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Process simulation and fabrication of advanced multi-step three-dimensional braided preforms

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The fundamentals of "multi-step" braiding for the fabrication of three-dimensional fibre preforms for composites have been studied. To facilitate the understanding of the complex multi-step braiding processes, a computer simulation algorithm has been developed. The simulation acts as a tool to allow the identification of individual yarn paths, number and location of yarn groups, and braid geometry. It was found that individual control of the rows and columns of yarn carriers on a Cartesian braiding bed allows for the fabrication of advanced "multi-step" braids; the micro-structural possibilities of three-dimensional braids are thus greatly extended. Some basic relationships of the braiding parameters have been identified. It has been concluded that the traditional four-step and two-step braidings are special cases of multi-step braidings. To verify the feasibility of the structures, experimental investigations have also been carried out. Innovative braid architectures have been designed and fabricated using a prototype multi-step braiding machine.

1. Introduction

The design and fabrication of preforms for advanced composites have gained considerable attention in the light of the recently developed three-dimensional 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. The fabrication process of these preforms directly determines the composite microstructure and the resulting mechanical and physical properties. Of special interest to date to the fibre composites community are the four-step, or Cartesian, and two-step braids which are three-dimensional in nature [1]. A brief summary of these braiding processes and preforms is supplied below.

1.1. Four-step braiding process

The four-step braiding process [2] 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 involve 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 termed because the relation between the shifting distance of rows and columns is one-to-one. Other braid patterns (i.e. 1×3, 1×5, etc.) are possible but they require different machine-bed configurations and a specialized machine. Track and column braiders of the type depicted in Fig. 1 may be used to fabricate preforms of rectangular cross-sections such as T-beam, I-beam, and box beam. Fig. 2 shows a four-step preform. Four-step braided composites offer excellent shear resistance and quasi-isotropic elastic behaviour due to their symmetric, intertwined structure. However, the lack of unidirectional reinforcement results in low stiffness and strength, and high Poisson effect in the braiding direction. To alleviate these deficiencies, some advanced techniques allow for axial yarns to be inserted into the structure during fabrication.

1.2. Two-step braiding process

The two-step braiding process [3] is so termed because it involves two distinct motions of each yarn carrier. The braid consists of an array of longitudinal (axial) yarns arranged in a prescribed configuration such as rectangular, circular, box, etc., and braider yarns positioned at select locations on the perimeter of the axial array. The shape of the axial yarn configuration determines the final shape of the preform. The braider yarns, which move along alternating diagonals of the axial array, interlink the axials and hold them in the desired shape. Fig. 3 shows a rectangular arrangement of axial yarns with the locations and paths of the braider yarns. Fig. 4 shows a preform produced by the two-step braiding. The two-step braided composite not only offers high stiffness and strength in the axial direction, but also yields

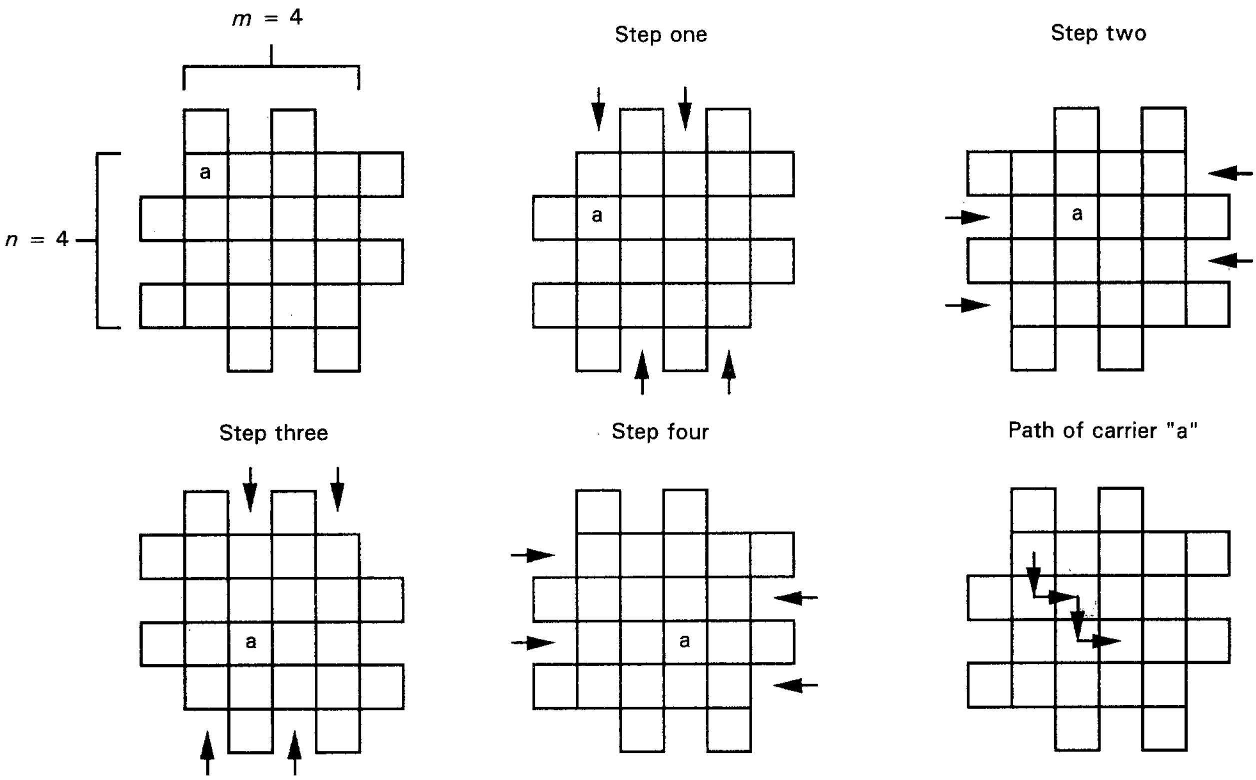

Figure 1 The four-step process. The square base array has four yarns on each side, therefore $m = 4$ and $n = 4$.

Figure 2 The four-step preform.

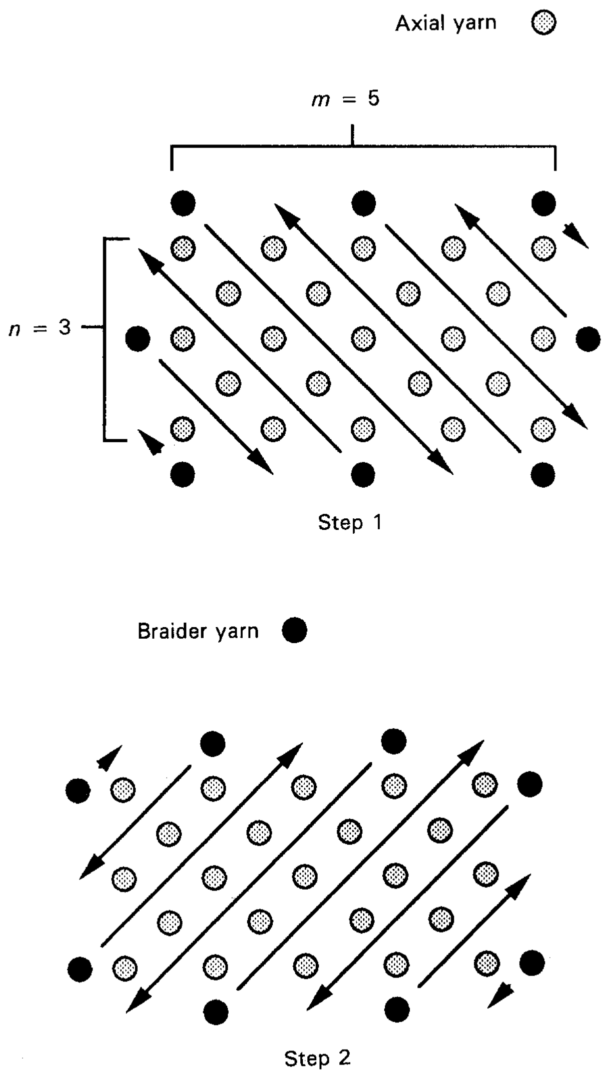

Figure 3 The two-step process. Counting only the number of outer axial yarns on a side gives $m = 5$ and $n = 3$.

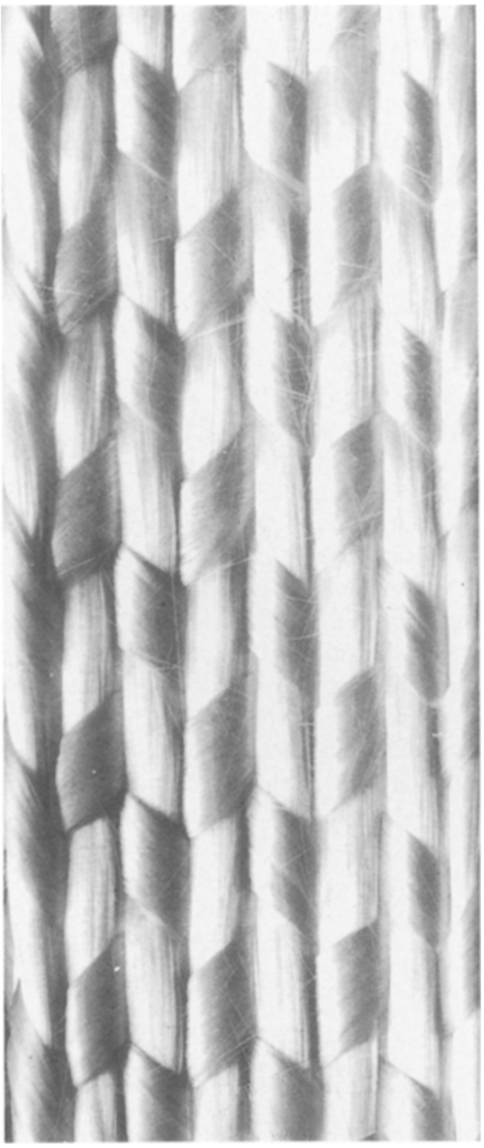

Figure 4 The two-step preform.

enhanced out-of-plane reinforcement in the transverse direction due to the presence of the braider yarns. Furthermore, the addition or removal of axial yarns during fabrication allows for on-line change of preform cross-section.

1.3. Research goals

In general, the advantages of three-dimensional braiding as a method of preforming for composites include the building-in of through-thickness reinforcements to prevent delamination, the ability to fabricate thick and complex shapes, and single-procedure net-shape preforming. Structural composites formed by this method which possess either a complex or thick cross-section may be designed to yield excellent tensile, flexural, and impact-resistant properties. It is therefore desirable to establish a fundamental understanding of the existing three-dimensional braiding processes and to extend this knowledge to form a general science base for three-dimensional braiding. To accomplish this task, a versatile Cartesian braiding simulation, and an equally versatile automated fabrication technique, are needed.

With this in mind, the objectives of this research have been to develop a computer simulation which will allow for the development of unique braid plans and identification of resulting preform architecture. Such a tool is essential for understanding fundamental relations in general Cartesian braiding. In addition, the design and construction of a machine capable of fabricating textile preforms with a general three-dimensional braid geometry is highly desirable. This would supply a means to verify, through direct fabrication, the feasibility of "multi-step" Cartesian braids.

2. Fundamental relations

As indicated in Section 1, the four-step braiding process involves four distinct Cartesian motions of groups of yarns termed rows and columns. The four-step process is further classified as 1×1, 1×3, 1×5, etc. depending on the relation between the shifting distance of rows and columns. The following discussion on four-step braiding is limited to the common 1×1 process as discussed by Li [4]. A given yarn array, again rectangular in shape, consists of inner and outer yarns. The inner yarn array of $m \times n$ (defined in Fig. 1) yarns determines the final shape of preform. The total number of yarns in an $m \times n$ slab is easily seen to be

$$\begin{aligned} N &= mn + m + n \\ &= (m + 1)(n + 1) - 1 \end{aligned} \tag{1}$$

In general, the number of yarn groups in an $m \times n$ slab is given by

$$G = mn/\mathrm{LCM}\,(m, n) \tag{2}$$

where G is the number of braider yarn groups and LCM (m, n) represents the least common multiple of m and n. All yarn groups have equal number of yarns, namely N/G. Further, the number of machine cycles (one machine cycle equals four steps) required for a yarn carrier in a four-step process to return to its original position (one repeat) will also be N/G.

In Section 1, the bed arrangement for the two-step process is defined by the number of outer axial yarns on each side of a rectangular array. Rectangular arrays need only be considered because this shape may be used multiple times to produce complex shapes.

In general, for an $m \times n$ axial array where m and n are the outside axial yarns in the width and thickness directions, respectively, the total number of axial yarns is given by [4]

$$N_a = 2mn - m - n + 1 \tag{3}$$

and the number of braider yarns is given by

$$N_b = m + n \tag{4}$$

Similar to the four-step process, the number of braider yarn groups or the number of sets of yarns which follow the same path may be calculated from

$$G = mn/\mathrm{LCM}\,(m, n) \tag{5}$$

Each yarn group contains the same number of braider yarns N_b/G. The similarity between the above expression and that obtained for the four-step process (Equation 2) should be noted.

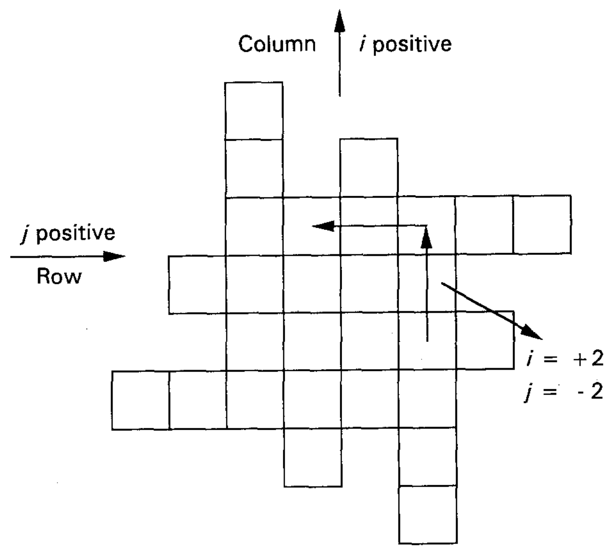

Figure 5 Sign conventions of i and j. Here, $C_1 = 2$, $C_2 = 2$, $R_1 = 2$, and $R_2 = 2$.

2.1. General relations

For a general Cartesian braiding process, one may ask the following questions. Why limit the shifting ratio of tracks to columns to 1×1, 1×3, etc., as described above? Indeed, why have only four steps in the braiding process? Is the two-step process a special case of the four-step process? All of these questions will be addressed in detail in Section 3. Before going on to this, it is necessary to extend the above equations to a "general" Cartesian braiding process.

2.1.1. Total yarns

Fig. 5 shows a general Cartesian braider-bed arrangement. For this case, there will be two columns which move two units of displacement and two rows which move two units of displacement. Also, there will be two columns which move one unit of displacement and two rows which move one unit of displacement. Using only absolute values of i and j, we let the number of columns which move i units and the number of rows which move j units be represented by

$$C_i = \text{total number of columns which move } i \text{ units} \quad (6)$$

$$R_j = \text{total number of rows which move } j \text{ units} \quad (7)$$

It may be readily seen that

$$C_{\text{tot}} = \sum_i C_i = \text{total number of columns} \quad (8)$$

$$R_{\text{tot}} = \sum_j R_j = \text{total number of rows} \quad (9)$$

$$iC_i = \text{number of column yarns outside the base array} \quad (10)$$

$$jR_j = \text{number of row yarns outside the base array} \quad (11)$$

With this, we see that the total number of yarns will be given by

$$N_{\text{tot}} = C_{\text{tot}} R_{\text{tot}} + \sum_i iC_i + \sum_j jR_j \quad (12)$$

As examples of the above classifications, we consider two cases. First, we take the special case of a four-step 1×1 process. For this case, $i = 1$ and $j = 1$ only. It can be seen that $C_1 = m$ and $R_1 = n$ and Equation 12 reduces to Equation 1. The next case is that of Fig. 5. Here we have $i = 1, 2$ and $j = 1, 2$. This gives us $C_1 = 2$, $C_2 = 2$, $R_1 = 2$, and $R_2 = 2$ as well as $1 \times C_1 = 2$, $2 \times C_2 = 4$, $1 \times R_1 = 2$, $2 \times R_2 = 4$. Using Equations 8–12 we find that $N_{\text{tot}} = 28$, which is in agreement with Fig. 5.

2.1.2. Yarn groups

For a general Cartesian braiding process, one would think that the number of yarn groups and number of yarns per group would be a function of i, j, C_i, and R_j. The notion of yarn groups, or groups of yarns which follow the same path, implies that after every machine cycle (for example, four-step, six-step, eight-step, etc.) any given yarn will occupy the previous position of another yarn within that group. Because only one yarn may occupy a given position at the end of a machine cycle, the number of machine cycles for a given yarn to return to its original position is equal to the number of yarns in that yarn group. However, this value is not readily obtainable analytically. This is mainly due to the virtually unlimited possibilities for machine-bed arrangement for any given set of C_i and R_j. It is for this reason we must turn to a process simulation to find the number of yarn groups and yarns per group for any given process.

3. Three-dimensional braiding process simulation

Computer simulation of track and column braiding has been of interest in recent years [5, 6]. It has been shown that by simulating the sequential Cartesian motion of braider yarn elements, the idealized spatial orientations of the yarns may be identified. This knowledge may then be coupled with a model of the packing of the yarns within the braid and become a useful tool in the design process. Past simulations have dealt with consistent track to column movement ratio such as 1×1, 3×1, etc. The goal of this work is to supply a more flexible simulation and to extract all information from the simulation results that may be useful in preform design.

3.1. Multi-step braiding simulation

The "multi-step braiding simulation" is an easy to operate, versatile tool designed to be used in conjunction with the multi-step braiding machine. This simulation package has been developed at the Center for Composite Materials of the University of Delaware [7]. The essence of this tool is explained below. A grid consisting of 14×10 squares representing possible carrier locations is graphically displayed. The user is free to choose any number of squares in defining a rectangular machine base array and is then prompted to define a single carrier (square) to be traced. Next, the desired machine cycle is entered. This may consist

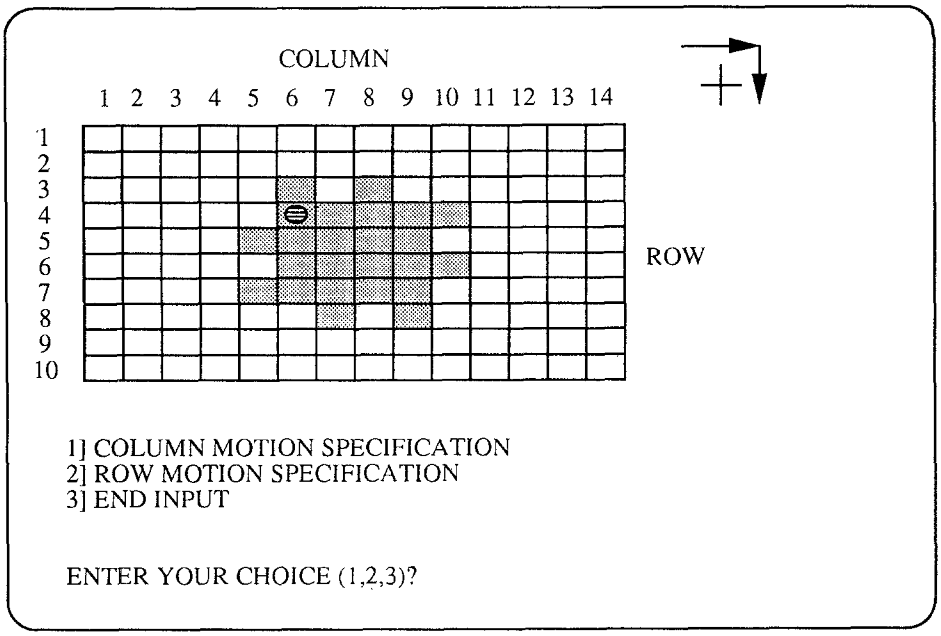

Figure 6 Sample screen for multi-step braiding simulation.

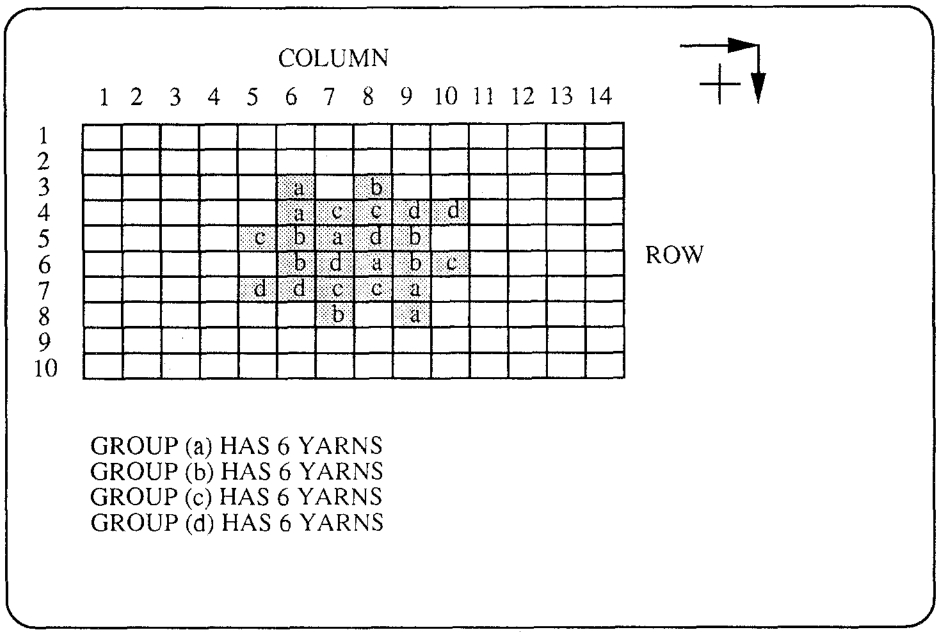

Figure 7 Sample simulation output showing yarn groups. Each yarn requires six machine cycles to return to its original position.

of any number of steps in a machine cycle (multiple steps) and any desired displacement of individual tracks/columns (i.e. values assigned to i, j, C_i, and R_j). Once finished, the program checks the entered machine cycle to see if all tracks/columns finish at their initial locations. Fig. 6 shows a typical screen which is prompting for the machine cycle. That is, the program asks for the column/row shifting sequence.

Once the machine cycle is programmed, the user has the following options: (1) an animated run through of consecutive machine cycles (step by step) may be carried out automatically or step-wise controlled by the user. This will continue until the defined tracer carrier returns to its original position after a set number of machine cycles; (2) the user may redefine the tracer carrier; (3) the user may view the path of the tracer carrier on the machine bed; (4) the planar projection of the tracer yarn's spatial orientation on to the sides of the simulated braid may be seen; (5) the program can determine the number of yarn groups, the number of yarns per group, and their location on the machine bed; (6) the unit cells, or the repeat geometry, of the simulated braid may be determined; and (7) a new bed arrangement may be set.

The options listed above which cover yarn groups and repeat geometry are of most importance when designing a braided structure and are therefore discussed in greater detail below. In addition, a few innovative braid cycles are introduced supplying testimony to the applicability of multi-step braiding.

3.1.1. *Identifying yarn groups and repeat geometry*

Yarn groups are sets of yarn tows which travel the same path. A multi-step braiding process may have multiple yarn groups and a varying number of yarns per group. The process simulation software records the location of a given yarn carrier at the end of each machine cycle until the carrier returns to its original position. The data are stored in a two-dimensional array whereby the same numerical value of an array element signifies a yarn in the same group. This process is continued until all the array elements are linked with numerical values. The simulation then displays the results by showing a single letter for the yarns in a given group. Fig. 7 shows an example output of a four-step 1×1 process with the bed pattern of Fig. 6.

The existence of yarn groups implies that sets of yarns trace the same path on the machine bed. After one complete machine cycle, each yarn in a group has moved to its leading yarn's location. This in turn implies that the braid geometry produced during one machine cycle (repeat) is the repeating geometry for the entire structure. That is to say, a cross-sectional slab of preform with the length produced during one repeat may be "stacked-up" on top of one another to reproduce the entire preform. It may now be seen that knowledge of this repeat braid geometry is essential for future prediction of braided composite properties.

The process simulation records the location of each yarn carrier at three discrete time increments; initial location, location at one half of the repeat, and location at one complete machine cycle. The data are contained in three separate two-dimensional arrays which are linked by the numerical values of the array's elements. A three-dimensional view of the repeat braid geometry may be graphically displayed where differently coloured line segments represent the individual yarns of the structure. These line segments are an idealization because actual yarn tows within the braid will deform and translate due to interaction between yarns. Fig. 8 shows an example of the repeat braid geometry produced by the above-mentioned bed arrangement and process (here shown in black and white). Additionally, this information may be incorporated into a finite element code for prediction of composite properties.

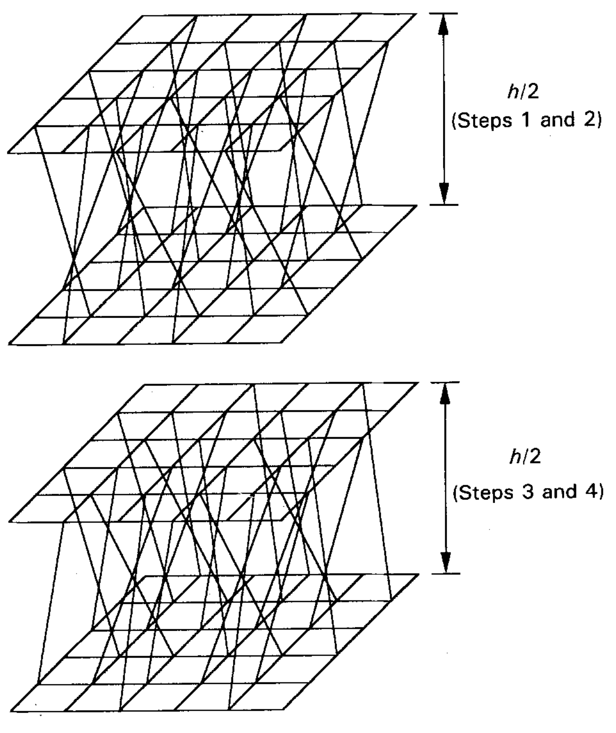

Figure 8 Sample simulation output for repeat braid geometry for four-step 1×1 braid cycle.

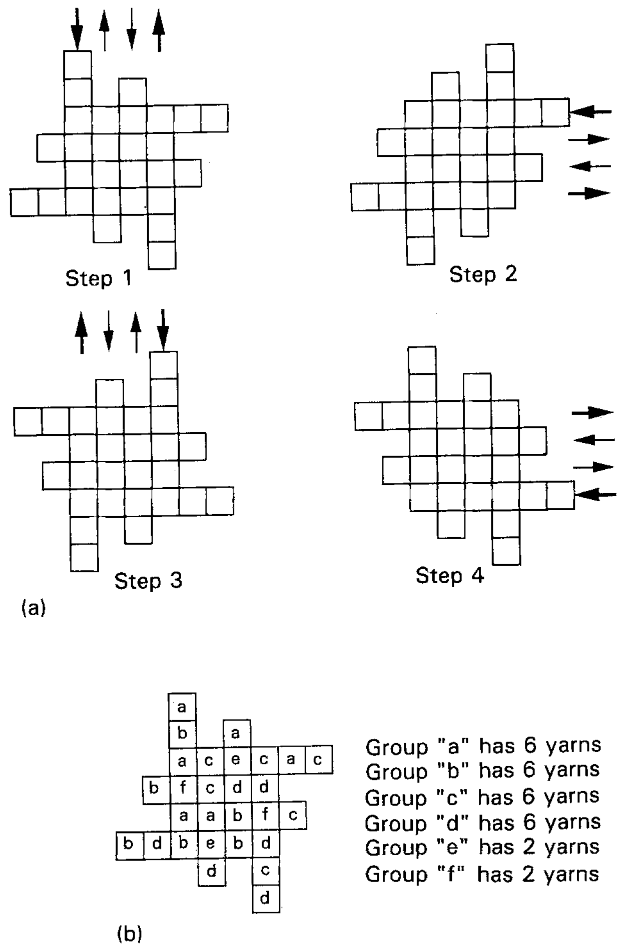

Figure 9 Four-step $2/1 \times 2/1$ braid cycle and yarn groups. (a) A four-step $2/1 \times 2/1$ braid cycle. Heavy arrows indicate two units of displacement. (b) Location of yarn groups.

3.1.2. *Simulated, innovative braid cycles*

Along with the possibility of having independent control of track/column motion and displacement comes the possibility of designing new braid cycles and, as a result, innovative braid structures. It may readily be seen that quite a large number of potential braid cycles exist. With this in mind, we introduce a few such braid cycles.

To exemplify the applicability of individual track/column displacement, consider the braid cycle shown in Fig. 9, which is identical to that of Fig. 5. Here, a base array of 4×4 yarns is used. This process is labelled four-step $2/1 \times 2/1$ because there are both 2 and 1 units of displacement for the rows and columns. The cycle yields a total of six yarn groups as is also

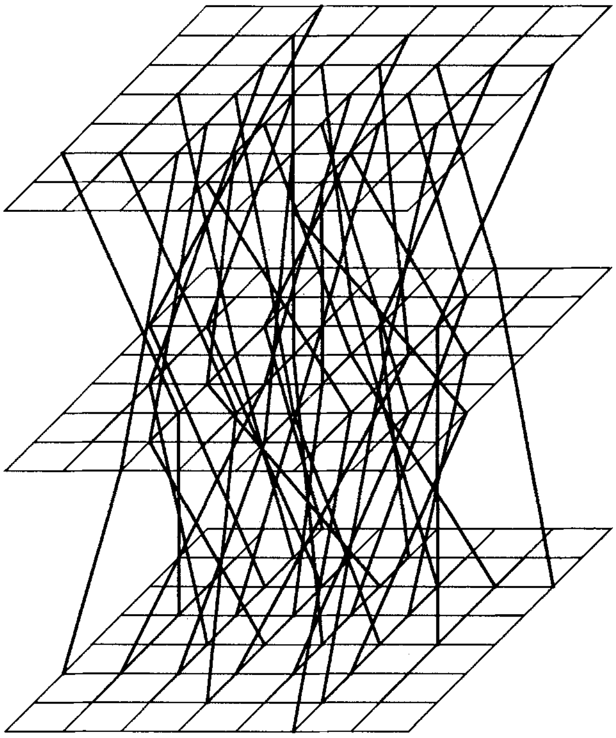

Figure 10 Sample simulation output of repeat braid geometry for four-step $2/1 \times 2/1$ braid cycle.

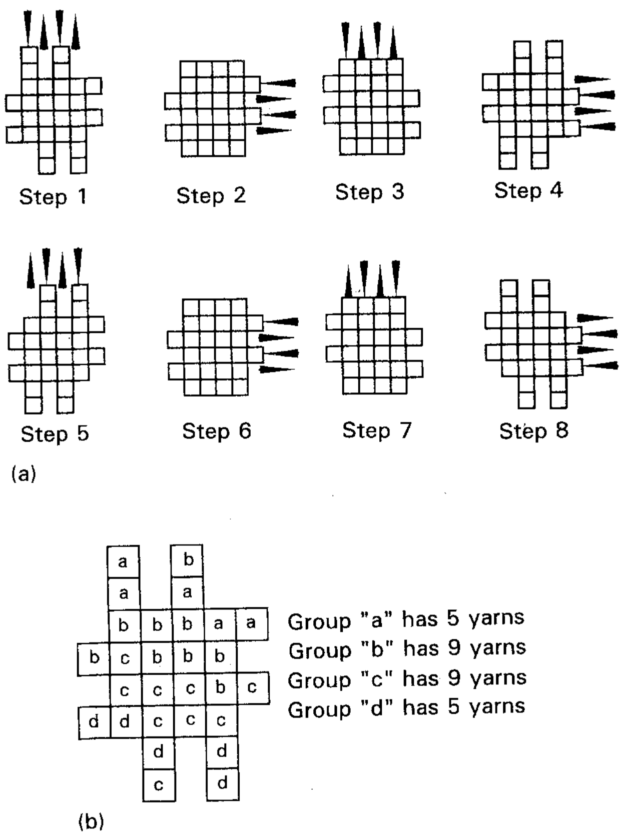

Figure 11 Eight-step 1×1 braid cycle and yarn groups. (a) Eight-step 1×1 braid cycle. (b) Location of yarn groups.

shown in the figure. The groups "e" and "f" tend to remain in the centre of the braid thereby serving to interlace the core of the structure with the other yarns. This allows for a distinction between yarns in different yarn groups leaving more room for design of the braid structure. Fig. 10 shows the repeat braid geometry of

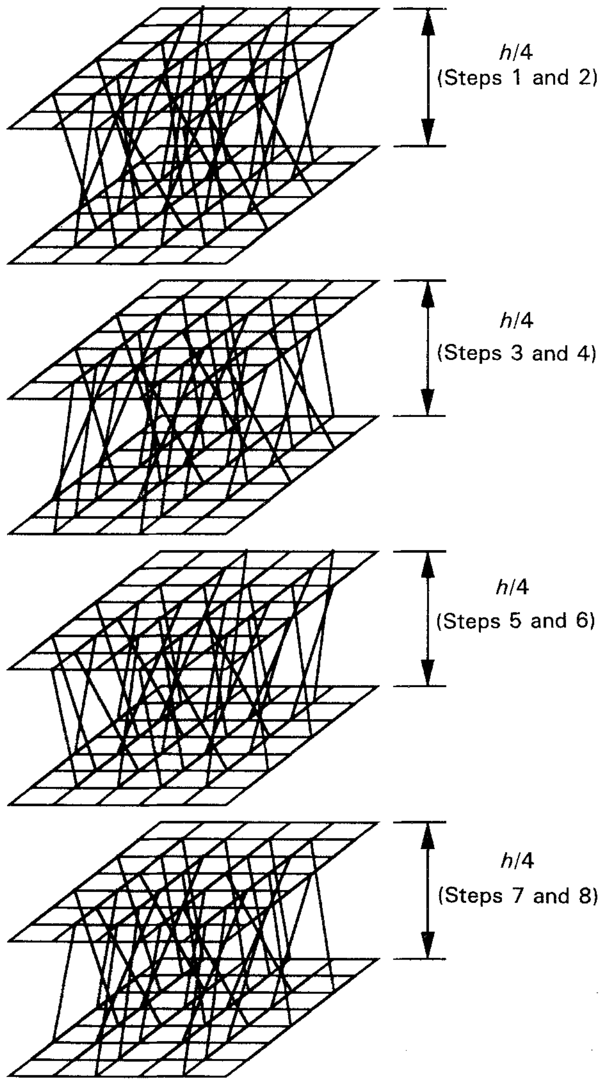

Figure 12 Sample simulation output of repeat braid geometry for eight-step 1×1 braid cycle.

the resulting architecture (here shown in black and white).

The process simulation is termed "multi-step" because any number of steps may be specified in a given machine cycle. As an example, consider the machine cycle depicted in Fig. 11. The cycle consists of eight steps with a one unit displacement for each. Again, a 4×4 base array was used. 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. This suggests an application to hybrid composites where high-performance fibres may be placed where needed while still benefiting from the structural and delamination resistant properties of the three-dimensional braid. Fig. 12 shows the repeat geometry of the structure.

3.1.3. Comparison of two-step and four-step braiding

We now address the question: "Is the two-step process a special case of the four-step process?" A four-step 1×1 pattern was run on the simulation and the paths of selected tracer yarns examined. It was found that a certain sub-set of the outer yarns for a given array

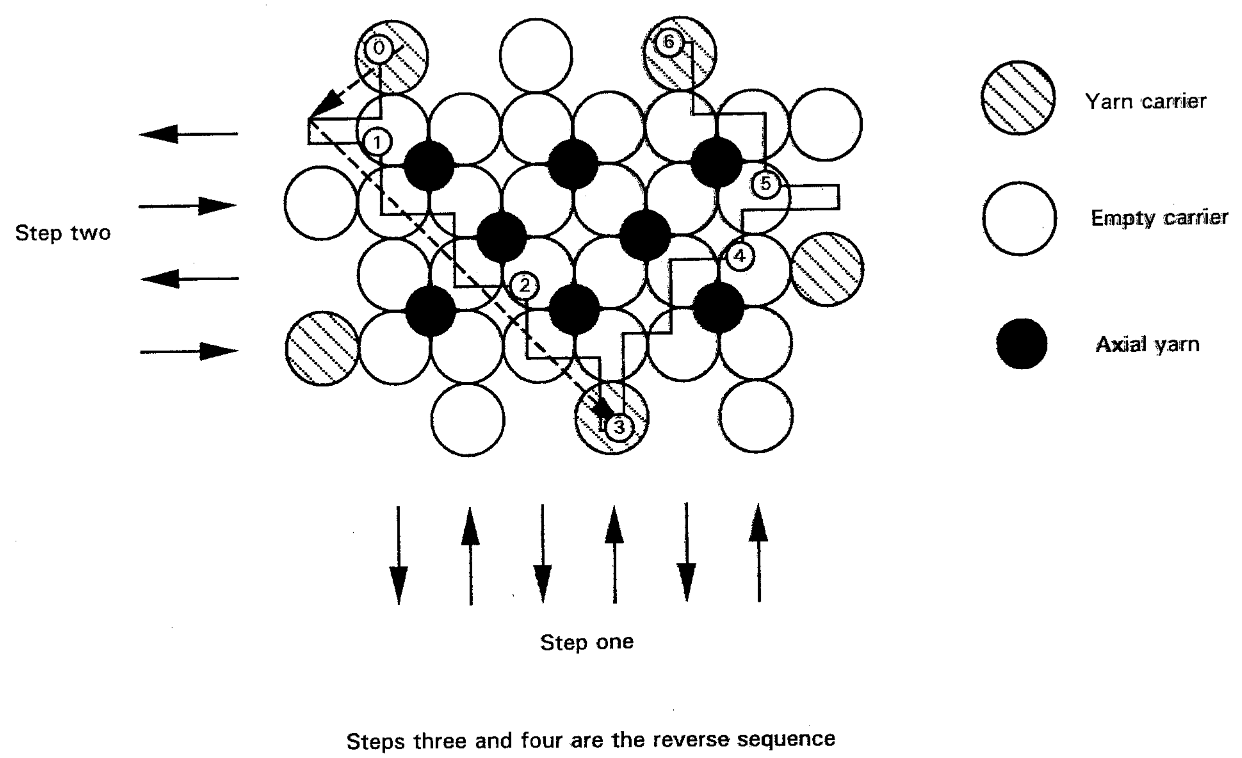

Figure 13 Schematic drawing showing selection and path of yarn carrier of four-step yarn array for two-step process. The yarn which occupies the initial position of "0" starts on a side having three axial yarns and takes $2 + 1 = 3$ machine cycles to complete its "two-steps".

sequentially traced the paths of a group of braider yarns in a two-step process. This suggests (and was later verified) that two-step braiding is, in fact, four-step braiding with axial yarn insertion and the employment of only selected outer yarn carriers. Fig. 13 shows a four-step 1×1 bed pattern which utilizes only selected outer yarn carriers. The black dots represent the axial array, here, a 3×2 array is shown. The path of one such braider yarn is seen to trace the familiar two-step pattern. In general, for a two-step axial array of $m \times n$, a four-step yarn array of $2m \times 2n$ is needed. This ensures an even number of tracks and columns which is required due to the symmetry of the process and resulting structure. After further investigation, it was also found that a braider yarn which starts on a side having m axial yarns will require $n + 1$ machine cycles to complete its two steps where m and n are interchangeable. This is exemplified in Fig. 13. At first, this may not seem plausible because an unequal number of machine cycles is needed for all braider yarns to complete two steps. Remember, however, that we are now dealing with a four-step "process" which, similar to the two-step "process", contains groups of yarns which follow the same path. This ensures that after a predetermined number of machine cycles, all braider yarns will come to occupy their initial locations.

3.1.4. Multi-step braiding

Ideally, any number of braider yarns may be chosen for the above example. This leads to the unification of three-dimensional braiding. No longer may we speak of two-step or four-step braiding as unique processes. They now become special cases of general "multi-step" braiding where axial yarns may be inserted at will and repeat geometry, along with yarn groups, tailor designed.

In design applications, one may ask, "How do I determine C_i, R_j and the number of steps to use in a given braiding process?" For the time being, there is not a definitive answer to this question. Final repeat geometry and yarn groups are complexly related to C_i, R_j, pitch length, and number of steps and may only hope to be quantified through practice. However, the following guide lines may be applied. (1) C_i, R_j and pitch length directly determine the yarn orientation distribution every two steps of the complete machine cycle. In other words, for a multi-step process, the total geometry may be "built up" from sub-geometries resulting from every two-steps. (2) The number of steps in a machine cycle is directly related to the number and location of yarn groups (i.e. the more steps there are, the more control there is over an individual yarn's path).

4. Multi-step braiding machine

An automation scheme for the manufacture of these advanced, multi-step braids has been developed. The machine is capable of fabricating braids with a wide variety of architectures, including axial reinforcement yarns, at a modest speed. Up to 240 yarn carriers and 207 axial yarns may be employed. The machine has been used to fabricate two-step, four-step, and innovative braids. Fig. 14 shows a photograph of the multi-step braiding machine. These innovative, multi-step braids give birth to exciting possibilities in preform design.

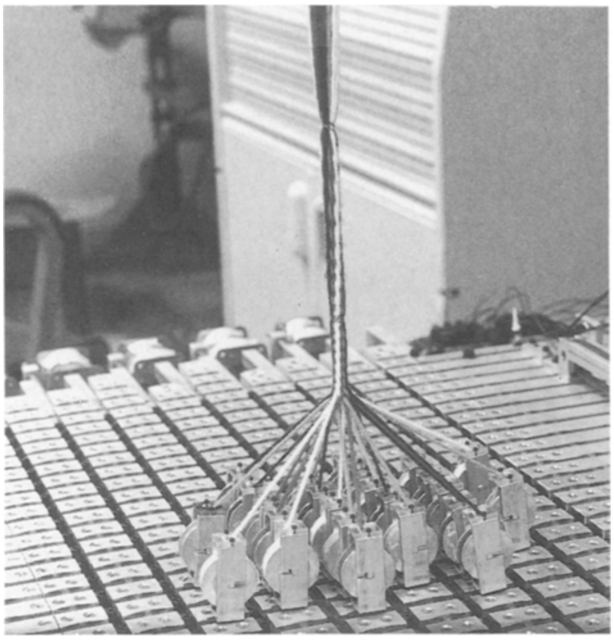

Figure 14 Prototype multi-step braiding machine.

5. Results and conclusion

The development of a computer simulation of a general Cartesian braiding process has led to an understanding of process fundamentals. The simulation allows for the identification of individual yarn paths, number and location of yarn groups, and braid geometry. Innovative braid geometries were simulated and the preforms fabricated 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 found which suggest an application to hybrid composites. These new and advanced braids, termed "multi-step" braids, are only possible with individual row/column control. The multi-step braiding process greatly extends the range of possible preform micro-structures.

The future of three-dimensional, advanced braids looks very exciting. It is within this realm of preforming technology that size, micro-structure, and even fibre placement via yarn group locations may be tailor designed. The knowledge of process–structure–property relations remains to be realized in order to appreciate fully the advantages of such a preforming technique.

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References

1. T. W. CHOU, "Microstructural Design of Fiber Composites" (Cambridge University Press, Cambridge, 1992).
2. R. FLORENTINE, US Pat. 4312'261, 26 January 1982.
3. R. McCONNELL, and P. POPPER, US Pat. 4719'837, 19 January 1988.
4. WEI LI, PhD dissertation, North Carolina State University, March 1990.
5. R. T. BROWN and E. D. RATLIFF, US Pat. 4621'560, 11 November 1986.
6. C. M. PASTORE and F. K. KO, *SAMPE Q.* **19** (4) (1988) 22.
7. T. D. KOSTAR, MS thesis, University of Delaware (1992).

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