ADVANCEMENTS IN BRAIDED MATERIALS TECHNOLOGY

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ABSTRACT

Until now, the automated material processes used to manufacture large, composite aerospace structures have been filament winding, automated tape layup, and fiber placement. An overview of the advancements in braided preform architectures and braiding machinery identify braiding as an attractive process alternative for composite manufacturers. State-of-the-art braiding equipment incorporates fully automated control over all braiding parameters, including translational and rotational control of the mandrel, a vision system for real-time inspection, a laser projection system and integrated circumferential winding. These technological advancements, in addition to the high rate of material deposition found with braiding approach the precision demonstrated by fiber placement systems and the cost efficiency found in filament winding and is applicable to the manufacture of large scale, structural preforms.

KEY WORDS: Braider, Carrier, Coverage, Unit Cell, Near Net Shape Preforming, Triaxial, Megabraider

1. INTRODUCTION

Historically, braiding has been recognized as a textile process enabling the production of commodities such as cordage and candlewick. These textile products are mass produced on standard braiding machinery using small denier yarns, such as cotton, nylon, polyester or fiberglass. Over the past century the standard braiders - braiding machinery with 144 or less carriers (spools of yarn) – have proven to be extremely economical. For example, the setup of a standard 3 carrier machine used to make candlewick requires less than five minutes of labor, and this one setup allows for a continuous run time of one week yielding over 3600 yards of braid.

With the onset of preform technology in the late 1940s, came a new interest in braid as a structural reinforcement rather than an end product. The unique “Chinese finger trap”-like architecture gives braided material a high level of conformability, allowing it to assume extremely complex shapes. Braid’s architecture and the efficiencies of the manufacturing process caught the attention of materials engineers, and in the 1980s, braid gained recognition as a viable alternative to woven or stitched fabric for structural reinforcement. Once braid's effectiveness was realized, so too was a need for larger braiding machinery that would include extensive process technology in order to meet the demands of technologically advanced applications.

2. MEGABRAIDERS

Engineers at General Electric Aircraft Engines (GEAE) were among the first to choose braid as an alternative to woven fabrics. GEAE engineers were looking to reduce the weight of the fan blade containment structure of their commercial jet engines that utilize a woven kevlar wrap. In subscale testing, braid proved to be more efficient than woven, knit and non-woven structures. Yet, the production width of the braided tape needed for the containment belt was in excess of twenty-two inches and standard braiding machines were not capable of producing a fabric of that width. In order to meet GEAE's requirements, A&P Technology designed and built a 400 carrier braiding machine. This new machine was capable of incorporating the number of ends necessary to create the desired width while maintaining the required coverage and the machine itself represented the first venture beyond standard braiding machinery.

Soon after the development of the 400 carrier braider, another customer approached A&P Technology with a need for a braided solution requiring the use of non-standard machinery. In the early 1990s, ASD Simula of Phoenix, Arizona wanted to use braid in the development of its side impact airbag for automobiles. In this application the "Chinese handcuff" action of the braid is used in reverse. By inflating a biaxial braid internally the braid expands in diameter and shrinks in length. ASD harnesses this phenomenon to create a device that is stowed in an elongated configuration. Upon inflation, the airbag self deploys into a position to cushion a vehicle occupant's head in event of a side impact.

While a braid made on any size machine would accommodate the requirement of shrinking in length while expanding in diameter, only braid made on an extremely large machine would meet the coverage requirements of this application. The tubular airbag needs to provide full coverage for the bladder at the inflated diameter, so that it can handle internal pressurization without damage. At the same time the structural requirements of the airbag require that the fibers are oriented at a low angle at the inflated diameter. This move towards lower angle reduces the effective width of each yarn and its contribution to coverage. Without full coverage, areas of the bladder would not be supported by the braid between yarn crossings. In these regions aneurysms in the bladder and consequential failure in the airbag system could occur.

In order to achieve the design criteria of low fiber orientation and high coverage simultaneously, A&P Technology chose to produce the braided structure on a 600 carrier braiding machine. This increase in machine size allowed for the production of a high coverage braid with small unit cells and the appropriate fiber orientation for the airbag braid. (A unit cell is a textile term describing the openings or voids between yarn crossings. Smaller unit cells imply that the interstices or openings between yarns are reduced in size.) The combination of small yarns and increased coverage optimized the braid design. The small yarns allowed for decreased friction and smoother deployment and the increased coverage (the increase in the number of yarn bundles) prevented the occurrence of aneurysms.

At this point, A&P Technology realized the potential for large braiders, Megabraiders, and established a line with machines ranging from 172 to 800 carriers. This range of sizes allowed braid designers a wide array of design options enabling an efficient method for product development, yet these development projects revealed a new set of issues surrounding the manufacture of braid for structural reinforcements.

3. DEMAND FOR GREATER EFFICIENCY

With the transition from the use of braid for candlewick to the use of braid for structural applications, including structural composites, came an increased demand for specific technical requirements. As stated earlier, braid's ability to conform to complex shapes is an attribute that attracts many designers to examine the use of braid. In addition, the braiding process is amenable to near net shape preform manufacturing. This type of manufacturing is ideal for those designers interested in a reduced layup time and a process that is repeatable.

The braiding machine places two or three sets of yarns simultaneously; therefore, in contrast to a series of unidirectional lamina, a braided composite is composed of a series of multi-directional plies having identical properties. Since the properties of each lamina are the same, the likelihood of delamination is reduced dramatically. In addition to a reduction in interlaminar stresses, previous testing has shown that braided laminates provide increased interlaminar strength and damage tolerance as a result of a nesting phenomenon at the ply interfaces. Testing in the NASA Advanced Composites Technology program showed that the damage tolerance of braided textile composites far exceeds that of standard laminates. Those results demonstrated at minimum a 3 to 1 advantage in toughness over typical laminated composites. According to the report, "the probable cause for these high values is that the crack did not propagate in a resin-rich layer between plies as in a laminate. Although the 2-D braids are still formed by putting down successive layers of material, nesting of the different plies does occur. When looking at the edge of the specimen, the crack path was not straight but rather followed a "scalloped" pattern going around the tows. Also, when examining the surface of the delamination, it appears that failure did not progress between layers of material but inside a braided layer" (Minguet, Fedro, and Gunther, p.86).

These proven structural advantages of braid architecture increased the demand for the Megabraiders to achieve the automation found in fiber placement technology while maintaining the efficiencies of standard braiders. Yet, this demand could not be answered in a linear fashion. In order to meet the needs of materials engineers, A&P Technology had to solve two issues. First, the large braiding machinery required to produce structural braids needed to approach the manufacturing efficiency found with standard braiders. Secondly, this economically feasible method of manufacture had to employ new process capabilities that guarantee repeatable manufacture of near net shape preforms.

3.1 New Process Economics Early experiences with the Megabraiding machinery described above proved that the process technologies and economics required for running large braiders differ greatly from those required for the previous generation of equipment.

Labor input in the braiding process is required during machine setup and very little human intervention is required during the run time. Machine setup involves the following:

1. twisting of the yarn
2. winding the twisted yarn onto bobbins
3. loading the bobbins onto the individual carriers on the braider
4. pulling the yarn from the individual bobbins to a common consolidation point, so the braid can begin to form
5. installing appropriate springs on the carriers that hold the bobbins, to obtain the correct amount of tension applied to individual yarns
6. installing the appropriate gear that provides the correct relative speed of the carrier bobbins and the take-up speed
7. installation of the appropriate size braider ring to define the braid formation pattern

By definition, steps 1 – 5 take a lot longer for large braiding machines than for small braiders, due to the increase in required bobbins; therefore the setup and consequently the labor associated with running the Megabraiders rose substantially. See Figure 1.

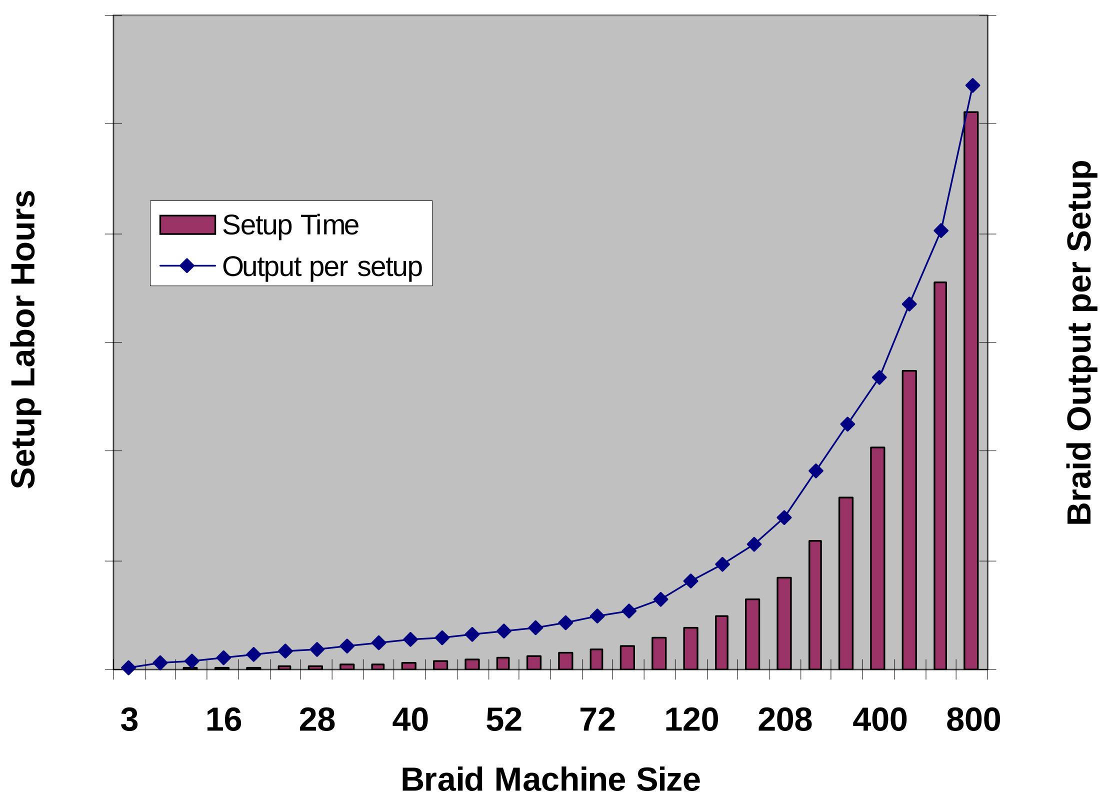
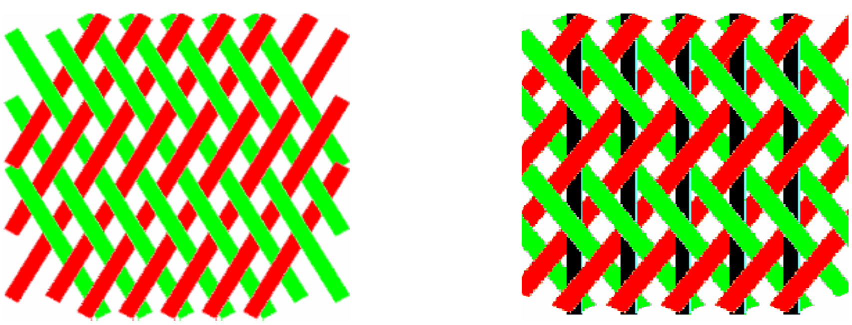


Figure 1

Of course, braid manufacturers expected this need for increased labor for larger machines. Similarly, though, the braid manufacturers expected an increase in material production on larger machines and although this increase in material output was discovered for large production runs, long runs were not found to be the standard. The old paradigm applied to standard braiding in which the product mix was well-defined (candlewick, fishing line, cordage, etc), so production runs were long and guaranteed, did not apply to the new markets for which structural braids are required. Instead, it was discovered that the Megabraider machinery produced such large amounts of braided material in a small amount of time, that one run would sate a customer's needs for that particular braid for a long period of time. Therefore, since demand for one particular product was not as frequent, the repeated setups of one product were not necessary. And without the repetition of specific machine setups, continual optimization of the setup and a consequent reduction in labor was denied. Furthermore, new processing techniques were required to enable proper formation of large braids. Achieving appropriate braid formation is more difficult for large diameter braids due to the increased number of yarn crossings and the accompanying rise in yarn to yarn friction. As a result, not only was time between setups quite long due to the large machine size, the setup activities tended to take place at a high point on the learning curve.

3.2 Required Process Capabilities The goal in manufacturing structural braids is to enable the automated fabrication of preforms that heretofore have been constructed by hand. As with any other automated preform construction, the braiding of net shape preforms needs to bring the same architectural features as those found in the hand lay-up process, while providing the economic efficiencies found with automated methods of manufacture, such as filament winding or fiber placement. The architectural requirements include:

3.2.1 ***Triaxial Architectures*** Typical hand lay-up composite preforms are composed of many lamina (layers) of various orientations that are engineered to provide the desired mechanical properties for the structure. Triaxial braid architectures (architectures containing a third set of yarns in the axial direction, shown in comparison to biaxial braid in Figure 2) can generate identical mechanical properties and have the added benefit of providing these properties within a single layer construction along with an intended reduction in interlaminar stresses. Yet, the previous generation of equipment is best suited for the braiding of biaxial constructions. When produced on standard braiders, triaxial braids often exhibit damage to the axial fibers, slight yet structurally significant misorientations, and oil contamination.



Biaxial Braid Triaxial Braid

Figure 2

3.2.2 ***Maintain Constant Angle or Constant Thickness On Complex Curvatures*** Since the woven or stitched plies are cut to size for the hand lay-up method a nearly constant angle on a part of complex geometry can be attained. Similarly, during hand lay-up the structure thickness is controlled easily by inserting the desired number of plies no matter the complexity of the geometry. In the braiding process individual tows are controlled independently allowing for exact thicknesses and guaranteeing optimization of material usage while meeting structural requirements. Yet, the control of the independent tows on standard braiding machinery is controlled by mechanical gears, therefore a change in gear designed to change the fiber angle requires an interruption of the machine run resulting in undesirable fiber orientations.

3.2.3 ***Partial Length Plies*** Furthermore, the hand lay-up method allows for the local buildup of thicknesses through the application of partial length plies. It is easy to cut woven or stitched fabric plies to the length required, in order to provide for localized increased thickness in highly loaded regions of the structure. Similar preform constructions are possible with some difficulty using previous generation braiding equipment.

4. INTEGRATION OF BRAIDING EFFICIENCIES AND PROCESS CAPABILITIES

As stated above, the individual architectural benefits of braid and the design options granted by large braiding machinery for preform technology warranted a revaluation of Megabraider machinery. While various changes to braiding machinery were being made to insure better structural braid architectures, such as treatment of axial fibers and control of mechanical gear ratios, the changes were being made independently of one another. And while, these individual improvements did prove beneficial, the large braiding machinery still lacked the integration necessary for the efficient manufacture of large, structural braids. A work cell was needed that would allow for a cost effective method of overbraiding large composite structures while surpassing the mechanical limitations of standard braiding machinery, in order to achieve the required process capabilities of structural reinforcements with precision.

In 2000, A&P Technology built such a work cell incorporating fully automated control over all braiding parameters, including rotational and translational control of the mandrel, a vision system for on-line inspection, a laser projection system, and circumferential winding. The 120 ft. cell, named Mantis because of its long, nimble appendages, handles mandrels up to 100 inches in diameter, up to fifteen feet in length and as heavy as two tons. This work cell allows for a dramatic reduction in setup time and the production of technologically advanced braided preforms with some added benefits, such as integral hoop winding and on-line inspection.

4.1 Reduced Labor Input A&P's new work cell allows for efficient utilization of large braiding machinery by incorporating electronic control over all braid work cell parameters. This enables a rapid convergence to the optimal setup for each new braid construction. As described below, the effect of a change in each machine parameter can be rapidly explored. This capability results in a Megabraider setup optimization requiring minutes instead of days. Once defined, this setup can be electronically saved for very rapid implementation in the manufacture of future products.

4.1.1 Manipulation of Machinery Proprietary auxiliary equipment in this work cell allows for the megabraiders to be picked up individually and placed into position within the work cell. As stated before, a large portion of the megabraider setup is included in the manual loading of spools onto the braiding machine. Having the ability to perform this manual element of setup outside of the work cell enables a decrease in down time and better utilization of the high cost capital equipment.

Furthermore, heavy, irregularly shaped mandrels do not hinder development time due to the ability of the auxiliary equipment to place the mandrels into position and control their movement precisely.

4.1.2 Automatic Adjustments of Machine Parameters Another labor intensive part of development time involves adjusting the tension on the individual yarns to the appropriate level, the installation of the appropriate gearing, and choosing the correct size braider ring. Until now, these adjustments were made manually, but with Mantis changes can be made automatically from one point of operation.

Various levels of tension can be tried within a matter of minutes, the gearing is electronic and can be changed during run time, and a patent pending "Iris" allows for quick trials of the appropriate braid formation diameter. Instead of manually changing the braider ring size until the appropriate size is found, the "Iris" increases and decreases in diameter electronically. The height of the braid formation point is also a very important characteristic of the machine setup and this too can be controlled electronically.

4.1.3 Learning Capability The control system has a robotic learning capability, which allows for quick returns to particular product setups and transition from manual mode to automatic mode. As the above machine parameters are changed during setup, these changes are electronically stored to file enabling a quick return to the correct setup requirements during the next run of the same product. Furthermore, any manual operations performed during setup can be "learned" by the control system and then repeated in an automatic, hence repeatable, fashion.

4.2 Increased Capability In addition to the increase in machine efficiency, the new work cell incorporates capabilities that expand the number of braided architectures that are possible to be manufactured. The integration of these capabilities represents a dramatic expansion of braid processing capabilities. As noted before, all of these capabilities can be executed in real time as the braid is manufactured, thereby improving the resulting quality.

4.2.1 No Limits to Fiber Orientation As stated above, a braided triaxial architecture is advantageous to composite structures since the likelihood of delamination is reduced, an increase in interlaminar strength and damage tolerance is provided, and fewer layers are required to achieve the mechanical properties needed. Therefore, the production of high quality braided triaxial architectures was a necessity for the success of Mantis. In order to avoid damage to the axial fibers and the resultant misorientation of fibers, control over fiber tension is automated in the work cell. This allows for straighter yarn paths and consistent tension, thereby guaranteeing consistent, effective triaxial architectures.

In addition to the control over axial fibers, A&P included an added feature of hoop winding which provides structural braids with additional benefits. The circumferential winding is an integral part of the braiding process offering:

1. the addition of a 90° reinforcement allowing for a quasi-isotropic architecture (0°, +/-45°, 90°). The construction of a 0°, +/-45°, 90° construction is shown in Figure 3.

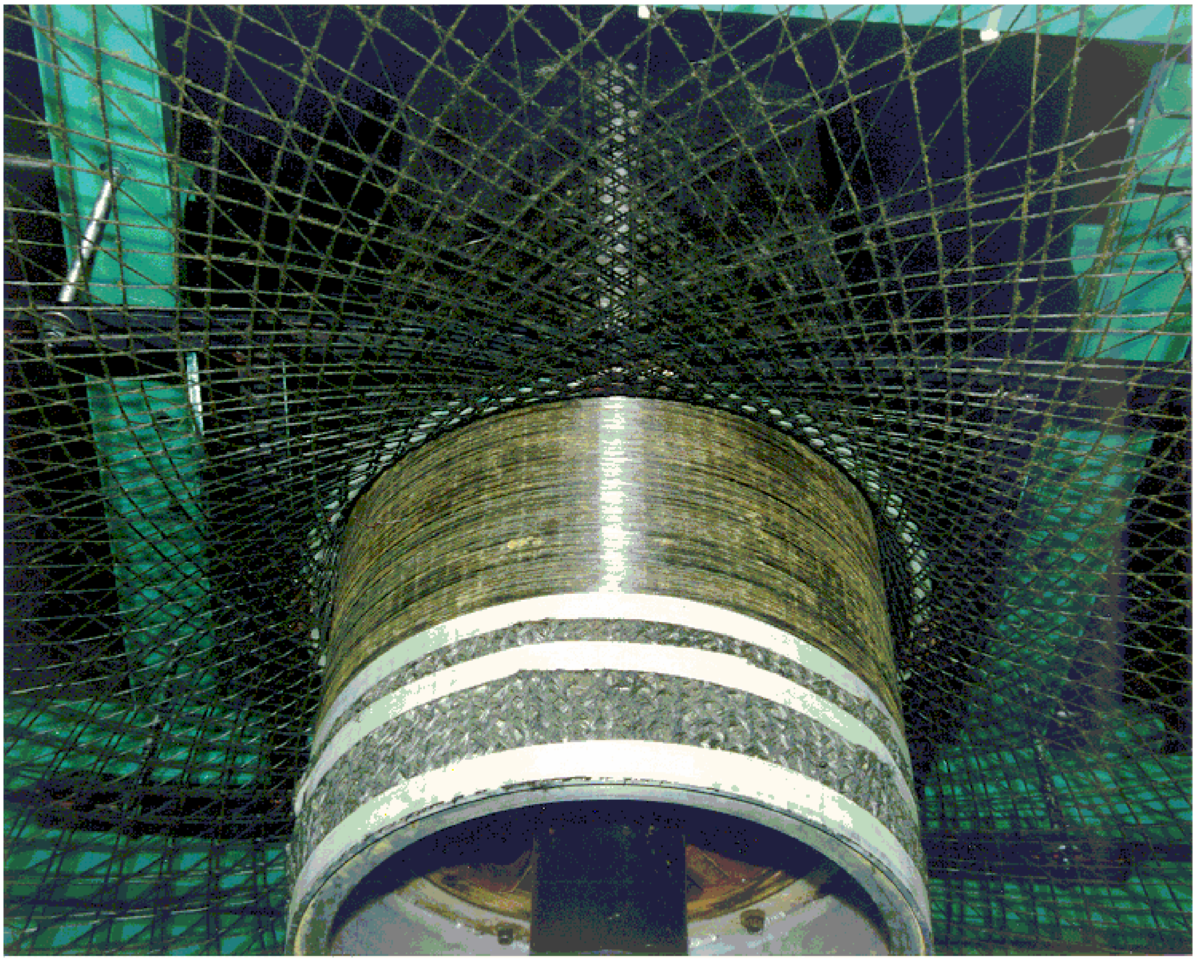


Figure 3

2. high degrees of hoop reinforcement for applications such as pressure vessels
3. localized circumferential stiffeners
4. anchor points for turnarounds within the braid preform
5. an inline method of debulking. The debulk effect of integral hoop wound plies is shown in Figure 4. Plies 3, 6 and 9 are wound and actually decrease the thickness of the preform as it is braided.

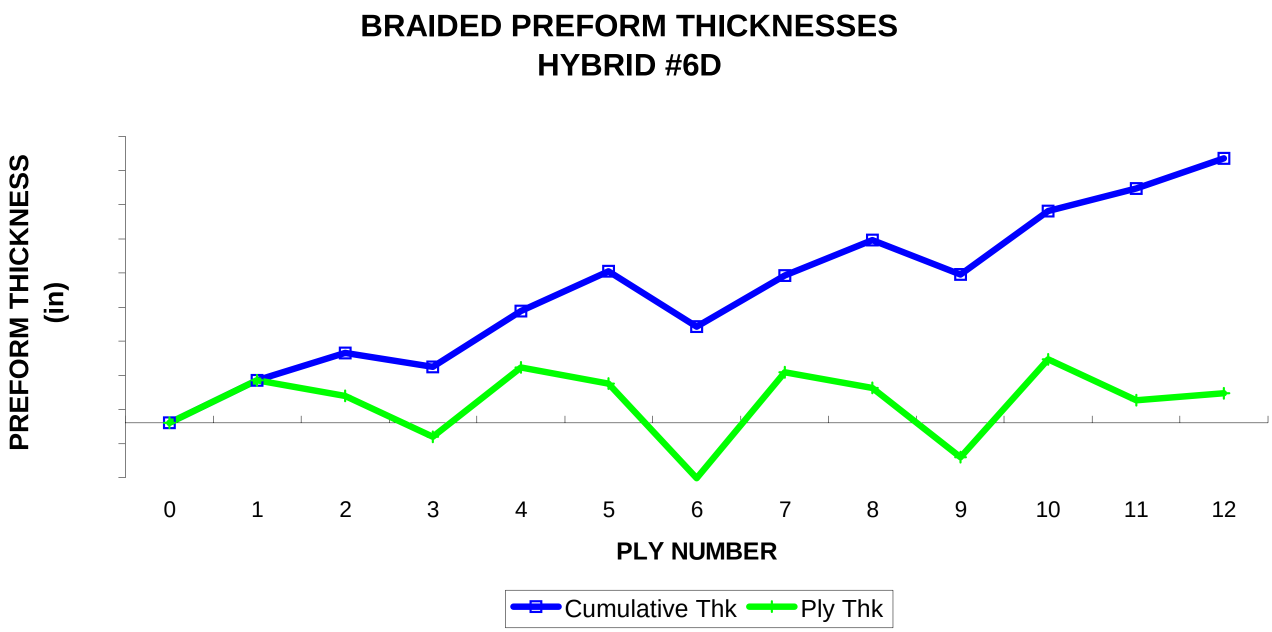


Figure 4

4.2.2 Exact Placement of Fibers All braiding parameters, motion controls, and end effectors employed by the overbraiding cell are integrated and controlled from one point of operation allowing for part-to-part repeatability. Individual tow bundles are controlled independently, like on standard braiding machinery, yet on Mantis the gearing is electronic allowing for a continuous run. Therefore if constant thickness is required on a part with changing cross-sections, the fiber angles of the individual tows can be changed without interrupting the braiding process, allowing for optimum fiber architectures.

4.2.3 Motion Control Furthermore, the Mantis is capable of manipulating a mandrel that is curved along its length in any direction and full rotation of the mandrel is possible. This allows for a uniform deposition of braid without interference from the contours of the mandrel.

4.2.4 Laser Projection System A laser projection system is also integrated in this system which allows for exact positioning of partial length plies. The cutting of these partial lengths is automatic guaranteeing exact termination points, and reducing unnecessary material usage by providing desired thicknesses.

Furthermore, one of the end effectors integrated into this work cell allows for the application of spray tackifier. This tackification process is helpful in the creation of partial length plies, since the tackifier prevents the individual fibers present at the cut edge of the ply from moving.

4.2.5 On-Line Inspection System Another feature of this work cell is its vision system which permits real time data collection on preform attributes such as fiber orientation, and detects defects like broken or damaged yarns. Similarly, a laser caliper is employed in real time fashion for measuring preform thickness. This dimensional data is collected and stored to file, offering a quick, qualitative method for assessing the results of process changes. Furthermore, since both data collection and data storage are automated, inspection records for each part are precise and guaranteed.

5. CONCLUSION

In conclusion, advancements in braiding technology have granted manufacturers of large composite structures the architectural benefits of braided reinforcements, as well as the economic efficiencies found with standard braiding. The use of braided reinforcements for large, structural preforms has increased dramatically over the past few years, signifying an eagerness to apply the structural advantages found with braid, as well as the cost efficiencies discovered in the fabrication of large composite parts. This rapid accumulation experience is very likely to lead to new braiding machinery concepts, and yet another generation of equipment for the braiding of large composite structures.

6. REFERENCES

1. Pierre J. Minguet, Mark J. Fedro, and Christian K. Gunther, “NASA Test Methods for Textile Composites,” July 1994.