# 7
# Braided structures

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## 7.1 Introduction

The design and fabrication of preforms for advanced composites has gained considerable attention in light of the recently developed 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 history of these preforms directly determines composite microstructure 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 [1].

### 7.1.1 2-D fabrics

2-D fabrics woven on a loom generally contain two sets of yarns. These yarn groups are interlaced at right angles, with the longitudinal yarns being referred to as warp yarns and the cross yarns as weft. A basic loom consists of two harnesses that control warp yarn separation, a shuttle that passes the weft yarn through the separated warp yarns, and a beat-up mechanism that compacts the fabric. By controlling the separation sequence of the warp yarns, different fabrics may be formed. Two-dimensional woven fabrics offer a high degree of yarn packing, enhanced impact resistance and cost-effective fabrication. However, some in-plane elastic properties, notably resistance to shear, and strength are sacrificed.

Knitted (2-D) fabrics contain chains of interlaced loops. Depending on the orientation of the looping yarn, knits may be classified as either warp or weft. In warp knitting, the looping yarns run in the warp or longitudinal direction and in weft knitting the yarns travel in the weft or horizontal direction. Both fabrics are formed using similar fabrication schemes. The most common mechanism used is the latch needle. Many such needles are employed simultaneously in fabricating the knit. As the process is repeated, the series of interlaced loops that are formed constitute the fabric. Knitted fabrics provide a high degree of formability and enhanced in-plane shear resistance. As a result, their application to high strain composites, such as inflatable skins, is readily apparent. Finally, increased directional stability can be obtained by adding laid-in yarns in the desired directions.

Perhaps the most simple way of adding through-the-thickness reinforcement is the stitching process. An industrial size sewing machine is usually employed whereby a needle is used to penetrate the layers of fabric and pull the stitching yarn through the preform. Though cost-effective, considerable fiber damage occurs through needle penetration. The resulting reduction in composite strength can be appreciable, making stitching an unattractive option. In recent years, novel stitching techniques have been developed where the fibers are effectively spaced to reduce breakage greatly during needle penetration.



### 7.1.2 3-D fabrics

3-D knitted fabrics are akin to their 2-D brothers. They may be produced by either weft knitting or warp knitting process. Additional strengthening is accomplished by the use of laid-in yarns in the mutually orthogonal direction. The knitted preform which deserves the most attention is the multiaxial warp knit. The knit consists of longitudinal, latitudinal and bias ($\pm\theta$) yarns held together by a through-the-thickness tricot stitch. These 3-D knits possess the characteristics of unidirectional laminates while enjoying enhanced stiffness and strength in the thickness direction.

3-D weaving is achieved through a modification of the traditional 2-D weaving process. The two main types of 3-D woven fabrics are angle-interlock and orthogonal structure. Angle-interlock weaving is carried out by utilizing multiple harnesses on a conventional loom. The shifting sequence of the harnesses determines the undulation of the warp yarns. Many geometric variations are possible owing to the unlimited combinations of loom configuration and harness sequencing. These multilayer interlocked structures are ideal for thick-section composites. The reinforcement in the thickness direction may be tailor designed to enhance composite impact resistance. However, the low shear performance and limit to shape geometry make woven fabrics an undesirable option in many applications.

Orthogonal woven fabrics possess three sets of mutually perpendicular yarns. Inherent in such a structure are matrix-rich regions between the intersections of the three sets of yarns. Fabrication of these preforms is accomplished by inserting alternating, in-plane yarns between the stationary thickness direction yarns. In this fashion, both Cartesian and cylindrical geometries are possible [2].

In summary, the limitations of the weaving, knitting and stitching processes include poor shear resistance, limited strength in the primary loading direction, and the inability to produce complexly shaped parts. These shortcomings, as will be seen, are largely overcome with the adaptation of braiding.

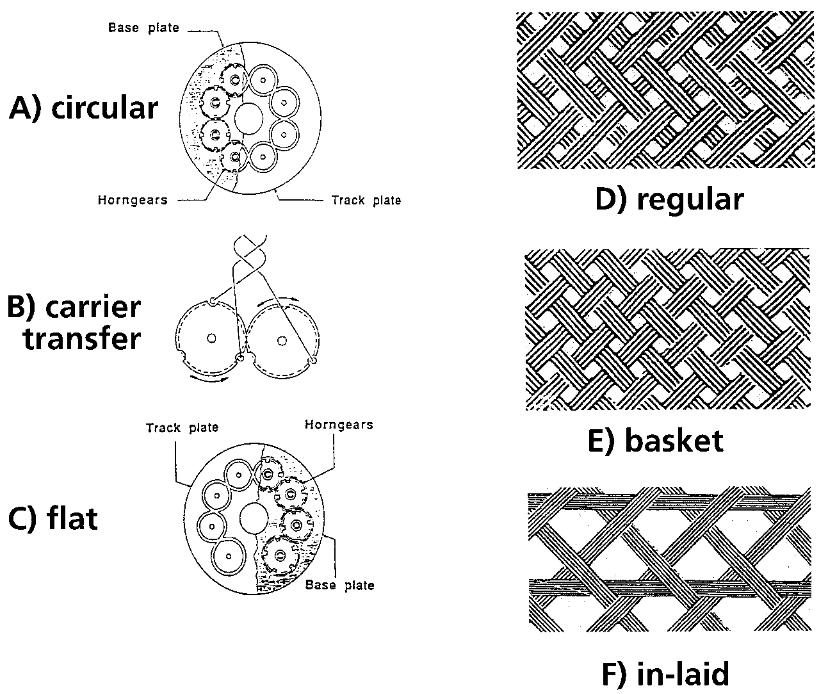
## 7.2 2-D braiding

Braided fabrics (2-D) may be either circular or flat, where the flat braid is a special case of the more common circular braid. The similarity between the machines used to form these fabrics suggests a starting point to further explain their structure.

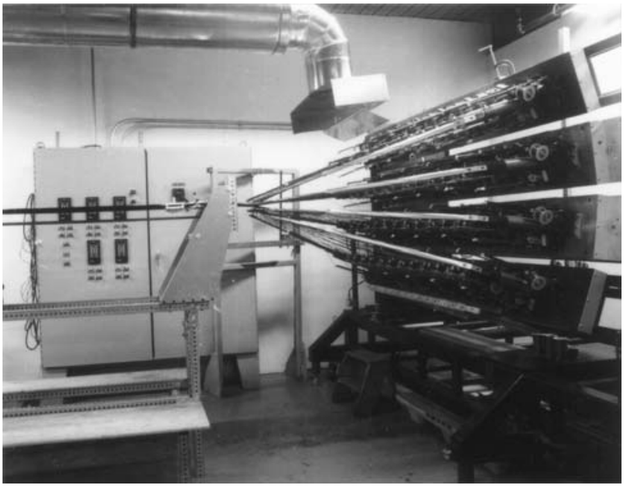
Traditional circular braiders utilize a horngear arrangement as shown in Fig. 7.1(a). The gear train is covered by a track plate which has intertwining tracks used to guide the yarn carriers.

The horngears 'pass' the yarn carriers to and from each other in an alternating fashion as shown in Fig. 7.1(b). For the case of flat braiders, the tracking system does not form a complete circle (Fig. 7.1c). In this configuration, the end horngears have an uneven number of slots which allow the yarn






*7.1* Mechanisms and samples of 2-D braids after [1].



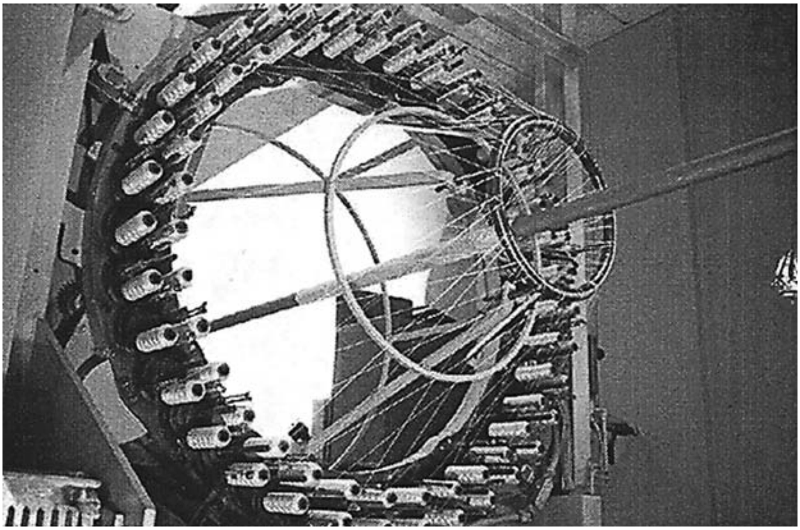
*7.2* A bank of flat braiders (compliments of Foster-Miller, Inc.).



carriers to reverse their paths and form a flat braid. Recently, flat braiding machines have been developed where a series of straight braider 'banks' are used to form thin-walled, structural shapes [3] (Fig. 7.2). Circular braids are usually formed over an axisymmetric mandrel which determines the final shape of preform. In addition, axial laid-in yarns may be used to increase longitudinal stiffness. Figure 7.1 also shows some common 2-D braids. By specifying the location of yarn carriers on the machine, different braiding patterns may be accomplished. The pattern of Fig. 7.1(d) may be loosely compared to a twill weave and that of Fig. 7.1(e) to a plain weave. Figure 7.1(f) shows a regular braid with axial in-laid yarns. Owing to the symmetric machine arrangement, braider yarns are oriented at equal and opposite angles about the longitudinal axis. This angle may be directly determined by machine operating conditions. A Wardwell 72 carrier circular braider is shown in Fig. 7.3. Finally, while 2-D braids offer cost-effective fabrication, the limitation in available braid geometry and their 2-D nature has restricted their use.

## 7.3 3-D braiding

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



*7.3* Wardwell 72 carrier circular braider (compliments of the Center for Composite Materials, University of Delaware).

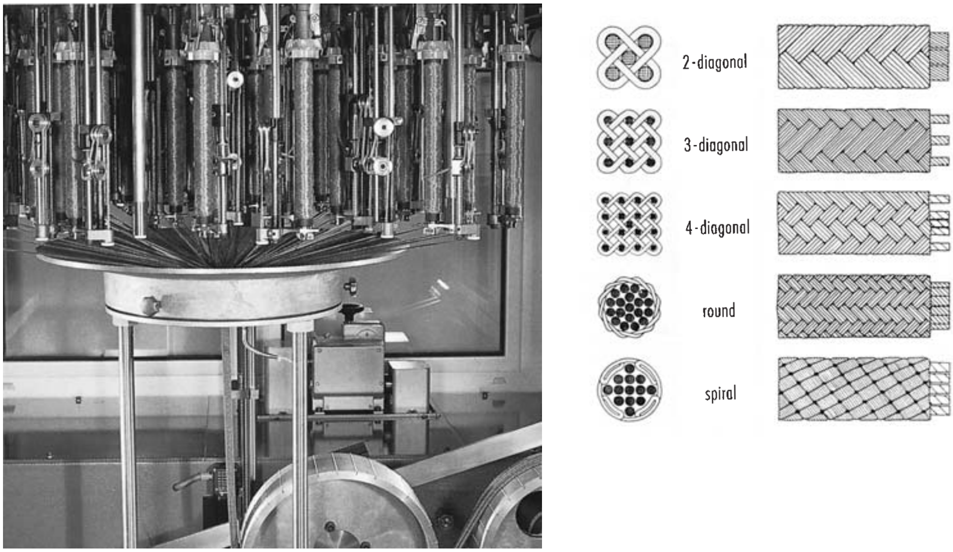


Horngear machines with square or circular arrangement are employed in the fabrication of solid braids (Fig. 7.4a). Present-day machines are limited to 24 yarn carriers and therefore limit the size and shape of preform. The micro-geometry of braid is also restricted and is shown in Fig. 7.4(b). As can be seen, the braider yarns form intertwined helical paths throughout the structure.

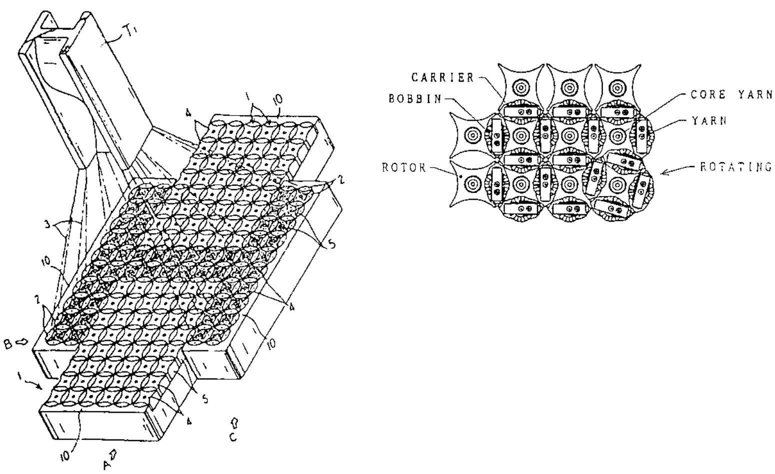
To allow for more flexibility in preform size, shape and microstructure, new braiding processes have been introduced. These include AYPEX [4], interlock twiner [5,6], 2-step [7], 3-D solid (Fig. 7.5) and Cartesian [8] which is more commonly referred to as four-step or track and column in the literature. An excellent recent review of textile preforming methods is supplied by Chou and Popper [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. track and column), we need only understand a single process and the structures that may be formed.

## 7.3.1 Cartesian braiding process

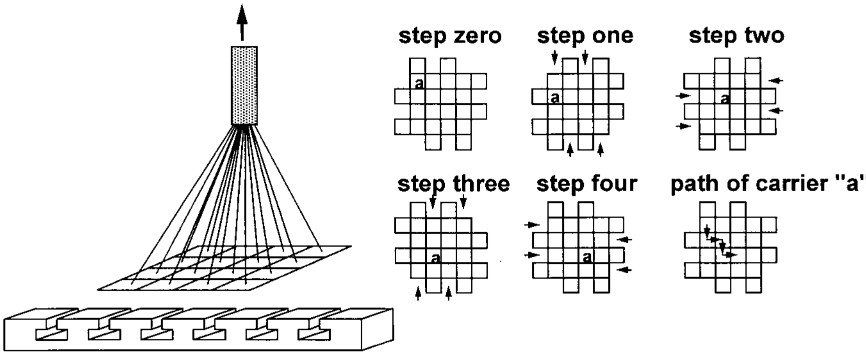
The basic Cartesian braiding process involves four distinct Cartesian motions of groups of yarns termed rows and columns. For a given step, alternate rows (or columns) are shifted a prescribed distance relative to each




*7.4* Solid braid fabrication and geometry.




*7.5* Method of advanced 3-D solid braiding (compliments of Toyoda Automatic Loom Works, Ltd).



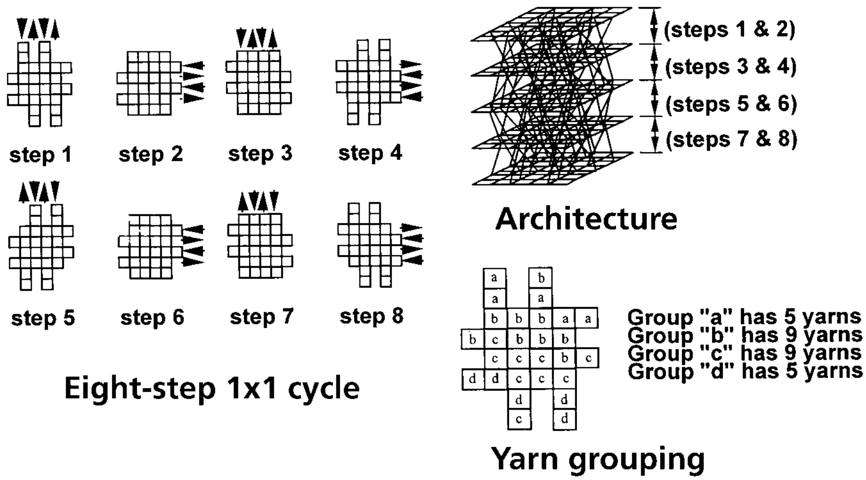

*7.6* The Cartesian braiding process.

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. 7.6). 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. Track and column braiders of the type depicted in Fig. 7.6 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 for axial yarns to be fed into the structure during fabrication.

### 7.3.2 Braid architecture, yarn grouping and shapes

If one allows for multiple steps in a machine cycle, independent displacement of tracks and columns, and non-braider yarn insertion, the Cartesian braiding process is capable of producing a variety of yarn architectures, hybrids and structures. Consider the eight-step braid cycle shown in Fig. 7.7, which also shows the phenomenon of yarn grouping.

Yarn groups are sets of yarn tows that travel the same path. A multistep braiding process may have multiple yarn groups and a varying number of



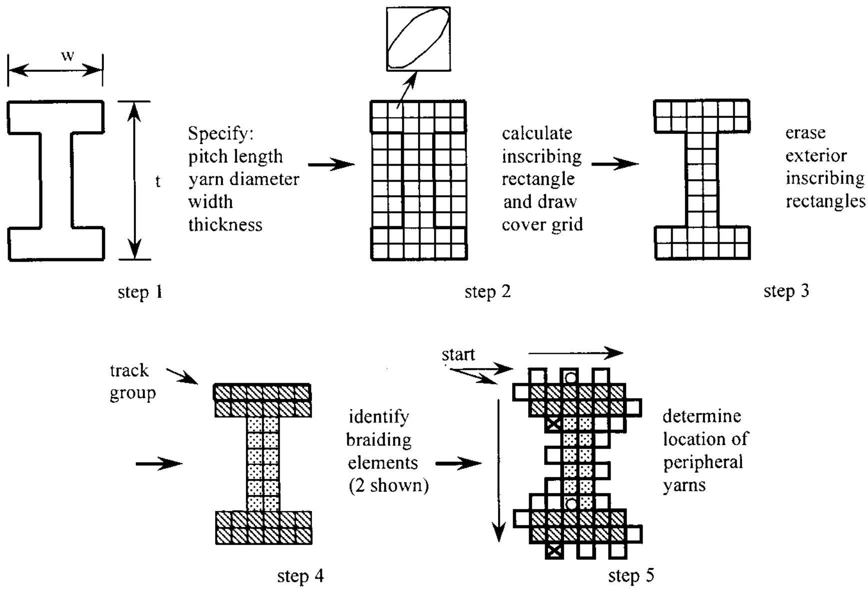

*7.7* Sample multiple step cycle showing idealized architecture (repeat geometry) and yarn grouping.



yarns per group. It is possible to tailor the location of the yarn groups within the preform cross-section. That is to say, the braid cycle (i.e. shifting sequence of tracks and columns) that will yield the desired grouping of yarns may be determined and different fibrous material utilized for the tows that make up a given group. In this way, unique hybrid composite materials may be formed which benefit both from the 3-D integrated nature of the braid and from the hybrid effect and select yarn placement.

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 (Fig. 7.7). It is possible, within Cartesian braiding process limits, to specify this braid architecture and determine the braid cycle which will yield it. It may be seen that knowledge of this repeat braid geometry is essential for future prediction of braided composite properties.

One way of producing a braided preform with a complex cross-sectional shape is through implementation of the universal method (UM) of braiding [10]. 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




*7.8* Five steps involved in implementing the universal method of braiding a complex shape.



to determine an appropriate braid plan. 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. The UM utilizes only one braiding pattern for a preform. It is essentially a series of four-step $1 \times 1$ braid cycles which isolate the 'rectangles' of the complex cross-section and braid them in sequence. This method is demonstrated in Fig. 7.8 using an I-beam as an example. Since any shape may be estimated through a suitable number of rectangular elements, the UM is applicable to curved shapes as well. Additionally, the approach may be readily implemented through appropriate computer code and is piece-wise applicable to variations of the cross-section along the length of the braid.

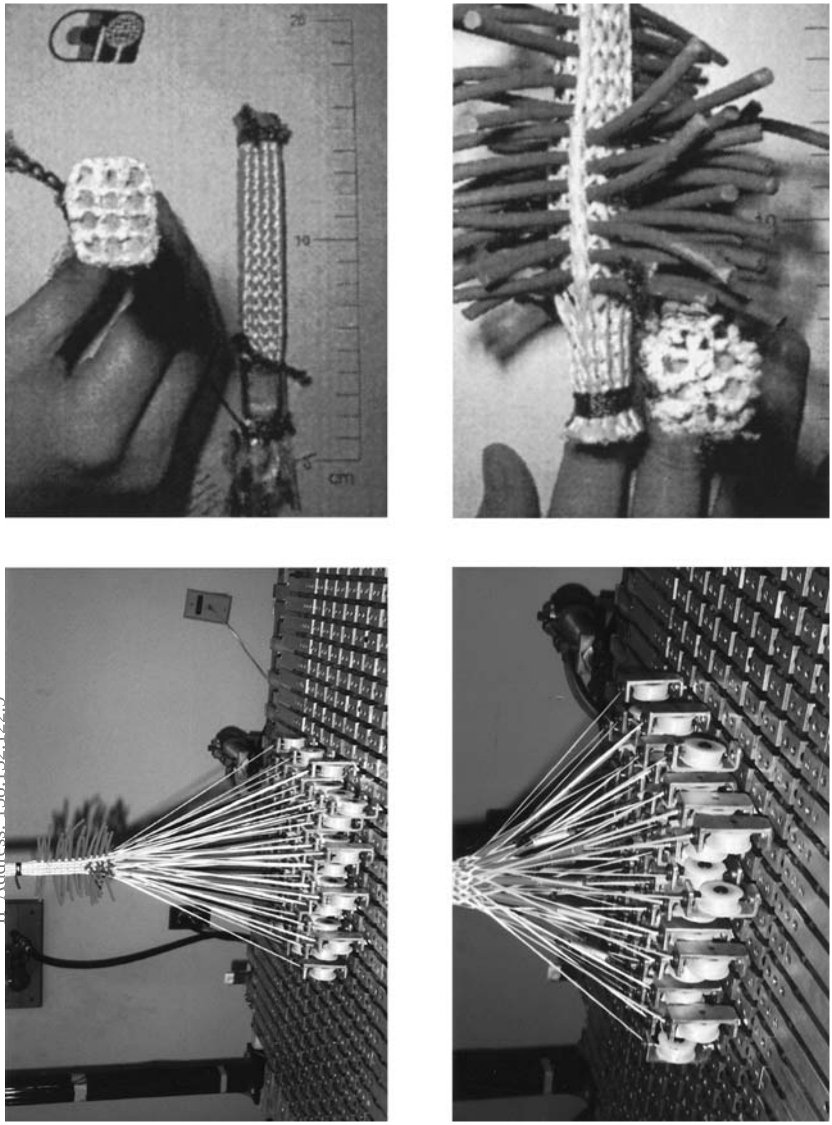
### 7.3.3 Fabrication of braided structures

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.

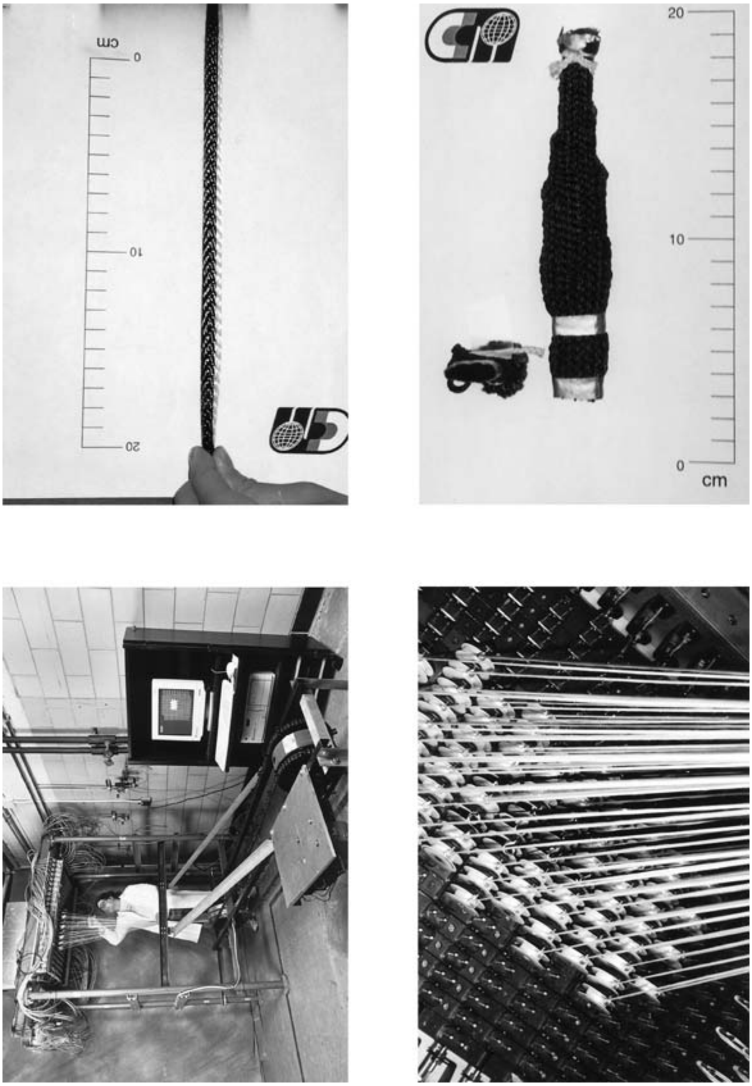
Inherent in the process of 3-D braiding is a limiting ratio of machine bed size to preform cross-sectional dimensions. The larger the spacing between yarn carriers on the machine bed (the spacing directly determines the amount of yarn a carrier can hold), the more difficult it becomes for the braid to be formed owing 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 [11]. 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 tracks and columns and the resulting yarn carrier spacing on a Cartesian braider's bed are important specifications. Figure 7.9 shows a 10 track by 24 column Cartesian braider that integrates stationary spacer tracks for the sole purpose of inserting axial (longitudinal) yarns. The transverse insertion (as seen in Fig. 7.9) is carried out manually. However, some advanced machines allow for this step of the process to be automated.

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. Figure 7.10 shows a 20 track by 20 column Cartesian braider that is capable of displacing each track and column independently. To accomplish this, small pneumatic cylinders are utilized in series for each track and column. As previously mentioned, this results in the ability to fabricate complexly shaped or hybrid (yarn grouping) preforms for specialized applications. Figure 7.10 shows some samples of the types of braids that may be formed on a machine with this capability.

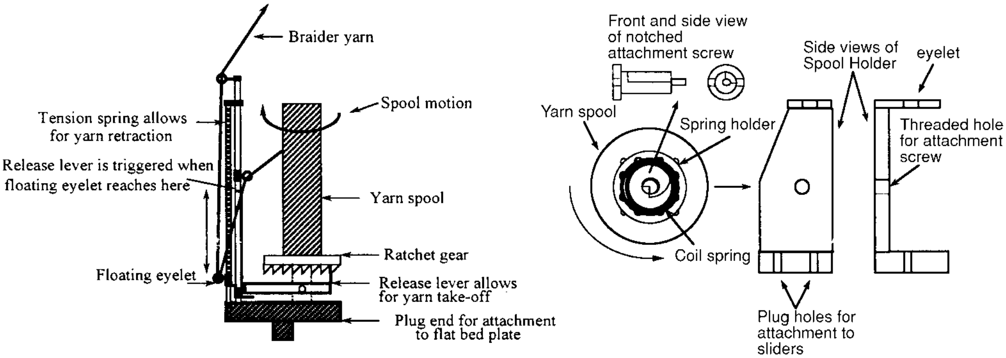
Take-up and compaction of the braid is a critical part of the process. For a continuous fabrication process, the braid must be drawn or taken up. Take-up is carried out after a complete machine cycle and before compaction. As a result, the take-up distance directly determines the braid pitch length (i.e. the 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 interyarn 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, interyarn 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 interyarn 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



7.9 A Cartesian (four-step) pneumatic braider with axial yarn insertion (compliments of the Center for Composite Materials, University of Delaware).




*7.10* A Cartesian (multistep) pneumatic braider with independent track and column control (compliments of the Center for Composite Materials, University of Delaware and Atlantic Research Corporation).




*7.11* Schematics of conventional and adapted yarn carriers utilized in braiding 2-D and 3-D preforms, respectively (adapted yarn carrier schematics compliments of Atlantic Research Corporation).

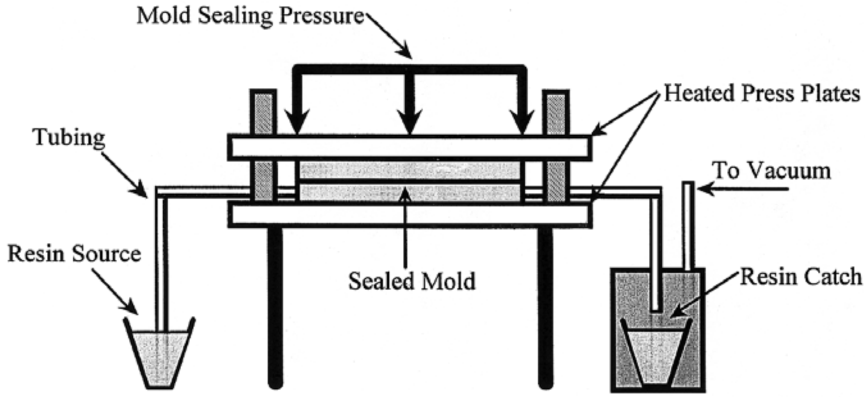


mentioned earlier, however, larger bed arrangements cause the braid to be 'pulled apart' and even a compaction step may not be enough to form the braid.

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. Figure 7.11 shows schematically the workings of both conventional and adapted yarn carriers used in braiding processes. For the adapted yarn carrier [11], rewind, tensioning and yarn feed are all accomplished through the yarn spool.

## 7.3.4 Braid consolidation

The standard approach to preform consolidation, utilizing a thermosetting resin, is resin transfer molding (RTM). RTM is a straightforward method of injecting a resin system into a preshaped mold cavity that contains the 3-D braided preform. Although ideal for low to mid volume production runs, issues such as preform wet-out and residual stress warpage frequently arise. To address these issues, such adaptations as the utilization of pre-impregnated yarn tows and room temperature cure resins are suggested. However, there is still much research to be done in this area. Additionally, the consolidation of complexly shaped parts presents a special challenge owing to the change in preform dimensions when it is removed from the braiding machine. Figure 7.12 shows a schematic of a typical RTM set-up used in the consolidation of 3-D braids.




*7.12* Schematic of typical RTM set-up for braid consolidation.



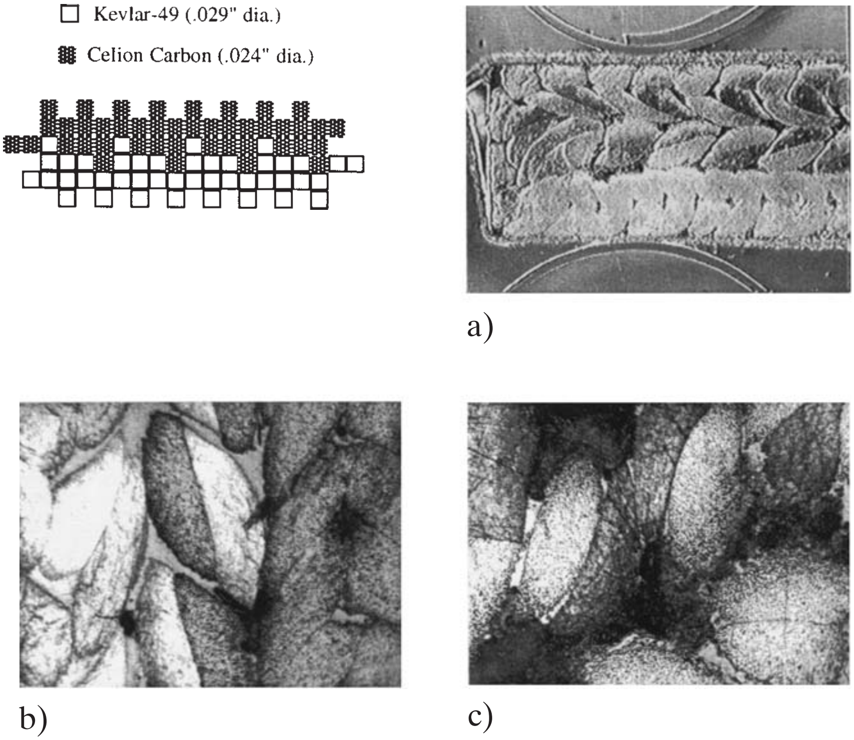
### 7.3.5 Braided composite characterization

The characterization of braided composite microstructure may be investigated at two scales. The first is the yarn tow size and the second is the fiber (or filament) level. Braid packing during preforming and consolidation may be determined by a number of factors such as yarn tension, yarn twist, braid compaction and molding pressure, injection pressure and resin viscosity. The final arrangement of yarns and fibers directly determines the final composite elastic and strength properties and must first be quantified in order to be related to the processing history.

The packing of yarns within a four-step $1 \times 1$ (mono-fiber) braided composite is fairly well documented [12–15]. However, when one deals with a hybrid or complexly shaped braided composite (which is possible with multiple step track and column braid cycles), the variation in braid microstructure may be significant. As an example, consider a microstructural cross-section of a two-sided hybrid composite which has been consolidated through RTM (Fig. 7.13). The unique yarn paths that result from the yarn group producing braid cycle cause an unorthodox yarn packing. The goal is to quantify this effect so that a basic understanding of yarn-to-yarn interaction and yarn cross-sectional deformation may be gained.

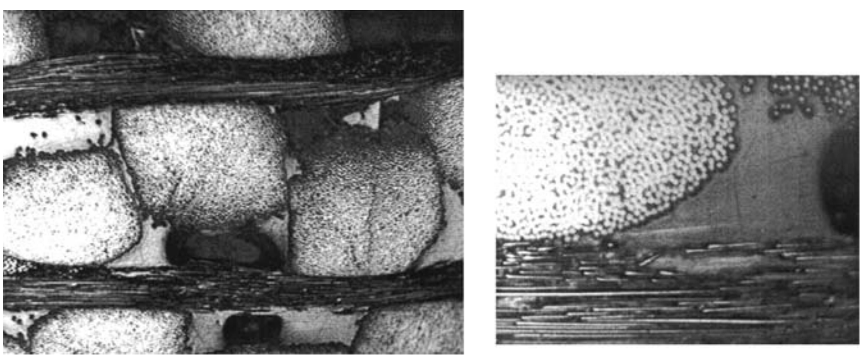
In Figure 7.14, the microstructure of a four-step $1 \times 1$ (Kevlar-49, 0.74 mm/0.029 in. diameter) braid with transversely inserted carbon tows (NG Corp., 0.30 mm/0.012 in. diameter) is shown. As expected, owing to the near uniform length-wise pressure from neighboring braider yarns, the transversely inserted carbon tows deform to a near rectangular cross-sectional shape. In return, they are also seen to cause a displacement and flattening of the braider yarn tows.

The calculation or measurement of braided composite fiber volume

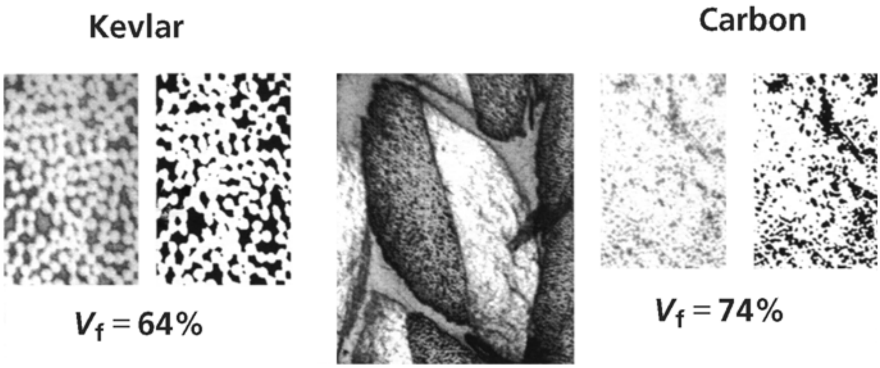



*7.13* Cross-sectional microstructure of two-sided hybrid composite braids showing the yarn packing (a) and yarn interaction among the different tows in the hybrid composite (b and c).





*7.14* Cross-sectional microstructure of a four-step braided composite with transverse carbon tow insertion.



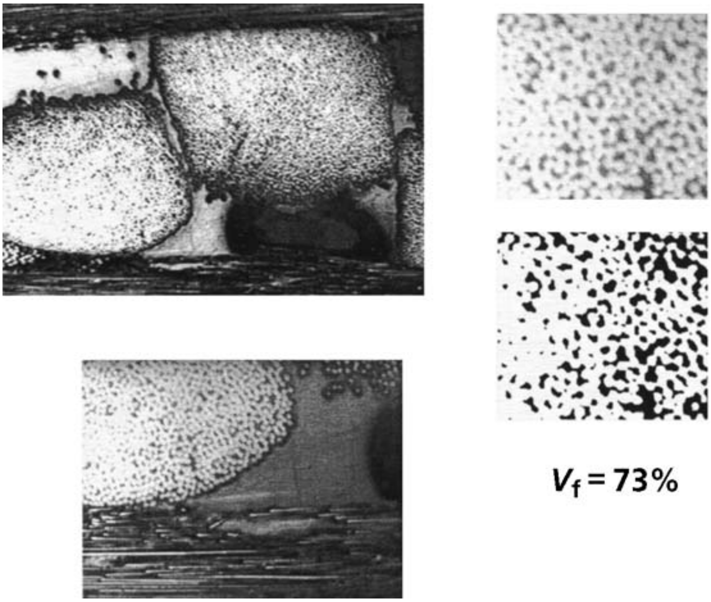

*7.15* Measurement of fiber volume fractions for the two-sided braided hybrid composite sample through digital analysis.



fraction is more readily obtained through the identification of a unit cell of the structure [1]. However, when dealing with multistep, multiple fiber and filler material braided composites, the identification of a unit cell is tedious. Here, some possible representative cells for some sample braided composite microstructures are suggested. Focus is then on the measurement of the fiber volume fraction within the tows of the cell so that it may be quantitatively related to the aforementioned observed yarn packing.

The measurement of the yarn tow fiber volume fraction may be carried out through use of digital image analysis. After a representative cell of the composite microstructure is chosen, a series of random image samples are picked from within the fiber bundles. These image samples are then thresholded. In other words, a gray-level value is chosen as a cut-off such that all image pixels above and below this value are made white and black, respectively. The pixels in the resulting binary (black and white) image may then be counted and a ratio of white pixels (fibers) to total pixels (fibers and matrix) computed. Ideally, this ratio should represent the fiber volume fraction within the yarn tow. It should be noted that some error is introduced by this method because of such factors as image resolution and improper thresholding.

Figure 7.15 shows the chosen representative cell for the two-sided hybrid composite. The measured fiber volume fractions for carbon and Kevlar are 74% and 64%, respectively. This rather high fiber volume fraction within the tows (packing fraction in the literature [16]) is comparable to that found in a four-step $1 \times 1$ braided composite [1,10,17–19]. It should be noted that the high fiber volume fraction measured in this sample is probably due to the high braid compaction during RTM of the preform. The slightly greater $V_f$ of carbon over that of Kevlar may be attributed to the smaller fiber diameter (about 7 μm) compared with that for the Kevlar filaments (about




*7.16* Measurement of the fiber volume fractions for the four-step 1 × 1 Kevlar braider, transversely inserted carbon fiber, hybrid composite sample.



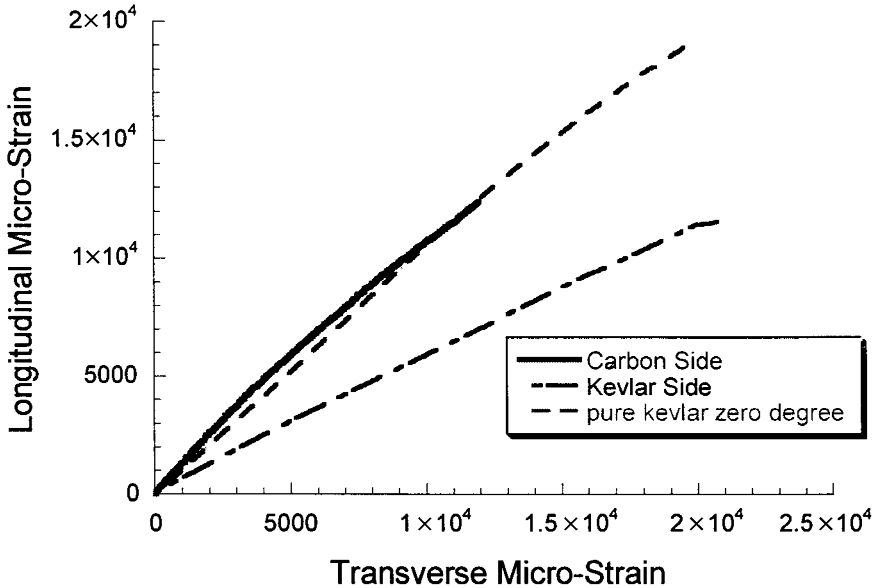
35 μm). The transversely inserted carbon tows of the braided composite shown in Fig. 7.16 have the effect of pinching the braider yarns at additional contact areas along their length. The net result is a more highly packed tow which yields a measured fiber volume fraction of 73%.

### 7.3.6 Braided composite performance

The prediction of the elastic and strength properties of 3-D braided composites presents an interesting challenge. Although much progress has been made in this area [1,14,15,20–23], there is still much to be done as it pertains to hybrid and complexly shaped braided composites. What is presented here is focused on the measured tensile response and hybridization effects of braided composites. The goal is to quantify some of the dominant parameters involved in determining the composite elastic constants so that 3-D braided hybrid composites of the future may be tailor designed to respond to the intended loading condition. Uniaxial tension tests were performed on a group of pure Kevlar and carbon/Kevlar hybrid composite samples (example shown in Fig. 7.13 with the braid cycle used for fabrication). From the literature [24], it is suggested that a strain gage size be selected such that its deformable length be greater than or equal to the unit cell size of the textile composite. This is to ensure that strain gage deformation corresponds to an average deformation across a representative unit of the braided composite microstructure. For the braided specimens in question, this size corresponds to the surface pitch length. The stress and strain data for each type of specimen (pure Kevlar and carbon/Kevlar hybrid) have been averaged and the results are presented below.

For the pure Kevlar (PK) braided samples, the measured longitudinal strain is plotted with respect to the transverse strain ($x - 1$ for clarity) in Fig. 7.17. The measured Poisson ratio, which is taken from the initial linear portion of the graph shown in Fig. 7.17, is reported to be near unity. This strongly suggests a material elastic response that is dominated by the fiber architecture. The presence of the matrix, which is in the order of 40% by volume, is negligible. The braided composite appears to be behaving in a truss-like fashion. For increased loading, the slightly decreasing, non-linear nature of the Poisson ratio also suggests a fiber alignment or locking-out effect. Comparison of the measured Poisson ratios for the PK and the carbon/Kevlar (CK) hybrid composite samples is also shown in Fig. 7.17. For the CK samples, the initial slope of the curves yields a Poisson ratio of





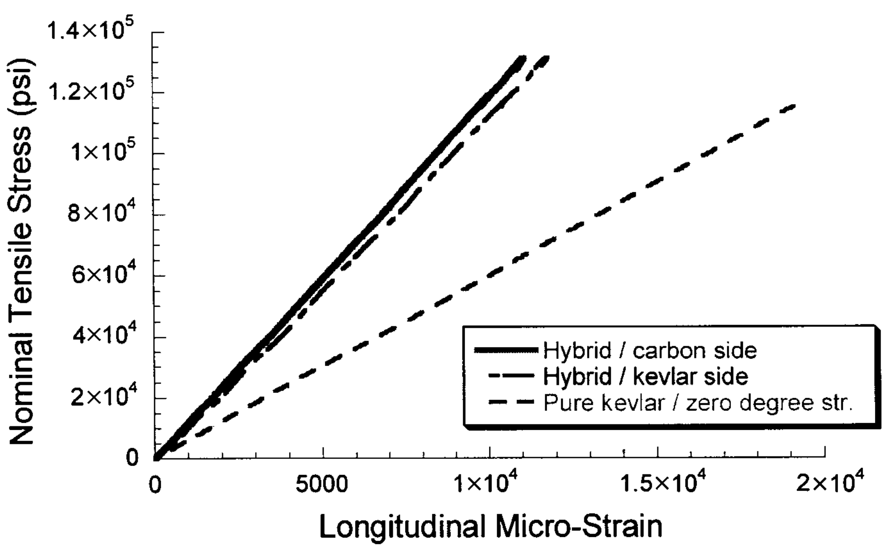

*7.17* Longitudinal vs. transverse strain in pure Kevlar and Kevlar/carbon hybrid tension samples.

1.2 and 0.8 for measurements taken on the carbon and Kevlar sides, respectively. Since the carbon-side Poisson measurement is within 20% of the PK ratio and if we assume that an isostrain condition exists in the longitudinal direction, it may be concluded that the more stiff carbon fibers dominate the transverse contraction. The presence of the high modulus carbon fibers also produces a more pronounced nonlinearity of the Poisson contraction. It is believed that the lower shear resistance of the carbon fiber, compared with the Kevlar material, magnifies the fiber alignment effect.

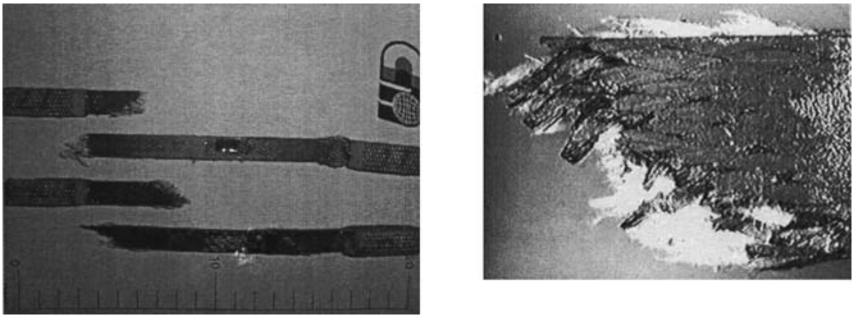
In Fig. 7.18, the nominal tensile stress is plotted versus the longitudinal strain. For both samples (PK and CK), a linear tensile stress–strain relation is seen to exist. The near equality of the slopes for the carbon and Kevlar sides of the CK sample determines that an isostrain condition exists in the longitudinal direction. The calculated tensile modulus for the PK sample is 41 GPa ($6 \times 10^6$ psi) while that for the CK sample (averaged) is 74 GPa ($10.7 \times 10^6$ psi).

The fracture of all the specimens was catastrophic. Linear stress–strain behavior was observed until the ultimate strength was reached, at which time sudden and total fracture occurred. The average ultimate strengths of the PK and CK samples are 793 MPa ($1.15 \times 10^5$ psi) and 896 MPa ($1.3 \times 10^5$ psi), respectively. The average failure strain of the composites is found to be 1.9% and 1.1% for the PK and CK specimens, respectively. Figure 7.19

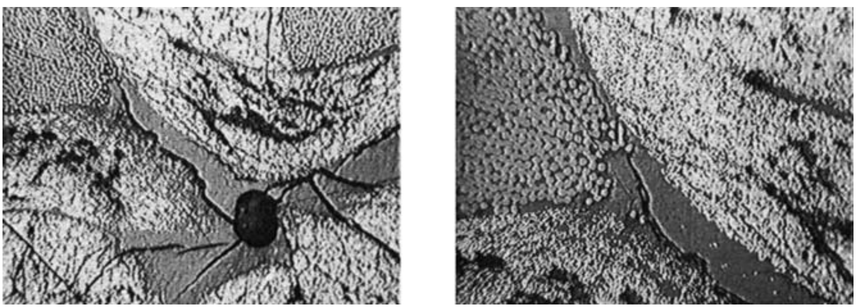





*7.18* Nominal tensile stress vs. longitudinal strain for pure Kevlar and Kevlar/carbon hybrid tension samples.



*7.19* Typical fracture of braided composite specimens (left) and fracture across the shear face in the Kevlar/carbon hybrid sample (right) (compliments of the Center for Composite Materials, University of Delaware).



*7.20* Micrographs showing crack initiation at a void within the intertow regions and propagation along the matrix/tow interface and crack arrest at the Kevlar interface.



shows typical fractured PK and CK specimens. For all samples, fracture occurred along a near 45° shear plane of the material (Fig. 7.19).

Observation of the fracture surface near the carbon/Kevlar interface region reveals a dominant growth of cracks in the thickness direction of sample. It is believed that near the carbon/Kevlar interface region, the exaggerated difference in transverse strain is adding to a 'pulling apart' of the carbon tows. The ultimate result is the breaking away of carbon tows from the matrix, carbon tow failure and final tow pull-out. A likely source for the crack initiation, as with many polymer matrix composites, is voids. Figure 7.20 shows a series of cracks which initiate at an internal void. The cracks are seen to take the paths with the highest driving potential (minimizing energy of the system) and the least resistance. The cracks appear eager to cross the carbon tows but reluctant to negotiate the Kevlar tows. This crack initiation, propagation and arrest sequence may prove to be an exploitable quality of hybrid composites.

## 7.4 Summary

Textile preforms offer a wide selection of fabrication techniques. Ranging from simple 2-D weaves to the more complex 3-D braids, these fibrous arrangements have much to offer the composite industry. 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 3-D braided composites is continuously being developed.

In general, the advantages of 3-D braiding as a method of preforming include the formation of a delamination resistant structure, 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 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 suggest an application to hybrid composites.



The development of prototype braiding equipment shows that a variety of structures may be automatically fabricated. Issues such as braid convergence, processing cost (time) and braid stability have also been addressed. 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. The consolidation of 3-D braided preforms is an issue in itself. While RTM offers a reliable method of preform infiltration, complexly shaped structural parts and open panel structures are but a few of the challenges that must be addressed.

Braided composite microstructural characterization is the first step towards a study of elastic performance. The extent of yarn deformation (packing) resulting from preform consolidation was discussed through composite cross-sectional micrographs. Through digital image methods, the fiber volume fraction of select hybrid composites was measured and representative cells of composite microstructure suggested. A comparison of the elastic performance of Kevlar/epoxy and carbon/Kevlar hybrid composites was presented. The tension test results show a linear stress–strain relationship for both specimen types within the range of the applied load. The calculated tensile moduli for the carbon/epoxy and hybrid composite were found to be 41 and 74 GPa, respectively. In addition, the Poisson ratio of near unity for both specimen types strongly suggests a fiber-dominated elastic material response. The difference in hybrid composite transverse strain due to the differing constituent fibrous materials is found to be appreciable. It is believed that this discrepancy in Poisson contraction causes the propagation of transverse cracks primarily within the carbon tows and ultimately leads to catastrophic composite failure. The initiation, growth and arrest of cracks due to the hybridization of the composite specimens were also observed to occur. Composite ultimate strength and strain to failure were found to be 793 MPa and 1.9% for the Kevlar/epoxy sample and 896 MPa and 1.1% for the carbon/Kevlar hybrid.



### 7.4.1 Future research

In its present state, the braiding of 3-D articles, be it accomplished through use of a Cartesian (track and column) braider or a horngear type machine, has an inherent handicap. This shortcoming is the braidable size and length of preform. 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. Additionally, fiber insertion techniques such as weaving and stitching may be coupled with the 3-D braiders of the future so that the maximum amount of fiber is introduced during the net shape braiding process. 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.

It is strongly believed that the use of computer solid modeling for the simulation of braided composite microstructure will bear much fruit. Once any 3-D braid, be it hybrid, complexly shaped or voided in nature, is adequately represented through a simulation, the prediction of composite mechanical properties will be easy.

## 7.5 References

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