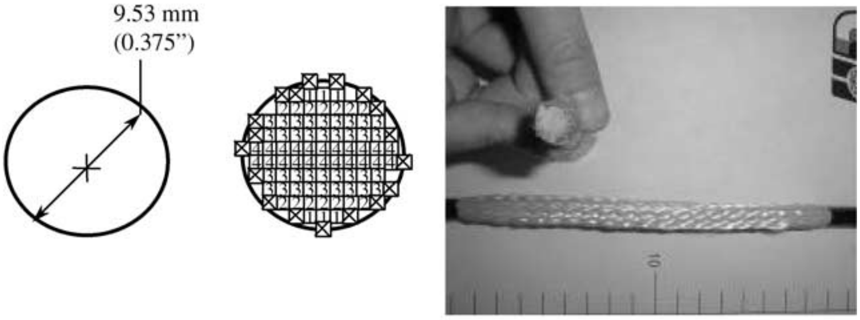
Not only may cross-sectional shapes consisting solely of simple rectangular elements be accurately fabricated, but shapes with curvilinear surfaces may also. As two sub-cases of these types of shapes, we shall consider both axi-symmetric and irregular. Although many shapes within these two categories may be specified and fabricated, a few examples will be presented for brevity.

The most fundamental axi-symmetric shape is the circle. It should be noted here that we are attempting to estimate a circular shape through a suitable use of



(a) (b)

Figure 8 Specified I-beam and resulting structure. (a) Drawn and dimensioned I-beam with resulting braid plan. (b) Photograph of fabricated I-beam.



(a) (b)

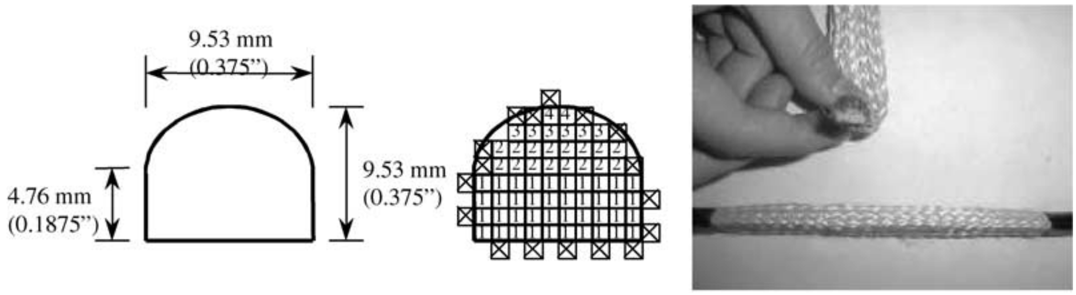
Figure 9 Specified circular shaft and resulting structure. (a) Drawn and dimensioned circular shaft with resulting braid plan. (b) Photograph of fabricated shaft.

rectangular elements. It is apparent that a large specified diameter of circle and a small fiber bundle (tow) size will result in a more accurate representation. However, the accurate fabrication of the desired circular shape will be accompanied by a large number of braid elements and, as a result, a longer fabrication time. In our present study, due to machine bed limitations, we consider a desired circular cross-section with a 9.53 mm (0.375 in.) diameter. Fig. 9a and b show both the determined braid plan and the resulting braid structure. It is seen that the required braid plan consists of four braid elements for a total of sixteen steps in a complete cycle. Peripheral yarns have been labeled with an x. Given the size limitations stated above, and the effect on estimation of a curvilinear surface utilizing rectangular elements, overall geometry and dimension of the cross-section are moderately accurate.

As an example of an irregular shape with a curvilinear surface, we consider that of a dome. This shape is chosen as to show a simple combination of a half circle and that of a rectangle. Fig. 10a and b show both the determined braid plan and the resulting braided structure. The four braid elements are clearly labeled. It should be noted here that *for all shapes, the specified macro-dimensions apply to the "in tension" braid*. In other words, while the braid is being fabricated, each of the fiber tows is in tension. The result is a smaller cross-section of braid and a more closely packed structure and filaments. During consolidation, for tooling purposes, these smaller dimensions are taken as the final composite dimensions. The issue of preform compaction during consolidation, and hence the "locking-in" of the microstructure, is one worth future investigation. *This is noted because the photographed preforms are not in tension and, as a result, tend to "puff up" and display exaggerated dimensions*.

3.1.3. Variations along the length

A braided preform may not only consist of a complex cross-section, but may also involve changes in the



(a) (b)

Figure 10 Specified dome shaft and resulting structure. (a) Drawn and dimensioned dome shaft with resulting braid plan. (b) Photograph of fabricated dome shaft.

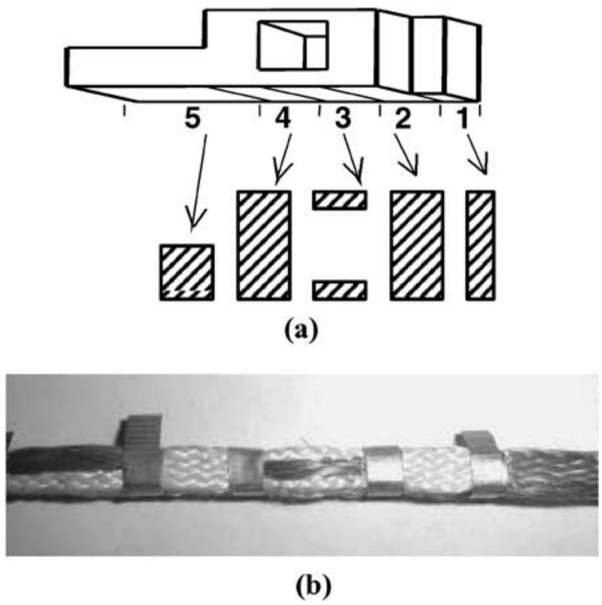


Figure 11 (a) Discretely changing complex shape and its cross-sections. (b) Photograph of discretely changing shape where shaded yarns are to be removed.

cross-section along its length. As we have seen, this adaptation of the Universal Method may be applied to the fabrication of virtually any shape. It is therefore a question of utilizing this method and algorithm for each subsequent cross-sectional shape. However, two separate cases must be identified here. The change in cross-section may occur discretely or continuously.

As an example of a discretely changing cross-sectional shape, consider the structural part shown in Fig. 11a and b. The varying cross-section of this preform may be broken into five separate cross-sections (labeled 1 to 5). For this fairly simple preform, it is seen that these five cross-sections are all rectangular in nature and, indeed, sections two and four are identical. It is now merely a question of applying the Universal Method algorithm to each cross-sectional shape. First, the largest shape (2) is drawn and the braid plan determined. The arrays which contain the data for this row/column shifting sequence are then stored in memory after being labeled as the second (2) shifting sequence. Each of the remaining cross-sections is then drawn, in any order, and the shifting sequence appropriately labeled and saved. For each cross-section, the number of complete cycles is equal to the number of pitch lengths formed. Therefore, each shifting sequence file is also assigned the correct number of complete cycles (pitch lengths) to carry out in order to form the correct length of each cross-section. The braiding machine is then loaded according to the braid plan for the largest cross-section (2) and braiding ensues in the proper sequence (1 to 5).

Whenever the cross-section being braided is smaller than the largest cross-section, there are a number of yarns which do not participate. These yarns are not interlaced into the braid and simply remain straight on the surface or interior of the preform. Once the final preform has been braided, these yarns may be cut away at both free ends. Fig. 11b shows the braided preform where the shaded yarns are those which need to be cut away. Although the removal of surface free yarns (corresponding to Sections 1 and 5) may be easily achieved, interior free yarns (Section 3) are not so easily removed. In practice, it may be necessary to consolidate the preform as is and perform a post machining operation.

A more imposing problem is that of forming a braid with a continuously changing cross-section. Three-dimensional row and column (Cartesian) braiding is, by its very nature, discrete. The shortest length of braid which may be formed for a particular cross-sectional shape is one pitch length. Theoretically, therefore, new braid plans may be established after each complete machine cycle in order to closely estimate a continuously changing cross-section. In practice, however, this is highly impractical. The best one can hope for is to separate the length of the desired braid into a reasonable number of discrete cross-sections. Fig. 12a shows a length of a fan blade, separated into four sections. At the end of each section, a minor reduction in cross-section is obtained by the incorporation of a suitable braid plan. Ideally, this reduction should only occur due to the removal of a single layer of unbraided yarns. For the gradual taper associated with a fan blade, the generated series of discontinuities may be "smoothed out" during consolidation due to the formability of the braid. The result is a seemingly continuous, varying cross-section of the final part. Fig. 12b shows a five section fan blade which was fabricated using polyester yarns. The abrupt changes in cross-section are due to the fairly large diameter yarn used (about 1/8 in.) but may be "smoothed out" during molding and consolidation.

4. Braids with surrogate material

There exists a number of three-dimensional braids which are a result of variations or extensions of

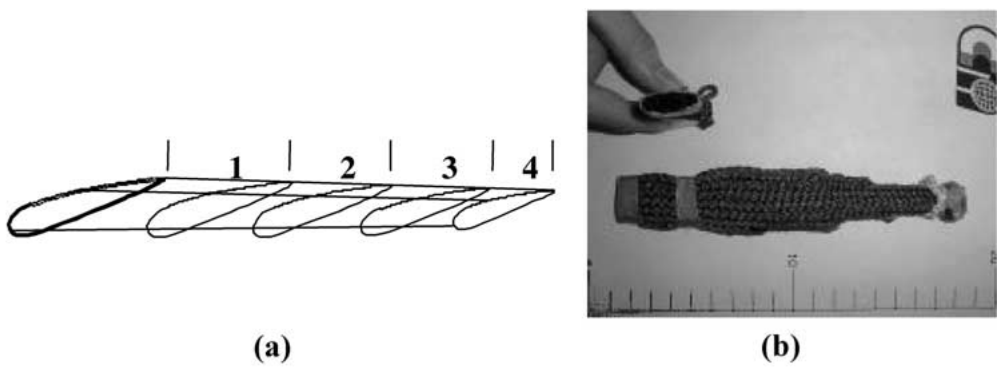


Figure 12 (a) Approximation of a continuously changing complex shape and (b) photograph of turbine blade fabricated using five discrete sections.

multi-step, Cartesian braiding. In general, these braids are referred to as those with surrogate material. In other words, additional fibrous, matrix, removable, or foreign (fasteners) material is employed during fabrication. For brevity, a few examples of each type of surrogate braid will be presented.

4.1. Axial and transverse yarn insertion

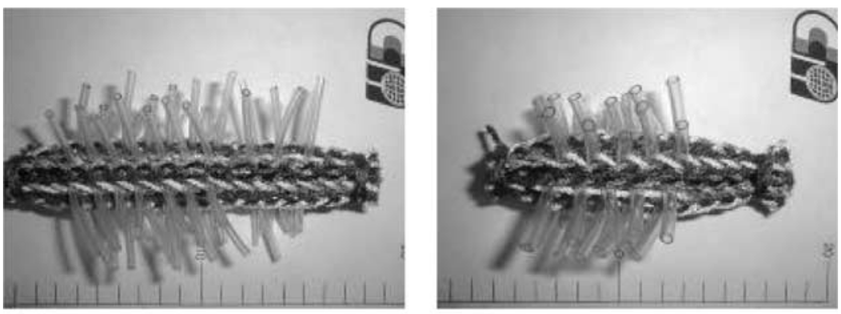
Consider axial and transverse tube insertion for a 3-D Cartesian braid. For this part of the study, transparent Tygon^{TM} tubing of a 3.175 mm (1/8 in.) OD has been inserted. The axial "tubes", as we shall see, may be any fibrous, filler, or removable material. What is important here is the resulting architecture due to the introduction of a foreign material in the axial direction. The placement of the axial tubes is such that the braider yarns wrap around them to form a new interior unit cell. An additional step of manually inserting tubes in the transverse directions may also be carried out. By inserting the 3.175 mm (1/8 in.) OD tubing in these transverse directions, the structure shown in Fig. 13a may be obtained. The use of a larger (4.763 mm (3/16 in.) OD) diameter tubing further distorts the interior structure, and hence the unit cells, of the braid (Fig. 13b).

The insertion of transparent tubing is useful for the study of braid architecture, but composite materials are made from high stiffness fibers. As an example to the feasibility of axial and transverse fiber reinforcement, a four-step (1×1) braid was formed using Kevlar-49^{TM} (4,560 denier) braider yarn tows and a base array of 8×8. Graphite fibers supplied by the Nippon Graphite Fiber Corp. (2,800 denier) served as a transverse insertion material. The graphite fiber was inserted manually between 4-step cycles but insertion may be easily automated. Fig. 14a and b show the braid plan and the transversely reinforced (single and both directions) preform.

Given the ability to insert axial and transverse yarns into a multi-step braid, some interesting possibilities become apparent. For example, a unique braid architecture, a braided hybrid, or a complex shaped part may have yarns inserted where additional stiffness is desired. If we consider the aforementioned I-beam, flange stiffness may be increased not only by select hybridization, but also by axial yarn insertion. Selection of the surrogate material itself is entirely up to the designer. Conductive material such as carbon, piezo-ceramic, metal, etc... may be placed within the microstructure of the braid to enhance or monitor material response to the end application. Indeed, the surrogate material may even be "filler" in nature or may be later removed to form a structure with voids.

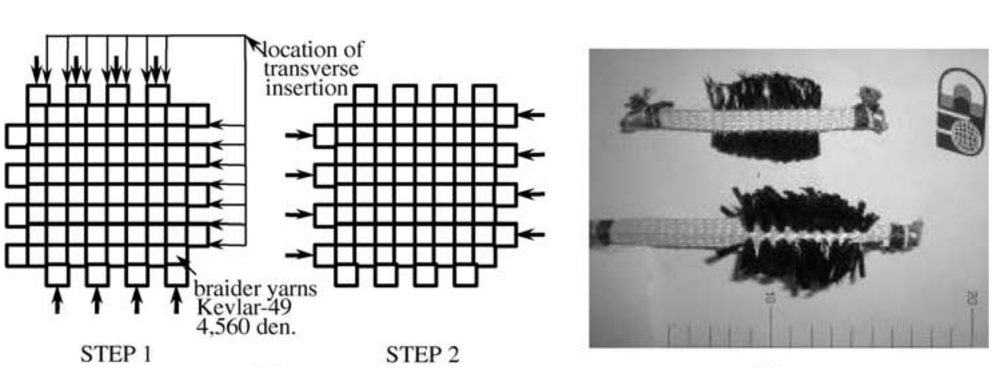
4.2. Fillers and fasteners

One of the methods utilized for the consolidation of select braids, due to inherent ease of implementation, was SCRIMP^{TM} and the resin system chosen, due to its low viscosity, was vinyl ester. SCRIMP^{TM} is a vacuum bag, resin injection system ideally suited for flat, thick preform sections. The consolidation method was employed here merely for the ease and low cost of application. It is not suggested as an optimal approach to complex 3D braid infiltration. Vinyl ester is approximately 50% by weight polystyrene. It is not unfeasible that a certain added weight percent of polystyrene may be absorbed



(a) (b)

Figure 13 Four-step braids with axial and transverse tube insertion. (a) Four-step braid with axial and transverse tube (1/8 in. OD) insertion. (b) Four-step braid with axial and transverse tube (3/16 in. OD) insertion.



(a) (b)

Figure 14 (a) A four-step braid plan with transverse carbon fiber insertion and (b) photograph of hybrid preform with transverse carbon fiber insertion.

into the vinyl ester resin during infiltration. It should be noted that the use of vinyl ester and polystyrene was for demonstration purposes, and may not, due to potential effects on matrix resin properties, prove a viable approach. What is of importance here is the introduction of a filler material during the preforming process, with the objective of "fluffing" the fibrous tows and "expanding" the fibers and braided fabric. Other examples of this concept include addition of a polymeric which is burned off prior to consolidation, or the addition of a structural particulate which may enhance overall composite performance.

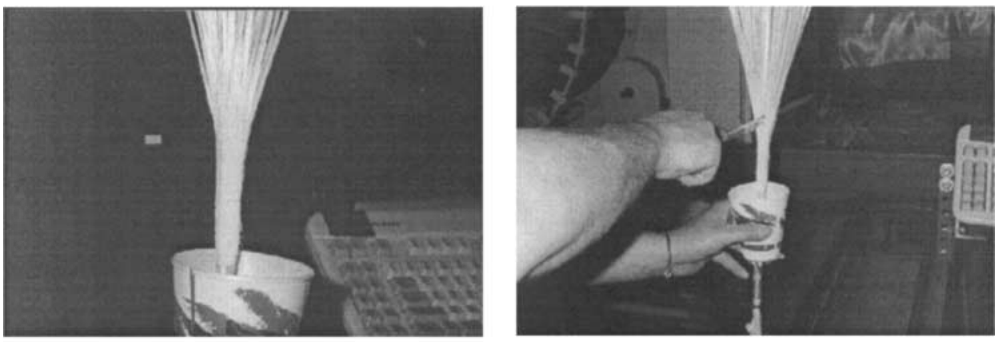
To support this hypothesis, set amounts of polystyrene, in powder form, were added to a four-step (Kevlar-49™) braid during fabrication. Approximately 10 grams of the powder was evenly distributed atop the braid convergence zone after each completed braid cycle. The powder was allowed to settle under the influence of gravity, a braid cycle was completed, and braid compaction was carried out to ensure proper packing of the polystyrene. Fig. 15 shows how the procedure was conducted along with the packing of the filler material within the braid. The idea behind this approach, summarized above in example form, is obtainment of "braid expansion" while maintaining a continuous load transfer medium between the yarn tows. Often, a small reduction in global fiber volume fraction of part may be required for 1) an optimized distribution of the available fiber and/or 2) an increase in part volume (i.e., use the fiber where and how it is most needed in the part). The above example of "braid expansion" is meant as a single example of how such a goal may be achieved.

As a final example of surrogate material addition, consider the braiding-in of fasteners. For brevity, only two types or functions of fasteners will be presented. These are fasteners used for the attachment of other structural members (i.e., threaded shafts and bolts), and fasteners used for the attachment of tubes, etc. (i.e., fluid injection and transfer).

When a threaded hole is required in a composite structural member (i.e., when there is no space for a nut/bolt to be utilized, etc.), the machining of the threads alone may cause severe fiber damage and sacrifice part strength. For these instances, an anchored, threaded shaft may be braided-in to the fibrous architecture and infused with matrix material to become a working part of the structure (Fig. 16a). When a fluid is to be introduced to a structure with voids (i.e., for heat transfer considerations), tube attachment pieces may be braided-in and made part of the final structure (Fig. 16b). What is at issue here is the process employed to consolidate such a complex braid/fastener configuration. The consolidation or densification of such a complex perform structure would prove challenging.

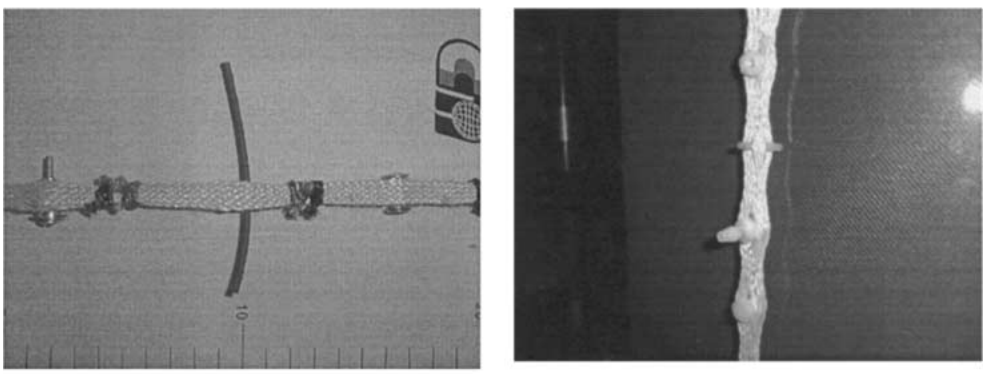
5. Structural voids

We may now take this idea of axial yarn insertion one step further. Suppose we wish to create braided composites with structural voids [5]. That is to say, we wish



(a) (b)

Figure 15 Polystyrene used as a filler material in a four-step braid. (a) Formation of a resin rich braided composite with polystyrene filler. (b) Braid and filler compaction to ensure proper braid expansion.



(a) (b)

Figure 16 The braiding-in of fasteners. (a) The braiding-in of fasteners for attachment of other structural members. (b) The braiding-in of fittings for fluid injection.

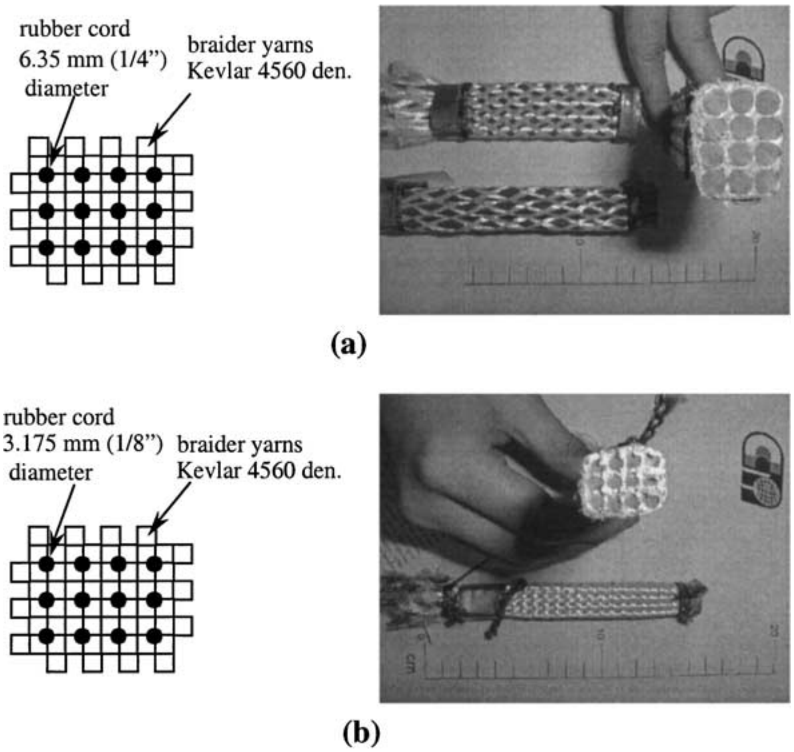


Figure 17 A four-step braid with silicone rubber as the axial array. (a) Braid with 6.35 mm (1/4 in.) diameter cord as axials. (b) Braid with 3.175 mm (1/8 in.) diameter cord as axials.

to remove material from non-load carrying domains of the braided composite. As a simple example, consider replacing select yarns of a Cartesian braid with silicone rubber cord. Silicone rubber is chosen because the high Poisson's ratio allows it to be pulled free from the polymer matrix after consolidation and easily removed from the composite. For a given braider yarn linear density (effective diameter), different diameter silicone rubber may be used depending on the desired void content and spacing of the braided reinforcing network. Fig. 17 shows a four-step (1×1) braid formed about a 4×3 axial array of silicone rubber cord. From Fig. 17a, there appears to be a maximum axial to braider diameter ratio for complete braid compaction to occur. The spacing caused by the 6.35 mm (1/4 in.) dia. rubber cord did not allow the Kevlar braider yarns (4,560 den.) to reach a completely packed (jammed) configuration. For comparison, Fig. 17b shows excellent braid compaction and formation about the axial array due to the smaller (3.175 mm (1/8 in.) dia.) silicone rubber used.

By design, the removal of material in the transverse or through the thickness direction may be required. As previously mentioned, transverse cord insertion is accomplished manually during braid formation. Ideally, this may be carried out at any time during the braid cycle and the cord inserted at any location (or to any depth of the cross-section). For example, silicone rubber cord (which was later removed after consolidation) was inserted at the indicated locations in Fig. 18 after each complete (four step 1×1) braid cycle. Fig. 18a shows the result of inserting 3.175 mm (1/8 in.) dia. silicone rubber cord while Fig. 18b shows the results of 6.35 mm (1/4 in.) dia. cord. For consolidation purposes, the cord shown was later trimmed to be flush with the braid surface.

Some of the many reasons for fabricating void filled structures include the removal of material (matrix) for the reduction of composite weight and the "expansion" of the braid cross-section so that load carrying fibers may be better deployed. The limited size cross-section of a braid which may be formed from a given machine bed size (indeed, the ratio of bed size to braid cross-section can be well over an order of magnitude and is an issue by itself) dictates the need for some form of

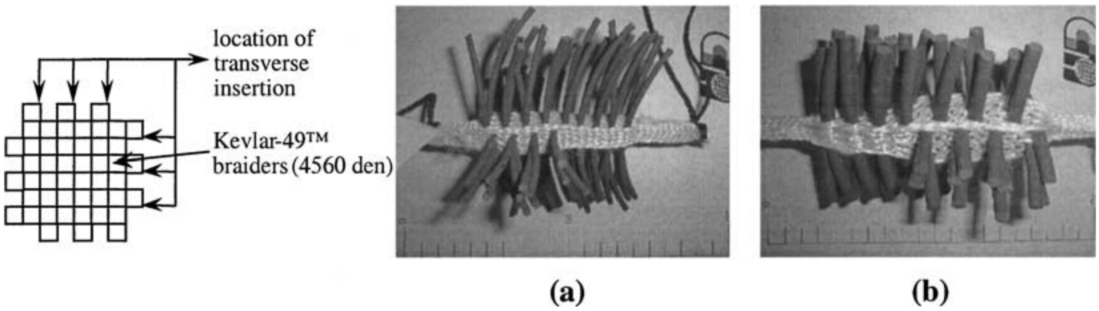


Figure 18 Four step braids with transverse silicone cord insertion. (a) Braid with 3.175 mm (1/8 in.) diameter cord. (b) Braid with 6.35 mm (1/4 in.) diameter cord.

braid “expansion”. In this way, the reinforcing, load carrying fiber is placed where needed. Naturally, for a given loading condition, the placement of the “holes” should also be such that local transverse “hole” stress is minimized.

6. Braiding equipment

The equipment used in the fabrication of 3-D Cartesian braided structures possesses five basic components. These are the machine bed, the actuating system, the take-up and braid compaction mechanism, the yarn carriers, and the interface/control system.

Inherent in the process of 3-D braiding is a limiting ratio of machine bed size to preform cross-sectional dimensions. The larger the spacing between yarn carriers on the machine bed (the spacing directly determines the amount of yarn a carrier can hold), the more difficult it becomes for the braid to be formed due to the “pulling apart” action of the yarns themselves. Some ingenious methods have been devised to overcome this limit to braidable cross-sectional size of preform [17]. However, as a rule, there is a trade-off between the length of preform and the cross-sectional size of preform which may be fabricated from a single machine set-up. With this aside, the number of rows and columns and the resulting yarn carrier spacing on a Cartesian braiders bed are important specifications. Fig. 19a shows a 10 row by 24 column Cartesian braider which integrates stationary spacer rows for the sole purpose of inserting axial (longitudinal) yarns. The transverse insertion, Fig. 19b, is carried out manually.

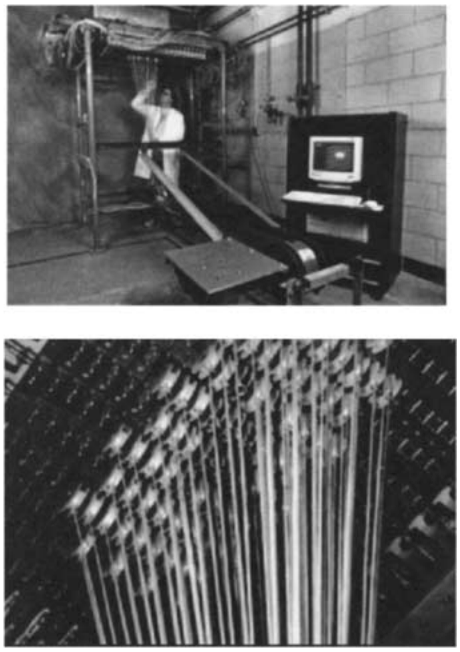
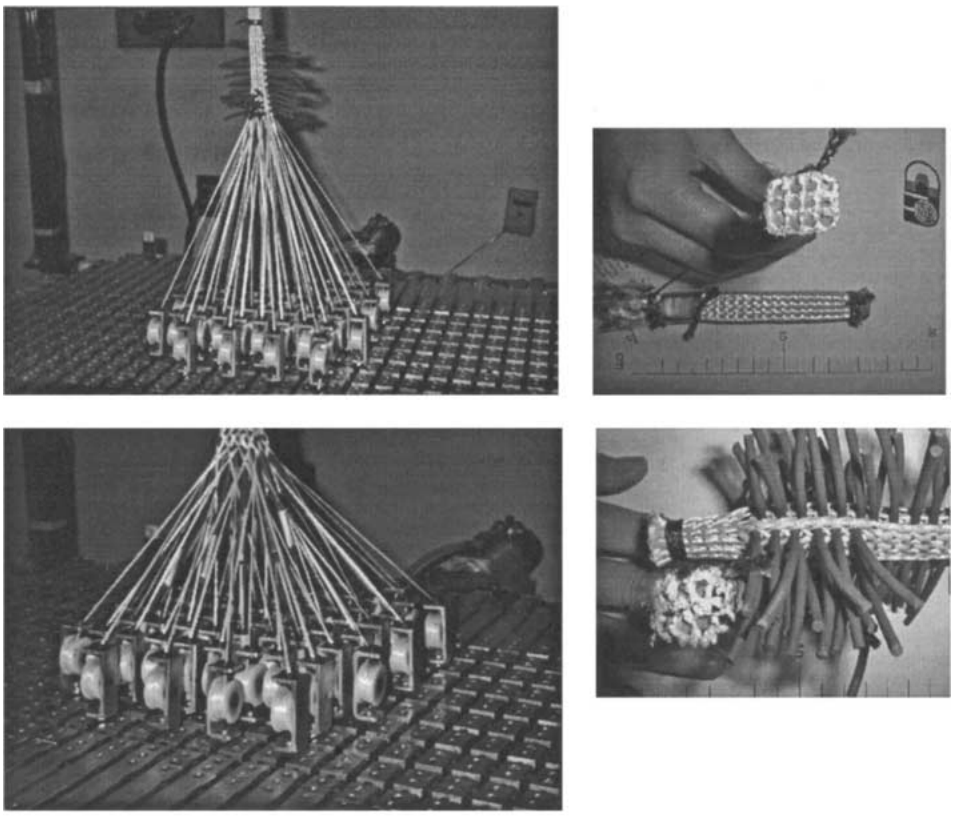


Figure 20 A Cartesian (multi-step) pneumatic braider with independent row and column control (compliments of the Center for Composite Materials, University of Delaware and Atlantic Research Corporation).

The actuating system of choice for the Cartesian braiding machines is pneumatic. When one considers the required displacement forces, precision of displacement, and number of actuators involved, a pneumatic drive system becomes an attractive option. Fig. 20 shows a 20 row by 20 column Cartesian braider which is capable of displacing each row and column



(a) **(b)**

Figure 19 (a) A Cartesian (4-step) pneumatic braider with axial yarn insertion (compliments of the Center for Composite Materials, University of Delaware) and (b) braids with transverse yarn insertion.

independently. To accomplish this, small pneumatic cylinders are utilized in series for each row and column. As previously mentioned, this results in the ability to fabricate complexly shaped or hybrid (yarn grouping) preforms for specialized applications.

Take-up and compaction of the braid is a critical part of the process. For a continuous fabrication process, the braid must be drawn or taken-up. Take-up is carried out after a complete machine cycle and before compaction. As a result, the take-up distance directly determines the braid pitch length (i.e., length of braid formed during one machine cycle) and resulting architecture. It is therefore essential to have precise control of the amount of take-up. This is most commonly accomplished by utilizing a motor in conjunction with a worm gear assembly. Without inter-yarn friction, the yarn orientation angle within the braid would be determined solely by the angle that the not-yet braided yarn makes with the braid axis. In reality, inter-yarn friction does exist and allows braider yarns to remain in place once compacted. As a result, a much greater orientation angle may be obtained. The idea behind the braid compaction is to pack the yarns up to the desired orientation and then allow inter-yarn friction and interlacing to hold the yarn in place. To the authors' knowledge, this is commonly accomplished by manually inserting a rod in the braid convergence zone and gently compacting the braid after each complete machine cycle. It is suggested that the next generation of Cartesian braiding machines incorporate an automated version of this critical step. As mentioned earlier, however, larger bed arrangements cause the braid to be "pulled apart" and even a compaction step may not be enough to form the braid.

The design requirements of a yarn carrier include compact size, maintained yarn tension, and yarn rewind. As a yarn carrier moves from the outside toward the center of the machine bed, the distance between carrier top and braided fabric shortens. The slack yarn so produced must be rewound by the yarn carrier or it will become entangled with other similar yarns.

7. Summary

Textile preforms offer a wide selection of fabrication techniques. It is within this processing science that true control of yarn placement may be realized, resulting in the fabrication of unique structures. Although past work has added greatly to the existing science base, a comprehensive approach to the complete design of three-dimensional braided composites is continuously being developed. In general, the advantages of 3-D Cartesian braiding as a method of preforming include the formation of a delamination resistant structure, the ability to fabricate thick and complex shapes, and a single procedure for net-shape preforming. Structural composites formed by this method which possess either a complex cross-section, a hybrid fiber arrangement, or a desired microstructure are tailor designed to yield the required performance for the intended application. Innovative braid geometries were introduced to demonstrate the feasibility of fabricating a wide range of preform architectures given an advanced braiding machine. Additionally, interesting distributions of yarn groups have been shown which suggests an application to hybrid composites.

The development of prototype braiding equipment shows that a variety of structures may be automatically fabricated. In its present state, the braiding of three-dimensional articles, be it accomplished through use of a Cartesian (row and column) braider or a horn-gear type machine, has inherent handicaps. The dominant limiting factors in braiding include: the entire supply of braiding yarns (packages or yarn carriers) must be moved, the machine size is large relative to the braidable cross-sectional size of preform, only limited lengths of braid may be formed, the range of fiber architecture is constrained by the process, and different machines are usually required to vary the braiding pattern. The development of advanced braiding processes and equipment is forever attempting to break free of these shackles. As it stands, 3-D braiding is only applicable, from a cost perspective, to the fabrication of high performance, specialized structural composite parts. Inventive, novel methods of braiding need to be developed where more "braid for the buck" is realized. It is suggested that the area of open structures be investigated so that the limited amount of braid which is formed is applied in an efficient manner. Special hybridization, use of piezo-ceramic materials, and the imbedding of lineal sensors may also make the high cost of these high-end-performance braided composites more attractive.

Glossary

3-D braiding: A family of braiding methods where a two-dimensional array of yarn ends are displaced through a set pattern on a machine bed to form a three-dimensional intertwined structure of fibers.

3-D Cartesian braiding: A special case of 3-D braiding where complete sets of yarn ends (termed rows and columns) are displaced in mutually orthogonal directions. Traditionally, four steps are associated with a braid cycle or complete, repeating shifting sequence of the rows and columns.

Track and column braiding: A special case of 3-D Cartesian braiding where rows of yarn ends are spaced a prescribed distance by placement in equally spaced grooves machined in a bar (or track). The tracks are then moved to displace the sets of yarn ends in a given row. Primarily, this method eliminates tolerance build up in the row direction which is associated with multiple yarn ends forming a row.

Multi-step braiding: Extended method of Cartesian (row and column) braiding where multiple steps may be employed in a given braid cycle. This ability is found to greatly increase the types of braidable structures. Arrays of axial posts, used for in-situ insertion of longitudinal yarns, are commonly integrated in a multi-step braiding scheme.

Braid cycle: A complete shifting sequence of rows and columns (or tracks and columns) atop the machine bed in order to create the displacement of yarn ends needed to intertwine the braided structure. A fundamental and necessary condition for a braid cycle is that all rows and columns have returned to their starting positions upon completion.

Machine bed: The surface on which the shifting of the rows and columns (or displacement of yarn ends) takes place. Traditionally, the machine bed associated with a Cartesian braiding process is planar, however, cylindrical and semi-spherical configurations have also been investigated.

Base array: The number and arrangement of yarn ends employed on the machine bed. By convention, rectangular "base arrays" have been employed on Cartesian braiders.

Yarn group: A set of yarn ends that, during a Cartesian braid cycle, follow the same path on the machine bed. This characteristic of Cartesian braiding may be exploited where a limited path is allowed for a given yarn group in order to obtain select grouping of the yarn within the cross-section of the braided structure.

"Effective yarn diameter": For a given Packing Factor (defined as ratio of filament cross-sectional area to tow cross-sectional area when viewing a normal cross-section of a tow embedded in a fabric), a tow cross-sectional area, while deformable to various shapes such as an ellipse, may be assumed constant. "Effective yarn diameter" is defined as the diameter of said tow while taking a circular shape.

Pitch length: The length of three-dimensional braid that is formed during one complete braid cycle. The pitch length is a process control parameter and is traditionally used to dictate the desired braid architecture.

"Hybrid" braid: A three-dimensional braid where by yarn groups and their corresponding paths (see above) have been selectively designed to group within a spatial region of the braid structure. The "special" yarn groups may then be filled with differing fibrous material (or removable material, etc...) to form a "hybrid" braid.

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