

# New Directions in Braiding

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## ABSTRACT

It is the intent of this manuscript to provide a general treatment of braiding: past, present, and future. A history and evolution of braiding, braiding machinery, and related engineering developments is provided with emphasis on the design, manufacture, and analysis of braided fabrics and composites. Some recent developments are briefly described, including:

1. a composite braider with axial yarns which interlace with the helicals, and in which the helical yarns do not interlace with each other – a machine now under commercial development,
2. a new braided structure, called the true triaxial braid, produced by the new machine or by proper carrier loading on a conventional Maypole braider; and
3. a computer controlled take-up system using image analysis to monitor and control braid formation.

Original work ongoing at Auburn University is described and involves Jacquard lace braids with open structures for use in composites, computer aided design (CAD), computer aided manufacturing (CAM), and analysis of ordinary and lace braids for composite applications. This paper is an expanded version of an invited presentation under the title “New Directions in Braiding” at a Fiber Society presentation in Bursa, Turkey, in the spring of 2010 [1].

## INTRODUCTION

Braiding has been identified as one of the key pre-forming technologies for producing low cost high volume composites [2]. The mechanical nature of braiding machines as well as the intrinsic properties of braided fabrics contributes to the overall engineering capacity of braided structures. Braiding is ideal for mixed material systems and rapid and limited production runs. Braids are used extensively in a multitude of industrial applications, including aerospace, automotive, civil infrastructure, engineered composite materials, marine, fashion, and textiles. Some examples of high performance

commercial applications include multifunctional tethers, surgical stents, engineered ropes, turbine fan casings, aircraft propellers, inflatable structural beams, rocket nozzles, bicycle frames and wheels, and monocoque vehicle chassis. Braiding is used extensively in manufacturing industrial products such as reinforced hose. As engineering design and manufacturing automation continue to improve, new applications of braids will be realized.

In order to present braiding as a viable composites pre-form technology it is important to provide some of its historical detail. The braiding machine design has been modified many times, as witnessed by the multitude of patents issued throughout the world. With each modification, the resulting products differ accordingly. The process parameters affect the characteristics of braided product and are thus important for a complete understanding of textile pre-form geometry of composite material reinforcement. This paper will provide a description of braiding technologies, both past and present, in order to provide context for current and future developments.

## Historical Context

Braiding has been an important process throughout history of transforming fibers to more useful forms. It is arguably the first textile process, practiced by ancient civilizations [3]. Smaller, natural-fiber strands were braided in order to produce larger, stronger structures such as rope. Several online encyclopedias and other sources place the origins of braided rope at more than 17,000 years ago [4]. Ancient Chinese and Japanese documents record that braiding was in use before 4,000 BC [5-6]. Braiding in the context of ancient history is simply considered the oblique interlacing of three or more strands [6-7]. The original braiding machine predates the Industrial Revolution [8]. As mankind became more sophisticated, so did the methods of producing textiles, including braids.

A modern definition of braiding is given by the German Industrial Standard DIN 60000 as “two or three-dimensional fabrics with even thread density

and closed fabric appearance whose braiding threads cross each other in diagonal direction to the selvage” [9]. Braids can be, cylindrical (round), flat, or a variety of other cross-sections.

Plaiting of three strands, in the manner of the hair style known as a pigtail, is the simplest braid [10]. Ancient cultural rituals called the Maypole dance, where individuals hold ribbons attached to a central point, often a tree, make synchronized movements, forming a braided fabric essentially around a mandrel, the pole or tree. *Figure 1* is a Maypole dance performed by children in Alabama from 1910. Mechanically emulating manual motions to produce braids led to the invention of braiding machines [11-14]. Many different types of braiding machines exist, ranging from simple to complex designs, capable of producing different types of braided fabrics [12-13].

## HISTORICAL REVIEW OF BRAIDING MACHINES AND PRODUCTS

The following sections will describe some of the most common braiding machines and their respective products, with emphasis on items of interest to composites manufacture. The evolution of braiding can be seen as a progression of modifications. Machine design affects product architecture, which is very important for analyzing and designing braided structures [16-17]. The accuracy of the analysis depends on accuracy of the fabric geometry which can be understood from the formation machine process details [18].



FIGURE 1. School Children Playing and Making Maypole Dance [15].

### Maypole Braiding Machines

The first braiding machine patent was issued in 1748 in Manchester, England [3]. The first braiding machine constructed of iron was built in 1767 in Barmen, Germany [5]. These types of braiding machines produce a thin walled braided/interlaced cylinder. They are identified as two dimensional (2-

D) braids (sometimes as biaxial) as opposed to 3-D braids that have yarns moving throughout the thickness. Machines of this style, (2D), are commonly found with sixteen or more bobbin carriers and are used extensively in the fabrication of cordage and ropes. *Figure 2* shows a typical Maypole braiding machine.

The gear train is typically circular, consisting of specialized gears called horn gears composed of a spur gear bottom and slotted gear top [19]. These gears move two sets of bobbin carriers in opposite directions so that the yarns interlace to form fabric. The location of braid formation is called the fell or braid formation point [20]. Motion of the bobbins is accomplished by horn gears (see *Figure 3* for details). The horn gear slots allow the gear train to pass bobbin carriers along a sinuous path, guided by a track plate. The track plate paths resemble intersecting sine waves (that are out of phase). Track plates may be above or beneath the horn gears depending on design [21]. The track plate geometry and horn gear type also determine operating speed [21]. Modern braiding machines range from 3 to 144 braiding bobbin carriers and may also include non-braiding, stationary carriers [22].

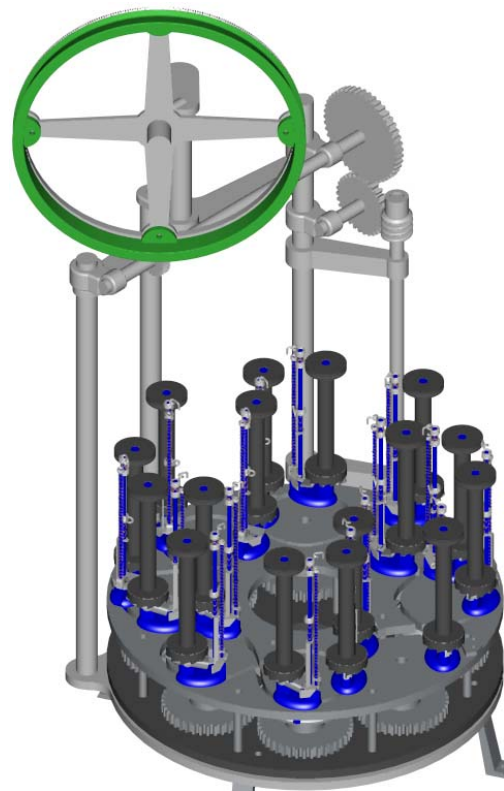


FIGURE 1. Typical Maypole Braiding Machine. A conventional Maypole braiding machine includes a gear train, a track plate, bobbin carriers, and a take-up mechanism.

In 2-D Maypole braiding machines, the gear train, horn gears and track plate paths are located toward the machine outer perimeter (*Figure 3*). As the number of bobbin carriers increases, the machine size and the product diameter increase. The increase in machine size is beneficial for including a mandrel or core material through the machine center. Allowing subsequent yarns to braid over the mandrel is called over-braiding [23]. The braiding yarns interlace on the mandrel surface and conform closely to its shape, provided it is without concavities. Over-braiding is a primary method for manufacturing composite fabric pre-forms. Pre-form refers to a fabric produced in or near the final composite form and serves as the structural reinforcement [24]. Complex 3-D shapes can easily be braided with 2-D braiding machines and a 3-D contoured mandrel. Mandrels can be rigid, inflatable, breakable, and even dissolvable, if their removal is desired [23-25].

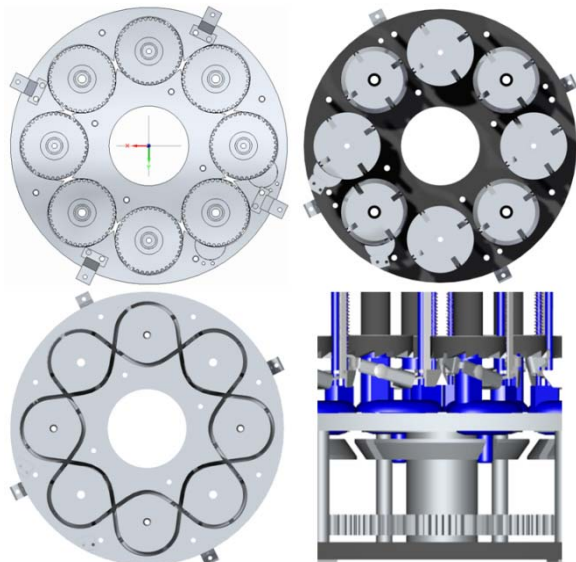


FIGURE 2. Maypole braiding machine components: spur gear train (top left), horn gear train (top right), track plate (bottom left), side view of horn gears and carriers (bottom right).

When the bobbin carriers are parallel to the machine axis, a significant amount of intra-yarn interaction occurs, which can prevent the formed fabric from pulling up tightly in the braid formation region. During the braiding process, the yarns must have suitable clearance with adjacent bobbin carriers' eyelets to prevent entanglement. Clearance can be accomplished naturally by geometry, i.e. yarns form a cone with the braid point, or artificially with the use of a forming ring. Forming rings force yarns to converge as well as permit forward and reverse direction braiding.

### **Bobbin Carriers**

A fundamental component for both 2-D and 3-D braiding machines is the bobbin carrier. Bobbin carriers allow yarns to be moved through the gear train and traverse the track plate. Bobbin carriers control the tension in the yarns, typically by interchangeable springs. Although many different designs and modifications exist, the basic intended function is to regulate the tension during braiding. In addition to controlling tension magnitudes, providing constant tension is also a desirable feature. *Figure 4* illustrates a common carrier configuration. The primary components include bobbin spindle, ratcheting mechanism, compression springs, and eyelets. A mathematical model revealing how spring stiffness, mass properties, and geometry affect the response for the bobbin carrier tension system has been presented [26].

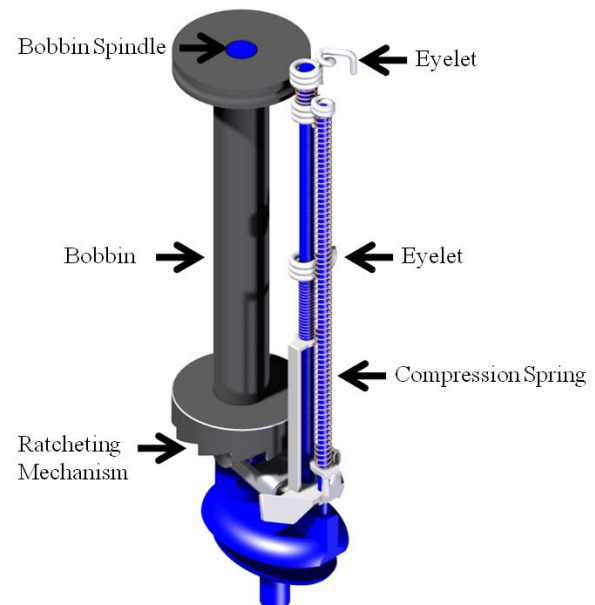


FIGURE 3. Typical braiding machine bobbin carrier.

### **2-D Maypole Braids**

Biaxial braid is the most basic and common form of 2-D braid, composed of yarns arranged in two directions. Among biaxial architectures, various repeating patterns may be produced. Terminology of these patterns depends on industry and application as textile and composite industries often use different names. The most common repeat patterns are 1/1, 2/2, and 3/3 where each yarn traverses according to the pattern description over and under adjacent yarns. These patterns are commonly referred to as diamond, regular, and Hercules, respectively.

For example, *Figure 5* depicts 1/1 and 2/2 patterns, where the blue yarn traverses over and under adjacent yarns and the black yarn traverses over two and under two yarns. The repeating pattern is determined by which carriers are utilized during the braiding operation.

### **Soutache Braiding Machine and Braid**

A Soutache braiding machine produces a narrow fabric similar to braids produced by plaiting of hair. Soutache braiding machines employ two horn gears and a Figure-eight track plate to interlace the yarns [78]. The number of horn gear slots depends on the number of carriers and required pattern. The Soutache braid and machine are the simplest of braiding technologies [5]. These machines can be very large as they are commonly used to manufacture rugs and reed and wicker furniture from coarse natural materials [79]. Furthermore, carrier carriages allow multiple yarns to follow the same path, thus making diamond architectures involving multiple yarns i.e. groups of yarns traveling over and under other groups. *Figure 6* shows a Soutache braiding machine. *Figure 7* is an example of a Soutache braid.

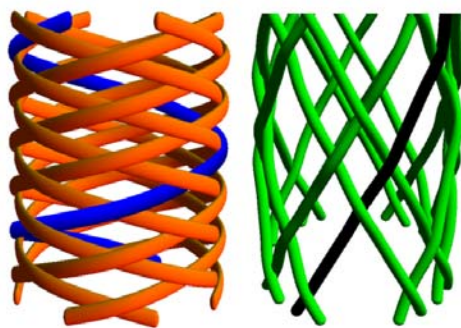


FIGURE 4. Biaxial diamond braid (left) and biaxial regular braid (right).

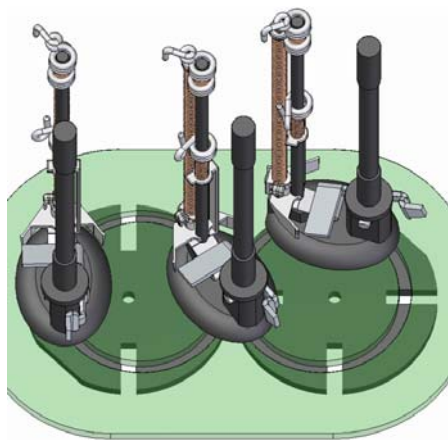


FIGURE 5. Soutache braiding machine with 4 slotted horn gears.

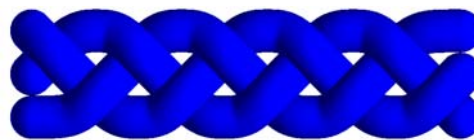


FIGURE 6. Three stranded Soutache braid.

### **Triaxial Braiding Machine and Triaxial Braid**

A simple modification to a Maypole braiding machine allows the insertion of stationary yarns. Utilizing horn gears with hollow axles permits yarns to be inserted along the direction of braiding. These yarns have various names including pillar, axial, static, middle end yarns, standing ends, warp, and stuffer yarns [27-29]. Axial yarns are employed to stabilize the fabric, increase strength and reduce elongation. It is possible to produce these triaxial braids with the aforementioned patterns. *Figure 8* is an example of diamond and regular braids with axial yarns. In this case of *Figure 8* the axial yarns are inserted in between the braiding (helical) yarns that are in diamond and regular configurations.

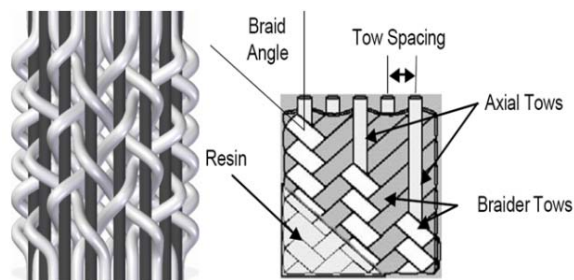


FIGURE 7. Triaxial 1/1 Braid (left) [30], Triaxial 2/2 braided composite (right) [31].

### **Flat Braiding Machines and Flat Braids**

Another modification to the Maypole braiding machine produces flat braids. By preventing the bobbin carriers from traveling about a complete circle, flat braids are produced. This flat geometry can be accomplished by modifying the track plate appropriately and removing a single horn gear or modifying two horn gears, and with appropriate adjustment for timing, it is possible to have carriers circle the terminal horn gears and continue in the opposite direction. When constructed in this manner, flat braids typically have an odd number of yarns. *Figure 9* demonstrates how the incomplete circular bobbin path produces a braid which is ultimately flattened. The terminal horn gears in the incomplete circle are larger in diameter and may have an odd number of slots to accommodate the carrier turn around [32]. The realization that the circle did not have to be complete opened the door for a variety of track shapes. A number of patents for flat braiding

machines were issued during the 1800's, including U.S. Patent title "Braiding Machine" which made provision for braiding stiff material such as hard brass [32].

### **Rotary Braiding Machines**

A U.S. Patent issued in 1890 describes a rotary braiding machine exhibiting certain improvements where opposing bobbin carriers travel in circular rather than a sinusoidal motion and only the yarns follow sinusoidal paths [33]. Rotary braiders represent an evolution of the Maypole braiding machines that employ significant modifications and greatly improve formation speed [19]. In traditional rotary braiding machines, counter rotating bobbin carriers move in perfect circles around banked edges of a bell so that the outer yarns interlace over and under inner yarns with the aid of deflector plates. In this way, the yarns, with low mass and inertia, undulate, rather than the bobbin carriers. Wardwell Braiding Machine Company manufactured rotary braiding machines called rapid braiders (*Figure 10*) [34]. These rapid braiding machines can produce various patterns but generally not triaxial braids. Although the machine speeds are higher, these machines are not well suited for conventional fibrous textile yarns (unless substantially twisted) or large composite over-braiding processes. Hence, they are typically used to braid wire for electromagnetic shielding and monofilaments as reinforcement for pressurized tubing.

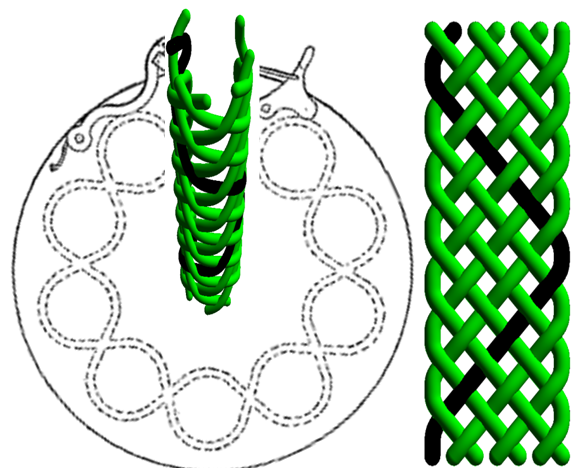


FIGURE 8. Flat braid as formed (left), Flat braid (right).

### **Lace Braiding Machine**

Lace is a decorative fabric used primarily in apparel and home furnishings. It is characterized by an open architecture formed by various stitches [35-36]. Fundamental motions are combined to form stitches and produce intricate patterns [37]. Braided lace employs open and complex topology due to the

independent motion of individual yarns [13, 35]. Braiding machines that produce bobbin lace are often referred to as lace, Jacquard, or Torchon braiding machines.

Lace braiding machines are specialized 2-D braiding machines commonly used in the production of fancy or lace fabrics. Lace machine technology can be traced to the 1800's in Europe and the United States. The modern lace braiding machine originated in Germany during the early 1900's and with the exception of a few technical improvements appears to be quite similar to the original [38]. Much like the Maypole machine, bobbins move in a sinuous path around the machine perimeter. However, each horn gear is individually controlled, allowing carriers to reverse direction at each machine cycle, thus permitting almost infinite pattern possibilities.



FIGURE 9. Wardwell Rotary Braiding Machine.

Lace braiding technology and machines are unique for several reasons. They began as the first computer controlled braiding machine utilizing a punch card and Jacquard mechanism consisting of cams and levers to control the motion of yarns. The lace industry was one of the first to exploit CAD systems for facilitating design and customer service [39]. These machines became a tool of artists and fashion designers and have been apparently ignored for use in industrial textiles and by composites engineers. Finally, lace braiding machines have a "beat-up" mechanism, consisting of a series of oscillating blades, which control the density of the fabric by yarn compaction during formation. The beat-up mechanism is required as yarns which do not traverse

around the circumference cannot be simply pulled into a tight structural configuration, anymore than a pick would move closely into the fell of the woven cloth without beat-up action. A lace braiding machine is shown in *Figure 11*.



FIGURE 10. Lace Braiding Machine.

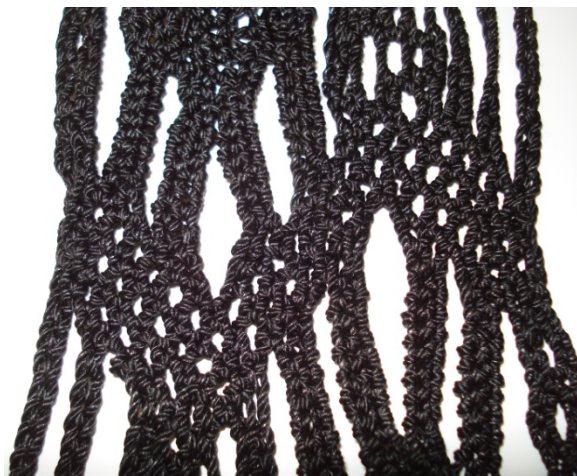


FIGURE 11. Braided Lace fabric.

*Figure 12* is an example of braided lace. Stitch control, varying tension among yarns, and the use of the beat-up mechanism create the open, lattice-like fabric structure.

### **3-D Braiding Machines**

During the 1960's the U.S. Government, as well as industrial and academic researchers, placed emphasis on developing 3-D braiding machines for their use in producing composite material pre-forms, namely carbon fiber composites. As a result many patents have emerged from this time period to the present. Research to determine the properties of 3-D braided fabrics and composites continues to this day. It should be noted however that 3-D braiding machines have been in use since the 1900's or earlier, producing unique fabrics, reinforcements, and

apparel trimmings [40-41]. Both 2-D and 3-D braids require synchronized motion of bobbin carriers and a take-up device. The design opportunities as well as challenges are more complex for 3-D braiding machines as the machines are inherently more complicated. Some 3-D machines have been constructed simply as modified Maypole braiding machines, using multiple concentric circular tracks of horn gears, with interconnections for carrier movement through the fabric thickness [41-43]. Most 3-D machines require some sort of beat-up mechanism.

Track plate geometries other than a cylindrical locus for horn gears enable the construction of complex—even solid—shapes with included holes and bifurcations, with or without the insertion of axial yarns. Modified track plates allow the construction of non-circular cross-section braids with reinforcement through the thickness. Transverse yarn interaction may occur throughout the thickness of the braid, resulting in solid structures with excellent toughness and de-lamination resistance. These horn gear based braiding machines represent the ultimate modified Maypole braiding machine.

The construction of a rectilinear track introduces the possibility of using a sliding mechanism for carrier motion rather than horn gears. Such braiding machines are often referred to as shuttle plate braiders [44]. Whereas 2-D braids find application in a large variety of industrial and consumer products, 3-D braids are almost exclusively used in fiber reinforced composites. Many examples of 3-D braids are found in scientific and engineering literature.

### **3-D Radial Braider**

The conventional orientation of bobbin carriers in both 2-D and 3-D braiding machines is either parallel with the machine axis or radially facing the center. However, braiding machines with bobbin carriers pointing radially inward to the braid point are known as radial braiding machines [23]. Placing the track plate such that the bobbin carriers face the braid point decreases friction by minimizing tension variation and intra-yarn interaction and thus reduces filament damage [23]. Atlantic Research Corporation developed a 3-D radial braiding machine. This design utilizes machine space effectively by placing bobbin carriers radially along braiding axis [10].

### **Contrast Between 2D Braiding and Weaving and Knitting**

Unlike weaving or knitting from a beam, each braiding carrier has an independent tension mechanism. Yarn tension variation between carriers

can cause fabric defects, structural and even visible. Braid angle has a preferred natural locus depending on yarn diameter, number of carriers, rotational speed of the carriers and take-up of the fabric, and mandrel diameter (if used). In general there is a lower limit called the jammed state in which the cover factor is 100 percent. Increasing the take-up relative to the rotational speed increases the braid angle, opens the structure and consequently reduces the cover factor. At startup or when any of the parameters are changed, the braid geometry makes a gradual change to the new equilibrium braid point and geometry, a process that may take minutes. If one can adjust the take-up speed appropriately this transition time and zone in the fabric can be minimized.

## **APPLICATIONS OF BRAIDING KNOWLEDGE BASE (OUR PREVIOUS WORK)**

### **Quality Control and Fault Detection in Braiding**

The importance of maintaining proper tension during the braiding process is paramount to ensure manufacturing quality. Equally important in composite manufacturing is the ability to predict and control the yarn geometry during the manufacture of complex shapes. CAE and CAM techniques have been implemented for ensuring quality control using servo motion control and machine vision [22].

Yarn tension directly affects braid formation [45]. Several papers address the importance of maintaining desired braid geometry during manufacture and emphasize that slight variations in reinforcement morphology have significant effect on final properties [46-47]. The braid formation point and braid angle and thus resulting pre-form geometry are related to yarn tension and production rate. The braided fabric geometry as cited in various papers pertains to steady state conditions, where braid geometry including mandrel shape remain constant [48]. However variations in process parameters required in achieving desired braid angles along fabric length, including mandrel cross section, require a settling time for the yarns to reach an equilibrium state. Thus predictive models which can be implemented using CAM are necessary to ensure design intent and manufacturing quality. Fabric formation transients observed in 2-D braids have been presented [22, 49]. Recently, dynamic material formation models have been developed to include both hollow braided fabric and braid-over-mandrel formations [50-51].

### **Analysis Techniques for Braided Fabrics**

Yarns in typical textile fabrics have been simplified using straightforward geometric models and have been analyzed with varying degrees of success [52-53]. Analysis techniques for braids have been

developed for both textile fabrics as well as composite materials. Accurately predicting the braid performance is difficult, requiring knowledge of the fibers within the yarn, interaction between yarns, and topologies of yarns and formed fabric [54]. Typically the fibers within the yarn will have some degree of twist. Additionally, friction within fabrics exists between the fibers. Geometry of the yarns including crimp must also be properly identified.

For analyzing braided textiles one must first consider the fabric geometry. Although textile structures in general consist of modeling complexities, including irregularities due to instabilities in fibers and yarns, some assumptions based on simplified geometry permit accurate analysis. Peirce developed a basic structural analysis technique of fabrics [52]. Brunnsweller extended this model and made the first specific geometric analysis of braids [53]. Peirce's model has been improved to include more realistic geometry by several researchers including Kemp and Shanahan and Hearle [55-56]. More recently, researchers have investigated braids from a formation standpoint to include specific geometric configurations, kinematic equations, the relationship of machine operation parameters, and the role of friction [57-60]. Predicting accurate geometry based on formation factors and machine parameters allows braids to be designed, manufactured, and analyzed. The compaction behavior of textile assemblies during manufacturing influences composite properties. Potluri and Sagar present a predictive model including resin permeability and fiber volume fraction [61].

Mechanical characterization of textile fabric and the predictive models that account for yarn bending and compression are used to generate FEA models [62-63]. Experimental characterization of a biaxial fabric including microscopic analysis to model the 3-D tow paths and resulting deformation under various loading regimes has been studied [64].

For braided composite materials, knowledge of the matrix and fiber interaction is required in addition to an accurate geometric description. Various micromechanics models are available that account for the yarn and matrix interaction. Elastic properties of braided composites can be predicted using the Fabric Geometry Model (FGM) [65]. This model relates the fiber architecture and material properties to a global stiffness matrix using micromechanics. Finite Element Analysis (FEA) has also been used to predict mechanical properties of braided fabrics and composites. FEA can be computationally intensive and relies on accurate geometry. For computational

expediency and effectiveness, these approaches use an idealized geometry called a unit cell to define a repeatable geometry. The unit cell or representative volume element is used to predict the overall properties of the composite. The use of computer controlled carrier movement (yarn placement) has allowed more complex structures to be produced, with larger and more complicated unit cells and theoretically without any representative volume element, thus work addressing these architectures is desired.

### **State of the Art Computer Aided Engineering (CAE) and Manufacturing of High Performance Composites**

Computer Aided Engineering (CAE) has been implemented by the textile industry for many years. Certainly, textile braiding has enjoyed various levels of computer aided manufacturing (CAM) for some time as well [13, 39]. The advent of 3-D braiding machines required prediction of yarn paths according to the machine pattern program [66]. Researchers have developed CAE systems of varying capability for 3-D and conventional rotary braiding machines [67]. The most advanced CAE systems involve numerically generating fabric pre-form geometry and corresponding pattern instructions sent to the machine. This information is utilized for performing required engineering analysis, such as FEA to predict performance before manufacture [68].

These CAE systems are used to optimize design parameters and are commonly utilized for 3-D braiding machines. However, such capabilities are relevant and necessary for developing an engineering knowledge base of lace fabric pre-forms as well. The pattern control inherent in lace braiding machines is similar to that used in state-of-the-art 3-D braiding machines. We are implementing such procedures to design lace braided fabrics and composites.

### **NEW DIRECTIONS**

In the early 1990's one of the groups of researchers at Auburn University explored the idea that a braiding machine represented the ultimate in multi-phase weaving. The ultimate is that half of the yarns on the machine are forming a two-yarn shed at any instant and that the other half of the yarns is being inserted into those sheds. With a conventional weaving machine, one machine cycle inserts one pick, whereas with a braiding machine, one revolution represents the insertion of half the total number of yarns running on the machine. This

realization led to the speculation that a really large braiding machine running at 1-5 revolutions per minute could produce a large braided cylinder which could be cut helically, following a yarn path and could produce a flat, woven fabric [69]. The lack of a beat-up process was a major stumbling block to the success of this idea. The beat-up on a Maypole braiding machine is essentially a pull-up, and the geometry is such that the pull-up is working at least a quarter of a revolution (actually as much as two revolutions) behind the position of the carrier. As the braiding machine gets larger, the number of yarn intersections over which the pull-up has to work becomes larger. Intra-yarn friction becomes too great to allow yarns to slide into a tight braid using just tension developed by the carrier as it progresses along its track (see *Figure 13*). During the process of discovering what would not work, other discoveries were made, including the true triaxial braid.

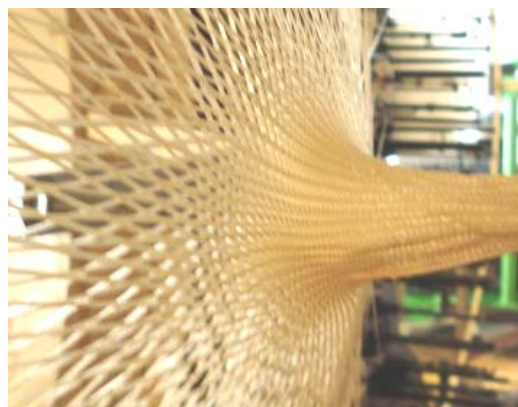


FIGURE 12. Yarn interaction affecting formation point.

### **True Triaxial Braiding Machine and True Triaxial Braid**

The researchers at Auburn developed a new braiding technology that allows a novel structure to be produced at high speeds [70-72]. This technology is a rotary braider with axial yarns, in which the oppositely rotating yarns interlace with axial yarns, but not with each other. *Figure 14* is a research prototype of the true triaxial braiding machine.

The product formed is called a true triaxial braid. It is a true, triaxial braided structure because axial yarns interlace the helical braiding yarns [72] and produce a structure similar to a conventional triaxial woven fabric. This structure differs from the conventional triaxial braid where axial yarns lie, without crimp, between braided yarns (*Figure 15*).



FIGURE 13. True Triaxial Braiding Machine.

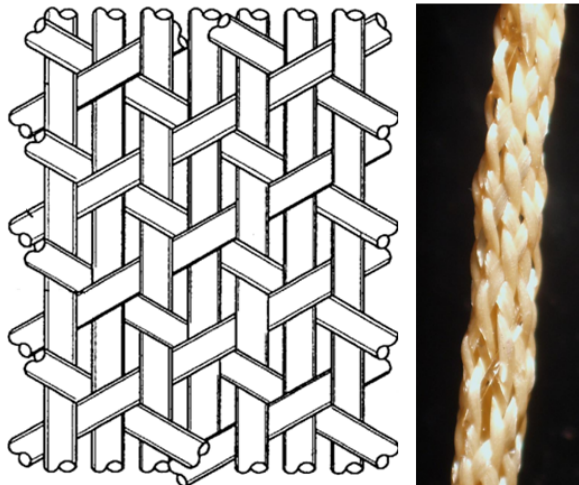


FIGURE 14. True Triaxial Braid CAD Model and True Triaxial braided rope [72]. Note that the some of the axial yarns interlace with the helicals while others do not. The interlacing axial yarns represent the True Triaxial structure.

A preliminary study of true triaxial braided composites found that the true triaxial braid “follows most of the trends of the traditional triaxial braid in effective stiffness properties as a function of braid angle, except for the axial modulus at higher braid angles, and a higher structural stability. At braid angles in excess of  $45^\circ$ , the ‘true’ triaxial braid shows an increase in axial stiffness. Therefore, the true triaxial braid does present a viable alternate that may offer advantages over the ‘traditional’ triaxial braid for certain applications” [73]. One unique application of true triaxial braids as a composite bushing is seen in Figure 16.

#### **Development of a Servo-Controlled Machine Vision Take-Up Device**

Work has been done to develop an instrumented, on-line platform for observation and control of braid formation during the manufacturing process [45]. Increasing the understanding of braiding process parameters will result in improved quality and pre-

form manufacturing capabilities. The manufacturing process of braiding can be improved by characterizing the braid performance according to machine parameters. Manufacturing complex braided composite components precisely according to intended design properties requires the ability to predict and control the braid architecture of pre-forms from the braiding machine parameters.



FIGURE 15. True Triaxial Braided Bearing: inner yarns are Teflon®; outer yarns are carbon fiber.

The CAE system of Figure 17 is presently being used for augmenting existing topological models to include dynamics, time response, and transient behavior of braid formation and machine components [26, 45, 48]. It is a four axis computer controlled take-up system, including three servo motors, braiding machine encoder, custom motion control, image analysis programs, and a machine vision system utilizing universal serial bus (USB) web cameras.

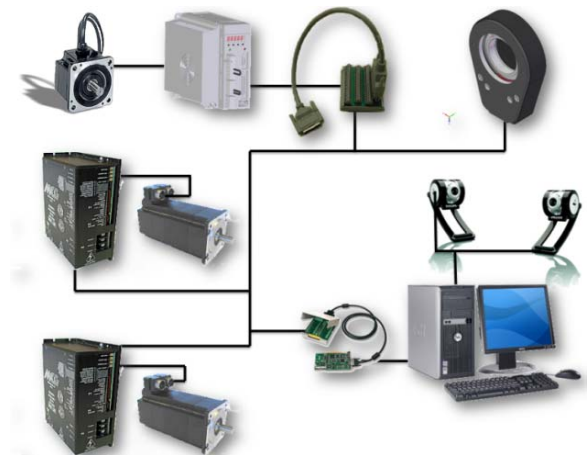


FIGURE 16. Computer controlled braiding system [74].

The vision acquisition system consists of USB web cameras, National Instruments LabVIEW software, and a light controlled environment. By acquiring and analyzing images, various braiding parameters such as position of fabric formation and yarn geometry including braid angle are monitored and measured in real time. The cameras are mounted in orthogonal planes, capable of tracking the braid with calibrated 3-D Cartesian coordinates. Cameras acquire images manually or automatically, when triggered by a signal received from the braiding machine encoder. Images are parsed from video to calculate braid point position and braid angle in real time.

### **Lace Braided Structures for Composite Pre-Forms**

Fabric preforms and the resulting fiber reinforced composites are a major impetus for much of the recent research (including our work) on braiding. Particular emphasis is being placed on using open, lace-braided structures for attaining minimum weight composites. Solid composite materials have been tested, proven, and are currently used by many engineering industries. However, it is not known exactly how well or to what extent lace structures will perform as pre-forms for structural composites [10]. The automated production of such structures is also difficult.

Two other organizations are known to be working in related areas. Braided tether has been produced by interconnected multi-stranded yarns using high performance fibers and lace braiding technology [75]. Based on the work pioneered at Brigham Young University, Delta 7 has produced a lace-like pre-form incorporating large carbon fiber tows for a bicycle frame [76]. The interlacing of these structures can also be done by hand, presumably around a removable mandrel, and subsequently cured to produce a bicycle frame; however, a modified 3-D braiding machine is in development [80]. *Figure 18* illustrates this commercially available open composite architecture.

### **Development of CAE Lace Design Tools**

Many challenges must be overcome to utilize lace braiding technology to produce predictable composite materials. Specific challenges in addition to those of conventional braiding design must be addressed in order to manufacture and use lace braiding for producing engineered structural composites: understanding lace design and manufacturing (lace braiding art), translation from paper versions of lace geometry i.e., point paper, conversion into machine instructions, simulation of lace and lace reinforced

composites, computer generation of geometry, modeling contacts between joints, braiding large yarns and forms, infusion of pre-forms, testing and validation.

Until the composites industry acquires the expertise required for designing lace, this problem will not be resolved. In particular, there are significant differences between lace and weaving point paper. Lace is considerably more complicated in that there are two horn gear cycles for each machine cycle, and in addition a particular carrier position may be loaded or unloaded on the machine.



FIGURE 17. Isotruss open composite architecture [77].

Looking at weaving point paper easily translates into a mental picture of the fabric; this is not necessarily so for lace braiding. Difficulties also arise from predicting the position of yarns according to a given pattern and tracking individual yarns throughout the braid. In addition, specific technical challenges exist due to the uniqueness of lace braiding machines, such as protecting yarns from the beat-up mechanism. Once the yarn path is known, a generative 3-D model in suitable CAD format must be produced for further analysis. *Figure 19* demonstrates the point paper and corresponding lace braid.

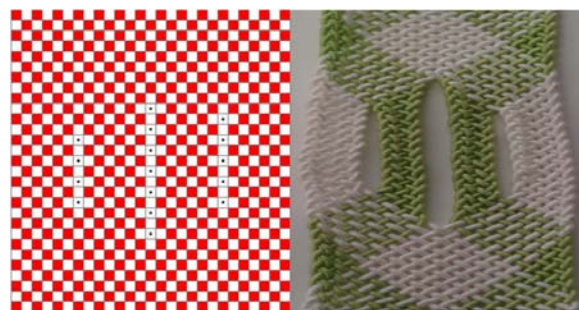


FIGURE 18. Point paper and corresponding lace braid.

Our braiding machine was supplied with software that can convert point paper design into machine

instructions. We have developed tools that translate point paper designs into visual structural renderings, and provide geometrical/mathematical descriptions of the structure that are a suitable starting point for analysis. Presently we are implementing the FGM to predict the elastic constants of a given architecture.

### **Infusion of Open Architectures**

Infusing the yarns in an open-lace structure with polymeric resin to produce a composite is challenging. The conventional method involves enclosing the pre-form in a bag or mold, evacuating the air, and infusing the pre-form yarns with resin. The pre-form structure must remain dimensionally stable or the vacuum and resin will distort the structure. Furthermore, resin is viscous and large yarns are difficult to thoroughly infuse. *Figure 20* shows how excess resin can form a thin film between yarns during infusion process.



FIGURE 19. Excess resin forms a thin film between yarns.

*Figure 21* shows an infused open braided structure without excess resin. Solving the thin film formation problem involved wrapping a porous material around the braid during vacuum infusion. In this way, excess resin was removed from the structure.

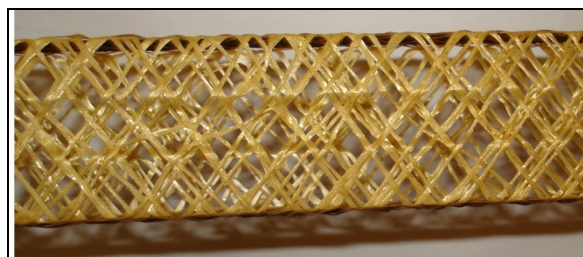


FIGURE 20. Successfully infused open structure braided composite.

### **Broader Impact**

The broader impact of this work involves evaluating lace braids for viability as structural composites. The research tools developed will allow for efficient utilization of materials and increased efficiency of engineering structures and will promote new value added products in textile and apparel industries with the additional manufacturing capability of high performance composite pre-form fabrics. The research communities of various scientific and engineering disciplines can benefit from the intrinsic

versatility of braiding made more accessible through this work to develop new applications. We see immediate applications in biomedical engineering, biomimicry, electronics, electrodynamic tethers, smart fabrics, and technical textiles.

### **CONCLUSIONS**

Braiding has been practiced for millennia and its use presently widespread. A brief history of braiding, braiding machinery and its evolution has been presented. A selection of literature has been presented to illustrate important developments in braiding to the present. The information presented is useful for innovation and engineering of braided materials and machinery. Several new developments have been presented including a machine vision system for observation and control of conventional braiding, and a true triaxial braided fabric architecture and production machine. A computer integrated manufacturing system is being developed for engineering lace braided pre-forms for fiber reinforced composites. Infusion of open architecture fiber reinforced composites is presented.

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