Consolidation and Interweaving of Composite Members by a Continuous Manufacturing Process

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CONSOLIDATION AND INTERWEAVING OF COMPOSITE MEMBERS BY A CONTINUOUS MANUFACTURING PROCESS

by

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A thesis submitted to the faculty of

Brigham Young University

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GRADUATE COMMITTEE APPROVAL

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This thesis has been read by each member of the following graduate committee and by
majority vote has been found to be satisfactory.

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ABSTRACT

CONSOLIDATION AND INTERWEAVING OF COMPOSITE MEMBERS BY A CONTINUOUS MANUFACTURING PROCESS

Sarita Lee Kesler
Department of Civil and Environmental Engineering
Master of Science

Recent research and development has resulted in a working prototype of an automated process for manufacturing IsoTruss® and other innovative open lattice composite structures which yields faster, and more predictable and consistent parts, while automatically consolidating individual members. This machine is sufficiently versatile to manufacture any type of open lattice structure fabricated from filamentary composite materials.

The objectives of the research in this thesis were two-fold: (1) to validate this new process for making IsoTruss structures; and (2) to measure the compression strength and stiffness of specimens produced on the machine.
In order to accomplish the first purpose, various parts were manufactured on this prototype machine, including: a six-node IsoTruss structure with single outer longitudinal members, a three-longitudinal member section of an inner longitudinal IsoTruss structure with consolidated members, and a two-bay IsoTruss panel structure. By creating and running patterns to make these parts, the hypothesis that the machine will make any geometry of IsoTruss structure was validated.

The second objective of this research was accomplished by testing the compression strength and stiffness of specimens manufactured with this automated process. Buckling versus compression failure of members was examined by varying member aspect ratios. The effect of intersecting helical members was also explored, as was the effect of changing the number of braiding bobbins used to consolidate members.

Testing showed that increasing the number of braiders increases consistency of the braided sleeves and reduces scatter in the results. The ratio of helical to longitudinal tows at a joint is directly related to the percent decrease in member strength at the joint. Compression failure of individual members is the preferred method of failure, because this type of failure absorbs significantly more energy.

This research proves that the manufacturing process will produce even the most complex IsoTruss geometries, with the necessary consolidation of individual members. Findings also indicate that a few modifications -- such as improved bobbins, more reliable switches, more accurate pulling system, etc. -- will enable this automated process to produce composite lattice structures with superior mechanical properties.
ACKNOWLEDGMENTS

It would have been impossible to accomplish this task without the help and direction of several people. Dr. David W. Jensen has been instrumental in my success, providing me direction and support throughout my project. I am also greatly indebted to the work of former student employees of the Center for Advanced Structural Composites (CASC) who laid the foundation for this research. Specifically, I would like to thank Keith Davis for his hard work on the IsoTruss® machine and more importantly, for the mentoring he provided for me. Tyler Evans has been a great help from beginning to end of my research, for which I am very grateful. All the other CASC members I have worked with have broadened my understanding, helped me to succeed in my work, and befriended me throughout my time working with them. My thanks also goes to Dave Anderson and his crew for their help.

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1 INTRODUCTION

If I were required to guess off-hand, and without collusion with higher minds, what is the bottom cause of the amazing material and intellectual advancement of the last fifty years, I should guess that it was the modern-born and previously non-existent disposition on the part of men to believe that a new idea can have value.

- Mark Twain -

In our modern society, progress is highly valued. Individuals and organizations are constantly working toward the creation and development of new ideas. New technologies replace old ones, and the world becomes better because of it. In such a society, the search for new good ideas is eclipsed in importance only by the development and application of the best ideas. Sometimes good, or even great ideas, are never able to be fully utilized because of the lack of full exploration of that idea.

The IsoTruss® is an illustration of a great idea. It is an open lattice advanced composite structure whose high strength-to-weight ratio makes it an innovative technology with many possible structural applications, from aerospace to bridge building [Jensen 2000]. Like any great idea, however, it must be developed in order to be able to be generally understood and widely used. Much research has already been performed to
test the strength and to demonstrate some of the uses of IsoTruss structures, but there are still two major obstacles that prevent IsoTruss from being used to its full potential.

The first is the difficulty for potential users to effectively understand and analyze IsoTruss structures. This difficulty will disappear with the release of software that is currently in development. This software will graphically illustrate and analyze IsoTruss structures and therefore allow designers to more easily use IsoTruss technology in their structural designs.

The second, and perhaps greater, obstacle to the universal use of IsoTruss structures has been the lack of an efficient manufacturing process. Initially, IsoTruss structures were fabricated either by hand or by filament winding. Hand winding is a very time-consuming, and therefore costly, process. Filament winding is faster, but lacks the flexibility needed to create advanced IsoTruss geometries. In addition, filament wound structures still require consolidation of individual members by hand or by precision matched molding after winding. Recent research and development, however, has resulted in a model of an automated process for making IsoTruss structures which allows faster and more predictable and consistent manufacturing of IsoTruss structures. A prototype machine was built to demonstrate this process.

The research documented in this thesis has two primary purposes: (1) to validate this new process for making IsoTruss structures; and (2) to measure the mechanical properties of specimens produced on the machine. In order to accomplish the first purpose, winding patterns were developed and run to show various geometries that could be manufactured on the prototype machine. The second purpose was accomplished by manufacturing test specimens with this automated process and performing compression
tests on them. From these tests the strength of members produced on the machine could be validated. In addition, buckling versus compression failure of members was also examined by varying the member aspect ratios. The effect of a consolidating braided sleeve was explored, as was the effect of different sizes of interweaving members.

This chapter describes the geometry and terminology of IsoTruss structures. An overview of past research on IsoTruss structures is presented; specifically, research regarding automation of creation of IsoTruss members. The scope of the research for this investigation is also set forth.

1.1 INTRODUCTION TO ISOTruss STRUCTURES

The IsoTruss, as shown in Figure 1.1, is a composite lattice structure composed of longitudinal and helical members. Multiple longitudinal members run the length of the structure spaced equally along a circumference about a central axis. These members primarily resist axial and bending forces. The helical members spiral around the central axis in a piecewise linear fashion intersecting the longitudinal members; thereby, creating pyramids with nodes at their peaks. Helical members primarily resist transverse shear and torsional forces, while stabilizing the longitudinal members against buckling.

The geometry of a specific IsoTruss structure is completely defined by the number of nodes around the circumference, $N$, the outer diameter, $D$, the number of full bays, $N_b$, and the overall length, $L$. Given these values, the locations of all the nodes and joints can be described by basic equations. First, however, it is helpful to define some relevant terms and geometric relationships.
Nodes are defined as the outermost points where clockwise and counterclockwise helical members intersect furthest from the central longitudinal axis. Anti-nodes are the innermost points where clockwise and counterclockwise helical members intersect closest to the central axis. Transition nodes are defined as the intersections between inner longitudinal, clockwise helical, and counterclockwise helical members. A bay is one repeating unit (from node to node) in the longitudinal direction, and has a length, $b$. A crown is a partial bay at the end of an IsoTruss structure for structural close-out. Each of these parts of an IsoTruss structure is depicted in Figure 1.2.
The view in Figure 1.2 is of an IsoTruss structure projected such that the distance from top to bottom is $D \cdot \sin \Theta$ (where $\Theta$ is a unique reference angle specific to each nodal configuration), rather than the maximum outer diameter, $D$ (see Figure 1.3 for visual clarification).

A configuration reference angle, $\Theta$, is useful when defining the coordinates of the intersections of an IsoTruss structure. As shown in the following figure, the reference angle, $\Theta$, (in degrees) is calculated by a simple expression:

$$
\Theta = \frac{360}{N}
$$

(1.1)

Note from Figure 1.2 that:

$$
L = bN_b + b + l_i
$$

(1.2)
Also, note that $l_1$ is a function of $b$ and can be represented as:

$$l_1 = c_1 b$$  \hspace{1cm} (1.3)$$

or:

$$c_1 = \frac{l_1}{b}$$  \hspace{1cm} (1.4)$$
Thus $c_1$ represents the fractional portion of $b$ between upper and lower transition nodes. Solving Equation 2 for $b$ yields:

$$b = \frac{L}{N_b + c_1 + 1} \quad (1.5)$$

where $c_1$ will be shown to be:

$$c_1 = \frac{\cos \Theta}{1 + \cos \Theta} \quad (1.6)$$

The outer radius, $R$, is simply:

$$R = \frac{D}{2} \quad (1.7)$$

Figure 1.5 shows that:

$$\delta_1 = R \left( \frac{\cos \Theta}{\cos \Theta/2} \right) \quad (1.8)$$

$$\delta_2 = R \cos \Theta \tan \Theta/2 \quad (1.9)$$

$$\delta_3 = R \sin \Theta - \delta_2 \quad (1.10)$$

Equation 10 can be simplified as follows:

$$\delta_3 = R \left( \frac{1 - \cos \Theta}{\sin \Theta} \right) \quad (1.11)$$

From similar triangles:

$$\frac{l_2/2}{\delta_3} = \frac{b}{D \sin \Theta} \quad (1.12)$$

By substituting from Equation 14 and some algebraic manipulation, it follows that:

$$l_2 = \frac{2bR}{D} \left( \frac{1 - \cos \Theta}{\sin^2 \Theta} \right) \quad (1.13)$$
Figure 1.5 Dimensions Shown on an End View of a 6-Node IsoTruss Structure

Figure 1.6 Section A-A of Figure 1.5: (a) Projected View, and (b) In-Plane Members Only
Recalling that:

\[ D = 2R \]  \hspace{1cm} (1.14)

and:

\[ \sin^2 \theta = 1 - \cos^2 \theta \]  \hspace{1cm} (1.15)

The resulting equation for \( l_2 \) can be written as follows:

\[
\begin{align*}
   l_2 &= b \left( \frac{1 - \cos \Theta}{1 - \cos^2 \Theta} \right) \\
   l_2 &= b \left( \frac{1 - \cos \Theta}{(1 - \cos \Theta)(1 + \cos \Theta)} \right) \\
   l_2 &= b \left( \frac{1}{1 + \cos \Theta} \right)
\end{align*}
\]  \hspace{1cm} (1.16) (1.17) (1.18)

By defining \( c_2 \) as the fractional portion of \( b \) relating to \( l_2 \), this equation can be further simplified:

\[ l_2 = c_2 b \]  \hspace{1cm} (1.19)

where:

\[ c_2 = \frac{1}{1 + \cos \Theta} \]  \hspace{1cm} (1.20)

Noting that:

\[ l_1 + l_2 = b \]  \hspace{1cm} (1.21)

and solving for \( l_1 \):

\[
\begin{align*}
   l_1 &= b - b \left( \frac{1}{1 + \cos \Theta} \right) \\
   l_1 &= b \left( \frac{1 + \cos \Theta - 1}{1 + \cos \Theta} \right) \\
   l_1 &= b \left( \frac{\cos \Theta}{1 + \cos \Theta} \right) = c_1 b
\end{align*}
\]  \hspace{1cm} (1.22) (1.26) (1.23)
Proving that:

\[ c_1 = \frac{\cos \Theta}{1 + \cos \Theta} \] (1.6)

Note that \( h \) is the actual length of a helical member from node to node, as shown in Figure 1.6. Its value can be calculated as follows:

\[ h = \sqrt{b^2 + D^2 \sin^2 \Theta} \] (1.24)

As shown in Figure 1.7, similar triangles in the plane of two opposing helical and two longitudinal members, yields:

\[ \frac{l_1}{l_2} = \frac{h_1}{h_2} \] (1.25)

![Figure 1.7 Similar Triangles Demonstrated on a 6-Node Projected View](image)

Substituting in the values for \( l_1 \) and \( l_2 \) from Equations 21 and 27 yields:

\[ \frac{l_1}{l_2} = \frac{\cos \Theta}{1 + \cos \Theta} \] (1.26)

or, simplifying yields:
\[
\frac{l_1}{l_2} = \cos \Theta \tag{1.27}
\]

Therefore, from Equation 28:

\[
\frac{h_1}{h_2} = \cos \Theta \tag{1.28}
\]

Noting that:

\[
h_2 = h_1 + h_2 \tag{1.29}
\]

Solving for \( h_2 \) and substituting into Equation 31 yields:

\[
h_1 = h_2 \cos \Theta = \left( \frac{h}{2} - h_1 \right) \cos \Theta \tag{1.30}
\]

or:

\[
h_1 = h \left( \frac{\cos \Theta}{1 + \cos \Theta} \right) = c_1 \frac{h}{2} \tag{1.31}
\]

Substituting back into Equation 32 and solving for \( h_2 \) yields:

\[
h_2 = \frac{h}{2} \left( \frac{1}{1 + \cos \Theta} \right) = c_2 \frac{h}{2} \tag{1.32}
\]

It is useful to note that the local buckling lengths of the longitudinal members are \( l_1 \) and \( l_2 \), and the local buckling lengths of the helical members are \( h_1 \) and \( h_2 \). It should be further noted that the anti-node is only constrained by an opposing helical in the same plane, and therefore a more conservative approach is to use \( 2h_1 \), rather than \( h_1 \) as the unsupported buckling length. The correct boundary conditions of this member can be represented as a pin-supported member that is rotationally restrained at each end and with a spring in the center which represents the stiffness of the intersecting helical member.

The relationships developed above can be used to determine the coordinates of all of the nodes, anti-nodes, and transition nodes for an IsoTruss structure. They are most
simply defined in polar coordinates. The locations of all the nodes are defined, in polar coordinates \((r, \theta, z)\), as:

Node:

\[
\left( R, i\theta, (j + 1 - \frac{1}{2 + 2\cos\theta})b \right) \quad i = 1, 2, \ldots N \quad j = 0, 1, \ldots N_b
\]  

(1.36)

Anti-nodes have the same circumferential location as nodes. The coordinates, \((r, \theta, z)\), of anti-nodes are defined by:

Anti-node:

\[
\left( R\cos\theta, i\theta, (j + \frac{\cos\theta}{2 + 2\cos\theta})b \right) \quad i = 1, 2, \ldots N \quad j = 0, 1, \ldots N_b + 1
\]  

(1.37)

The inner longitudinal members are located circumferentially halfway between two adjacent nodes with the same longitudinal coordinate. They intersect the helical members where the clockwise helical members intersect the counterclockwise helical members (at a point other than a regular node or an anti-node) twice in each bay. The coordinates, \((r, \theta, z)\), of the transition nodes are defined by (1\textsuperscript{st} and 2\textsuperscript{nd} intersection locations, respectively):

Transition nodes:

\[
\left( \frac{R\cos\theta}{\cos\left(\frac{\theta}{2}\right)}, (i - \frac{1}{2})\theta, j b \right) \quad i = 1, 2, \ldots N \quad j = 0, 1, \ldots N_b + 1
\]  

(1.38)

\[
\left( \frac{R\cos\theta}{\cos\left(\frac{\theta}{2}\right)}, (i - \frac{1}{2})\theta, (j + \frac{\cos\theta}{1 + \cos\theta})b \right) \quad i = 1, 2, \ldots N \quad j = 0, 1, \ldots N_b + 1
\]  

(1.39)

Another type of IsoTruss structure has an outer grid of members in addition to the inner grid previously described. In this case, additional longitudinal members are placed at the nodes and additional helical members wrap around these outer longitudinal
members in a piecewise linear manner, as shown in Figure 1.8. This creates another node referred to as an outer node. Its polar coordinates are:

**Outer node:**

\[
\left( R \cos \frac{\Theta}{2}, (i-\frac{1}{2})\Theta, (j + \frac{\cos \Theta}{2 + 2 \cos \Theta})b \right) \quad i = 1, 2, \ldots N \quad j = 0, 1, \ldots N_b + 1
\]  

(1.40)

![Figure 1.8 IsoTruss Structure with Outer Longitudinal and Helical Members (Double Grid)](image)

End views of double-grid IsoTruss structures with 6, 8, and 12 nodes are shown in Figure 1.9.

![Figure 1.9 End View of Double-Grid IsoTruss Structure Configurations: 6-Node, (b) 8-Node, and (c) 12-Node](image)
IsoTruss structures need not have a full inner or outer grid. Several combinations of inner and outer members can be created. For example, a specific IsoTruss structure could comprise inner helical members and outer longitudinal members only, as shown in Figure 1.10 (a). Alternatively, another IsoTruss structure could have a set of inner longitudinal members, inner helical members, and outer helical members (see Figure 1.10 (b)). Various other combinations of inner and outer helical and longitudinal members could also be constructed. It should be noted, however, that inner helical members, which provide structural rigidity, are necessary for the structure to be correctly defined as an IsoTruss structure.

![Figure 1.10 Other Possible Configurations of IsoTruss Structures: (a) Outer Longitudinal Members and Inner Helical Members; and, (b) Inner Longitudinal Members with Outer and Inner Helical Members](image-url)
IsoTruss members are typically made from tows of carbon fiber, although fiberglass, aramid, boron, or any other type of fiber may also be used. A tow of fiber is a bundle of individual fibers. For example, a 12K tow of carbon fiber contains 12,000 individual carbon fibers. The fiber can either be pre-impregnated with resin, or coated with resin as the structure is being wound. The resin, when cured, serves primarily as an adhesive, to hold the fibers together and to transfer forces between fibers by shear. It is the fibers that resist the applied loads. Because of the geometry of IsoTruss structures, applied loads are resisted axially by the fibers, thereby taking advantage of the high tensile and compressive stiffness and strength of the fibers. The result is a high-strength, stiff, light-weight structure weighing as little as 9% of a steel structure of equivalent strength [Black 2003]. Indeed, its high strength-to-weight ratio is one of the most attractive features of IsoTruss structures. Additionally, IsoTruss structures are corrosion resistant because of their use of advanced polymer composite materials, and highly damage tolerant because of their multiple structural redundancy [Carroll 2006].

1.2 Previous Related Research

IsoTruss structures have been the subject of extensive research in the past [Ferrell 2005, Jones 2002, Keller, 2002, McCune 2001, Phillips 2001, Scoresby 2003, Weaver 1999, Winkel 2001]. The most significant, with regard to the current research, was performed by Hansen [2004]. In order to maintain the correct geometry of IsoTruss structures under loads, helical members are often interwoven with longitudinal members, or in other words the tows which make up a helical member pass through the tows of a longitudinal member. This reduces the straightness of the individual fiber paths and thus decreases their compressive strength. Hansen found that a highly interwoven joint
exhibits a 30.5% reduction in strength over a member without a joint. Whereas an encapsulated joint, in which the helical member tows simply pass around the longitudinal member, has only a 4.6% reduction in the strength of the longitudinal member.

Hansen also studied the effects of different consolidation methods on longitudinal compressive strength. He created a machine that consolidated individual members with a braided or a coiled sleeve, or by twisting the longitudinal member. He found that consolidating with a braided sleeve results in the highest quality joint. Therefore, the specimens manufactured for current research were consolidated exclusively with braided sleeves.

A composite braiding machine similar in concept to the one used in Hansen’s research is in use at Morton Thiokol Company [Freger 2005]. There are three groups of fiber carriers: one set that has a fixed position, which is used for axial reinforcement, and two other sets that carry braiding reinforcement, one that travels clockwise, and the other that travels counter-clockwise.

1.3 Scope of Research

The primary objective of this research is the validation of the new machine concept developed for the creation of IsoTruss structures. Various winding patterns were developed and run, with various samples created to show that the machine concept can, in fact, make a fully-consolidated IsoTruss structure.

In addition, compression tests were performed on specimens manufactured on the machine to address the following four issues: (1) the strength of straight members consolidated by braiding with the IsoTruss machine; (2) the degradation of strength of the straight members due to interweaving with intersecting helical members; (3) the effects
of different sizes of intersecting helical members on the strength of the longitudinal member; and, (4) the buckling versus compression failure of straight, braided members. By addressing each of these issues, many of the questions regarding the merits and value of the IsoTruss machine concept are satisfactorily resolved. Furthermore, the lessons learned in doing this research will guide future development of the IsoTruss machine concept thereby allowing continued advancement of the great idea that is IsoTruss.
2 THE ISOTRUSS MACHINE

In order to more efficiently and consistently produce all types of IsoTruss® structures, a machine concept was developed. This concept can also produce IsoTruss Panels, or any other variation of an open lattice structure, such as an isogrid structure [Isogrid Design Handbook 1975]. All previously existent automation concepts employed in IsoTruss structure manufacturing were based on traditional filament winding techniques. While filament winding can be used to make simple IsoTruss geometries, more advanced IsoTruss geometries cannot be created in this manner. Additionally, this technique inhibits integral consolidation of IsoTruss members. Thus, it became necessary to develop an entirely new manufacturing technique.

Development of the machine presented in this chapter preceded this research but a full description of the machine is included here because no other documentation exists. Improvements to the machine and process were part of this research and are included in this documentation.

A first conceptual prototype was developed to demonstrate the method for intersecting members in a continuous fabrication process. This prototype is pictured in Figure 2.1.
A second conceptual prototype was developed to demonstrate the continuous fabrication method of one-eighth of an 8-node IsoTruss. Methods for consolidation of the longitudinal member and for intersecting helical and longitudinal members were demonstrated with this prototype, pictured below in Figure 2.2.

The third prototype (shown in Figure 2.3) demonstrated the continuous fabrication process for a 6-node IsoTruss with outer longitudinal members and inner helical members. This specific geometry is significant because it cannot be produced by
filament winding techniques. The prototype developed shows the necessary movements of the fibers in order to create an IsoTruss.

![Picture of Conceptual Prototype III](image)

**Figure 2.3 Picture of Conceptual Prototype III**

A team of students used these prototypes to develop a concept that would not only produce IsoTruss structures, but would be easily modified to produce all sizes and types of open lattice structures. This patented technology is the only concept of its kind currently in existence.

The machine that was invented consists of a *braiding wall*, where the geometry of the IsoTruss is defined; a *support structure* onto which the wall is mounted; an *electrical system* which signals what is to happen on the wall; and, a *control system* which tells the wall what to do and when to do it. Each of these principal systems of the machine is further described in this chapter, as well as additional systems that must be further developed in order to fully automate the creation of IsoTruss structures, namely, a shape definition system, a pulling mechanism, and a transition system.
2.1 THE BRAIDING WALL

There are three important things that need to happen to wind an IsoTruss structure. First, the fibers on the braiding wall must move in such a way as to create the correct geometry of the IsoTruss structure desired; for simple IsoTruss structures, this can be done with a basic open braid. Secondly, interweaving must occur at the joints, or in other words, when a group of fibers crosses another group, the fibers must spread out and weave through each other. Finally, consolidation of individual IsoTruss members must occur. Hansen’s research showed that the most effective method of consolidation of members is braiding [2004]. Therefore, the new machine required the ability to braid a sleeve around individual members, to interweave fibers at the joints, and to braid the members in such a way that the IsoTruss geometry is created. This requires a machine that can concurrently perform two braiding actions and a weaving action. Such a machine is more complex than existing 3-D braiders.

There are many machines currently in existence that braid very effectively. Generally they consist of a circle of horn gears which move bobbins in a maypole braiding pattern. However, in order to create the geometry for any IsoTruss structure and braid individual members, a more complex system had to be developed. A two-dimensional grid, or “wall” of horn gears was conceptualized which would allow for movement of fiber held on bobbins in many different paths, theoretically allowing the machine to create any type or size of IsoTruss structure. The braiding wall is composed of several parts: 1) panels, which provide the track on which the bobbins can travel; 2) switches, which direct the bobbins along a specified track; 3) a drive system, which moves the bobbins along the track; and, 4) bobbins, which hold the fiber. Each of these components is described in further detail in this section.
2.1.1 **Panel Design**

The panel is the central structural component of the machine. Most of the parts of the machine are mounted to the panel in one way or another. Additionally, there are grooves in the panel which serve as the “railroad track” of the machine. The bobbins move along the track in the panel. The track is critical in determining the geometries that can be created on the machine. For these reasons, the panel is a key element of the machine.

In order to create the IsoTruss geometry, interweave the joints, and also consolidate the members, it is necessary for the bobbins to travel in braiding patterns, as well as weaving patterns, all on the same track system. To do this, a grid was created, over which the bobbins can travel in any direction. This was accomplished by creating an array of adjacent circular paths on which the bobbins travel, and switch between—the “railroad tracks” (see Figure 2.4). The switch mechanism, described in the following section (Section 2.1.2), determines whether the bobbin stays on the same circular path, or transfers over to the adjoining circle.

![Figure 2.4 Bobbin Paths Controlled by Switches](image-url)
By combining quarter circle path segments in different arrangements, a variety of paths can be created. In fact, any complex path can be represented by a combination of quarter circle segments. Therefore, a braiding wall of this type is capable of sending a bobbin along any desired path, thereby allowing the creation of any braiding or weaving pattern, or a combination of two or more braiding and/or weaving patterns on the same machine.

The total panel thickness was chosen as 1.0 inch (2.54 cm). Before defining the exact geometry of the track intersection, appropriate dimensions for the circles, which in reality represent horn gears, was established, as described below in Section 2.1.3. A diameter of 4 inches (10.16 cm) was chosen for the horn gear diameter. The track intersection was designed by placing two 3.80 inch (9.65 cm) outer diameter, 3.08 inch (7.82 cm) inner diameter circles spaced 4.00 inches (10.16 cm) apart center to center, as shown in Figure 2.5. Tangent guides were placed between the two circles to allow the bobbin to travel smoothly from one circle to the other, as shown in Figure 2.6. The unshaded portion of Figure 2.7 represents the portion of the panel that was machined to a depth of 0.5 inches (1.27 cm) to create the track for the bobbin to follow. Additionally, the section in the intersection of the circles was machined out completely to allow the switch to be inserted into the intersection and operated from the back of the panel.
Figure 2.5 Adjacent Track Alignment

Figure 2.6 Track Intersection Geometry

Figure 2.7 Machined Path in Panel
The panel built incorporates an array of five circles by five circles with intersections between each circle. Additionally, a 1.38 inch (3.51 cm) diameter hole was machined in the center of each circle for a drive shaft to come through the wall; the shaft being part of the drive system, which is discussed in Section 2.1.3. A completed panel is shown in Figure 2.8.

Figure 2.8 Picture of Modular Panel
2.1.2 **Switch Design**

As mentioned previously, the function of the switch is to determine which path the bobbin will follow. The bobbin can either continue along the circle it is on, or it can be transferred over to the adjacent circle; the position of the switch mechanism determines which will occur.

The design of the switch plugs can be easily understood by inspection of Figure 2.9. The fundamental part of the switch design consists of two plugs. When one is raised, the bobbin will travel a specified path. Alternately, if the other is raised, the bobbin will travel a different path. For example, if the x-plug (the center plug) is extended and the y-plug is retracted, the bobbin will continue along the circle it is currently on. Alternatively, if the y-plug is extended and the x-plug is retracted, the bobbin will proceed through the intersection and transfer to the adjacent circle. The two plugs are shown and labeled in Figure 2.10.

![Figure 2.9 Switch Design from Track Intersection](image-url)
A switch was designed that extends and retracts the plugs according to the path desired using a single action. The switch is powered by a magnetic push type tubular solenoid, series S-25-125-H. When the solenoid receives a signal voltage, it “fires,” or extends its plunger, until the signal is released. The force with which it fires depends on the voltage sent to the solenoid. A higher voltage delivers a larger force; however, a resulting loss in allowable “on” time occurs, which is, in effect, a reduction in duty cycle. Each solenoid draws 0.5 amps.

The solenoid plunger is screwed into the x-plug. Therefore, firing the solenoid pushes the x-plug out. The x-plug has one small pin on each side which fits into one end of a rocker arm. The other end of each rocker arm is attached to one of the two components of the v-plug. A pin goes through the rocker arms and the plugs and is fixed in the switch housing. The fixed location of the pin provides a pivot location for the
rocker arms, forcing the v-plug to retract when the x-plug extends and vice versa. This movement is illustrated in Figure 2.11. The two-piece switch housing also serves to provide a necessary horizontal reaction on the plugs. Because the rocker arms transfer forces eccentrically, the housing is needed to force the plugs to travel straight in and out. An assembled switch mechanism is pictured in Figure 2.12.

![Figure 2.11 Rocker Arm Schematic: a) neutral position; and, b) operational position with x-plug extended and v-plug retracted](image1)

![Figure 2.12 Picture of Assembled Switch Mechanism](image2)
When extended, the plugs must protrude enough to react against the bobbin blade (which is 0.4 inches (1.02 cm) tall), determining the path of the bobbin. However, the plugs cannot extend more than 0.5 inches (1.27 cm), because this would cause them to protrude beyond the panel surface, impeding bobbin movement. Therefore, the absolute maximum extension is 0.5 inches (1.27 cm) and the absolute minimum extension is 0.15 inches (0.38 cm). Several factors influence this minimum extension length, including the travel of the solenoid, the length of the solenoid shaft, and the depth the solenoid shaft is screwed into the x-plug. For this machine these factors were controlled to provide about 0.25 to 0.45 inches (0.635 to 1.143 cm) of extension.

By default, the v-plug is extended. When the solenoid receives an electrical signal, the shaft is pushed and the x-plug is extended. The v-plug is retracted due to the action of the rocker arms. When the electrical signal stops, a spring at the end of the shaft returns the x-plug to the retracted position and the rocker arms react to move the v-plug back to its original position. Figure 2.13 shows switches in the panel in their default position.

Figure 2.13 Picture of Switch Mechanism in Panel
2.1.3 Drive System Design

In order for the bobbins to move along the desired path, a drive system is required. The drive system consists of the following: 1) horn gears, which move the bobbin on the track; 2) drive shaft, which turns the horn gears; 3) drive gears, which turn the drive shaft; and, 4) a motor, which turns the gears. Each of these components is described in further detail below.

The horn gear and drive gear diameter was determined to be 4.0 inches (10.2 cm) as stated earlier. This dimension is a characteristic length of the machine because it directly affects all other dimensions in the plane of the wall. For example, the dimensions of the track on the panel are determined based on the size of the horn gear. Additionally, the size of the bobbin is limited to the space it can take up on the horn gear, since two bobbins on adjacent locations on the horn gear cannot overlap each other.

The purpose of the horn gear is to move the bobbin along the track. Therefore, the horn gear was designed with four mouths, or notches, at 90° intervals around the circumference, as shown in Figure 2.14. The bobbins are held in the horn gear mouths and move along the tracks by the turning horn gears.

Figure 2.14 Picture of Horn Gear
Each horn gear is turned by a drive shaft which is attached with a set screw. The shaft passes through a bearing in the panel and attaches, by means of a lock collar, to another bearing mounted in a bar behind the panel, referred to hereafter as a bearing bar (shown in Figure 2.15).

![Figure 2.15 Picture of Bearing Bars on Back of Machine](image)

The shaft has a 1.25 inch (3.175 cm) outer diameter and a 0.10 inch (0.254 cm) wall thickness. A press-fit bearing supports the front end of the shaft. The shaft is hollow to allow the longitudinal fiber payout shaft inside. The fibers for the longitudinal members are held on bobbins behind the machine on a bobbin rack, as shown in Figure 2.16. These fibers pass through the machine by way of the longitudinal payout shafts which are placed as needed through the centers of drive shafts (shown in Figure 2.17).
Figure 2.16 Picture of Longitudinal Fiber Bobbin on Rack on Back of Machine

Figure 2.17 Picture of Longitudinal Fiber Payout Shaft Extending from Front of Machine
Near the bearing bars at the back of the machine, a gear is attached to each shaft with a set screw (see Figure 2.18). A two-dimensional grid of gears turns the shafts, thereby turning the horn gears and allowing for movement of the bobbin. Figure 2.19 shows that the gears are connected by a chain to the motor.
2.1.4 BOBBINS

The bobbins are common braiding bobbins with an essential modification. Important components of the bobbin include the spool, which holds the fiber, and the sheave wheels. The sheave wheels allow the fiber to be removed from the spool and, together with the springs, allow some recoil to take-up loose fiber. A guide mechanism at the top of the bobbin prevents the fiber from wrapping around the bobbin or becoming otherwise entangled in an undesirable manner. The overall design of the bobbin is such that the bobbin holds the fiber with 2.5 pounds (11 N) of tension and allows up to 5 inches (12.7 cm) of fiber take-up.

Figure 2.20 shows the original bobbin and a bobbin with a modified base. The base of the bobbin was modified to facilitate integration with the track system on this machine. The critical changes in the bobbin base were in the blade at the base of the bobbin and the design of the plate above the blade.
As a horn gear turns with a bobbin in its mouth, the bobbin blade reacts against the track, guiding the bobbin along the desired path. A modified base was designed with a long, narrow blade (1.25 inch (3.175 cm) by 0.25 inch (0.635 cm)) so that the bobbin can be easily guided along the track by the movement of the horn gears. The length of the blade is important in order to bridge the gap in the track created when the v-plug is raised and allow the bobbin to transfer to an adjacent horn gear. The new blade design allows for easy travel of the bobbin along the track and across the switches.

The plate above the blade at the base was also redesigned to be larger, with a constant thickness of 0.125 inches (0.318 cm) and with a gradual chamfer on the edges to allow it to be held securely between the horn gear and the panel, as shown in Figure 2.21.

Figure 2.21 Picture of Bobbin on Horn Gears
Additionally, the sheave wheels were redesigned to work more effectively with pre-impregnated carbon tows on the bobbins. The inside width of the new sheave wheel is 0.25 inches (0.635 cm), large enough to allow a 12K carbon fiber prepreg tow to fit easily on the wheel. The new wheels were milled from Delrin in order to reduce sticking of the fiber to the bobbin.

2.2 Support Structure

The machine is mounted onto a custom-designed support structure. The primary function of this structure is to raise the machine off the ground, allowing easier access and creating additional space for wiring. Additionally, the support structure creates a location for the pulling mechanism (described later in Section 2.6) to react against the machine, since there is not enough space on the panels for this to happen.

The support structure is basically a table built from steel sections. Adjustable feet are mounted on the base to allow the machine to be leveled. On top of the table, four steel channels connect to the edges of the wall panels by steel angles. At the rear of the wall, these same channels are attached by angles to vertical bars which support the bearing bars. The bearing bars are horizontal bars across the back of the machine with holes containing bearings, into which the drive shafts are placed. The support structure is shown in Figure 2.22.

2.3 Electrical System

The electrical system has two main functions: 1) to provide power to the switches; and, 2) to receive and send signals in order to fire the switches at the correct time, set certain parameters for the motor, and control the emergency stop. The main components
required to accomplish this are the DC power supplies, the inverter, the relays, the PXI Chassis and cards, the SB-68 connector box, the wiring, the emergency stop, the mechanical and optical encoders, and the control program. Each of these components are described in greater detail in this section.

2.3.1 DC POWER SUPPLIES

A total of three power supplies are used to transmit signals and power the switches. A GW Instek® GPS-3030D DC power supply with a maximum voltage rating of 30 volts, shown in Figure 2.23, sends control signals to the inverter (described in Section 2.3.2), which in turn, controls the motor. The inverter requires control signals to be received at 24 volts.
The switches run off a Xantrex XHR 40-25 DC power supply (shown in Figure 2.24), which is rated at 0 to 40 volts output voltage and 0 to 25 amps output current. An adjustable voltage is used because the solenoids can transmit a higher force if a higher voltage is supplied. However, if a higher voltage is used, the solenoid has a lower duty cycle, or in other words, the solenoid, and in turn the switch, can be on a smaller percentage of the time. Therefore, it is advantageous to be able to adjust the voltage depending on force and duty cycle desired. For this research, the power supply was set to 30 volts, which allows one-quarter duty cycles. Since each switch draws 0.5 amps, the total current output limits the number of switches that can be fired at once to 50. However, the over-voltage protection has been set to allow only 28 switches to fire at any given time to protect the switches.

A third power supply is used to supply 5 volts to the relays and the mechanical and optical encoder. A GW Instek® GPS-1850D DC power supply with a maximum
Figure 2.24 Picture of Adjustable Voltage Power Supply

A voltage rating of 18 volts is currently being used at 5 volts (see Figure 2.25). The function of the relays is explained in Section 2.3.3.

Figure 2.25 Picture of Five Volt Power Supply to Relays
2.3.2 MD65 AC Drive (The Inverter)

The inverter is an MD65 AC Drive, shown in Figure 2.26. By changing the frequency of the power supplied to the motor, the inverter tells the motor what speed to run and whether to run in forward or reverse. Additionally, the inverter provides an output signal which is directly related to the torque of the motor. This signal is monitored because a sudden increase in torque is often indicative of a problem. Therefore, when the torque value rises above a certain threshold value, the control program automatically stops the machine.

![Figure 2.26 Picture of MD-65 AC Drive](image)

2.3.3 ER-8/16 Relays

The machine uses electromagnetic relays to control the solenoids and to send signals to the inverter. When a relay between the power supply and a solenoid receives a signal from the control program via the PXI-6508 cards, magnets close the switch and complete the circuit to the power supply, thereby firing the solenoid.
Two different configurations of relay boxes from National Instruments are used: the ER-16 and the ER-8, shown in Figure 2.27, with 16 and 8 relays per box, respectively. Each ER-16 is paired with an ER-8 for a total of 24 relays per pair. Six such pairs (a total of 144 relays) are used to control the three panel machine. Each box is powered by 5 DC volts, and connected to a ground.

![Figure 2.27 Picture of Relay Boxes Connecting to a SC-2054 Cable Adapter (right)](image)

Each pair of relay boxes is connected to a SC-2054 Cable Adapter, which is in turn connected to a 6508 card in the PXI chassis. This is demonstrated graphically in Figure 2.28. There are two 6508 cards in the PXI chassis. The second is connected to only one SC-2054 cable adapter.
The majority of the relays connect the solenoid power supply to the solenoids. However, six relays in one ER-8 are used to send signals to the inverter. When the relay closes, the power goes through the relay to the solenoid or the inverter.

2.3.4 PXI CHASSIS AND CARDS

The function of the PXI Chassis and Cards (pictured in Figure 2.29) is to interface between the computer and the electrical system of the machine. The PXI chassis has 8 slots. The first slot is connected to the controller (i.e., the computer). The other slots connect to other hardware. The second slot contains a PXI-6224 card, which is connected to the SCB-68 Shielded Connector Box, described in Section 2.3.5. The third and fourth slots contain PXI-6508 cards which connect to SC-2054 Cable Adapters, which are in turn connected to the relays, described above in Section 2.3.3. The other four slots are currently empty.
The PXI-6224 card is a multi-function data acquisition card that can send and receive both digital and analog signals. The PXI-6508 cards are configured to send digital signals.

2.3.5 SCB-68 Shielded Connector Box

The SCB-68 Shielded Connector Box pictured in Figure 2.30 serves primarily as an easy connector between the PXI-6224 card in the PXI Chassis and various signals, including the optical encoder, the mechanical encoder, the emergency stop, and the inverter for the motor.

2.3.6 Wiring

Most of the wiring is required for the switches. Each of the 132 switches is connected to a relay and to ground. As mentioned above, each pair of relay boxes
contains a total of 24 relays. The 24 wires from the relays are connected to a wiring hub in the back of the control rack (see Figure 2.31). There they are regrouped into sets of 20 and routed to the panels. Each panel has 40 switches in the interior intersections, so there are two sets of 20 on each panel. Additionally, there are 12 switches on the interfaces between the panels, which were wired with one set of wires. The switches are numbered accordingly.
2.3.7 **Emergency Stop**

An emergency stop button (Figure 2.32) has been provided to stop the machine in case of emergency. The wires to the inverter, which controls the motor, pass through the emergency stop. Three of these wires are connected to terminals inside of the emergency stop. When the emergency stop is pressed, the signals from these three wires are interrupted, stopping the motor. A fourth terminal in the emergency stop is connected to the PXI-6224 card and sends a signal to the control program that the emergency stop has been pressed. This stops the program.

![Figure 2.32 Picture of Emergency Stop](image)

2.3.8 **Mechanical Encoder**

The mechanical encoder, pictured in Figure 2.33, is used to indicate when the switches should fire. A set of four arms on a wheel are coupled to a drive shaft so that the wheel turns at the same rate as the horn gears. When one of the copper encoder arms touches the brush, the circuit is complete and a signal is sent to the control program.
Thus a signal is sent and a new set of switches fire every quarter turn of the horn gears.
The brush is powered with 5 DC volts from the 5 volt power supply. The arms are connected to the PXI-6224 through the SCB-68 shielded connector box.

2.3.9 Optical Encoder

The primary function of the optical encoder (Figure 2.34) is to measure the angle of rotation of the horn gears. This angle can be used, instead of the mechanical encoder, to indicate when the next set of switches should fire. Because it is a 12 bit encoder, the angle of rotation is represented by a number between 0 and 4095 ($2^{12} - 1$). Therefore, the reading is accurate to about 0.09°. This encoder is also powered by the 5-volt power supply and is connected to the computer through the PXI-6224 card and the SCB-68 connector box.
2.4 CONTROL PROGRAM

The theory behind the control program is quite simple. First, the program needs to tell the motor to turn on, which direction to run, and how fast to run. The most important function of the program is to tell the machine which switches to fire and when to fire them. In order to do this, the program must receive position feedback information from the encoders. The program also receives and responds to voltage signals from the inverter.

The program was written using LabVIEW version 7.1 because it interfaces automatically with the National Instruments hardware used on the machine. LabVIEW is a graphical programming tool created by National Instruments. The program consists of
a front panel, which is the user interface, and a block diagram, where the graphical programming is done.

A control array is used to tell the program which machine switches to fire and in what sequence. Each column in the array represents one switch and each row represents one time step, or a quarter turn of the horn gears. Ones and zeros are used to indicate if each switch should be fired in a given time step. For example, if the value in the first row and column is a 0, then the first switch will remain in its default position (v-plug extended) in the first time step. If, in the next row, there is a 1 in the first column, then during the second time step, the relay corresponding to the first switch closes. This closes the circuit, sending power to the solenoid and causing the first switch to fire, extending the x-plug. If there is a 0 in the first column on the third row, then the solenoid for the first switch will release after the second time step, returning the switch to the default position (the v-plug is extended) for the third time step. In this manner, the position of each switch is defined for each time step by the control array.

The mechanical encoder sends a signal to the control program when the horn gears have gone through a quarter turn, thereby indicating to the program that the next line of the control array (the next time step) should be executed. This causes a different set of solenoids to fire and release, changing the bobbin path. In this manner, the encoder and the control array work together to indicate to the machine which switches should fire when, allowing the machine to fire a new set of switches at each quarter turn of the horn gears.

The control array must contain exactly 136 columns and may contain as many rows as necessary. Columns 1 through 133 each represent one switch, except column
131, which is unusable because of a burned out relay. Columns 134 and 135 are currently not used. Column 136 is used for a programmed stop; when there is a 1 in column 136 the program stops the machine after the previous line. If neither the programmed stop, nor the user stops the program before the last line of the control array is reached, the program returns to the start of the array when it reaches the last row. Generally, this is the desired action since a repeating pattern is used to create the IsoTruss. However, it is sometimes useful to have the program stop at the end of an array. For example, when the bobbins are being placed on the machine before the actual winding begins. Creating the control array is explained more completely in Chapter 3.

On the front panel (shown in Figure 2.35) the user enters necessary information, can change certain parameters, and views output from the program. In order for the program to run, the user must enter the path for a text file containing a control array. Since the control array determines what the machine will make, this is the most important, and the only essential, user input. Other parameters that the user can define include the line in the array to start from, which is useful for testing new bobbin patterns, the limiting torque value, and the direction and speed of the motor. Another important control on the front panel is the stop button. When this button is pressed all the switches are released, the motor is turned off, and the program stops.

The front panel displays a lot of information to the user. The grid of LEDs on the bottom of the front panel represents the switches. When the program directs a switch to fire, the LED on the front panel corresponding to that switch lights up. The front panel also has an LED that lights up when the mechanical encoder arm is in contact with the encoder brush. The group of LEDs above the user input box tells the user which of
several possible issues caused the program to stop. The dial shows the torque value from the inverter. A sudden increase in this value represents a problem with the machine (e.g., gears jamming) and will cause the machine to stop if the limiting value in the input section is set correctly.

2.5 Shape-Definition System

The importance of the shape-definition system cannot be overlooked. The function of this system is to hold the fibers in the correct geometry until the part is cured. In the future, a system could be developed such that an infinite length of IsoTruss could
be created and cured. At this point in the research, relatively primitive forms of shape-definition are still being used.

Two types of mandrels were designed and built for this research. The first was built for the longitudinal member specimens without helical members passing through. The purpose of this mandrel was simply to hold the specimen in tension while it is removed from the machine, taken to the oven and cured. The mandrel was composed of 32 inch (81 cm) segment of c-channel with a pin and a clamp at each end (pictured in Figure 2.36). The specimen was braided around the pins and afterwards clamped at both ends to preserve tension.

![Figure 2.36 Picture of Mandrel for Longitudinal Members](image)

The second mandrel was slightly more complicated due to the need to hold helical members in the correct locations to create the correct transition node geometry. This was accomplished with two different v-shaped sections, one tall and one short. These v-sections are attached to 4.5 inch (11 cm) c-channel sections and bolted together as the specimen is being wound. After winding is complete, another section with a clamp is attached to each end and clamped down to maintain tension in the specimen. This mandrel with a specimen attached is shown in Figure 2.37.
2.6 Pulling Mechanism

The function of the pulling mechanism is to continuously pull members away from the wall, allowing continuous braiding of lattice structures. In more advanced machines of this type, the pulling system should be integral with the shape-definition system. However, for current research, a stand-alone manual pulling mechanism was designed to put tension on the fibers and allow consistent pulling of the fibers.

The pulling mechanism consists of a rolling attachment location, a hand-operated winch, and a base structure that provides stability. The attachment’s primary purpose is to provide a location where the fibers can attach to the pulling device and be held at a predetermined elevation. The pulling device is currently a simple boat winch that allows small discrete pulling movements. This allows measurable, nearly consistent pulling of the fibers, which is necessary to create consistent parts on the machine. The base structure holds the winch at the same elevation as the attachment location and attaches to
the machine, providing the reaction necessary to keep the pulling mechanism from sliding towards the machine due to tension in the fibers. The pulling mechanism is shown in Figure 2.38.

2.7 TRANSITION SYSTEM

The transition system is another vital part of the machine. The function of a transition system is to get the fibers from the bobbins on the machine onto the shape-definition system. The nature of this system depends entirely on the shape-definition system. Therefore, the transition system will be developed as more advanced shape-definition systems are developed. For this research, shape-definition was so simple that a transition system was not necessary.
3 WINDING PATTERNS

In order to create an IsoTruss® structure on a three-dimensional braiding machine, a pattern for the movement of the bobbins has to be conceptualized, developed, and communicated to the machine. As mentioned in Chapter 2, the winding pattern is communicated to the machine through a control array, which is input into the control program. The creation of this control array is the subject of this chapter. First, the description of the general process of creating the array is described. This is followed by a discussion of the modular programming concept used to develop the majority of the winding patterns. Finally, specific patterns developed to prove the validity of the IsoTruss machine concept are presented.

3.1 FROM CONCEPT TO CONTROL ARRAY

IsoTruss geometry has been described previously, as well as the general concept of the control array that the control program uses to wind the IsoTruss structure. What remains to be described is how one creates a control array to create an IsoTruss structure. This process involves several steps. First, a graphical representation is created which illustrates the location of each bobbin at each time step. Second, this graphical representation is translated into a binary array of ones and zeros. Last, this array is validated by computer representation and by testing on the machine.
For this research, PowerPoint was used to graphically represent the movement of the bobbins. A master slide, shown in Figure 3.1, was created which depicts a 5 by 15 array of circles, representing the horn gears. The arrows represent the direction the horn gears turn. Because the horn gears are all turned by one set of gears attached to one motor, the direction of rotation of the horn gears is not independent, and alternates from one gear to the next.

![Figure 3.1 Master Slide for Winding Pattern Creation](image)

A set of slides is created in which each individual slide represents one time step, or one-quarter turn of the horn gears. Circles are used to represent the locations of the bobbins. At each time step the bobbin will move, either to the next gear, or to the next position on the same gear. By moving the bobbins in specific patterns, and with certain motions relative to the other bobbins, specific geometries can be created. These patterns are described in more detail in the sections that follow.

The set of slides can be used to create the control array in Excel. Each column is labeled with the appropriate switch, and each line represents a time step. The slides are used to determine which switches must fire in each time step. When a switch needs to fire, a “1” is placed in the appropriate column and line, as shown in Figure 3.2. Then the
values in a separate sheet are set equal to the first sheet. Excel puts ones where there are ones and zeros in the cells that were empty on the first sheet (see Figure 3.3). When saved as a text file, this sheet becomes the control array.

As creation of the control program developed, this process was simplified and became more automated. A program developed in LabVIEW indicates the switches to be fired in each time step. The user interface is a set of LEDs that represent the switches. For each time step the user clicks on each switch that needs to fire. This program creates the associated control array and writes it to a text file. This can be used as a stand-alone program to create simple arrays or it can be used as a step in the creation of complex patterns using modular programming, as explained in Section 3.2.
The control array is validated using a simpler version of the control program which simply lights up LEDs for the switches that fire in each time step. A user who understands the machine and the control arrays can check to be sure that the control array triggers the right switches at the right time. The pattern can also be tested on the machine using bobbins holding spools with string. This ensures not only that the bobbins move along the desired path, but also that the planned movements actually create the desired structure.

3.2 A Modular Program

Though the process described above is relatively straight-forward, the implementation of the process to create patterns that will make parts of IsoTruss structures is a little more complicated. Several things must happen on the wall for an
IsoTruss to be made, including: 1) consolidating the longitudinal members with braided sleeves; 2) stalling and consolidating (with a braided sleeve or by twisting) helical members; 3) crossing helical members through other helical members; and 4) crossing helical members through longitudinal members. Each of these sub-patterns is developed independently and combined such that the timing works out (i.e., all the bobbins are in the right place at the right time) and no bobbins collide. Each of these sub-patterns is described in the following sections along with a description of how to combine these elements to create a complete winding pattern and control array.

The machine built for this project is not large enough to create and consolidate an entire 6- or 8-node IsoTruss structure. Therefore, this research focused primarily on a section of an IsoTruss structure. One longitudinal member with crossing helical members was made to represent one-eighth of an 8-node IsoTruss structure. Therefore, the patterns that follow are for the creation of this one-eighth section of IsoTruss structure.

3.2.1 **BRAIDING A SLEEVE AROUND THE LONGITUDINAL MEMBERS**

As mentioned previously, the section created on the current machine includes only one longitudinal member. Therefore, this longitudinal member was placed in the center of the wall. Although only one longitudinal member was created, nine longitudinal member payout tubes were used for the longitudinal member fibers to pass through in order to allow for maximum interweaving with the helical member fibers at the joint. The locations of the longitudinal payout shaft are represented by the orange dots in Figure 3.4.
Figure 3.4 Locations of Longitudinal Payout Shafts

The braiding bobbins travel around the longitudinal payout shafts in such a way that a full braid is created. The braiding pattern was based on a maypole braiding pattern in which half the bobbins travel in a clockwise direction, and the other half in a counterclockwise direction. The key is that each bobbin must alternate between being on the inside and on the outside of passing bobbins. For example, a given clockwise bobbin will pass a counter-clockwise bobbin on the outside; then it will pass another counter-clockwise bobbin, this time on the inside; and the pattern repeats itself. In this manner a full-braid is created.

On a circular braiding machine, this pattern is simple to create and almost an automatic result, given the correct number of horn gears and braiding bobbins. Since the machine developed for this project is a square arrangement of horn gears, the creation of a braiding pattern proved to be slightly more complicated. Aside from the necessity that one path allow for counter-clockwise movement, and the other clockwise movement, it is also necessary that the length of the counter-clockwise path be equal to the length of the clockwise path. In other words, the number of quarter-circle segments that make up the
two paths has to be the same so that the clockwise bobbins make a complete revolution in the same amount of time as the counter-clockwise bobbins.

Initially, a clockwise and a counter-clockwise path were created around the longitudinal tubes. This path, pictured below in Figure 3.5, proved to be a full braiding pattern when using four braiding bobbins. However, when eight braiding bobbins are used, this pattern produces a pseudo-braid in which the braiders travel outside, inside, inside, inside instead of outside, inside, outside, inside as in a full-braid.

In order to create a full-braid winding pattern that works for eight braiders, several possibilities were explored and some over-arching concepts were discovered. An example is used to illustrate these concepts.

The paths outlined above in Figure 3.5 are each a combination of 28 quarter circle segments and therefore take a total of 28 time steps. If eight braiding bobbins are desired, there will be four in each direction. The first step is to choose the initial locations of the bobbins such that all the bobbins traveling in one direction are on the outside, and the others are on the inside. The dark blue path is the counter-clockwise path. Let these dark blue counter-clockwise bobbins be on the outside first and the light
blue clockwise bobbins be on the inside. The initial locations do not have to be equally spaced; however, the simplest patterns are created by spacing the bobbins as equally as possible. One possible option is shown in Figure 3.6.

![Figure 3.6 Possible Initial Locations of Braiding Bobbins](image)

In order to check if the path works, it is necessary only to check the relative locations of the bobbins when the dark blue bobbins cross the light blue bobbins. This occurs at the half-way point between the initial bobbin locations shown in Figure 3.6. These new locations are shown in Figure 3.7.

![Figure 3.7 Crossing Locations of Braiding Bobbins](image)
In order for the braiding pattern to create a full braid, all of the dark blue bobbins must be on the inside of the light blue bobbins at this time step. As can be seen in Figure 3.7, this is not the case. Therefore, the starting locations chosen do not work for this braiding pattern. In actuality, no possible starting locations work for this braiding pattern. Therefore, a new pattern was conceptualized and is pictured in Figure 3.8. The process described above confirms that this pattern works for eight braiders. Note that this braiding pattern has the same number of time steps as that shown above, but works for eight braiders. The locations of the bobbins at each time step are shown in Appendix A.

Figure 3.8 Braiding Pattern for Eight Braiders

Once a braiding pattern has been developed, the array is written that creates this braided sleeve on the machine. This array can be used alone or combined with other arrays to create a more complex pattern. For this research, the braiding pattern was used alone and as one element of a complete winding pattern.
3.2.2 **Stalling and Consolidating Helical Members**

To create an entire IsoTruss structure a machine would hold a set of helical bobbins for each helical member. Each bobbin would hold one or more tows and the number of bobbins would depend on the total member size desired, as well as the degree of interweaving desired. There are two helical members for each node of an IsoTruss structure. For example, for an 8-node IsoTruss structure with inner longitudinal and inner helical members, there would be eight sets of helical bobbins traveling clockwise and eight sets of helical bobbins traveling counter-clockwise. Each set of helical bobbins begins between two longitudinal members. While a sleeve is being braided around the longitudinal members, the helical members are also being consolidated, either by a braided sleeve, or by twisting of the members. As mentioned previously, a braided sleeve is the best method of consolidation; however, because of limited space on the machine, sometimes twisting helical members is used as an acceptable alternative method of consolidation.

Unlike longitudinal members, the helical members must move around the machine and are therefore on bobbins. Because of this, consolidation of helical members is slightly more complicated and requires more space. The machine design does not allow a bobbin to stop at any time; it must always be going somewhere. For this reason, what is referred to as a stalling pattern was developed. Stalling is the method by which the helical bobbins are kept in a designated area. This is done for one of two reasons, either to wait for the desired length of braided sleeve to be created around a longitudinal member, or to allow a braided sleeve to be created around the helical member itself.

The most basic method for keeping the bobbins from traveling out of a designated area would be to simply send the bobbin around the same gear for the desired number of
time steps. However, this method twists the fiber tows, which reduces fiber straightness and could cause kinking and possibly break the individual fibers, reducing the member strength. Another method for stalling sends the bobbins around figure-eight patterns. This method successfully avoids twisting the individual fibers. These figure-eight paths take up more space; however, if oriented correctly, two bobbins can be placed on each figure-eight path and the paths may be adjacent. Therefore, the net space required to stall helical bobbins is one horn gear per bobbin.

For this research, space and the total number of bobbins were limited; therefore eight was the maximum number of helical bobbins used per helical member. Eight helical bobbins can be stalled on four figure-eight patterns. The stalling paths for each pair of helical bobbins are shown in Figure 3.9. The locations of each of the bobbins at each time step are shown in Appendix A.

The bobbins require eight time steps (quarter turn of the horn gear) to complete one iteration of the stalling pattern. This can be repeated any number of times necessary.
If the helical member is to be consolidated with a braided sleeve, a braiding pattern, similar to those described above, would be created around the helical member bobbins. Alternately, the helical members could be consolidated by twisting of the helical members. In this case, the helical members are sent around a continuous path that does not cross itself. Any such path will twist the fibers around each other. The twisting pattern used in this research is shown in Figure 3.10. For this research, helical members were consolidated by twisting, not by braiding, due to the limited number of bobbins.

![Figure 3.10 Helical Bobbin Twisting Pattern](image)

3.2.3 HELICAL MEMBERS INTERSECT EACH OTHER

Once the helical members have been consolidated for a time, the clockwise members cross the counter-clockwise members to form the nodes and anti-nodes. On a full-size machine, this process will be a simple progressive movement of the helical bobbins in their respective directions. In order to obtain maximum structural stability, interweaving at the node should occur. This is achieved by creating the paths of the individual bobbins such that they cross the paths of bobbins heading the opposite direction. Since the size of the machine used in this research is limited, only one
longitudinal member was created (and no nodes were created); therefore this part of the process was not necessary.

3.2.4 Helical Members Intersect Longitudinal Members

Once a sufficient length of the longitudinal member has been consolidated and the helical members have been consolidated with a crossing in the middle, the helical members can cross through the longitudinal members to create the transition nodes. Two sets of helical members cross each longitudinal member simultaneously from opposite directions, one clockwise set and one counter-clockwise set. The crossing pattern used in this research is shown in Figure 3.11. The locations of each bobbin at each time step for this process are shown in Appendix A.

3.2.5 Combining the Elements

For each of the elements described above, a winding pattern is created and used to write an array that can be used by the control program. Next, the elements must be combined in such a way that an IsoTruss with the desired geometry is constructed. This
requires a combination of the above elements in the correct order and with the correct timing.

During most of the winding pattern, the longitudinal tows are being consolidated by a braided sleeve. This element is repeated a number of times while the helical member bobbins are also consolidated either by braiding or twisting. If by braiding, the helical member bobbins stall while other bobbins form a braided sleeve around them. If by twisting, the helical members twist a designated number of times after which they stall while braiding of the longitudinal members is completed. Then, the helical members cross the longitudinal members. When all of this is complete, the entire process is repeated. Each time the process is carried out, one node or one anti-node is created. Performing this process twice creates one bay of the IsoTruss.

Because the correct lengths of members must be created and consolidated, timing is also an important consideration in creating the complete winding pattern. The number of times the braiding pattern and stalling pattern are repeated must be determined based on the desired geometry. Additional restrictions exist due to the nature of the machine and winding patterns. Because the gears are all meshed, all gears turn all the time. Therefore, no bobbin can wait, or stay in the same place. For this reason, the number of steps of each element of the winding pattern must be taken into consideration and accounted for when combining the elements to form a complete winding pattern array.

This somewhat complex process is accomplished in a spreadsheet. One worksheet is created for each element of the winding pattern. A program is created that combines the elements in the correct order, taking into account the timing requisite for each element. This program allows the user to enter the desired geometry and outputs the
array into another worksheet. The complete worksheet can be saved to a text file and used by the control program to make an IsoTruss structure. The code for the program used to create the arrays for the specimens used for this research is included in Appendix B.

3.3 PROOF OF CONCEPT

The specimens created and tested for this research prove the method employed by this machine works to create joints. However, in order to demonstrate that the machine will create any IsoTruss structure, a number of winding patterns were developed and run on the machine. The winding patterns for three of these structures are described below.

3.3.1 THREE LONGITUDINAL MEMBERS

In order to show that the machine can produce a traditional IsoTruss structure with inner longitudinal and helical members, a winding pattern was developed and tested for an IsoTruss section with three longitudinal members. This section includes nodes, anti-nodes, and transition nodes, which are all of the joint types in an IsoTruss structure. Therefore, because the machine can make this section of IsoTruss, it follows that a larger machine can make a complete IsoTruss structure.

For the three longitudinal member section, two longitudinal payout shafts were used for each longitudinal member. Any number of tows could be fed through these two shafts, so the size of the member is not limited. However, interweaving of the longitudinal and helical members at the transition nodes is limited. Two braiders were used to consolidate each longitudinal member. Each helical member was made with two helical bobbins. Helical members were consolidated by twisting them.
The elements of the winding pattern are the same as those described above, namely: 1) consolidation of longitudinal members by braiding; 2) stalling helical member bobbins; 3) twisting helical members; 4) crossing helical members; and, 5) interweaving helical members and longitudinal members. The initial position of all bobbins and the braiding paths for longitudinal consolidation are shown in Figure 3.12. The purple circles represent the braiding bobbins. The blue and green circles represent the helical member bobbins; green are traveling from left to right and blue from right to left. The patterns for each element of the winding pattern are included in Appendix A. The Excel program used to combine the elements correctly is included in Appendix B.

![Figure 3.12 Initial Positions of Bobbins for Three Longitudinal Winding Pattern](image)

3.3.2 SIX-NODE ISO TRUSS

The most complex IsoTruss geometry, and one that cannot be created continuously on most machines currently in existence, is one with outer longitudinal and inner helical members. Therefore, a winding pattern was developed that would create a 6-node IsoTruss with outer longitudinal and inner helical members. Because of the size of the machine, members could not be consolidated. However, other patterns
demonstrate that the members could be simultaneously consolidated, if a larger machine were used.

The desired IsoTruss geometry was achieved by sending each helical member outside a longitudinal member, then inside the next member, then outside, then inside, and continuing in this manner. Because of the limited space on the machine as well as timing requirements, the pattern developed is somewhat complex. A picture of a completed IsoTruss made from string is shown in Figure 3.13.

![Figure 3.13 Picture of 6-Node IsoTruss Made with Machine](image)

### 3.3.3 ISOTruss Panel

IsoTruss panel structures can also be made on the machine. A pattern was developed to make a simple two-bay IsoTruss panel. Two longitudinal payout tubes were
used for each longitudinal member and the members were consolidated with a coiled sleeve. The coiled sleeve is similar to a braided sleeve; however, only clockwise or counter-clockwise bobbins are used to consolidate members. The helical members were made with one bobbin per helical member and remained unconsolidated. With additional space, all members could be consolidated by braided sleeves and more bobbins could be used for each helical member. The initial position of each bobbin as well as the helical member bobbin path is shown in Figure 3.14. The red circles represent the bobbins used for consolidation of the longitudinal members. The blue circles represent the helical member bobbins. The locations of all the bobbins at each time step are shown in Appendix A.

Figure 3.14 Initial Bobbin Positions for IsoTruss Panel Structure
4 TESTING

In addition to developing a manufacturing process for IsoTruss® structures, one of the primary goals of this research was to validate the quality of parts made on the machine. Other questions regarding IsoTruss members and joints were also explored. A test matrix defined configurations of specimens to fabricate and test in order to resolve these questions. Specimens listed in the test matrix were manufactured and prepared for testing. Compression tests were performed on the specimens. Each step in this process is discussed in further detail in this chapter.

4.1 TEST MATRIX

Several questions about members and joints of IsoTruss structures were explored in this research, including the following:

1) How do longitudinal members created and consolidated on this machine perform compared to those manufactured by other methods in previous research?

2) Does the number of braiding bobbins affect the longitudinal member compressive strength?

3) How does the buckling failure of individual members compare to compression failure?
4) How does varying the number of tows composing the helical members affect the strength of longitudinal members?

Answers to these questions were found by creating specimens of different configurations and testing them in compression. The following configurations were made to address each question respectively:

1) Longitudinal members with no joints of varying diameters;
2) Longitudinal members with varying number of braiding bobbins;
3) Both long and short longitudinal members; and,
4) Longitudinal members with different numbers of intersecting helical members.

A test matrix was created that includes each of these configurations. The test matrix, shown in Table 4.1, includes 60 total specimens. For statistical purposes, five of each selected configuration were made and tested.

<table>
<thead>
<tr>
<th>Tows per Helical Member</th>
<th>Number of Braiding Tows</th>
<th>L &gt; L&lt;sub&gt;cr&lt;/sub&gt;</th>
<th>Number of Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A</td>
<td>8</td>
<td>Yes</td>
<td>5</td>
</tr>
<tr>
<td>N/A</td>
<td>8</td>
<td>No</td>
<td>5</td>
</tr>
<tr>
<td>N/A</td>
<td>4</td>
<td>Yes</td>
<td>5 5 5 5</td>
</tr>
<tr>
<td>N/A</td>
<td>4</td>
<td>No</td>
<td>5 5 5 5</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>No</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>No</td>
<td>5</td>
</tr>
</tbody>
</table>

A number of longitudinal member specimens with no joints were created. These were made by simply pulling a predetermined number of tows through the longitudinal payout tubes and braiding a sleeve around them with either four or eight braiding
bobbins. These members were made in long and short segments. The lengths of the long and short specimens were determined such that the long specimens would fail in buckling and the short specimens would fail in compression. These lengths were determined by first calculating the load at strain failure as follows:

\[ P = \varepsilon_f E A \]  
(4.1)

where the strain at failure, \( \varepsilon_f \), and the modulus of elasticity, \( E \), used were those obtained by Hansen for braided specimens without joints [2004]. These values are:

\[ \varepsilon_f = 0.0103 \text{ in./in. (cm/cm)} \]  
(4.2)

\[ E = 17.6 \times 10^6 \text{ psi (121 GPa)} \]  
(4.3)

The theoretical buckling length, \( L_{cr} \), was calculated at this load using Euler’s buckling equation:

\[ L_{cr} = \frac{\pi \sqrt{EI}}{P} \]  
(4.4)

The long specimens were made longer than the theoretical buckling length to ensure buckling failure would occur, and the short specimens were cut shorter than the theoretical buckling length to ensure that compression failure would occur.

Longitudinal members were also created with helical member tows passing through them, representing one transition node of an 8-node IsoTruss with a 16.25 inch (41.3 cm) outer diameter and an 8.0 inch (20.3 cm) bay length. These were made with an interwoven joint, where the helical member bobbins weave through the longitudinal member payout shafts, causing the helical member tows to interweave with the longitudinal member tows. The number of tows making up the helical members was also varied.
All specimens were manufactured using TCR Composites pre-impregnated fiber. T300C-12K-200NT carbon fiber, impregnated with UF3325-95 room-temperature storage resin (lot number T10311-07, spool 33, manufactured 11/03), was used for longitudinal members. The helical members, as well as the braided sleeves, were fabricated from Kevlar-49-4560 fiber impregnated with UF3330-100 braidable resin (lot number T20510_06, spool 1).

4.2 SPECIMEN MANUFACTURING AND PREPARATION

The manufacture and preparation of the test specimens listed in the test matrix involved several steps, including: (1) machine set-up; (2) winding the specimen on the machine; (3) curing the part; (4) preparing the part for testing; and, (5) measuring the properties of the specimen. Each of these steps is described in further detail in this section.

4.2.1 MACHINE SET-UP

Machine set-up involved winding spools with fiber and getting the bobbins into position. Spools were wound with tows of carbon fiber by hand and placed on bobbins behind the machine. These tows were fed through the longitudinal member payout tubes and attached to the pulling mechanism.

Bobbins for helical member tows and braiding tows were fed onto the machine from the sides. In order for all the bobbins to arrive at their correct positions at the same time, the bobbins had to be fed onto the machine at designated time steps. The pattern developed to move the bobbins into place for the specimens with intersecting helical
members is included in Appendix A. The helical and braiding bobbins were loaded with spools of Kevlar fiber and the tows were attached to the pulling mechanism.

4.2.2 WINDING THE SPECIMEN

Fabrication began by opening the correct winding array in the control program and running the program. The bobbins follow the paths determined by the control array to create the desired part. It is only necessary for the user to crank the winch on the pulling mechanism to advance the part. The process of pulling is still relatively unsophisticated in that the user watches the braiding of the part to determine when full coverage is achieved. At that point, it is time to advance the part and let the braiding continue.

In order to cure the part in an oven, the part must be held in tension. This is done by attaching the part to a mandrel as the part is being wound. When winding of the part is complete, the mandrel is clamped down onto the part, and the part is removed from the machine. The part is ready to be cured.

4.2.3 SPECIMEN CURING

Curing was performed in a Quincy Lab, Inc. bench oven model 21-350E with a programmable process controller. The controller allowed for specific control of the curing cycle. The resin systems for both the carbon fiber and the Kevlar fiber require a 5°F (2.8°C) per minute ramp up to 310°F (154°C), followed by one hour at 310°F (154°C), and a 5°F (2.8°C) per minute ramp cool down to 150°F (66°C). The oven used was able to closely approximate this cycle, as illustrated by the following figure (Figure 4.1 Curing Cycle). This figure shows the desired curing cycle, and the temperature
readings from the oven controller and from a thermometer. The chart shows that the oven reading is not always completely accurate, but sufficient to approximate the desired curing cycle.

![Figure 4.1 Curing Cycle](image)

4.2.4 Specimen Preparation

The cured specimens were removed from the mandrel and cut to the appropriate lengths. As noted above, the lengths of the specimens were calculated such that the desired failure mode, compression or buckling, would result from compression tests. In order to achieve a smooth cut, perpendicular to the neutral axis, and avoid delamination, a LECO® VC-50 diamond blade chop saw was used (see Figure 4.2). Each cut took approximately two minutes.
The cut specimens were mounted in the test fixtures. The test fixtures were designed to apply a compression load through the end of the specimen. In order to achieve this, the specimens had to be cut perpendicular to the neutral axis, and the load had to be applied through a smooth surface. A three piece test fixture was designed that would ensure this.

A steel base piece was used to apply the load. An aluminum mounting piece was attached to the base piece to hold the specimens in their designated location. Between the base piece and the mounting piece a hardened steel shim was placed to prevent yielding of the base piece and ensure the load was applied uniformly to the entire specimen. The three pieces of the test fixture are shown in Figure 4.3.

The specimen was mounted into the aluminum mounting piece, making sure that the end of the specimen was flush with the bottom of the mounting piece. The mounting piece was bolted to the shim and the base piece. The load was applied through the base
piece, which was slightly wider than the shim and aluminum piece to avoid improper introduction of loads into the specimen. A specimen mounted in the test fixture is shown in Figure 4.4.

4.2.5 **Measuring Specimen Properties**

The cross-sectional area of each specimen was measured in order to correctly calculate the ultimate stress. Although several specimens were cut from each part, the
area and fiber volume fraction were calculated just once for each part. A small sample section was taken from each part and measurements were taken on the sample.

The area was calculated by taking a picture of the end of a sample at 10X magnification with an Olympus SZX12 microscope. PAX-it!™ Software captured the picture and was used to adjust the image. The dark portion of the picture was highlighted and the area was calculated (see Figure 4.5).

![Figure 4.5 Pictures for Area Calculations: (a) 10X Picture, (b) Highlighted Area](image)

In order to calculate the fiber volume fraction, it was first necessary to encapsulate the end of a sample in 2-ton Devcon® epoxy. Next, this end section was polished with a LECO® Spectrum System 2000 polisher. In order to get the quality necessary for accurate measurements, a progression of 320 grit, 600 grit, 1200 grit, and finally 1200 fine was used. The fiber volume fraction was calculated by taking pictures of various sections of the sample at 50X magnification with an Olympus GX51 microscope. PAX-it!™ Software was used to adjust the image, highlight the fibers, and calculate the percent of total area that is highlighted, or fiber volume fraction.
4.3 TESTING PROCEDURE

Testing involved set-up, data acquisition, and afterwards, data reduction. Each of these steps is explained in further detail in this section.

4.3.1 TEST SET-UP

Testing was done with an MTS Testing Machine, model number 244.41, with a 110 kip capacity load cell, model number 661.23A-02. The specimens, mounted in test fixtures, were held in the testing machine using hydraulic wedge grips. The load was transferred through shear to the test fixture, through compression to the specimen. The specimens were loaded at a rate of 0.007 in./min. (0.0178 cm/min.) to failure. The testing machine was controlled with MTS TestStar software.

4.3.2 DATA ACQUISITION

An MTS Extensometer, model 634.12E-24, measured the strain. MTS TestWare data acquisition software reported displacement, time, load, and strain. This data was written to a file which could be used later for calculations.
4.3.3 **Data Reduction**

The data from the file created by the TestWare software was added to a worksheet in an Excel file. The data was consolidated using a variation of a macro written by Jones [2000]. The modified macro made calculations from the data, consolidated the number of data points, added force-displacement and stress-strain diagrams, and reported the ultimate strength and modulus of elasticity on a separate summary sheet. The code for this macro is included in Appendix B.
5 RESULTS

This chapter presents the results of experimental work performed in this research. The statistical analysis performed on the data set is briefly described. Numerical results of compression testing of specimens failed in buckling and in compression are presented. The properties of the specimens are also included.

5.1 STATISTICAL ANALYSIS

Not every specimen performs exactly the same. However, statistically, if a large number of tests are performed, the majority of specimens will have properties similar to the mean. It is necessary to note, however, that some specimen properties may not be similar to the mean; this specimen is referred to as an outlier. Therefore, in order to find the approximate value of the mean with a limited number of samples, it is necessary to eliminate the results from any outliers that would skew the data. For this research, Chauvenet’s criterion was used to determine if any data points were outliers.

Chauvenet’s criterion is based on the probability of any point being an outlier. If $n$ measurements are taken, the probability of any measurement deviating far from the mean is not likely more than $1/n$. Chauvenet’s criterion is actually more restrictive. It states that if the probability of a measurement being a particular deviation from the mean is less than $1/2n$, that measurement can be eliminated. In other words, it is likely an outlier and would skew the data if it were considered [Holman 1989].
For this research, five specimens were manufactured and tested for each configuration. For five data points, the ratio of maximum acceptable deviation to standard deviation is 1.65, according to Chavenet’s criterion [Holman 1989]. For each set of specimens this ratio was calculated for both the ultimate strength and the modulus of elasticity. The average, \( x_m \), was calculated as follows:

\[
x_m = \frac{\sum_{i=1}^{n} x_i}{n}
\]

(5.1)

where \( n \) is the number of measurements taken (\( n = 5 \) in this research). The unbiased or sample standard deviation, \( \sigma \), is generally used when there are less than 20 measurements [Holman 1989]:

\[
\sigma = \left[ \frac{\sum_{i=1}^{n} (x_i - x_m)^2}{n-1} \right]^{1/2}
\]

(5.2)

The deviation of the sample from the mean is:

\[ d_i = x_i - x_m \]

(5.3)

According to Chauvenet’s criterion, as noted above, for five measurements, the ratio of the deviation of the sample to the standard deviation must be less than 1.65; or,

\[ \left| \frac{d_i}{\sigma} \right| \leq 1.65 \]

(5.4)

These calculations indicated that no measurements could be rejected from those data sets based on Chauvenet’s criterion.
5.2 RESULTS FOR SPECIMENS FAILED IN BUCKLING

This section presents the measured properties and the results of compression tests of each specimen failed in buckling. The properties measured were area and fiber volume fraction. From the area, the moment of inertia of a circular cross-section was calculated as follows:

\[ I = \frac{4A}{\pi} \]  

(5.5)

The results reported include the ultimate strength, ultimate stress, and modulus of elasticity, and buckling factor, \( k \), for each specimen. The buckling factor is calculated as follows:

\[ k = \frac{\pi}{L} \sqrt{\frac{E}{P_{cr}}} \]  

(5.6)

The specimens are organized in sets based on the number of tows.

5.2.1 9-TOW LONGITUDINAL MEMBER

The buckling specimens with nine longitudinal tows were all cut from one part. The measured area, fiber volume fraction, and moment of inertia are listed in Table 5.1.

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>9_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Tows</td>
<td>9</td>
</tr>
<tr>
<td>Area [in.(^2) (cm(^2))]</td>
<td>0.0100 (0.0646)</td>
</tr>
<tr>
<td>Fiber Volume Fraction</td>
<td>60%</td>
</tr>
<tr>
<td>Moment of Inertia [in.(^4) (cm(^4))]</td>
<td>7.98E-06 (3.32E-04)</td>
</tr>
</tbody>
</table>

Figure 5.1 shows the force-displacement diagram for each nine-tow specimen failed in buckling, as well as a curve that represents the average of all the specimens.
Table 5.2 gives the measured length, ultimate strength, and modulus of elasticity of each specimen, and the calculated ultimate stress and buckling factor.

Table 5.2 Summary of 9-Tow Buckling Specimens Results

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>Length, L [in. (cm)]</th>
<th>Ultimate Strength, F [lbf (N)]</th>
<th>Ultimate Stress, ( \sigma_u ) [ksi (MPa)]</th>
<th>Modulus of Elasticity, E [ksi (GPa)]</th>
<th>Buckling Factor, k</th>
</tr>
</thead>
<tbody>
<tr>
<td>9_3_1</td>
<td>2.00 (5.08)</td>
<td>769.2 (3422)</td>
<td>76.80 (529.2)</td>
<td>15960 (110.0)</td>
<td>-0.45 0.644</td>
</tr>
<tr>
<td>9_3_2</td>
<td>2.08 (5.28)</td>
<td>648.5 (2885)</td>
<td>64.75 (446.1)</td>
<td>26400 (181.9)</td>
<td>1.64 0.870</td>
</tr>
<tr>
<td>9_3_3</td>
<td>2.04 (5.19)</td>
<td>720.9 (3207)</td>
<td>71.98 (495.9)</td>
<td>19400 (133.6)</td>
<td>0.24 0.717</td>
</tr>
<tr>
<td>9_3_4</td>
<td>2.09 (5.30)</td>
<td>645.0 (2869)</td>
<td>64.40 (443.7)</td>
<td>13930 (96.01)</td>
<td>-0.86 0.631</td>
</tr>
<tr>
<td>9_3_5</td>
<td>2.07 (5.26)</td>
<td>658.8 (2931)</td>
<td>65.78 (453.2)</td>
<td>15400 (106.1)</td>
<td>-0.56 0.660</td>
</tr>
<tr>
<td>mean</td>
<td>688.5 (3063)</td>
<td>68.74 (473.6)</td>
<td>18220 (125.5)</td>
<td>0.704</td>
<td></td>
</tr>
<tr>
<td>standard deviation</td>
<td>54.62 (242.9)</td>
<td>5.453 (37.57)</td>
<td>4991 (34.39)</td>
<td>0.098</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.9%</td>
<td>7.9%</td>
<td>27.4%</td>
<td>13.9%</td>
<td></td>
</tr>
</tbody>
</table>
5.2.2 18-TOW LONGITUDINAL MEMBER

The eighteen-tow buckling specimens were all cut from the same part. Table 5.3 lists the properties of this part. The results of compression tests on the specimens are shown in Figure 5.2 and summarized in Table 5.4.

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>18_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Tows</td>
<td>18</td>
</tr>
<tr>
<td>Area [in.² (cm²)]</td>
<td>0.0204 (0.132)</td>
</tr>
<tr>
<td>Fiber Volume Fraction</td>
<td>61%</td>
</tr>
<tr>
<td>Moment of Inertia [in.⁴ (cm⁴)]</td>
<td>3.31E-05 (1.38E-03)</td>
</tr>
</tbody>
</table>

Figure 5.2 Force-Displacement Diagram for 18-Tow Buckling Specimens
Table 5.4 Summary of 18-Tow Buckling Specimens Results

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>Length, L [in. (cm)]</th>
<th>Ultimate Strength, F [lbf (N)]</th>
<th>Ultimate Stress, ( \sigma_u ) [ksi (MPa)]</th>
<th>Modulus of Elasticity, E [ksi (GPa)]</th>
<th>Buckling Factor, k</th>
<th>d/( \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>18_2_1</td>
<td>3.97 (10.1)</td>
<td>1214 (5401)</td>
<td>59.55 (410.3)</td>
<td>11000 (75.76)</td>
<td>-1.60</td>
<td>0.435</td>
</tr>
<tr>
<td>18_2_2</td>
<td>3.95 (10.0)</td>
<td>1293 (5753)</td>
<td>63.44 (437.1)</td>
<td>17400 (119.9)</td>
<td>1.04</td>
<td>0.534</td>
</tr>
<tr>
<td>18_2_3</td>
<td>3.97 (10.1)</td>
<td>1173 (5216)</td>
<td>57.52 (396.3)</td>
<td>15280 (105.3)</td>
<td>0.16</td>
<td>0.522</td>
</tr>
<tr>
<td>18_2_4</td>
<td>3.96 (10.0)</td>
<td>1255 (5585)</td>
<td>61.58 (424.3)</td>
<td>14520 (100.1)</td>
<td>-0.15</td>
<td>0.495</td>
</tr>
<tr>
<td>18_2_5</td>
<td>3.96 (10.1)</td>
<td>1042 (4634)</td>
<td>51.09 (352.0)</td>
<td>16230 (111.9)</td>
<td>0.56</td>
<td>0.574</td>
</tr>
<tr>
<td>mean</td>
<td></td>
<td>1195 (5318)</td>
<td>58.64 (404.0)</td>
<td>14890 (102.6)</td>
<td>0.512</td>
<td></td>
</tr>
<tr>
<td>standard deviation</td>
<td>97.11 (431.9)</td>
<td>4.763 (32.82)</td>
<td>2427 (16.72)</td>
<td>0.051</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.2.3 27-TOW LONGITUDINAL MEMBER

Two sets of specimens were made with 27 tows: one set with four braiding bobbins (the same number as all other parts); and, another set with eight braiding bobbins. For each set of specimens, two parts were made. Table 5.5 and Table 5.6 give the properties of the two parts made with four braiding bobbins. The force-displacement diagrams for these specimens are shown in Figure 5.3. The results for the specimens cut from these parts are contained in Table 5.7.

Table 5.5 Part 27(4)_2 Properties

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>27(4)_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Tows</td>
<td>27</td>
</tr>
<tr>
<td>Area [in.(^2) (cm(^2))]</td>
<td>0.0319 (0.206)</td>
</tr>
<tr>
<td>Fiber Volume Fraction</td>
<td>56%</td>
</tr>
<tr>
<td>Moment of Inertia [in.(^4) (cm(^4))]</td>
<td>8.09E-05 (3.37E-03)</td>
</tr>
</tbody>
</table>

Table 5.6 Part 27(4)_3 Properties

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>27(4)_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Tows</td>
<td>27</td>
</tr>
<tr>
<td>Area [in.(^2) (cm(^2))]</td>
<td>0.0320 (0.206)</td>
</tr>
<tr>
<td>Fiber Volume Fraction</td>
<td>55%</td>
</tr>
<tr>
<td>Moment of Inertia [in.(^4) (cm(^4))]</td>
<td>8.14E-05 (3.39E-03)</td>
</tr>
</tbody>
</table>
Figure 5.3 Force-Displacement Diagram for 27-Tow Buckling Specimens Consolidated with 4 Braiding Tows

Table 5.7 Summary of 27-Tow Buckling Specimens Results (4 Braiders)

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>Length, L [in. (cm)]</th>
<th>Ultimate Strength, F [lbf (N)]</th>
<th>Ultimate Stress, $\sigma_u$ [ksi (MPa)]</th>
<th>Modulus of Elasticity, $E$ [ksi (GPa)]</th>
<th>Buckling Factor, $k$</th>
<th>d/\sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>27(4)_2_1</td>
<td>3.83 (9.74)</td>
<td>1931 (8591)</td>
<td>60.57 (417.3)</td>
<td>14700 (101.3)</td>
<td>-1.05</td>
<td>0.645</td>
</tr>
<tr>
<td>27(4)_2_2</td>
<td>4.02 (10.2)</td>
<td>1714 (7625)</td>
<td>53.75 (370.4)</td>
<td>14780 (101.8)</td>
<td>-1.02</td>
<td>0.655</td>
</tr>
<tr>
<td>27(4)_3_1</td>
<td>4.02 (10.2)</td>
<td>1600 (7119)</td>
<td>50.04 (344.8)</td>
<td>20500 (141.3)</td>
<td>1.12</td>
<td>0.801</td>
</tr>
<tr>
<td>27(4)_3_2</td>
<td>4.03 (10.2)</td>
<td>1731 (7702)</td>
<td>54.14 (373.0)</td>
<td>18020 (124.1)</td>
<td>0.19</td>
<td>0.719</td>
</tr>
<tr>
<td>27(4)_3_3</td>
<td>4.07 (10.3)</td>
<td>1880 (8361)</td>
<td>58.78 (405.0)</td>
<td>19550 (134.7)</td>
<td>0.76</td>
<td>0.712</td>
</tr>
<tr>
<td>mean</td>
<td>3.95 (10.0)</td>
<td>1771 (7880)</td>
<td>55.46 (382.1)</td>
<td>17510 (120.6)</td>
<td>0.706</td>
<td>0.706</td>
</tr>
<tr>
<td>standard deviation</td>
<td>7.5%</td>
<td>133.7 (594.6)</td>
<td>4.215 (29.04)</td>
<td>2680 (18.47)</td>
<td>0.062</td>
<td>8.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The properties of the two parts made with eight braiding bobbins are listed in Table 5.8 and Table 5.9. The results of the compression tests of specimens cut from them parts are shown in Figure 5.4 and Table 5.10.

<table>
<thead>
<tr>
<th>Table 5.8 Part 27(8)_1 Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen Name</td>
</tr>
<tr>
<td>Number of Tows</td>
</tr>
<tr>
<td>Area [in.$^2$ (cm$^2$)]</td>
</tr>
<tr>
<td>Fiber Volume Fraction</td>
</tr>
<tr>
<td>Moment of Inertia [in.$^4$ (cm$^4$)]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5.9 Part 27(8)_3 Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen Name</td>
</tr>
<tr>
<td>Number of Tows</td>
</tr>
<tr>
<td>Area [in.$^2$ (cm$^2$)]</td>
</tr>
<tr>
<td>Fiber Volume Fraction</td>
</tr>
<tr>
<td>Moment of Inertia [in.$^4$ (cm$^4$)]</td>
</tr>
</tbody>
</table>
Figure 5.4 Force-Displacement Diagram from 27-Tow Buckling Specimens Consolidated with 8 Braiding Tows

Table 5.10 Summary of 27-Tow Buckling Specimens Results (8 Braiders)

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>Length, L</th>
<th>Ultimate Strength, F</th>
<th>Ultimate Stress, $\sigma_u$</th>
<th>Modulus of Elasticity, E</th>
<th>Buckling Factor, k</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[in. (cm)]</td>
<td>[lbf (N)]</td>
<td>[ksi (MPa)]</td>
<td>[ksi (GPa)]</td>
<td></td>
</tr>
<tr>
<td>27(8)_1_1</td>
<td>4.02 (10.2)</td>
<td>1880 (8361)</td>
<td>-0.01</td>
<td>59.88 (412.5)</td>
<td>21040 (144.9)</td>
</tr>
<tr>
<td>27(8)_1_2</td>
<td>4.04 (10.3)</td>
<td>1949 (8668)</td>
<td>1.08</td>
<td>62.07 (427.7)</td>
<td>18570 (128.0)</td>
</tr>
<tr>
<td>27(8)_3_1</td>
<td>4.03 (10.2)</td>
<td>1938 (8622)</td>
<td>0.92</td>
<td>62.38 (429.8)</td>
<td>17090 (117.7)</td>
</tr>
<tr>
<td>27(8)_3_2</td>
<td>3.98 (10.1)</td>
<td>1818 (8085)</td>
<td>-1.00</td>
<td>58.49 (403.0)</td>
<td>26670 (183.8)</td>
</tr>
<tr>
<td>27(8)_3_3</td>
<td>3.98 (10.1)</td>
<td>1818 (8085)</td>
<td>-1.00</td>
<td>58.49 (403.0)</td>
<td>13250 (91.30)</td>
</tr>
<tr>
<td>mean</td>
<td></td>
<td>1880 (8364)</td>
<td>60.26 (415.2)</td>
<td>19320 (133.1)</td>
<td>0.701</td>
</tr>
<tr>
<td>standard deviation</td>
<td>63.05 (280.4)</td>
<td>1.882 (12.96)</td>
<td>4985 (34.35)</td>
<td>0.094</td>
<td></td>
</tr>
<tr>
<td>mean</td>
<td></td>
<td>1880 (8364)</td>
<td>60.26 (415.2)</td>
<td>19320 (133.1)</td>
<td>0.701</td>
</tr>
<tr>
<td>standard deviation</td>
<td>63.05 (280.4)</td>
<td>1.882 (12.96)</td>
<td>4985 (34.35)</td>
<td>0.094</td>
<td></td>
</tr>
</tbody>
</table>
5.2.4 36-TOW LONGITUDINAL MEMBER

Two parts were made from 36 tows for buckling specimens. Table 5.11 and Table 5.12 list the properties of these parts. Figure 5.5 and Table 5.13 show the results of the compression tests of the specimens cut from these parts.

Table 5.11 Part 36_2 Properties

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>36_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Tows</td>
<td>36</td>
</tr>
<tr>
<td>Area [in.² (cm²)]</td>
<td>0.0416 (0.269)</td>
</tr>
<tr>
<td>Fiber Volume Fraction</td>
<td>55%</td>
</tr>
<tr>
<td>Moment of Inertia [in.⁴ (cm⁴)]</td>
<td>1.38E-04 (5.74E-03)</td>
</tr>
</tbody>
</table>

Table 5.12 Part 36_3 Properties

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>36_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Tows</td>
<td>36</td>
</tr>
<tr>
<td>Area [in.² (cm²)]</td>
<td>0.0424 (0.273)</td>
</tr>
<tr>
<td>Fiber Volume Fraction</td>
<td>59%</td>
</tr>
<tr>
<td>Moment of Inertia [in.⁴ (cm⁴)]</td>
<td>1.43E-04 (5.95E-03)</td>
</tr>
</tbody>
</table>
5.3 RESULTS FOR SPECIMENS WITHOUT JOINTS FAILED IN COMPRESSION

This section presents properties of and the results of the compression tests for the specimens that failed in compression. The area and fiber volume fraction of each

---

**Figure 5.5 Force-Displacement Diagram for 36-Tow Buckling Specimens**

**Table 5.13 Summary of 36-Tow Buckling Specimens Results**

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>Length, L [in. (cm)]</th>
<th>Ultimate Strength, F [lbf (N)]</th>
<th>d/σ</th>
<th>Ultimate Stress, (\sigma_u) [ksi (MPa)]</th>
<th>Modulus of Elasticity, E [ksi (GPa)]</th>
<th>d/σ</th>
<th>Buckling Factor, k</th>
</tr>
</thead>
<tbody>
<tr>
<td>36_2_1</td>
<td>4.44 (11.3)</td>
<td>1973 (8776)</td>
<td>-0.92</td>
<td>47.39 (326.5)</td>
<td>24390 (168.0)</td>
<td>1.49</td>
<td>0.927</td>
</tr>
<tr>
<td>36_2_2</td>
<td>4.53 (11.5)</td>
<td>1962 (8730)</td>
<td>-1.00</td>
<td>47.14 (324.8)</td>
<td>20050 (138.1)</td>
<td>0.57</td>
<td>0.827</td>
</tr>
<tr>
<td>36_2_3</td>
<td>4.50 (11.4)</td>
<td>2273 (10110)</td>
<td>1.21</td>
<td>54.60 (376.2)</td>
<td>14710 (101.3)</td>
<td>-0.57</td>
<td>0.661</td>
</tr>
<tr>
<td>36_3_2</td>
<td>4.53 (11.5)</td>
<td>2218 (9865)</td>
<td>0.82</td>
<td>52.33 (360.6)</td>
<td>14550 (100.2)</td>
<td>-0.60</td>
<td>0.674</td>
</tr>
<tr>
<td>36_3_3</td>
<td>4.46 (11.3)</td>
<td>2087 (9282)</td>
<td>-0.11</td>
<td>49.24 (339.3)</td>
<td>13220 (91.08)</td>
<td>-0.88</td>
<td>0.675</td>
</tr>
<tr>
<td>mean</td>
<td>2102 (9352)</td>
<td>50.14 (345.5)</td>
<td></td>
<td>17380 (119.8)</td>
<td></td>
<td></td>
<td>0.753</td>
</tr>
<tr>
<td>standard deviation</td>
<td>140.5 (625.0)</td>
<td>3.242 (22.34)</td>
<td></td>
<td>4709 (32.45)</td>
<td></td>
<td></td>
<td>0.119</td>
</tr>
<tr>
<td></td>
<td>6.7%</td>
<td>6.5%</td>
<td></td>
<td>27.1%</td>
<td></td>
<td></td>
<td>15.8%</td>
</tr>
</tbody>
</table>
manufactured part are given. The results for each specimen including ultimate strength, ultimate stress, and modulus of elasticity are also presented.

5.3.1 9-Tow Longitudinal Member

All of the compression specimens were cut from the same 9-tow part. The area and fiber volume fraction of this part are listed in Table 5.14. The compression test results of these specimens are shown in Figure 5.6 and Table 5.15.

Table 5.14 Part 9_4 Properties

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>9_4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Tows</td>
<td>9</td>
</tr>
<tr>
<td>Area [in.² (cm²)]</td>
<td>0.0103 (0.0663)</td>
</tr>
<tr>
<td>Fiber Volume Fraction</td>
<td>56%</td>
</tr>
</tbody>
</table>

Figure 5.6 Force-Displacement Diagram for 9-Tow Compression Specimens
Table 5.15 Summary of 9-Tow Compression Specimens Results

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>Length, L [in. (cm)]</th>
<th>Ultimate Strength, F [lbf (N)]</th>
<th>Ultimate Stress, ( \sigma_u ) [ksi (MPa)]</th>
<th>Modulus of Elasticity, E [ksi (GPa)]</th>
<th>d/( \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>9_4_1</td>
<td>1.50 (3.80)</td>
<td>1166 (5186)</td>
<td>113.5 (782.1)</td>
<td>23920 (164.8)</td>
<td>1.15</td>
</tr>
<tr>
<td>9_4_2</td>
<td>1.50 (3.81)</td>
<td>938.2 (4173)</td>
<td>91.35 (629.4)</td>
<td>22040 (151.9)</td>
<td>0.68</td>
</tr>
<tr>
<td>9_4_3</td>
<td>1.49 (3.77)</td>
<td>996.8 (4434)</td>
<td>97.05 (668.7)</td>
<td>15860 (109.3)</td>
<td>-0.86</td>
</tr>
<tr>
<td>9_4_4</td>
<td>1.50 (3.81)</td>
<td>927.8 (4127)</td>
<td>90.34 (622.4)</td>
<td>14550 (100.3)</td>
<td>-1.19</td>
</tr>
<tr>
<td>9_4_5</td>
<td>1.53 (3.89)</td>
<td>1097 (4879)</td>
<td>106.8 (735.8)</td>
<td>20170 (139.0)</td>
<td>0.21</td>
</tr>
<tr>
<td>mean</td>
<td></td>
<td>1025 (4560)</td>
<td>99.81 (687.7)</td>
<td>19310 (133.0)</td>
<td></td>
</tr>
<tr>
<td>standard deviation</td>
<td></td>
<td>103.4 (459.9)</td>
<td>10.07 (69.36)</td>
<td>3998 (27.55)</td>
<td></td>
</tr>
</tbody>
</table>

5.3.2 18-TOW LONGITUDINAL MEMBER

The 18-tow specimens were all cut from the same part, the properties of which are listed in Table 5.16. The results of the compression tests of these specimens are found in Figure 5.7 and Table 5.17.

Table 5.16 Part 18_1 Properties

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>18_1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Tows</td>
<td>18</td>
</tr>
<tr>
<td>Area [in.² (cm²)]</td>
<td>0.0202 (0.130)</td>
</tr>
<tr>
<td>Fiber Volume Fraction</td>
<td>58%</td>
</tr>
</tbody>
</table>
Table 5.17 Summary of 18-Tow Compression Specimens Results

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>Length, L [in. (cm)]</th>
<th>Ultimate Strength, F [lbf (N)]</th>
<th>d/σ</th>
<th>Ultimate Stress, σ_u [ksi (MPa)]</th>
<th>Modulus of Elasticity, E [ksi (GPa)]</th>
<th>d/σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>18_1_1</td>
<td>2.00 (5.08)</td>
<td>1859 (8269)</td>
<td>-0.32</td>
<td>92.17 (635.0)</td>
<td>16080 (110.8)</td>
<td>-0.67</td>
</tr>
<tr>
<td>18_1_2</td>
<td>1.97 (4.99)</td>
<td>2111 (9389)</td>
<td>1.28</td>
<td>104.7 (721.1)</td>
<td>16520 (113.8)</td>
<td>-0.55</td>
</tr>
<tr>
<td>18_1_3</td>
<td>1.98 (5.02)</td>
<td>1831 (8147)</td>
<td>-0.49</td>
<td>90.80 (625.6)</td>
<td>15530 (107.0)</td>
<td>-0.82</td>
</tr>
<tr>
<td>18_1_4</td>
<td>1.82 (4.62)</td>
<td>2025 (9066)</td>
<td>0.74</td>
<td>100.4 (691.6)</td>
<td>20369 (140.3)</td>
<td>0.49</td>
</tr>
<tr>
<td>18_1_5</td>
<td>2.02 (5.13)</td>
<td>1718 (7640)</td>
<td>-1.21</td>
<td>85.16 (586.7)</td>
<td>24190 (166.7)</td>
<td>1.53</td>
</tr>
<tr>
<td>mean</td>
<td></td>
<td>1909 (8490)</td>
<td></td>
<td>94.63 (652.0)</td>
<td>18530 (127.7)</td>
<td></td>
</tr>
<tr>
<td>standard</td>
<td></td>
<td>157.5 (700.5)</td>
<td></td>
<td>7.808 (53.80)</td>
<td>3689 (25.42)</td>
<td></td>
</tr>
<tr>
<td>deviation</td>
<td></td>
<td>8.3%</td>
<td></td>
<td>8.3%</td>
<td>19.9%</td>
<td></td>
</tr>
</tbody>
</table>

5.3.3 27-TOW LONGITUDINAL MEMBER

These 27-tow specimens failed in compression were also made in two varieties: with four braiding bobbins and with eight braiding bobbins. The properties of and results
for specimens cut from part 27(4)_1 are listed in Table 5.18 and Table 5.19, respectively. The force-displacement diagrams for these specimens are found in Figure 5.8. The properties of the part made with eight braiding bobbins, 27(8)_2, are found in Table 5.20. The results of compression tests on specimens from this part are enumerated in Figure 5.9 and Table 5.21.

Table 5.18 Part 27(4)_1 Properties

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>27(4)_1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Tows</td>
<td>27</td>
</tr>
<tr>
<td>Area [in.² (cm²)]</td>
<td>0.0310 (0.200)</td>
</tr>
<tr>
<td>Fiber Volume Fraction</td>
<td>54%</td>
</tr>
</tbody>
</table>

Figure 5.8 Force-Displacement Diagram for 27-Tow Compression Specimens Consolidated with 4 Braiding Tows
### Table 5.19 Summary of 27-Tow Compression Specimens Results (4 Braiders)

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>Length, L [in. (cm)]</th>
<th>Ultimate Strength, F [lbf (N)]</th>
<th>Ultimate Stress, $\sigma_u$ [ksi (MPa)]</th>
<th>Modulus of Elasticity, E [ksi (GPa)]</th>
<th>$d/\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>27(4)_1_1</td>
<td>1.97 (5.00)</td>
<td>3259 (14500)</td>
<td>105.2 (724.6)</td>
<td>15440 (106.4)</td>
<td>-1.10</td>
</tr>
<tr>
<td>27(4)_1_2</td>
<td>2.00 (5.08)</td>
<td>3056 (13590)</td>
<td>98.60 (679.4)</td>
<td>15560 (107.2)</td>
<td>-0.97</td>
</tr>
<tr>
<td>27(4)_1_3</td>
<td>2.00 (5.07)</td>
<td>2980 (13260)</td>
<td>96.15 (662.5)</td>
<td>16620 (114.5)</td>
<td>0.18</td>
</tr>
<tr>
<td>27(4)_1_4</td>
<td>1.98 (5.03)</td>
<td>2849 (12670)</td>
<td>91.92 (633.4)</td>
<td>17190 (118.5)</td>
<td>0.80</td>
</tr>
<tr>
<td>27(4)_1_5</td>
<td>1.96 (4.98)</td>
<td>3025 (13450)</td>
<td>97.60 (672.5)</td>
<td>17450 (120.2)</td>
<td>1.08</td>
</tr>
<tr>
<td>mean</td>
<td></td>
<td>3034 (13490)</td>
<td>97.89 (674.5)</td>
<td>16450 (113.4)</td>
<td></td>
</tr>
<tr>
<td>standard deviation</td>
<td></td>
<td>148.7 (661.7)</td>
<td>4.800 (33.07)</td>
<td>921 (6.345)</td>
<td></td>
</tr>
</tbody>
</table>

### Table 5.20 Part 27(8)_2 Properties

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>27(8)_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Tows</td>
<td>27</td>
</tr>
<tr>
<td>Area [in.$^2$ (cm$^2$)]</td>
<td>0.0310 (0.200)</td>
</tr>
<tr>
<td>Fiber Volume Fraction</td>
<td>54%</td>
</tr>
</tbody>
</table>
Figure 5.9 Force-Displacement Diagram for 27-Tow Compression Specimens Consolidated with 8 Braiding Tows

Table 5.21 Summary of 27-Tow Compression Specimens Results (8 Braiders)

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>Length, L [in. (cm)]</th>
<th>Ultimate Strength, F [lbf (N)]</th>
<th>d/σ</th>
<th>Ultimate Stress, σ_u [ksi (MPa)]</th>
<th>Modulus of Elasticity, E [ksi (GPa)]</th>
<th>d/σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>27(8)_2_1</td>
<td>1.96 (4.99)</td>
<td>2811 (12500)</td>
<td>-1.51</td>
<td>90.81 (625.7)</td>
<td>16300 (112.3)</td>
<td>-0.81</td>
</tr>
<tr>
<td>27(8)_2_2</td>
<td>1.98 (5.02)</td>
<td>3004 (13360)</td>
<td>0.48</td>
<td>97.05 (668.7)</td>
<td>17710 (122.0)</td>
<td>0.91</td>
</tr>
<tr>
<td>27(8)_2_3</td>
<td>1.95 (4.95)</td>
<td>2987 (13290)</td>
<td>0.30</td>
<td>96.49 (664.8)</td>
<td>17520 (120.7)</td>
<td>0.68</td>
</tr>
<tr>
<td>27(8)_2_4</td>
<td>1.93 (4.91)</td>
<td>3066 (13640)</td>
<td>1.12</td>
<td>99.05 (682.5)</td>
<td>15870 (109.4)</td>
<td>-1.33</td>
</tr>
<tr>
<td>27(8)_2_5</td>
<td>1.99 (5.05)</td>
<td>2921 (12990)</td>
<td>-0.38</td>
<td>94.37 (650.2)</td>
<td>17410 (120.0)</td>
<td>0.55</td>
</tr>
<tr>
<td>mean</td>
<td></td>
<td>2958 (13160)</td>
<td></td>
<td>95.55 (658.4)</td>
<td>16960 (116.9)</td>
<td></td>
</tr>
<tr>
<td>standard deviation</td>
<td>96.98 (431.4)</td>
<td>3.133 (21.59)</td>
<td></td>
<td>822.1 (5.664)</td>
<td>4.8%</td>
<td></td>
</tr>
</tbody>
</table>
5.3.4 36-Tow Longitudinal Member

The properties of the part from which the 36-tow specimens were cut are reported in Table 5.22. Figure 5.10 shows the force-displacement diagrams for these specimens and Table 5.23 catalogs the results.

Table 5.22 Part 36_1 Properties

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>36_1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Tows</td>
<td>36</td>
</tr>
<tr>
<td>Area [in.$^2$(cm$^2$)]</td>
<td>0.0411 (0.265)</td>
</tr>
<tr>
<td>Fiber Volume Fraction</td>
<td>61%</td>
</tr>
</tbody>
</table>

Figure 5.10 Force-Displacement Diagram for 36-Tow Compression Specimens
### Table 5.23 Summary of 36-Tow Compression Specimens Results

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>Length, L [in. (cm)]</th>
<th>Ultimate Strength, F [lbf (N)]</th>
<th>Ultimate Stress, ( \sigma_u ) [ksi (MPa)]</th>
<th>Modulus of Elasticity, E [ksi (GPa)]</th>
<th>d/( \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>36_1_1</td>
<td>1.99 (5.06)</td>
<td>4094 (18210)</td>
<td>99.54 (685.8)</td>
<td>18440 (127.1)</td>
<td>-0.05</td>
</tr>
<tr>
<td>36_1_2</td>
<td>1.97 (5.00)</td>
<td>3439 (15300)</td>
<td>83.61 (576.0)</td>
<td>19120 (131.7)</td>
<td>0.19</td>
</tr>
<tr>
<td>36_1_3</td>
<td>1.98 (5.02)</td>
<td>3739 (16630)</td>
<td>90.90 (626.3)</td>
<td>16430 (113.2)</td>
<td>-0.78</td>
</tr>
<tr>
<td>36_1_4</td>
<td>1.96 (4.98)</td>
<td>3756 (16710)</td>
<td>91.32 (629.2)</td>
<td>22950 (158.1)</td>
<td>1.57</td>
</tr>
<tr>
<td>36_1_5</td>
<td>2.03 (5.14)</td>
<td>3483 (15490)</td>
<td>84.70 (583.6)</td>
<td>15980 (110.1)</td>
<td>-0.94</td>
</tr>
<tr>
<td>mean</td>
<td></td>
<td>3702 (16470)</td>
<td>90.01 (620.2)</td>
<td>18580 (128.1)</td>
<td></td>
</tr>
<tr>
<td>standard</td>
<td></td>
<td>262.2 (1166)</td>
<td>6.375 (43.92)</td>
<td>2775 (19.12)</td>
<td></td>
</tr>
<tr>
<td>deviation</td>
<td></td>
<td>7.1%</td>
<td>7.1%</td>
<td>14.9%</td>
<td></td>
</tr>
</tbody>
</table>

### 5.4 RESULTS FOR SPECIMENS WITH JOINTS FAILED IN COMPRESSION

The properties of and results of compression tests for the specimens with joints, that is, with intersecting helical members, are presented in this section. The area and fiber volume fraction of each part are listed, as well as the results of compression tests of the individual specimens.

#### 5.4.1 FOUR HELICAL BOBBINS

Four parts were made from which specimens were cut for testing. The cross-sectional area and fiber volume fraction of these four parts are listed in Tables 5.24 – 5.27. The results of the compression tests of these specimens, the ultimate compression strength and stress and modulus of elasticity are summarized in Figure 5.11 and Table 5.28.
### Table 5.25 Part H4_2 Properties

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>H4_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Tows</td>
<td>18</td>
</tr>
<tr>
<td>Area [in.² (cm²)]</td>
<td>0.0203 (0.132)</td>
</tr>
<tr>
<td>Fiber Volume Fraction</td>
<td>54%</td>
</tr>
</tbody>
</table>

### Table 5.26 Part H4_3 Properties

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>H4_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Tows</td>
<td>18</td>
</tr>
<tr>
<td>Area [in.² (cm²)]</td>
<td>0.0210 (0.136)</td>
</tr>
<tr>
<td>Fiber Volume Fraction</td>
<td>57%</td>
</tr>
</tbody>
</table>

### Table 5.27 Part H4_4 Properties

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>H4_4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Tows</td>
<td>18</td>
</tr>
<tr>
<td>Area [in.² (cm²)]</td>
<td>0.0205 (0.132)</td>
</tr>
<tr>
<td>Fiber Volume Fraction</td>
<td>59%</td>
</tr>
</tbody>
</table>
Table 5.28 Summary of 4 Helical Tow Joint Specimens Results

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>Length, L [in. (cm)]</th>
<th>Ultimate Strength, F [lbf (N)]</th>
<th>Ultimate Stress, $\sigma_u$ [ksi (MPa)]</th>
<th>Modulus of Elasticity, E [ksi (GPa)]</th>
<th>d/$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H4_1_1</td>
<td>1.87 (4.75)</td>
<td>1300 (5784)</td>
<td>-1.05</td>
<td>63.26 (435.9)</td>
<td>0.33</td>
</tr>
<tr>
<td>H4_1_2</td>
<td>1.99 (5.06)</td>
<td>1521 (6766)</td>
<td>0.00</td>
<td>74.00 (509.8)</td>
<td>1.19</td>
</tr>
<tr>
<td>H4_2_1</td>
<td>1.81 (4.60)</td>
<td>1324 (5891)</td>
<td>-0.93</td>
<td>64.67 (445.6)</td>
<td>-1.16</td>
</tr>
<tr>
<td>H4_2_2</td>
<td>1.72 (4.37)</td>
<td>1852 (8239)</td>
<td>1.70</td>
<td>90.44 (623.1)</td>
<td>-0.36</td>
</tr>
<tr>
<td>H4_3_2</td>
<td>1.88 (4.77)</td>
<td>1576 (7011)</td>
<td>0.32</td>
<td>74.97 (516.5)</td>
<td>0.40</td>
</tr>
<tr>
<td>H4_4_1</td>
<td>1.88 (4.79)</td>
<td>1493 (6643)</td>
<td>-0.09</td>
<td>72.89 (502.2)</td>
<td>-0.58</td>
</tr>
<tr>
<td>mean</td>
<td></td>
<td></td>
<td></td>
<td>73.37 (505.5)</td>
<td></td>
</tr>
<tr>
<td>standard deviation</td>
<td></td>
<td></td>
<td></td>
<td>200.1 (890.1)</td>
<td>13.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.720 (66.97)</td>
<td>13.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4332 (29.85)</td>
<td>26.3%</td>
</tr>
</tbody>
</table>

Figure 5.11 Force-Displacement Diagram for 4 Helical Tow Compression Specimens
5.4.2 EIGHT HELICAL BOBBINS

The specimens with eight helical tows composing the helical members were cut from three parts. The properties of these parts are found in Table 5.29 - Table 5.31. Figure 5.12 shows the force-displacement diagrams for these specimens. In Table 5.32, the results of the compression tests are summarized.

Table 5.29 Part H8_1 Properties

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>H8_1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Tows</td>
<td>18</td>
</tr>
<tr>
<td>Area [in.² (cm²)]</td>
<td>0.0209 (0.135)</td>
</tr>
<tr>
<td>Fiber Volume Fraction</td>
<td>52%</td>
</tr>
</tbody>
</table>

Table 5.30 Part H8_2 Properties

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>H8_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Tows</td>
<td>18</td>
</tr>
<tr>
<td>Area [in.² (cm²)]</td>
<td>0.0205 (0.133)</td>
</tr>
<tr>
<td>Fiber Volume Fraction</td>
<td>67%</td>
</tr>
</tbody>
</table>

Table 5.31 Part H8_3 Properties

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>H8_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Tows</td>
<td>18</td>
</tr>
<tr>
<td>Area [in.² (cm²)]</td>
<td>0.0202 (0.130)</td>
</tr>
<tr>
<td>Fiber Volume Fraction</td>
<td>63%</td>
</tr>
</tbody>
</table>
**Table 5.32 Summary of 8 Helical Tow Joint Specimens Results**

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>Length, L [in. (cm)]</th>
<th>Ultimate Strength, F [lbf (N)]</th>
<th>Stress, $\sigma_u$ [ksi (MPa)]</th>
<th>Modulus of Elasticity, E [ksi (GPa)]</th>
<th>d/$\sigma$</th>
<th>d/$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H8_1_1</td>
<td>2.01 (5.09)</td>
<td>1121 (4986)</td>
<td>0.25</td>
<td>53.75 (370.4)</td>
<td>26081</td>
<td>179.7</td>
</tr>
<tr>
<td>H8_2_1</td>
<td>1.69 (4.29)</td>
<td>1111 (4940)</td>
<td>0.16</td>
<td>54.11 (372.8)</td>
<td>14170</td>
<td>-0.30</td>
</tr>
<tr>
<td>H8_2_2</td>
<td>1.81 (4.60)</td>
<td>1249 (5554)</td>
<td>1.31</td>
<td>60.83 (419.1)</td>
<td>17370</td>
<td>0.22</td>
</tr>
<tr>
<td>H8_2_3</td>
<td>1.79 (4.53)</td>
<td>917.5 (4081)</td>
<td>-1.45</td>
<td>44.70 (308.0)</td>
<td>11490</td>
<td>-0.74</td>
</tr>
<tr>
<td>H8_3_1</td>
<td>1.94 (4.92)</td>
<td>1059 (4710)</td>
<td>-0.27</td>
<td>52.39 (360.9)</td>
<td>11030</td>
<td>-0.81</td>
</tr>
<tr>
<td>mean</td>
<td></td>
<td>1091 (4854)</td>
<td>53.16</td>
<td>366.3</td>
<td>109.4</td>
<td></td>
</tr>
<tr>
<td>standard</td>
<td>119.6 (532.2)</td>
<td>5.750 (39.62)</td>
<td>6161 (42.45)</td>
<td>38.4%</td>
<td>38.4%</td>
<td></td>
</tr>
</tbody>
</table>

**5.5 SUMMARY**

The results of all the specimens are summarized in Table 5.33. Figure 5.13 shows the average force-displacement diagrams for the specimens failed in compression. Figure
5.14 is the average force-displacement diagrams for the specimens with intersecting helical members. A combination of both diagrams is found in Figure 5.15.

<table>
<thead>
<tr>
<th>Number of Tows</th>
<th>Number of Braiders</th>
<th>Ultimate Strength, $F$ [lbf (N)]</th>
<th>Ultimate Stress, $\sigma_u$ [ksi (MPa)]</th>
<th>Modulus of Elasticity, $E$ [ksi (GPa)]</th>
<th>Buckling Factor, $k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimens Failed in Buckling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>4</td>
<td>688.5 (3063)</td>
<td>68.74 (473.6)</td>
<td>18220 (125.5)</td>
<td>0.704</td>
</tr>
<tr>
<td>18</td>
<td>4</td>
<td>1195 (5318)</td>
<td>58.64 (404.0)</td>
<td>14890 (102.6)</td>
<td>0.512</td>
</tr>
<tr>
<td>27</td>
<td>4</td>
<td>1771 (7880)</td>
<td>55.46 (382.1)</td>
<td>17510 (120.6)</td>
<td>0.706</td>
</tr>
<tr>
<td>27</td>
<td>8</td>
<td>1880 (8364)</td>
<td>60.26 (415.2)</td>
<td>19320 (133.1)</td>
<td>0.701</td>
</tr>
<tr>
<td>36</td>
<td>4</td>
<td>2102 (9352)</td>
<td>50.14 (345.5)</td>
<td>17380 (119.8)</td>
<td>0.753</td>
</tr>
<tr>
<td>Specimens Failed in Compression</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>4</td>
<td>1025 (4560)</td>
<td>99.81 (687.7)</td>
<td>19310 (133.0)</td>
<td>N/A</td>
</tr>
<tr>
<td>18</td>
<td>4</td>
<td>1909 (8490)</td>
<td>94.63 (652.0)</td>
<td>18530 (127.7)</td>
<td>N/A</td>
</tr>
<tr>
<td>27</td>
<td>4</td>
<td>3034 (13490)</td>
<td>97.89 (674.5)</td>
<td>16450 (113.4)</td>
<td>N/A</td>
</tr>
<tr>
<td>27</td>
<td>8</td>
<td>2958 (13160)</td>
<td>95.55 (658.4)</td>
<td>16960 (116.9)</td>
<td>N/A</td>
</tr>
<tr>
<td>36</td>
<td>4</td>
<td>3702 (16470)</td>
<td>90.01 (620.2)</td>
<td>18580 (128.1)</td>
<td>N/A</td>
</tr>
<tr>
<td>Specimens with Interwoven Joints Failed in Compression</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>4</td>
<td>1511 (6722)</td>
<td>73.37 (505.5)</td>
<td>16480 (113.6)</td>
<td>N/A</td>
</tr>
<tr>
<td>18</td>
<td>8</td>
<td>1091 (4854)</td>
<td>53.16 (366.3)</td>
<td>16030 (110.4)</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Figure 5.13 Average Force-Displacement Diagrams for Compression Specimens
Figure 5.14 Average Force-Displacement Diagrams for Specimens with Joints
(18 Longitudinal Tows and 4 Braiding Bobbins)
Figure 5.15 Average Force-Displacement Diagrams for All Compression Specimens
6 DISCUSSION OF RESULTS

This chapter presents a discussion of the results in view of the questions explored in this research. Each of the questions is treated individually to identify what, if any, conclusions can be reached.

6.1 COMPARISON WITH PREVIOUS RESEARCH

Previous research performed by Hansen [2004] on 36-tow longitudinal members consolidated by 6 braiding tows yielded an average ultimate strength of 6.7 kips (29.7 kN), an ultimate stress of 167.5 ksi (1155 MPa), and a modulus of elasticity of 17,600 ksi (121 GPa). The averages for specimens of varying sizes tested in this research are listed in Table 6.1.

<table>
<thead>
<tr>
<th>Number of Tows</th>
<th>Ultimate Strength, F [lbf (N)]</th>
<th>Ultimate Stress, $\sigma_u$ [ksi (MPa)]</th>
<th>Modulus of Elasticity, E [ksi (GPa)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>1025 (4560)</td>
<td>99.81 (687.7)</td>
<td>19310 (133.0)</td>
</tr>
<tr>
<td>18</td>
<td>1909 (8490)</td>
<td>94.63 (652.0)</td>
<td>18530 (127.7)</td>
</tr>
<tr>
<td>27</td>
<td>3034 (13490)</td>
<td>97.89 (674.5)</td>
<td>16450 (113.4)</td>
</tr>
<tr>
<td>36</td>
<td>3702 (16470)</td>
<td>90.01 (620.2)</td>
<td>18580 (128.1)</td>
</tr>
<tr>
<td>mean</td>
<td>95.59 (658.6)</td>
<td></td>
<td>18220 (125.5)</td>
</tr>
<tr>
<td>standard deviation</td>
<td>4.29 (29.53)</td>
<td></td>
<td>1231 (8.48)</td>
</tr>
<tr>
<td>standard deviation</td>
<td>4.5%</td>
<td></td>
<td>6.8%</td>
</tr>
</tbody>
</table>
The average ultimate strength for the 36-tow member is consistently 44.8% lower than that in previous research. Figure 6.1 compares the results of previous research to the results of this research.

![Figure 6.1 Ultimate Compression Strength as a Function of Number of Tows per Longitudinal Member](image)

The trend of the data points from the current research does not pass through the origin, as would be expected. This is likely due to multiple longitudinal member tows on one bobbin. For nine longitudinal member tows, there was only one tow per bobbin. However, for 18 longitudinal member tows there were two tows per bobbin, for 27 tows there were three tows per bobbin, and for 36 tows there were four tows per bobbin. When multiple tows are wound on a single spool, tows are generally not as straight and kinks and bends form on the spool. This causes a decrease in strength. A line plotted through the origin and through the 9-tow member data point shows a projected strength...
for each configuration if there had not been multiple tows on a spool. The projected strength for a 36-tow member is 38.8% less than that in previous research.

The ultimate stress should remain constant regardless of member size. Figure 6.2 shows the variation in ultimate stress with a change in the number of tows.

![Figure 6.2 Ultimate Compression Stress as a Function of Number of Tows per Longitudinal Member](image)

The standard deviation of the ultimate stress is relatively small, 4.5%, as shown in Table 6.1. If the data is adjusted for multiple tows on a spool, the standard deviation becomes only 1.1%. This indicates that cause of the reduction of strength from previous research is likely not due to inconsistencies, but instead something that consistently affected manufacturing or testing of the specimens. Possible explanations for this reduced strength could include:

- Each bobbin can provide a maximum total of 2.5 lbs (11.1 N) of tension per bobbin on the tows. In reality, only a fraction of this maximum was
achieved, with no means of determining the exact amount. This is less than the 5 lbs (22.2 N) of desired tension per tow, and may have caused decreased straightness in the longitudinal member fibers, thus reducing the strength of the part.

- The material used in this research was manufactured three years ago, whereas the material used for the cited previous research was less than a year old. The shelf life for the material used at room temperature is one year. This means that after one year, the material properties become an issue. This alone could be the cause of the decreased strength of test specimens.

- The fiber volume fraction for the specimens tested in this research averaged 57.6%, while that for the previous research was 65.4%. This 12.2% decrease in fiber volume fraction is also likely a symptom of decreased fiber straightness, possibly due to older material, and would likely lower member strength.

Although the specimens ultimate strength is lower than that in previous research, probable sources of this decrease are discernable and can be remedied. Future modifications to the machine and its related systems will likely eliminate most, if not all, of these causes of degradation in strength.

Figure 6.3 shows the axial stiffness for different number of tows. The 36-tow members tested in this research had an average stiffness 8.6% higher than the average for specimens of the same size tested in previous research. This increase in axial stiffness is due to the 5.6% increase in modulus of elasticity, in combination with the 2.8% larger
area of specimens tested in this research. The larger area is a result of the lower fiber volume fraction of specimens manufactured for this research.

A comparison of results obtained for specimens with joints in this research is compared to those obtained in previous research in Figure 6.4. In Hansen’s research, specimens with joints had 36 tows per longitudinal member and 14 tows per helical member [2004]. For this research, specimens with joints had 18 tows per longitudinal member and 4 or 8 tows per helical member. Therefore, ultimate compression stresses are plotted for the different ratios of helical member tows to longitudinal member tows. This plot shows that the decrease in member strength due to increased percentage of helical tows is proportionally less than in previous research.
6.2 **INFLUENCE OF NUMBER OF BRAIDING BOBBINS**

Four sets of 27-tow longitudinal members were made: two with four braiding bobbins and two with eight braiding bobbins. One of each was tested to failure in compression and the other in buckling. The average results for these tests are summarized in Table 6.2.

<table>
<thead>
<tr>
<th>27-Tow Member</th>
<th>Ultimate Strength, F [lbf (N)]</th>
<th>Ultimate Stress, $\sigma_u$ [psi (MPa)]</th>
<th>Modulus of Elasticity, $E$ [ksi (Gpa)]</th>
<th>Fiber Volume Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression Failure</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Braiders</td>
<td>3034 (13490) 4.9%</td>
<td>97890 (674.5)</td>
<td>16450 (113.4)</td>
<td>5.6% 54%</td>
</tr>
<tr>
<td>8 Braiders</td>
<td>2958 (13160) 3.3%</td>
<td>95550 (658.4)</td>
<td>16960 (116.9)</td>
<td>4.8% 54%</td>
</tr>
<tr>
<td>Buckling Failure</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Braiders</td>
<td>1771 (7880) 7.5%</td>
<td>55460 (382.1)</td>
<td>17510 (120.6)</td>
<td>15% 55%</td>
</tr>
<tr>
<td>8 Braiders</td>
<td>1880 (8364) 3.4%</td>
<td>60260 (415.2)</td>
<td>19320 (133.1)</td>
<td>26% 56%</td>
</tr>
</tbody>
</table>

Figure 6.4 Ultimate Compression Stress as a Function of Ratio of Helical Tows to Longitudinal Tows

Table 6.2 Comparison of Number of Braiding Bobbins
The following observations can be made from this data:

- Increasing the number of braiding bobbins from four to eight decreased the ultimate compression strength 2.5%. The buckling failure load, however, increased by 6.2%. These differences are within the normal scatter, and therefore not significant.

- It is also notable that the standard deviation was decreased by 33.1% and 55.6% in compression and buckling, respectively, by increasing the number of braiders from four to eight. This indicates that the data is much less scattered when more braiders are used. Specimens manufactured with eight braiding bobbins were visibly more consistent than those manufactured with four braiding bobbins.

- The modulus of elasticity increased by 3.1% and 10.4% in compression and buckling, respectively, by increasing the number of braiding bobbins from four to eight.

- The fiber volume fraction increased by 1.2% by doubling the number of braiding bobbins.

6.3 Buckling Versus Compression Failure

Buckling failure differed greatly from compression failure, as shown by the sample force-displacement diagrams of both failures shown in Figure 6.5.
Buckling failure exhibited gradual bowing of the part until failure occurred, at which point a large decrease in load capacity took place. For specimens failed in compression the load increased with no discernable bowing in the specimen until initial failure occurred. At this point a small decrease in capacity was followed by an increase in capacity. This occurred several times until finally a point was reached when the capacity dropped to near zero. This type of failure takes a lot of energy and is advantageous in design.

Figure 6.6 shows the average force-displacement curves for 9-tow specimens tested in buckling and compression. The area under the average compression failure
curve is 130 in.-lbf (14.7 N-m). The area under the average buckling curve was only 18.6% of this value, or 24.2 in.-lbf (2.74 N-m).

![Graph showing compression and buckling forces and displacements.](image)

**Figure 6.6 Comparison of Buckling and Compression Failure for 9-Tow Average**

Figure 6.7 compares the average ultimate stress values for buckling and compression failure. Because the lengths of buckling specimens were different for different size members to ensure buckling failure, results of different configurations cannot be compared directly and therefore specific conclusions about relationships between different configurations should not be drawn from this figure. However, it can be noted that buckling failure occurs at a lower stress than compression failure, as it should.
6.4 **Influence of Number of Helical Bobbins**

The effect of interweaving helical members through the longitudinal member is seen by examining the results for the compression tests of specimens with varying number of helical tows, shown in Table 6.3.

<table>
<thead>
<tr>
<th>Helical Tows</th>
<th>Ultimate Strength, F [lbf (N)]</th>
<th>$\sigma$</th>
<th>Ultimate Stress, $\sigma_u$ [ksi (MPa)]</th>
<th>Modulus of Elasticity, E [ksi (GPa)]</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1909 (8490)</td>
<td>8%</td>
<td>94.63 (652.0)</td>
<td>18530 (127.7)</td>
<td>20%</td>
</tr>
<tr>
<td>4</td>
<td>1511 (6722)</td>
<td>13%</td>
<td>73.37 (505.5)</td>
<td>16480 (113.6)</td>
<td>26%</td>
</tr>
<tr>
<td>8</td>
<td>1091 (4854)</td>
<td>11%</td>
<td>53.16 (366.3)</td>
<td>16030 (110.4)</td>
<td>38%</td>
</tr>
</tbody>
</table>

Figure 6.7 Comparison of Ultimate Compression Stress for Buckling and Compression Failure

Table 6.3 Summary of Results for Different Number of Helical Tows
Table 6.3 shows that the standard deviation for both ultimate strength and modulus of elasticity increases as the number of intersecting helical tows increases. This indicates that intersecting helical tows decreases the consistency of the data.

Figure 6.8 shows that the ultimate strength decreases with increased number of helical tows, as one would predict. In fact, this reduction in strength is closely related to the ratio of helical tows to longitudinal tows. For four helical tows this ratio is 22%, and the reduction in strength is 21%. For eight helical tows the ratio is 44% and the reduction in strength is 43%. Hansen’s research showed similar results; interweaving 14 helical tows through 36 longitudinal tows (a ratio of 39%) yielded a 39% reduction in strength. Thus the effect of helical tows interweaving with longitudinal tows is fairly predictable.
7 CONCLUSIONS AND RECOMMENDATIONS

The purpose of this research was to validate the newly developed manufacturing process for IsoTruss® structures. This validation was two-pronged. The first validation was achieved by developing winding patterns and control arrays for various geometries and manufacturing these parts on the machine. This was done to demonstrate the ability of the machine to make IsoTruss and other open lattice structures. The second validation involved making composite specimens similar to those manufactured in previous research, testing these specimens, and comparing their results to those obtained in previous research. This demonstrated the viability of manufacturing quality parts using this machine.

This section outlines the conclusions reached in this research. Some recommendations for future research and development of IsoTruss structures manufacturing technology are also listed. First, the conclusions and recommendations regarding the test specimens are presented. Then the recommendations regarding control array creation are offered. Finally, conclusions and recommendations about the machine and manufacturing process are put forth.

7.1 REGARDING THE TEST SPECIMENS

Consolidated longitudinal member specimens did not perform as well as those manufactured and tested in previous research. Causes of this phenomenon include
winding multiple tows on a single spool, lack of necessary tension in the fibers during manufacturing and curing, and using out-dated prepreg. Performance of future specimens manufactured will be much improved with the necessary continued development of specific systems of the manufacturing process. These developments are addressed in Section 7.3.

The following conclusions are reached based on specimen test results:

- Increasing the number of braiders tends to increase the consistency of the braid and reduces the scatter of data in the results.
- Compression failure of individual members is the preferred method of failure.
- The ratio of helical to longitudinal tows at a joint is directly related to the percent decrease in member strength due to the joint and the relationship is nearly 1 to 1.

In order to get more conclusive results, the following are recommended:

- Quantify the influence of tension in longitudinal member fibers by compression tests of similar parts that were manufactured with different amounts of tension on the fibers during manufacture and cure.
- Quantify the influence of the age of material on the material properties by testing similar parts made with different aged materials.

7.2 REGARDING CONTROL ARRAY CREATION

The process currently being used to create the control array is problematic. It demands an in-depth understanding of movement patterns of the bobbins required for different geometries. It also requires a large investment of time to go through the steps to
create and validate the winding pattern and write the control array. Overall it is a laborious process with a steep learning curve.

Fortunately, this research has uncovered some underlying “rules” of winding patterns that can be programmed. In addition, since the winding patterns are modular in nature, computers can easily string together an array of previously defined patterns to form any geometry.

Therefore, time should be invested in the development of a completely automated control array creation process. This may involve the use of traffic algorithms to create the winding patterns. A computer program should be designed to combine modules in such a way that any geometry of IsoTruss can be created by simply entering a few inputs.

7.3 REGARDING THE MACHINE

The patterns created and the parts made validate the hypothesis that the machine will make IsoTruss structures. The creation of specimens for testing demonstrated that transition joints can be created and consolidated. Testing of the winding pattern for the part with three longitudinal members showed that nodes and anti-nodes can also be created using this machine. The 6-node IsoTruss with outer longitudinal members and inner helical members showed that the most complex IsoTruss geometry can be made using this machine. On a larger machine, elements from each of these patterns would be combined to create and consolidate any IsoTruss structure.

The two bay IsoTruss panel winding pattern run on the machine demonstrated the versatility of the machine and that this type of structure can be made on this machine. This also shows that the machine is not limited to round structures. It is conceivable that any open lattice structure could be created on this type of machine.
The following improvements should be made to the machine:

(1) Bobbins must be redesigned to allow carbon fiber to come off the spools without fraying. Specifically, the guide mechanism at the top of the bobbin must be replaced with a wheel to reduce friction.

(2) The method of fiber payout from the spool should be improved (possibly by incorporating a level-wind worm mechanism).

(3) Bobbins should provide more tension to increase fiber straightness.

(4) Switches must be redesigned to be more reliable. A pin connection to the solenoid should be used instead of a threaded rod. Also, eccentricities should be reduced to minimize binding.

(5) Solenoids should be double-throw, allowing for considerably less frequent switching.

(6) A splined shaft should be used to prevent slippage of the drive gears and the horn gears.

(7) Front-to-back positioning of machine parts (i.e. gears, bearings, etc.) must be fixed and wandering should be prevented.

In addition, more research is still necessary to develop shape-definition and transition systems. A pulling mechanism should also be incorporated that is programmable to eliminate any variation in braiding coverage of parts. By improving these systems, a complete manufacturing process will be created for the fast, reliable, and consistent fabrication of IsoTruss structures.
REFERENCES


APPENDIX A  WINDING PATTERNS

A.1  BRAIDING A SLEEVE WITH EIGHT BRAIDERS

In this pattern, the yellow circles represent the locations of the longitudinal payout tubes. The tows coming out of these tubes are consolidated by eight braiders, represented by the dark and light blue circles. The bobbins represented by dark blue circles follow the dark blue path, counter-clockwise around the longitudinal member. The bobbins represented by light blue circles follow the light blue path clockwise around the longitudinal member. These paths create a full braid, consolidating the longitudinal member. The same path could be used to consolidate a helical member by stalling the helical members within the braiding paths.
These seven steps are repeated four times for one complete revolution of the braiders. Any number of braider revolutions may be strung together to braid any length of longitudinal or helical member.

A.2  STALLING PATTERN FOR EIGHT BOBBINS

The following eight steps are the stalling pattern for eight bobbins. The same pattern could be expanded to stall any number of bobbins. In the following illustrations, the circles that represent the bobbins and the paths are colored differently simply for ease in determining the paths of each bobbin.
A.3 HELICAL MEMBERS CROSS THROUGH LONGITUDINAL MEMBER

In the following illustrations, the yellow circles represent the locations of the longitudinal payout tubes, through which the longitudinal member fibers pass. The dark and light blue circles represent the bobbins that consolidate the longitudinal member by braiding. During this phase of the pattern, these bobbins stall while the helical members cross through the longitudinal member. The helical member bobbins are represented by red and green circles. The red set travel from left to right, and the green set travels from right to left, following the arrows through the longitudinal member fibers. This pattern takes 24 time steps.
A.4 THREE LONGITUDINAL MEMBERS PATTERNS

There are seven modules, or sub-patterns, involved in the three longitudinal member pattern. They are:

1) Consolidation of the longitudinal member by braiding.

2) Consolidation of the helical members by twisting.
3) Stalling of helical member bobbins.

4) Helical members crossing helical members to form nodes and anti-nodes.

5) Helical members crossing longitudinal members to form transition nodes.

For these slides, the purple circles represent braiding bobbins, and the green and blue circles represent helical member bobbins. For a full IsoTruss® the helical bobbins represented with green circles are traveling counter-clockwise around the perimeter of the IsoTruss® and the other helical bobbins, represented by blue circles, are traveling clockwise. The yellow circles represent the locations through which the longitudinal member tows pass through the longitudinal payout tubes.

A.4.1 CONSOLIDATION OF LONGITUDINAL MEMBERS BY BRAIDING

The following set of steps consolidates the longitudinal members by braiding. These twelve steps are repeated throughout the entire process.
A.4.2 Consolidation of Helical Members by Twisting

While the longitudinal members are being braided, the helical members are being twisted. This is a two step pattern that is done twice for one full twist of the member. It can be repeated any number of times depending on the amount of twisting desired in the members.
A.4.3 Stalling Helical Member Bobbins

After being twisted, the helical members usually need to stall while the longitudinal member is braided. This is an eight step process that can be repeated any number of times.
A.4.4 HELICAL MEMBERS CROSS HELICAL MEMBERS

When the correct distance of the longitudinal member has been consolidated with a braided sleeve, the helical members cross each other forming the nodes or anti-nodes. This is an eight step process that occurs once for each node or anti-node.
A.4.5 HELICAL MEMBERS CROSS LONGITUDINAL MEMBERS

After the helical members have crossed each other, they twist and stall once again while braiding around the longitudinal member continues. Then the helical members cross the longitudinal members to form a transition node. This twelve step process occurs once to create each transition node.
A.5 **SIX-NODE ISOTruss® PATTERN**

Because of limited space on the machine, the pattern used to create a six-node IsoTruss® had to be very compact. It is, therefore, difficult to visualize. The paths followed by the clockwise helical member bobbins are dark and light green. The paths followed by the counter-clockwise helical member bobbins are dark and light orange. The blue and yellow circles represent the locations of the longitudinal member payout tubes. Because this IsoTruss® has an even number of nodes and outer longitudinal members, there are two distinct sets of helical members traveling in each direction. One set travels on the inside of all the longitudinal members represented by yellow circles, and outside all the longitudinal members represented by blue circles, while the other set does the opposite. This is true for both the helical members traveling clockwise and those traveling counter-clockwise. This twelve step pattern is repeated once for each bay.
A.6 **ISOTruss Panel Pattern**

In the pattern that follows, the yellow circles represent the longitudinal payout tubes, through which longitudinal members pass. The longitudinal members are consolidated with a coiled sleeve. The bobbins that create the coiled sleeve are represented by red circles. The helical members are represented by blue circles.
A.7  PATTERN TO MOVE BOBBINS INTO POSITION FOR TEST SPECIMENS

The following pattern is used to get the bobbins into the correct locations.

Bobbins are loaded onto the machine from the right and left center gears.
APPENDIX B   EXCEL CODE

B.1 LONGITUDINAL MEMBER WITH INTERSECTING HELICAL MEMBERS

Private Sub CreateTextFile_Click()
    Dim nBraid As Integer  ' This is the number of half braids between heli crossings
    Dim nHeli As Integer
    Dim nTwist As Integer
    Dim nStall As Integer
    Dim index As Integer
    Dim cell As String
    Dim entry As String
    Dim starti As Integer
    Dim storeindex As Integer

    nBraid = Sheets("Input").range("H14").Value  'total number of times to repeat the 14 step braid pattern
    nHeli = Sheets("Input").range("H16").Value   'this is the number of stalls plus the number of half twists
    nTwist = Sheets("Input").range("C5").Value  'user-specified number of half twists

    'Check to be sure the input is valid
    If nBraid < 1 Then
        Sheets("Input").range("C4").Interior.ColorIndex = 3
        MsgBox "Bay Length is Invalid", vbOKOnly, "Error"
    End If
    ElseIf nTwist < 0 Or nHeli < nTwist Then
        Sheets("Input").range("C5").Interior.ColorIndex = 3
        MsgBox "Number of Heli Twists in Invalid", vbOKOnly, "Error"
    End If

    'Clear out spreadsheet we will be filling in
    Application.Run "ClearSpreadsheet"

    'Fill in the braiding pattern for the heli twisting and stalling
    index = 0
    For i = 1 To nBraid  'Loop through repeating braiding pattern
        If i = 1 Then  'first 3 braiding lines are the end of the braider stalling pattern to make the array repeating
            For j = 1 To nTwist
                cell = "A" & j & "J" & 3
                Application.Wait (600)
            Next
            index = index + nTwist
        Else
            For j = 1 To nTwist
                cell = "A" & j & "J" & (index + j)
                Application.Wait (600)
            Next
            index = index + nTwist
        End If
    Next
End Sub
starti = 4
For j = 1 To 3
    index = index + 1
    cell = "A" & index
    Sheets("Macro created").range(cell).FormulaR1C1 = "=Braiders Stalling'!'R[" & 13 - index + j & "]C[2]"
Next j
Else
    starti = 1
End If
For j = starti To 14  'Loop through each line of 7 lines of the repeating braiding pattern
    index = index + 1
    cell = "A" & index
    Sheets("Macro created").range(cell).FormulaR1C1 = "=Braiding'!'R[" & 2 - index + j & "]C[2]"
Next j
Next i

'Fill in the heli pattern
nStall = nHeli - nTwist

'Helis twist nTwist times
index = 0
For i = 1 To nTwist
    For j = 1 To 4  'Because there are 4 steps for a quarter twist
        index = index + 1
        cell = "A" & index
        entry = Sheets("Macro created").range(cell).FormulaR1C1
        Sheets("Macro created").range(cell).FormulaR1C1 = entry & "+ 'Heli Twisting'!'R[" & 2 - index + j & "]C[2]"
    Next j
Next i

'Helis stall until almost the end
For i = 1 To nStall
    For j = 1 To 8              'Because there are 8 steps for the stalling pattern
        index = index + 1
        cell = "A" & index
        entry = Sheets("Macro created").range(cell).FormulaR1C1
        If i = 1 And j = 1 Then   'The first line of stalling code goes only once
            Sheets("Macro created").range(cell).FormulaR1C1 = entry & "+ 'Heli Stalling'!'R[" & 3 - index & "]C[2]"
        ElseIf i = nStall And j = 8 Then   'The last time run line 10 instead of 9 and line 10 instead of first twisting line
            Sheets("Macro created").range(cell).FormulaR1C1 = entry & "+ 'Heli Stalling'!'R[" & 3 - index & "]C[2]"
        Else
            Sheets("Macro created").range(cell).FormulaR1C1 = entry & "+ 'Heli Stalling'!'R[" & 3 - index & "]C[2]"
        End If
    Next j
Next i
Sheets("Macro created").range(cell).FormulaR1C1 = entry & "+ 'Heli Stalling'!R[" & 4 - index + j & "]C[2]"

index = index + 1
cell = "A" & index
entry = Sheets("Macro created").range(cell).FormulaR1C1
Sheets("Macro created").range(cell).FormulaR1C1 = entry & "+ 'Heli Stalling'!R[" & 5 - index + j & "]C[2]"

Else
    Sheets("Macro created").range(cell).FormulaR1C1 = entry & "+ 'Heli Stalling'!R[" & 3 - index + j & "]C[2]"
End If
Next j
Next i

'Helis twist nTwist times
For i = 1 To nTwist
    For j = 1 To 4 'Because there are 4 steps for a quarter twist
        If (i <> 1 Or j <> 1) Then 'don't do it the first time, since the stall code handles it
            index = index + 1
            cell = "A" & index
            entry = Sheets("Macro created").range(cell).FormulaR1C1
            Sheets("Macro created").range(cell).FormulaR1C1 = entry & "+ 'Heli Twisting'!R[" & 2 - index + j & "]C[2]"
        End If
    Next j
    Next i

'Helis cross

'Stall the braiders
'the first 3 lines you do just once to get the braiders into stalling position
index = index + 1
cell = "A" & index
Sheets("Macro created").range(cell).FormulaR1C1 = "='Braiders Stalling'!R[" & 3 - index & "]C[2]"

index = index + 1
cell = "A" & index
Sheets("Macro created").range(cell).FormulaR1C1 = "='Braiders Stalling'!R[" & 4 - index & "]C[2]"

For i = 1 To 3 'braiders stall 3 times for the helis to cross
    For j = 1 To 8 '8 steps to stall
        If (i = 3 And (j = 7 Or j = 8)) Then 'the last time the last two lines should be replaced by different lines
            'those lines actually replace the first 3 lines of the normal braiding code that happens during heli twisting
            'therefore don't do anything here
        End If
    Next j
    Next i
ElseIf (i = 1 And j = 1) Then 'the first time do line 3, the rest of the time use 3a
index = index + 1
cell = "A" & index
Sheets("Macro created").range(cell).FormulaR1C1 = "='Braiders Stalling'!R[" & 4
- index + j & "]C[2]"
Else
index = index + 1
cell = "A" & index
Sheets("Macro created").range(cell).FormulaR1C1 = "='Braiders Stalling'!R[" & 5
- index + j & "]C[2]"
End If
Next j
Next i

'Add the helis crossing
index = index - 24 'to get back to beginning of stalling pattern
For i = 1 To 24 'Because there are 28 steps to cross the helis
index = index + 1
cell = "A" & index
entry = Sheets("Macro created").range(cell).FormulaR1C1
Sheets("Macro created").range(cell).FormulaR1C1 = entry & "+ 'Heli Crossing'!R["
& 2 - index + i & "]C[2]"
Next i

'Now we have to repeat a slight variation for the bobbins to come back across and get to
their initial positions

storeindex = index
For i = 1 To nBraid 'Loop through repeating braiding pattern
If i = 1 Then 'first 3 braiding lines are the end of the braider stalling pattern to
make the array repeating
starti = 4
For j = 1 To 3
index = index + 1
cell = "A" & index
Sheets("Macro created").range(cell).FormulaR1C1 = "='Braiders Stalling'!R["
& 13 - index + j & "]C[2]"
Next j
Else
starti = 1
End If
For j = starti To 14 'Loop through each line of 7 lines of the repeating braiding
pattern
index = index + 1
cell = "A" & index
Sheets("Macro created").range(cell).FormulaR1C1 = "=Braiding!R[" & 2 - index + j & "]C[2]"

Next j
Next i

'Fill in the heli pattern
nStall = nHeli - nTwist

'Helis twist nTwist times
'this time we want to start on the next line to twist the heli bobbins that are now there
index = storeindex
For i = 1 To nTwist
    For j = 1 To 4  'Because there are 4 steps for a quarter twist
        index = index + 1
        cell = "A" & index
        entry = Sheets("Macro created").range(cell).FormulaR1C1
        Sheets("Macro created").range(cell).FormulaR1C1 = entry & "+ 'Heli Twisting'!R[" & 3 - index + j & "]C[2]"
    Next j
Next i
'do one more twist line to get to the start of the stalling pattern
index = index + 1
cell = "A" & index
entry = Sheets("Macro created").range(cell).FormulaR1C1
Sheets("Macro created").range(cell).FormulaR1C1 = entry & "+ 'Heli Twisting'!R[" & 

3 - index + j & "])C[2]"

'Helis stall until almost the end
For i = 1 To nStall
    For j = 1 To 8  'Because there are 8 steps for the stalling pattern
        index = index + 1
        cell = "A" & index
        entry = Sheets("Macro created").range(cell).FormulaR1C1
        If i = 1 And j = 1 Then  'The first line of stalling code goes only once
            Sheets("Macro created").range(cell).FormulaR1C1 = entry & "+ 'Heli Stalling'!R[" & 
            & 3 - index & "])C[2]"
        ElseIf i = nStall And j = 8 Then  'The last time run line 10 instead of 9 and line 10 instead of first twisting line
            Sheets("Macro created").range(cell).FormulaR1C1 = entry & "+ 'Heli Stalling'!R[" & 
            & 4 - index + j & "])C[2]"
        Else
            index = index + 1
            cell = "A" & index
            entry = Sheets("Macro created").range(cell).FormulaR1C1
            Sheets("Macro created").range(cell).FormulaR1C1 = entry & "+ 'Heli Stalling'!R[" & 
            & 5 - index + j & "])C[2]"
        End If
    Next j
Next i

'
Sheets("Macro created").range(cell).FormulaR1C1 = entry & "+ 'Heli Stalling'!R[" & 3 - index + j & "]C[2]"

End If
Next j
Next i

'Helis twist nTwist times
'this time we can start at the same place but we want to stop one line early to get to the
right returning location
For i = 1 To nTwist
For j = 1 To 4  'Because there are 4 steps for a quarter twist
If i = nTwist And j = 4 Then
  'do nothing
ElseIf (i <> 1 Or j <> 1) Then 'don't do it the first time, since the stall code handles it
  index = index + 1
  cell = "A" & index
  entry = Sheets("Macro created").range(cell).FormulaR1C1
  Sheets("Macro created").range(cell).FormulaR1C1 = entry & "+ 'Heli Twisting'!R[" & 2 - index + j & "]C[2]"
End If
Next j
Next i

'Helis cross

'Stall the braiders
'the first 2 lines you do just once to get the braiders into stalling position
index = index + 1
cell = "A" & index
Sheets("Macro created").range(cell).FormulaR1C1 = "='Braiders Stalling'!R[" & 3 -
  index & "]C[2]"

index = index + 1
cell = "A" & index
Sheets("Macro created").range(cell).FormulaR1C1 = "='Braiders Stalling'!R[" & 4 -
  index & "]C[2]"

For i = 1 To 3  'braiders stall 3 times for the helis to cross
For j = 1 To 8  '8 steps to stall
If (i = 3 And (j = 7 Or j = 8)) Then  'the last time the last two lines should be
  replaced by different lines
  'those lines actually replace the first 3 lines of the normal braiding code that
  happens during heli twisting
  'therefore don't do anything here
ElseIf (i = 1 And j = 1) Then  'the first time do line 3, the rest of the time use 3a
  index = index + 1
  cell = "A" & index
Sheets("Macro created").range(cell).FormulaR1C1 = "='Braiders Stalling'!R[" & 4 - index + j & "]C[2]"

Else
    index = index + 1
    cell = "A" & index
    Sheets("Macro created").range(cell).FormulaR1C1 = "='Braiders Stalling'!R[" & 5 - index + j & "]C[2]"
End If
Next j
Next i

'Add the helis crossing
'this time use the back pattern
index = index - 24 'to get back to beginning of stalling pattern
For i = 1 To 24 'Because there are 28 steps to cross the helis
    index = index + 1
    cell = "A" & index
    entry = Sheets("Macro created").range(cell).FormulaR1C1
    Sheets("Macro created").range(cell).FormulaR1C1 = entry & "+ 'Heli Crossing Back'!R[" & 2 - index + i & "]C[2]"
Next i

'Copy the information from column one over to 136 columns
Application.Run "CopyOver", index

End Sub

B.2 THREE LONGITUDINAL MEMBERS

Private Sub btnWriteArray_Click()

Dim nBraid As Integer
Dim nTwist1 As Integer
Dim nTwist2 As Integer
Dim nStall1 As Integer
Dim nStall2 As Integer
Dim index As Integer
Dim cell As String
Dim entry As String

'Get Values from Spreadsheet
nBraid = Sheets("Input").range("nBraid").Value
nTwist1 = Sheets("Input").range("nTwist1").Value * 2 'We want the number of half twists
nTwist2 = Sheets("Input").range("nTwist2").Value * 2 'ditto
nStall1 = Sheets("Input").range("nStall1").Value

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nStall2 = Sheets("Input").range("nStall2").Value

'Clear out the spreadsheet we will put the array in
Application.Run "ClearSpreadsheet"

'Fill in the braiding pattern
index = 0
For i = 1 To nBraid 'Loop through repeating braiding pattern
    For j = 1 To 12 'Loop through each line of 12 lines of the repeating braiding pattern
        index = index + 1
        cell = "A" & index
        Sheets("Winding Array").range(cell).FormulaR1C1 = "='Braiding Longis'!R[2-index+j & "]C[2]"
    Next j
Next i

'Now let's do the helis
index = 0
'first the inplane helis
'twist
For i = 1 To nTwist1 'the number of half twists
    For j = 1 To 2 'Because there are 2 steps for a half twist
        index = index + 1
        cell = "A" & index
        entry = Sheets("Winding Array").range(cell).FormulaR1C1
        Sheets("Winding Array").range(cell).FormulaR1C1 = entry & "+ 'Heli Twisting'!R[2-index+j & "]C[2]"
    Next j
Next i
'stall
For i = 1 To nStall1 'the number of stalls
    For j = 1 To 8 'Because there are 8 steps to stall
        index = index + 1
        cell = "A" & index
        entry = Sheets("Winding Array").range(cell).FormulaR1C1
        Sheets("Winding Array").range(cell).FormulaR1C1 = entry & "+ 'Heli Stalling'!R[2-index+j & "]C[2]"
    Next j
Next i
'switch
For i = 1 To 9 '8 steps to switch plus one line that replaces the 1st twist line
    index = index + 1
    cell = "A" & index
    entry = Sheets("Winding Array").range(cell).FormulaR1C1
    Sheets("Winding Array").range(cell).FormulaR1C1 = entry & "+ 'Heli Switching'!R[2-index+i & "]C[2]"

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Next i
'twist again
For i = 1 To nTwist1 'the number of half twists
    For j = 1 To 2 'Because there are 2 steps for a half twist
        If (i > 1 Or j > 1) Then 'Skip the first time because it needs to be different after
            index = index + 1
            cell = "A" & index
            entry = Sheets("Winding Array").range(cell).FormulaR1C1
            Sheets("Winding Array").range(cell).FormulaR1C1 = entry & "+ 'Heli Twisting'!R[" & 2 - index + j & "]C[2]"
        End If
    Next j
Next i
'cross
For i = 1 To 12 '12 steps to cross
    index = index + 1
    cell = "A" & index
    entry = Sheets("Winding Array").range(cell).FormulaR1C1
    Sheets("Winding Array").range(cell).FormulaR1C1 = entry & "+ 'Heli Crossing'!R[" & 2 - index + i & "]C[2]"
Next i
'second the heli nodes
'twist
For i = 1 To nTwist2 'the number of half twists
    For j = 1 To 2 'Because there are 2 steps for a half twist
        index = index + 1
        cell = "A" & index
        entry = Sheets("Winding Array").range(cell).FormulaR1C1
        Sheets("Winding Array").range(cell).FormulaR1C1 = entry & "+ 'Heli Twisting'!R[" & 2 - index + j & "]C[2]"
    Next j
Next i
'stall
For i = 1 To nStall2 'the number of stalls
    For j = 1 To 8 'Because there are 8 steps to stall
        index = index + 1
        cell = "A" & index
        entry = Sheets("Winding Array").range(cell).FormulaR1C1
        Sheets("Winding Array").range(cell).FormulaR1C1 = entry & "+ 'Heli Stalling'!R[" & 2 - index + j & "]C[2]"
    Next j
Next i
'switch
For i = 1 To 9 '8 steps to switch plus one line that replaces the 1st twist line
    index = index + 1
cell = "A" & index
entry = Sheets("Winding Array").Range(cell).FormulaR1C1
Sheets("Winding Array").Range(cell).FormulaR1C1 = entry & "+'Heli Switching'!R[" & 2 - index + i & "]C[2]"

Next i
'twist again
For i = 1 To nTwist2 'the number of half twists
   For j = 1 To 2 'Because there are 2 steps for a half twist
      If (i > 1 Or j > 1) Then 'Skip the first time because it needs to be different after switching
         index = index + 1
         cell = "A" & index
         entry = Sheets("Winding Array").Range(cell).FormulaR1C1
         Sheets("Winding Array").Range(cell).FormulaR1C1 = entry & "+'Heli Twisting'!R[" & 2 - index + j & "]C[2]"
      End If
   Next j
Next i
'cross
For i = 1 To 12 '12 steps to cross
   index = index + 1
   cell = "A" & index
   entry = Sheets("Winding Array").Range(cell).FormulaR1C1
   Sheets("Winding Array").Range(cell).FormulaR1C1 = entry & "+'Heli Crossing'!R[" & 2 - index + i & "]C[2]"
Next i

'Copy the information from column one over to 136 columns
Application.Run "CopyOver", index

End Sub

B.3 UNIVERSAL SUB-ROMUTES

This subroutine is used by all array writing subroutines to delete everything in the spreadsheet before it fills in the new array.

Sub ClearSpreadsheet()

   Sheets("Macro created").Select
   cells.Select
   Selection.ClearContents

End Sub
This subroutine is used by all array writing subroutines to copy the formulas from
the first column over to the other columns.

Sub CopyOver(lastindex As String) ' Copies information from A1 to A"lastindex" over
to column EF

    Dim selrange   As String

    Sheets("Macro created").Select
    selrange = "A1:A" & lastindex
    range(selrange).Select
    selrange = "A1:EF" & lastindex
    Selection.AutoFill Destination:=range(selrange), Type:=xlFillDefault
    range(selrange).Select

End Sub

B.4 DATA REDUCTION MACRO

Sub reduce()

    Dim col As String
    Dim row As String
    Dim ultrow As Integer
    Dim lastrow As Integer
    Dim cells As String
    Dim sheet As String
    Dim loc As String
    Dim sname As String
    Dim value As Double
    Dim i As Integer

    'get sheet name
    sname = ActiveSheet.Name
    'find the last row of data
    col = "A"
    lastrow = 12
    Application.Run "FindLast", col, lastrow
    lastrow = ActiveCell.row
    'make the displacement and force positive
    For i = 12 To lastrow
        value = Range("A" & i).value
        Range("A" & i).value = -value
        value = Range("D" & i).value

End Sub
Range("D" & i).value = -value
Next i

'calculate the positive strain
Range("E10").Select
ActiveCell.FormulaR1C1 = "strain"
Range("E11").Select
ActiveCell.FormulaR1C1 = "in/in"
Range("E12").Select
ActiveCell.FormulaR1C1 = "=-RC[-2]"
cells = "E12:E" & lastrow
Selection.AutoFill Destination:=Range(cells)

'calculate stress
Range("F10").Select
ActiveCell.FormulaR1C1 = "stress"
Range("F11").Select
ActiveCell.FormulaR1C1 = "psi"
Range("F12").Select
ActiveCell.FormulaR1C1 = "=RC[-2]/R1C11"
Range("F12").Select
cells = "F12:F" & lastrow
Selection.AutoFill Destination:=Range(cells)

'find the ultimate values
Range("J2").Select
ActiveCell.FormulaR1C1 = "failure load (lbf)"
Range("J3").Select
ActiveCell.FormulaR1C1 = "ultimate strength (lbf)"
Range("J4").Select
ActiveCell.FormulaR1C1 = "ultimate stress (psi)"
Range("J5").Select
ActiveCell.FormulaR1C1 = "strain at yield (in./in.)"
Range("K2").Select
ActiveCell.FormulaR1C1 = "=MAX(R[10]C[-2]:R[110]C[-2])"
Range("K3").Select
ActiveCell.FormulaR1C1 = "=MAX(R[9]C[-7]:R" & lastrow & ") &lastrow & "C[-7])"
Range("K4").Select
ActiveCell.FormulaR1C1 = "=MAX(R[8]C[-5]:R" & lastrow & ") &lastrow & "C[-5])"

'find strain associated with ultimate stress
ultrow = 12
found = False
While (found = False)
    loc = "F" & ultrow
    If (Range(loc).value = Range("K4").value) Then
        found = True
    Else
        ultrow = ultrow + 1
    End If
Wend
Range("K5").Select
ActiveCell.FormulaR1C1 = "+R" & ultrow & "C5"

'calculate E
Range("J6").Select
ActiveCell.FormulaR1C1 = "E (psi)"
Range("K6").Select
ActiveCell.FormulaR1C1 = "=(R[-2]C/R[-1]C)"
Range("L6").Select
ActiveCell.FormulaR1C1 = "end point"
Range("K7").Select
ActiveCell.FormulaR1C1 = "=(R[599]C[-5]-R[281]C[-5])/(R[599]C[-6]-R[281]C[-6])"
Range("L7").Select
ActiveCell.FormulaR1C1 = "2 points"
Range("L8").Select
ActiveCell.FormulaR1C1 = "least squares fit"

'copy data to summary
Sheets("Summary").Select

'find the right row
row = 1
col = "D"
found = False
While found = False
loc = col & row
If (Range(loc).value = sname) Then
found = True
End If
row = row + 1
If (row = 100) Then
If (col = "D") Then
col = "P"
row = 1
Else
Return
End If
End If
Wend
row = row - 1

'fill in the data
If (col = "D") Then
Range("F" & row).Select
ActiveCell.FormulaR1C1 = "=" & sname & "!R2C11"
Range("H" & row).Select
ActiveCell.FormulaR1C1 = "=" & sname & "!R3C11"
Range("I" & row).Select
ActiveCell.FormulaR1C1 = "=" & sname & "!R4C11"
Range("J" & row).Select
ActiveCell.FormulaR1C1 = "=" & sname & "!R5C11"
Range("K" & row).Select
ActiveCell.FormulaR1C1 = "=" & sname & "!R8C11"
Else
    Range("R" & row).Select
    ActiveCell.FormulaR1C1 = "=" & sname & "!R2C11"
    Range("T" & row).Select
    ActiveCell.FormulaR1C1 = "=" & sname & "!R3C11"
    Range("U" & row).Select
    ActiveCell.FormulaR1C1 = "=" & sname & "!R4C11"
    Range("V" & row).Select
    ActiveCell.FormulaR1C1 = "=" & sname & "!R5C11"
    Range("W" & row).Select
    ActiveCell.FormulaR1C1 = "=" & sname & "!R8C11"
End If

'get the area from the summary
found = False
While found = False
    If (col = "D") Then
        If (Range("C" & row).value = ") Then
            row = row - 1
        Else
            found = True
            Sheets(sname).Select
            Range("J1").Select
            ActiveCell.FormulaR1C1 = "area (in2) ="
            Range("K1").Select
            ActiveCell.FormulaR1C1 = "=Summary!R & row & "C9"
        End If
    Else
        If (Range("O" & row).value = ") Then
            row = row - 1
        Else
            found = True
            Sheets(sname).Select
            Range("J1").Select
            ActiveCell.FormulaR1C1 = "area (in2) ="
            Range("K1").Select
            ActiveCell.FormulaR1C1 = "=Summary!R & row & "C21"
        End If
End If
Wend
Application.Run "AddCharts"

End Sub

Sub AddCharts()
    Dim sname As String
    Dim lastrow As Integer
    Dim col As String
    'get sheet name
    sname = ActiveSheet.Name
    'find the last row of data
    col = "A"
    lastrow = 12
    Application.Run "FindLast", col, lastrow
    lastrow = ActiveCell.row
    'set some cells data
    Range("H10").Select
    ActiveCell.FormulaR1C1 = "Consolidated"
    Selection.Font.bold = True
    Range("H11").value = "Displacement"
    Range("I11").value = "Force"
    Range("J11").value = "Strain"
    Range("K11").value = "Stress"
    Range("H12").value = 0
    Range("I12").value = 0
    Range("J12").value = 0
    Range("K12").value = 0
    Range("J15").value = 0
    Range("K15").value = 0
    Range("J16").value = 0.0001
    Range("K16").value = 1
    Range("J17").value = 0.0002
    Range("K17").value = 2
    'Add the force-displacement chart
    Charts.Add
    ActiveChart.ChartType = xlXYScatterSmooth
    ActiveChart.SetSourceData Source:=Sheets(sname).Range("A12")
    ActiveChart.SeriesCollection.NewSeries
    ActiveChart.SeriesCollection(1).XValues = "=" & sname & ":" & !R12C1:R & lastrow & ":C1"
    ActiveChart.SeriesCollection(1).Values = "=" & sname & ":" & !R12C4:R & lastrow & ":C4"
ActiveChart.Location Where:=xlLocationAsObject, Name:=sname
With ActiveChart
  .HasTitle = False
  .Axes(xlCategory, xlPrimary).HasTitle = True
  .Axes(xlCategory, xlPrimary).AxisTitle.Characters.text = "Displacement (in.)"
  .Axes(xlValue, xlPrimary).HasTitle = True
  .Axes(xlValue, xlPrimary).AxisTitle.Characters.text = "Force (lbf)"
End With
ActiveChart.Axes(xlCategory).Select
With ActiveChart.Axes(xlCategory)
  .MinimumScale = 0
  .MaximumScaleIsAuto = True
  .MinorUnitIsAuto = True
  .MajorUnitIsAuto = True
  .Crosses = xlAutomatic
  .ReversePlotOrder = False
  .ScaleType = xlLinear
  .DisplayUnit = xlNone
End With
ActiveChart.HasLegend = False
' add a series for the consolidated data
ActiveChart.SeriesCollection.NewSeries
ActiveChart.SeriesCollection(2).XValues = "=" & sname & "'!R12C8:R" & lastrow & "C8"
ActiveChart.SeriesCollection(2).Values = "=" & sname & "'!R12C9:R" & lastrow & "C9"
ActiveChart.SeriesCollection(3).Select
  Selection.Delete
' Add the stress-strain chart
Charts.Add
ActiveChart.ChartType = xlXYScatterSmooth
ActiveChart.SetSourceData Source:=Sheets(sname).Range("E12:F12")
ActiveChart.SeriesCollection.NewSeries
ActiveChart.SeriesCollection(1).XValues = "=" & sname & "'!R12C5:R" & lastrow & "C5"
ActiveChart.SeriesCollection(1).Values = "=" & sname & "'!R12C6:R" & lastrow & "C6"
ActiveChart.Location Where:=xlLocationAsObject, Name:=sname
With ActiveChart
  .HasTitle = False
  .Axes(xlCategory, xlPrimary).HasTitle = True
  .Axes(xlCategory, xlPrimary).AxisTitle.Characters.text = "Strain (in./in.)"
  .Axes(xlValue, xlPrimary).HasTitle = True
  .Axes(xlValue, xlPrimary).AxisTitle.Characters.text = "Stress (psi)"
End With
ActiveChart.HasLegend = False
'add a series for the consolidated data
ActiveChart.SeriesCollection.NewSeries
ActiveChart.SeriesCollection(2).XValues = "=" & sname & "!R12C10:R" & lastrow & "C10"
ActiveChart.SeriesCollection(2).Values = "=" & sname & "!R12C11:R" & lastrow & "C11"

'add a series for the trendline
ActiveChart.SeriesCollection.NewSeries
ActiveChart.SeriesCollection(3).XValues = "=" & sname & "!R15C10:R50C10"
ActiveChart.SeriesCollection(3).Values = "=" & sname & "!R15C11:R50C11"
ActiveChart.SeriesCollection(3).Select
ActiveChart.SeriesCollection(3).Trendlines.Add(Type:=xlLinear, Forward:=0, Backward:=0, DisplayEquation:=True, DisplayRSquared:=False).Select
ActiveChart.SeriesCollection(3).Trendlines(1).DataLabel.NumberFormat = "0.00"
ActiveChart.SeriesCollection(4).Select
Selection.Delete

End Sub

Sub FindLast(col As String, row As Integer)

    Dim found As Boolean
    Dim loc As String

    found = False
    While (found = False)
        loc = col & row
        If (Range(loc).Value = "") Then
            found = True
        End If
        row = row + 1
    Wend
    row = row - 2
    loc = col & row
    Range(loc).Select

End Sub
Appendix C  Suggested Improvements to Machine

C.1 Panel Design Improvements

- Bevel on panel front and back to allow for insertion and removal
- Incorporate bolt holes for panel handles for insertion and removal of panel
- Increase panel stiffness by increasing panel thickness
- Make panels vertically modular
- Directly connect panel to bearing bars to allow for modular removal
- Modify panel-panel interface to reduce gap

C.2 Switch Design Improvements

- Switches should be front-loading
- Reevaluate tolerances
- Single-body housing (box- or u-shaped)
- Eliminate eccentricities by using two axles and four slider arms
- Maximize force by using stronger solenoids, using the strongest portion of travel, and using higher voltage
- Use pin connection to connect solenoid to switch plugs
- Use double-throw solenoids, or a bi-stable mechanism, to allow for less switching
- Make switch bodies longer to reduce binding
- Make slider arms wider for increased stability
- Use steel for axles, slider arms, and pins
- Modify x-plug and v-plug designs to reduce surface contact with panel
- Deeper countersinks at panel interface so that cap crew heads to not impede sliding bobbins
- Have extra travel in the solenoid
- Eliminate sharp corners on plugs

C.3 Drive System Design Improvements

- Use splined shaft
- Make shaft longer to allow for longer switches and more space for access
- Consider a larger horn gear diameter to allow more space for switches and larger bobbins
- Reevaluate mouth size on horn gear
• Bevel horn gear
• Incorporate spacer on horn gear
• Secure gears and horn gears to drive shaft with lock rings or H-clips
• Drive and horn gear should slip-fit on splined shaft
• Remove material on horn gear between mouths to improve switch visibility (making it X-shaped)
• Bevel on vertical edges of mouths
• Gears should have a number of teeth divisible by four
• Method must be developed for keeping all gears in the same plane

C.4 BOBBINS DESIGN IMPROVEMENTS

• Provide more fiber retraction
• Provide more tension on fibers
• Incorporate level-wind mechanism
• Make upper section of bobbin removable from base
• Make bobbin align to front and back of horn gear, not to back of horn gear and front of wall
• Make the bobbin compatible with pre-preg fibers by modifying the following: spool, fiber contact materials, pay-out mechanism at top of bobbin
• Evaluate fiber capacity (possibly increase)
• Reevaluate chamfer angle on the blade
• Incorporate a swivel guide for fiber
• Bevel the horn gear interface edges

C.5 SUPPORT STRUCTURE IMPROVEMENTS

• Larger spacing from panels to bearing bars to allow more access
• Bearing bars attach to other side of support frame allowing for disassembly from rear
• Bearings press-fit from the back so they don’t wander out
• Design a new method for gripping longitudinal payout shafts (possibly spring clips)
• Incorporate longitudinal tow tensioning device onto rear of machine
• Add panel stiffeners to top of the machine wall as integral part of design
• Add cover over top and sides of machine as integral part of design
• Mounting frame should allow machine to be horizontally and vertically modular
• Incorporate tensioning devices on back of machine for longitudinal member tows
C.6 Electrical System Improvements

- Provide better wire shielding
- Use better cable routing
- Move diodes into cabinet