High-Impact Textile Joining for UAV Landing Application: Tensile Testing of Textiles

Sponsor:
SLO Sail and Canvas

by

MF² Textile Engineering
“Bit of a stretch”

Patrick Michniuk
pmichniu@calpoly.edu

Matthew Ferretti
mferrett@calpoly.edu

Jennifer Ford
jiford@calpoly.edu

Mechanical Engineering Department
California Polytechnic State University
San Luis Obispo
2016
Statement of Disclaimer

Since this project is a result of a class assignment, it has been graded and accepted as fulfillment of the course requirements. Acceptance does not imply technical accuracy or reliability. Any use of information in this report is done at the risk of the user. These risks may include catastrophic failure of the device or infringement of patent or copyright laws. California Polytechnic State University at San Luis Obispo and its staff cannot be held liable for any use or misuse of the project.
Table of Contents

Chapter 1: Introduction
Chapter 2: Background
Chapter 3: Design Development - Stitching Pattern
Chapter 4: Design Verification - Stitching Pattern
Chapter 5: Final Design - Stitching Pattern
Chapter 6: Instron Fixture Design
Chapter 7: Conclusions and Recommendations
References
List of Figures

Figure 1. UAV catch net
Figure 2. Red Webbing overlapping at a 2” x 2” intersection
Figure 3. Current stitching pattern used for UAV catch nets
Figure 4. Instron tensile testing clamps for 2” and 4” webbing, 50kN max force
Figure 5. Ametek fixtures for tensile testing
Figure 6. Kelvin-Voigt material model
Figure 7. Strain vs. Time diagram for a Kelvin-Voigt material
Figure 8. Hypothetical model of joint loading modes
Figure 9. Exploded view of finite-element model
Figure 10. Graphical results of finite-element test vs. real data
Figure 11. Finite-element model of base stitching pattern under peel loading
Figure 12. Juki AMS automated sewing machine
Figure 13: Overview of new stitch patterns for testing
Figure 14. Original Peel Failure Material Setup
Figure 15a. Peel Failure on Stitching
Figure 15b. Failed 2”x2” Webbing Intersection
Figure 16. Selected peel failure material setup
Figure 17. Peel testing setup in Instron machine
Figure 18. Peel failure sample piece - stitching failure
Figure 19. Selected shear failure test
Figure 20. Shear testing setup in Instron
Figure 21. Webbing failure material setup
Figure 22. Stitched webbing failure material setup
Figure 23. Log strain data taken from dial indicator and position sensor
Figure 24. Stress-strain data taken from dial indicator and position sensor
Figure 25. Scale model of UAV catch net
Figure 26. Peel testing results for original & final pattern
Figure 27. Shear testing results for original & final pattern
Figure 28. Shear & peel test results graph for straight stich spacing in a circular test pattern
Figure 29. Final pattern
Figure 30. Basic structure of the custom fixture
Figure 31. Custom fixture concepts
Figure 32. Custom fixture assembly for fixture A
Figure 33. Custom fixture assembly for fixture B
Figure 34a. Shaft machining process
Figure 34b. Completed shaft
Figure 35. Welded fixtures
Figure 36a. Pilot hole drilled in fixture
Figure 36b. 2-inch hole drilled in fixture
Figure 37a. Completed fixture A
Figure 37b. Completed fixture B
Figure 38. Fixtures in Instron machine during testing
Figure 39. Fixture moment issue and revised fixture model
List of Tables

Table 1. Range of values for tensile test, different stitch patterns, in peel and shear
Table 2. Range of values for tensile test, different stitch densities, Straight Stitch O Pattern
Table 3. Range of values for tensile test, different stitch densities, Zig Zag O Pattern
Table 4. Bill of Materials for Fixture A
Table 5. Cost analysis
Table 6. Fixture analysis results
Table A1. Requirements for Testing Procedures
Table A2. Requirements for New Sewing Pattern
Table A3. Decision Matrix for Custom Fixture Concepts
Table A4. Data Analysis Template and Example
Executive Summary

The main objective of this project is to improve upon the current stitching pattern used in UAV catch net applications with the intention of lengthening their useable life cycle. To achieve this, a testing setup and procedure has been developed to produce material strength and stiffness data for nylon-webbing strap, and for sewn intersections of the same strap material. The current stitching pattern was tested, and quantitatively characterized based on strength and stiffness. New stitching designs were generated and tested using the same procedure, and the results compared. This allowed for the selection of the most optimized stitching pattern that achieves the longest life without failure of the stitching or the base material (webbing).

Our testing procedure is comprised of two main tensile tests; one that tests the stitching intersection in shear failure, and the other in peel failure. Force and displacement data is output through the data acquisition system for each of the tests, which yields stress-strain data that can be analyzed to characterize the relative strength and stiffness of each setup. The test procedure outlines in detail the loading of the test specimen into the machine, the setup for the machine, and the setup for the data acquisition system.

Our stitching pattern redesign begins with a failure model based on theoretical assumptions about how each independent stitched joint is loaded. This theoretical analysis is complimented by our experimental data, to determine what characteristics contribute to the strength of the stitching pattern. The main design goal is to improve the design in peel failure, which is the primary failure mode for nets currently in use. Pattern redesign is an ongoing and iterative process; and thus, additional testing iterations could result in an even more improved design.
Chapter 1: Introduction

I. Sponsor Background and Needs
The Unmanned Aerial Vehicle (UAV) that the net is intended to catch has a wingspan of 12 feet, weighs approximately 400 lbf, and flies at 100 miles per hour at the initial point of impact. The net system is comprised of a single vertical net, accompanied by two horizontal nets, that are meant to absorb the kinetic energy of the UAV, and bring it to a complete stop without damaging either the plane or the net. The vertical net is supported at each of its four corners, and is held at a neutral position (no sag, and no stretch). The two horizontal nets are placed directly below and behind the vertical net, and are supported in a similar manner (but also include a slight, yet insignificant amount of pre stretch due to the weight of the nets, ~150 lbf). The intention with this setup is that the vertical net absorbs the majority of the kinetic energy as elastic strain energy, then as the plane falls (after being slowed) the two horizontal nets catch it to prevent damage from hitting the ground. Figure 1 below shows the current net layout and size.

Figure 1. UAV catch net

There are three different intersection sizes that are used in the complete net design:
1”x 1” for all interior intersections
1”x 2” for all edge intersections
2”x 2” for all corner intersections
An intersection is defined as the sewable area resultant of webbing overlap. Webbing is defined as the base material that the nets are constructed out of, prior to any sewing occurring. Both of these can be seen below in Figure 2.

![Image](image1.png)

Figure 2. Red Webbing overlapping at a 2” x 2” intersection

II. Formal Problem Definition:
The main objective of this project is to create a stitching pattern that delivers an end product (full size catch net) that is stronger and has a longer usage life than the existing pattern. The existing pattern can be seen below in Figure 3. The current pattern is comprised of 178 stitches.

![Image](image2.png)

Figure 3. Current stitching pattern used for UAV catch nets

In order to achieve a better design, it was also necessary to create standardized testing procedures for the material and stitching intersections, in order to have a way to quantify which design is more effective in delivering higher strength values. Thus, the main goal of the project is twofold: to create testing procedures that allow for a way to quantify the strengths of different patterns; then to iterate
through the process of creating different patterns, testing them, and comparing the results of those
tests to previous patterns.

**III. Objective/Specification Development:**
Our alternative stitching patterns will be created with the intention of improving the already existing
design based on the engineering specifications from the customer’s requirements. The details of this
can be seen in Table 2 in Appendix A. In short, our goal is to produce a stitch pattern that can more
effectively and repeatedly catch the UAV without the stitching peeling apart or the base materials
failing. Ideally, the new stitching pattern will have a shorter cycle time, speeding up the production
process as well. The customer requirements and functional requirements that we will consider
include:

- **Customer requirements:** performance, high life cycle, testability, manufacturability / cycle
time
- **Functional requirements:** peel strength, shear strength, webbing, abrasion, stiffness, cost

Webbing width and the base material will not be altered during this process; the only aspect of the
design that will be changed is the stitch pattern itself, and possibly the stitching material. These
constraints have been specified by our client. The geometry of the net produced by our design will
have the same 24” center distance between webbing intersections as the current iteration.
Additional information on our design requirements can be seen in Appendix A.

**IV. Project Management:**
Matthew Ferretti’s primary responsibilities will include leading the new stitch pattern design and
theoretical analysis, and ensuring timely communications with SLO Sail and Canvas regarding all
aspects of our project as a whole. Matt is also going to use the Juki computer software to generate
new stitching patterns for usage in the sewing machines.

Patrick Michniuk will lead testing of the different current and future stitching patterns. This includes
actual testing, as well as creation of the testing specimens, and analysis of the testing results. Patrick
will also ensure that proper documentation of the project progress takes place.

Jennifer Ford is leading the design process for the fixtures used in our testing procedure. This includes
conceptual design and ideation for the fixture and analysis of the chosen concept. Jennifer will also
lead the manufacturing of the two fixtures and verification that it will perform as planned for each
test setup.

All team members will ensure will help contribute to the generation of possible alternative stitching
patterns that will perform their desired operation longer than those currently in use. Additionally, it is
the responsibility of all team members to ensure that proper safety measures are in place while
testing. Time spent testing will be shared fairly evenly among all team members.
Chapter 2: Background

1. Testing
There are many American Society of Testing and Materials (ASTM) standards related to testing the strength of various types of textiles and on certain terminology related to textiles. While none of the existing standards are directly applicable to testing and characterizing our system, there are many we can use to help develop our testing procedures. The most pertinent have the following designations:

- D76 Specification for Tensile Testing machines for Textiles
- D123 Terminology Relating to Textiles
- D751 Standard Test Methods for Coated Fabrics
- D2256 Standard Test Method for Tensile Properties of Yarns by the Single-Strand Method
- D4848 Terminology Related to Force, Deformation and Related Properties of Textiles
- D5034 Standard Test Method for Breaking Strength and Elongation of Textile Fabrics (Grab Test)
- D5587 Fabric Tear Strength Testing (Trapezoid Test)
- D7744 Standard Test Methods for Tensile Testing of High Performance Polyethylene Tapes

Reported failure data for the base material (webbing) is minimal at best, and lacks details on any testing procedure utilized to determine such data. Appendix D shows the only material data that we could find on webbing, which includes failure strength for 1” webbing (reported at 4200 lbs). Additionally, there are no standardized tests performed after the fabrication of a completed net, or even a single joint of stitched overlayed fabrics. Our testing procedure helps fill this gap in testing standards of stitched textiles.

Our project requires various testing methods to determine the capabilities of the completed sewing patterns for use in the UAV net. We have designed our testing procedure primarily based off of the ASTM D5034 test standard and the Typical Instron Tensile Test Procedure utilized in the Cal Poly Composites Lab. We have collected data on the strength and stiffness of the stitched webbing. There are several different test setups that were used, which are discussed below in Chapter 4.

During our first test, we determined that there was a need for a customized fixture to hold the webbing material in the Instron. During this initial test, the sample failed at the webbing within the jaws of the Instron. Therefore, we found it necessary to develop a method of securing the test pieces that will not cause the specimen to fail at the clamp jaw.

First, our sponsor provided us with “dogbone” test pieces with reinforced ends to go inside the Instron clamps. We believed the reinforced ends of these samples would be strong enough to withstand failure in the webbing due to the Instron’s clamping mechanism. We were provided with several dogbone style test pieces for each type of test we are performing. An example of these can be seen in the yellow highlighted areas of Figure 21.
We performed a test on a stitched webbing piece; this sample did fail at the stitching and the test was successful. However, the unstitched dogbone samples still failed at the clamp, right above the edge of the extra piece on the end, thus, failing to provide us with reliable test results. Since it is necessary to verify the strength of the unstitched material, we will need to implement an alternate clamping mechanism that can grip the material without affecting the results of the test.

To eliminate the stress concentration at the clamp jaw, it was necessary to produce a custom fixture. There are a number of current fixtures of this nature in existence, some produced by Instron, and some by third party companies. Figure 4 below shows the Instron models for 2” and 4” strap width testing:

![Figure 4. Instron tensile testing clamps for 2” and 4” webbing, 50kN max force](image)

Ametek manufactures several different fixtures for use in tensile testing as well. Figure 5 shows a few of the different models they have. The maximum testing force for their different models ranges from 1kN to 100kN.

![Figure 5. Ametek fixtures for tensile testing](image)
For our fixture, we decided to design our own specifically for our tests, based on these pre-existing models, and on the design needs of our own testing setup. The details of our design can be seen in Chapter 6.

II. Stitching pattern and textile failure

The Juki Automated Sewing Machine (AMS) can be reprogrammed to sew different stitching patterns, though it is currently only designed to stitch the current 1”x1” stitch pattern. Any changes to the stitching pattern in the past has been programmed directly into the machine using the onboard touch screen, but this process is cumbersome and unintuitive. For our new stitching patterns, we have a desktop copy of the Juki AMS software, which allowed us to draft new designs independent of the sewing machine, then use a flash drive to upload it to the machine to run. This CAD-type program made it easy to draft up new ideas quickly from our own computers, then stitch them using the JUKI machine.

Initial testing of our materials shows two interesting material property characteristics:

1. Strains reach very high values under normal conditions, upwards of 40%
2. The base webbing material exhibits characteristics of viscoelasticity

There is a good amount of literature on both of these material properties. Because strains reach significantly above 5%, logarithmic strain is going to be used instead of normal engineering strain. This is a common practice in engineering test design. Details of this can be seen in Chapter 5 in the Strain Measurement section. The main resource used for this was Basic Engineering Plasticity: An Introduction with Engineering and Manufacturing Applications by Rees.

The main characteristics of a viscoelastic material are:

1. Creep: under constant loading (stress), the material will begin to increase deformation (strain) with time
2. Relaxation: When held at constant deformation (strain), the stress felt in the material will decrease with time
3. Effective stiffness of the material is rate dependent

There are several different material models for viscoelasticity; but since our strain values are so high (significantly above 5%), a linear model can only be used as an estimation, and the actual model is non-linear. The three main linear viscoelastic models are:

1. Maxwell Model
2. Kelvin-Voigt Model
3. Standard Linear Solid Model

Much of this information on viscoelastic materials was obtained from Mechanical Behavior of Materials by Meyers and Chawla.
While our actual material model is nonlinear due to the high strains present, several different sources agree that the Kelvin-Voigt model for linear viscoelasticity is effective in predicting the expected behavior of seatbelt strap material, which is made up of the same components as the webbing used in our system (Nachbar, 1969) (Paulitz, 2005). The Kelvin-Voigt model is based on the increase in strain of a viscoelastic material after experiencing sudden deformation, and being subject to constant stress. This phenomenon is defined as creep. Kelvin-Voigt materials are modeled as a spring and damper in parallel, as shown below in Figure 6.

![Figure 6. Kelvin-Voigt material model](image)

The Strain vs. Time relationship under the aforementioned loading conditions as predicted by this model are as shown in Figure 7.

![Figure 7. Strain vs. Time diagram for a Kelvin-Voigt material after undergoing sudden deformation, and held under constant stress](image)

Note that for Figure 7, the t1 point is where the stress is released, and the material relaxes back to its zero deformation state.
While all of the current literature on the topic (namely seat belt strap) shows that our experimental data should agree with the Kelvin-Voigt linear viscoelastic model, additional testing will still need to be conducted to verify that this specific type of viscoelastic behavior applies to our material.
Chapter 3: Design Development - Stitching Pattern

I. Overview of Failure Theory
The new stitching patterns were developed based on the data acquired in our tests, our theoretical failure model, and a finite-element model of the system subjected to similar loading as the real design. Through testing and design iteration, an accurate model of joint loading has been developed. In our model, loading is modeled in two sections: force applied parallel to the joint in “shear,” and force applied perpendicular to the joint in “peel” (see Figure 8 below). Vertical shear is being modeled as creating a uniform tensile loading in the thread. Our initial belief was that the resistance of the material to this type of stress will depend on the number of stitches in the material. This was later verified through testing.

According to our model, peel shear (part B of Figure 8 below) is a function of perpendicular material displacement and is equated as the sum of uniform tensile and localized loading. Resistance to peel is determined by the geometry of the stitch pattern, and the concentration of stitches in a given area vs. the displacement in that area.

The schematic in Figure 8 served as the foundation of our modeling. As development continued, the model was refined with more complex considerations, including: how increasing the number of stitches significantly in a given area affects the strength of the base material, and how the geometry of the stitching gives way to stress concentrations. What was to be determined was what the optimal balance of stitches per given area is. A finite element analysis model (detailed in the following section) was developed to assess these considerations and to produce design iterations that will yield the best combination of peel and shear strength.

These initial calculations assumed all materials we are using in the net have linear elastic properties. We had planned on refining these calculations in future iterations by incorporating the viscoelastic properties of the nylon material we were to obtain through testing. Testing of the base material was to commence once the Instron fixture had been completed. Due to setbacks with that side of the project, the viscoelastic properties were never obtained and we were unable to revise these basic calculations. Regardless, the calculations in their primitive form served us very well and were more than accurate enough to allow us to develop the necessary test patterns.
Will need 2 equations

(A)

- Vertical shear as pictured creates uniform tensile loading in thread

- Approximated by:

\[ f = \frac{F}{n-1} \]

where \( F \) = nominal loading
\( f \) = thread tensile force
\( n \) = \# of nodes

- \( n-1 \) will be individual thread divisions

(B)

- "Peel" shear equation will be function of material displacement

- Let displacement at any given point be designated as \( \delta x \)

Figure 8. The initial hypothetical model of net joint loading modes
II. Finite Element Model

The finite element model we developed focuses on a single stitched joint of the net. Because of the complexity involved in developing a finite-element model of a material composed of thousands of individual fibers, the model was simplified as much as possible. The model consisted of two 6” long nylon straps held together by polyester stitching. Because we did not yet have the measured material properties of the nylon and polyester when work on the model commenced, the properties of these materials were sourced from the manufacturers’ websites.

The stitching was modeled as a 3D wire with a circular beam profile, and the nylon straps were modeled as a 3D solid extrusion with plane thickness 0.05 inches. According to estimates from SLO Sail and Canvas, the actual stitching pattern would have several hundred stitch pieces to model. In order to have our model run in an acceptable amount of time, we had to scale down the finite-element stitch pattern to a fraction of the size of the original. The scaled model consisted of 50 stitches, whereas the actual stitch pattern consisted of 178. By scaling loading factors in an equal proportion, we could obtain accurate results with a model that runs significantly faster. An exploded view of the model showing all components can be viewed in Figure 9.

![Figure 9. Exploded view of finite-element model](image)

Figure 9 is a display of an exploded view of the finite element model assembly, with the polyester stitch pattern (reduced to 50 stitches) shown between the two nylon straps.

Material properties and loading parameters were adjusted until an accurate model of the loading was achieved. To verify the model, displacement loading was applied to the finite-element model and the
resulting stress in each component was measured as a function of displacement, in the same way we made measurements with the real samples on the Instron machine. When plotted against real-world test results, we verified that the model was accurate to within 10-15% of the actual results. A graph comparing the force vs. displacement results of the finite element test against the real test results can be found in Figure 10.

![Force vs. Displacement](image)

**Figure 10. Graphical results of finite-element test vs. real data**

Figure 10 is a graph of the force vs. displacement data with the finite element analysis data (red) plotted against real-world data obtained in the Instron machine (blue). Note the dip in the test data, which is due to stress relaxation in the material when the procedure was momentarily stopped.

With the accuracy of the model verified, we then used the model to assess what we had initially believed: that there are localized stress concentrations in areas where peel is the greatest. Localized stress resulting from a peel test is visible in Figure 11 below.
Figure 11 is a representation of the finite-element analysis results of a peel test, with the stitching isolated from the model. Note the extreme stress concentration in the top right fiber, where the peel was focused.

Our finite element model successfully confirmed our hypothesis that stress concentrations developing during peel testing will be a function of localized displacement. In addition to model verification, we had originally intended for the finite-element model to serve as a testbed for future stitch patterns as well. However, this application was shelved due to the lengthy process of incorporating new designs into the model. It was much faster to produce new patterns with SLO Sail and Canvas’s machinery and perform real-world tests immediately.
III. Test Pattern Design & Production

SLO Sail and Canvas uses Juki AMS sewing machines (Figure 12) to produce their nets. These machines have software built into their control systems that allow existing stitch patterns to be modified. However, the built-in module is rudimentary at best, and does not allow for complicated stitch patterns to be produced from scratch. Therefore, Juki programming software was acquired directly from the manufacturer and was distributed to a team member. Once the Juki software was up and running on a team member’s computer, several test patterns were produced and then transferred to the Juki machinery via USB. Figure 13 contains an overview of the test patterns produced.

Figure 12. Juki 1900 Automated Sewing Machine
The following specifies each pattern displayed in Figure 13. Clockwise from top left: simple “X” pattern; the basic circular pattern consisting of a straight stitch pattern running around the circumference of the base circle and a zigzag pattern on top of that; a circular pattern with an “X” in its center that combines the top two designs; a design consisting of two concentric circles.

The first pattern we tested was a simple “X” pattern (as shown in the top left of Figure 13). This pattern was run to test two parameters. The first was just to ensure that the patterns produced on our software could be carried over to the machine and produce actual stitches. We were successful in this regard. The second was to assess the effect of the corner stress concentration during a peel test. With this pattern, we expected to see a lower initial failure strength in peel due to the extreme stress...
concentration at the corner of the pattern. We expected the ultimate strength in peel to be quite high, due to the fact that once half of one line had failed, the Instron machine would then have to pull apart the entire second line at once.

The second pattern we produced for testing was a simple circular pattern (as shown in the top right of Figure 13). This pattern was developed to assess whether a circular shape could eliminate the stress concentration in the corner of the pattern during the peel test. The pattern consists of two stitches: the first is a simple straight stitching pattern that goes around the circumference of the core circle; the second is a zigzag pattern that covers the straight pattern and weaves back and forth over the circumference of the circle. The combination of straight and zigzag patterns allows us to place many stitches in the circular pattern, while keeping the individual stitch entry points far enough away from each other to avoid compromising the strength of the base material.

The final two patterns pictured in this section were two experimental iterations based off of the circular design. The bottom right design was an attempt to combine the strengths of both the circular pattern and the plain “X” pattern. During peel testing, the pattern was expected to retain the same initial failure strength of the circular pattern, while also retaining the increased ultimate failure strength we expected to see with the “X” pattern.

The bottom left design was a simple iteration on the circular pattern from the top right, consisting of the same design, but with a concentric circle added to the center of the test piece. It was expected to have similar failure properties as the simple circular pattern during peel testing, but an increased shear strength due to the overall higher stitch density.

A third similar pattern, consisting of a center circle and four additional circles in each corner of the pattern, was also considered. This pattern was scrapped due to complexity, since it approached the limit of what was possible on the Instron machine and would have been an incredibly inefficient design even if it had increased strength properties.

During testing, we found the circular pattern to be the most effective (full testing details are available in Chapter 4). Once we had verified that the circular pattern was the most effective, many more iterations were made upon the circular design. These iterations were identical in shape to the design pictured in the top right of Figure X, but had varying stitch densities in both the zigzag stitching across the circle, and the linear pattern beneath it. By producing many stitch patterns of the same design with varying densities, we hoped to determine the optimal stitch density that would provide the highest possible strength without compromising the base material.

V. Thread Size & Material
All nets produced thus far have used 92V polyester threads. These threads have performed reliably according to our sponsor, so we will continue to use the 92V polyester threads for stitch pattern development. However, the small size of these threads dictates a denser stitching. The current pattern consists of approximately 178 stitches, which requires a fairly high cycle time and thus
reduces production efficiency due to requiring a high number of bobbin changes (as more thread is used). At the start of the project, our sponsor had requested research into alternative thread sizes (specifically 138V and 207V) as well as alternative thread materials, most notably nylon. Ultimately, utilizing larger threads in our test patterns may have made it possible to reduce the cycle time and increase the efficiency of net production without compromising strength. However, as the project continued, SLO Sail and Canvas reported that their client for the net had experienced technical challenges with the system it is a part of. Because of this, the client requested as few variables with the net be changed as possible so that they may better isolate variables as they troubleshoot the system. For this reason, we did not experiment with different sizes of thread, and used 92V material throughout the project.
Chapter 4: Design Verification - Stitching Pattern

I. Standardized testing procedure
In order to verify new stitching designs, the existing design had to first be tested to assess how and where failure was occurring. Because there is currently no standardized test procedure for textile stitching, the first primary objective was to develop such a test. In order for our tests to yield applicable data for redesigning a stronger stitch pattern, we also had to determine a hypothetical loading scenario that the net experiences as the UAV impacts it. We believe that the net can fail in two common ways, the tests for which are described in III-C and III-D. Depending on the location of the UAV on the net, the strips will react differently, pulling at each other in tension towards the main impact and peeling apart at the intersections.

All tests will be performed on an Instron universal testing machine. Our detailed testing procedure, as well as the formal safety requirements, can be seen below in Appendix G. Our test specimens cannot be clamped directly into the jaws of the tensile tester, and instead require the usage of a custom fixture to ensure a reduced stress concentration to yield accurate test results. We manufactured this fixture ourselves, and all the details of this can be seen in Chapter 6.

The tests produce several datasets for the different material and stitching test set ups. We looked at both load and displacement data from the Instron machine, as well as the geometry of the specimen being tested, to obtain stress-strain and stiffness curves for the different test pieces. Stress/strength data was normalized per unit width of the webbing material. Strain data collection is discussed later in “IV. Strain Measurement.”

III. Test current stitching pattern
When testing the current stitching pattern used by SLO Sail and Canvas in their nets, we focused on the 1”x1” webbing, since that is the most common failure point of the net according to SLO Sail and Canvas, who currently do a lot of repair work on nets that come out of the field. We tested for the two primary failure mechanisms: failure of the stitching, and failure of the base material. These will be observed in each of the four types of tests discussed below. The data and analysis of these tests are in Chapter 4, section V of this report.

III-A. Test 1: Peel Failure
This test is for what our sponsors are most concerned about; it is more representative of how the net actually fails, in the worst loading case. During impact, the webbing is peeled apart and the stitching can break. Originally, we planned to test the webbing as shown in Figure 14. The material was held in the Instron hydraulic grips at the highlighted areas. The red arrows indicate the direction the fabric
was pulled in. The two pieces when sewn are parallel and on top of each other, to be stretched out as shown below, to simulate failing along the edge of the stitching pattern, highlighted in blue.

![Figure 14. Original Peel Failure Material Setup](image)

However, the stitching actually starts to fail at the corners. A more detailed drawing of this type of failure is shown in Figure 15a and an actual failed piece in Figure 15b.

![Figure 15a. Peel Failure on Stitching](image)  ![Figure 15b. Failed 2”x2” Webbing Intersection](image)

Thus, our selected testing orientation is shown in Figure 16 with the dogbone pieces directly clamped in the Intron machine. The pieces are sewn perpendicular to each other, as they are for the actual net. When the webbing is under a load, the material twists and pulled such that the corners fail first. The test for Peel Failure was also used to test our new stitching pattern prototypes. The actual test setup in the Instron machine is displayed in Figure 17.

![Figure 16. Selected Peel Failure Material Setup](image)
Our initial test of this pattern showed that the stitching begins to fail at the specified corner and the stitching continues to break diagonally across the stitched square. That sample piece is shown in Figure 18. The green identifies the sewn portion. We tested this piece to complete failure and observed the stitching ripping and unraveling itself from the strap. Our further peel testing was pretty consistent with these results. Sometimes, the denser stitching patterns resulted in actual webbing failure, ripping the base material while some of the stitching remained intact.

![Figure 17. Peel testing setup in Instron](image)

![Figure 18. Peel Failure Sample Piece - stitching failure](image)

**III-B. Test 2: Shear Failure**
This test for shear failure was used to represent how the webbing fails when in direct tension, without any twisting of the material. The pieces are sewn parallel to each other as shown in Figure 19. We observed the differences in failure types and performance of each piece. It is important to compare how an increase in strength in one failure mode effects the other. The actual setup for the Instron and the failure of one of our pattern prototypes is shown below in Figure 20.

![Figure 19. Selected Shear Failure Test](image1)

![Figure 20. Shear testing setup in Instron](image2)

**III-C. Test 3: Webbing Failure**

This test was planned to be used to confirm the documented tensile failure of the unstitched webbing material. According to our sponsor’s webbing supplier, the nylon fails at about 4200 lbf for 1” wide material and 6000 lbf for the 2” wide material. This information can be seen in the data sheet in Appendix D. We planned on using the Instron tensile test machine and a custom fixture to verify that the webbing fails at this point. The orientation of the testing piece is shown in Figure 21.
Unfortunately, we were unable to complete this test and get accurate data. The Instron machine provided is primarily used to testing metal and composite pieces, which generally break within a few inches. Therefore, the machine only has 4 inches of stroke, that is, 4 inches the testing pieces can be pulled or compressed. This worked well for our peel and shear testing, as the stitching failed within a couple of inches. For the unstitched base material however, 4 inches is not enough. The webbing wrapped around the fixture stretches significantly as the load is applied. When we ran tests, we hardly reached 600 lbf of loading before reaching the end of the stroke. We did not account for just how much the webbing would have to be pretensioned in the fixture before running the test. In order to verify the actual strength of the webbing material, either a machine with a longer stroke should be used, the fixture improved to allow for ratcheting and pretensioning, or a different fixture design that eliminates the need for the extra wrapping material without damaging the clamped ends. Detailed information about the custom fixture and ways to improve it are included in Chapter 6.

**III-D. Test 4: Stitched Webbing Failure**

This test was planned to be used to observe the effects of the stitching on the 1” webbing material. At the stitching location, the base material becomes very stiff. We wanted to observe how the stitching effects the tensile strength of the webbing. The desired material setup is shown in Figure 22 below. This test required the use of the custom fixture so the webbing ends would not fail in the Instron grips. We were unable to complete these tests with any original or prototype patterns as we were unable to complete a solution for the base webbing setup, as discussed previously. The effects of the stitching on the base material is an aspect of the intersection design we hope can be investigated in the future.
IV. Strain Measurement

The most direct way to measure strain for our setup is using the extensometer following standard lab procedures to ensure correct usage. For our application, however, we will want to measure strain when close to failure, and thus, would risk damaging the extensometer should the material fail during testing. Because of this, the extensometer will not be used to measure strain directly in our testing procedures.

Instead, we used the definition of strain, the initial gauge length of the test piece, and basic position/displacement measurements taken from the setup to calculate strain experimentally. One shortcoming of this method, however, is that the stiffness/elasticity of the entire Instron tensile tester setup will cause error in our measurements, as we will be measuring the “change in length” of the entire system, not just our material.

To address this problem, we set up a test where we collected strain data using two different methods:

1. Using the position sensor on the Instron test machine
2. Using a dial indicator placed between the two clamp heads

The two data sets were compared, and it was found that there was 2% or less error between the two measurements, verifying our assumption that we can assume the stiffness of the test machine as very large in comparison to the test specimen. The data from this experiment can be seen below:
Thus, strain data will be generated using actuator position data, and the standard definition of logarithmic strain.

$$\varepsilon = \ln\left(\frac{L}{L_0}\right)$$

Log strain is used because the strains found in textile systems are very high even for low loading conditions. Log strain is recommended for systems where normal engineering strain is above 5%, which is true for the vast majority of textiles, including all of the ones that we are testing.

### IV. Scale model of net
We created a scaled down version of the net that we can use to observe how the webbing system acts under loading to help validate testing methods. This net can be seen below in Figure 25.
The catch net was designed to be 5’ long and 5’ wide, with webbing intersections 6” apart from center to center. This setup gives us a total of 100 sewing intersections. Compare this to the geometry of the actual net, which is 64’ by 64’, and has webbing intersections 24” apart from center to center. Creation of this net was used to get an idea of cycle times in manufacturing of the net, which came out to an average of 40 seconds per stitch pattern (for 1” x 1”). This gives us a minimum time of 1.1 hours to manufacture this single scale net.

In looking at new designs, decreasing the amount of stitches in each stitching intersection will decrease the cycle time of sewing each intersection. The current design has 178 stitches in each intersection, and if we can decrease this number and save even a few seconds off the sewing time for each intersection, we can ultimately decrease the total production time of the net substantially. Not factored into this cycle time is the amount of time that it takes to change the bobbin on the machine, which needs to be done after approximately every 30-40 sewing intersections. This takes a little over a minute, and adds a significant amount of manufacturing time to the production of each net. Decreasing the amount of stitches in each intersection will help mitigate this issue as well, as less stitches will necessitate less bobbin changes.

V. Testing Results - Stitch Pattern
For both the original pattern and all improved pattern concepts we performed 5 runs for peel and 5 runs for shear testing. The maximum failure loads for each group of tests varied by about 100 lbf. This was most likely due to poor process control for the Juki Automated Sewing Machine. Although each group of test pieces for a specific pattern were made in one sitting, it is possible that not setting the thread tension for the Juki allowed for too much variation. Therefore, to best represent the pattern failures we analyzed the average runs for each test. These results are displayed below.
As shown on the left of Figure 26, the original pattern first failed at 430 lbf/in before dropping down and spiking back up for a maximum stress failure of 450 lbf/in at 440 lbf. Referring back to Figure 3 of the original pattern drawing, the first failure occurred after a top corner of the pattern failed. The maximum failure occurred when the loading met a corner of the same side with the stitched midline. Although it met a higher load after the initial failure, the initial failure is more important.

The final pattern had the same initial and maximum failure, peaking at a maximum stress of 644 lbf/in at 631 lbf. This can be observed on the right of Figure 26. This pattern has a 43% increase in peel strength. One of the clear advantages of the circle pattern is that there are no corners; the stress concentration present in the original pattern is better distributed across an arc length. It is also interesting that both the original and final patterns reached initial failure at about the same log strain value, 0.21 to 0.23. It may be worth investigating the use of a smaller circle pattern with a similar zigzag pattern to observe if the material reaches a higher strain at the same load. This may allow for the whole net to stretch out and deflect even more than our chosen pattern before complete failure.

![Figure 27. Shear testing results for original pattern (left) and final pattern (right)](image)

As can be seen above in Figure 27, the results were very close for the shear tests; the original pattern failed at 1486 lbf/in and the final pattern failed at 1341 lbf/in, within 10% of the original pattern. Although the chosen final pattern did not perform as well, shear failure is not the primary loading concern. The peel and shear tests performed model pure peel and shear failure as an approximation and simple representation of the complete system. In reality, the loading is a complex combination of peel and shear.

Table 1 shows the maximum force before breaking for some of the different patterns that we tested. The original performed better in shear than all of the patterns we created, which we expected to be the case due to it having a rectangular geometry. It’s important to note, though, that shear is not the primary form of failure for these stitching intersections in their actual application. Since peel has
substantially lower failure values, our goal was to design for peel without compromising shear strength.

We ultimately decided to go with the O pattern for a number of reasons:

1. The X pattern only reached its peak value of strength after a good portion of it had already failed, which is not desired
2. The XO pattern had marginally better properties at the expense of significantly higher cycle times, which is also undesirable
3. The O pattern offers the best tradeoff between strength in our shear and peel tests, as the loading force is distributed across the same stitch cross sectional area independent of loading conditions

V. Testing Results - Stitch Density
In addition to testing different patterns, we also looked into changing the stitch density (meaning varying the spacing between the straight stitches, and the spacing and length of the zig-zag style stitch). We tested this after selecting our final pattern, which ended up being a circle with the largest possible diameter that still allowed it to fit inside the available webbing intersection. We chose to test straight stitching and zig zag stitching separately, to get an idea of how each one affects the overall system. it is important to note that low stitch density patterns fail by pulling apart at the stich, while high stitch density patterns tend to fail in the base material, as opposed to the stitch pulling apart. Thus, there exists an optimum point that maximizes the increase in strength that more stitches provides, without overdoing it with so many stitches that the base material starts to fail.

Table 2 below shows the range of values for a set of 5 peel and 5 shear tests for stitch spacing ranging from 0.5mm to 1.5mm. Figure xx. shows how ultimate strength changes with straight stitch spacing, and although only 3 data points are shown, it seems to be the case that the relationship is nonlinear. In the future, more tests can be run at different spacing values to help prove and characterize this relationship, and help determine the most optimized stitch density.

Table 2. Range of values for tensile test, different stitch densities, Straight Stitch O Pattern
We also tested different densities of zig zag stitching pattern; the range of data can be seen in Table 3 below for 5 shear and 5 peel tests.

**Table 3. Range of values for tensile test, different stitch densities, Zig Zag O Pattern**

<table>
<thead>
<tr>
<th>Stitch Length, Width [mm]</th>
<th>Shear [lbf]</th>
<th>Average</th>
<th>Peel [lbf]</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test Runs</td>
<td></td>
<td>Test Runs</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>988 1000 1080 1085 1087</td>
<td>1048</td>
<td>296 354 369 371 381</td>
<td>354.2</td>
</tr>
<tr>
<td>0.75, 2.5</td>
<td>1232 1241 1278 1281 1315</td>
<td>1269.4</td>
<td>461 495 497 502 510</td>
<td>493</td>
</tr>
<tr>
<td>1.00, 2.5</td>
<td>1105 1122 - - -</td>
<td>1113.5</td>
<td>356 371 380 383 407</td>
<td>379.4</td>
</tr>
</tbody>
</table>
Chapter 5: Final Design - Stitching Pattern

Based on all of our testing, for our final design stitch density we selected a zig zag stitching width of 2.5mm, and a spacing of 0.75mm, as well as straight stitching with 0.5mm spacing underneath. This was the optimum value based on our tests. The overall diameter of our pattern is 18mm which is the largest that can fit inside the 1” x 1” stitching intersection. Figure 29 above shows the geometry of our final pattern.

Despite the improvement that our new pattern has over the current one used, we believe that additional tests could help determine how the straight and zig zag stitching works in unison, and would potentially provide more useful data to be used in optimizing the pattern design further.
Chapter 6: Instron Fixture Design

I. Design Development
The purpose of the fixture is to secure the fabric to the Instron such that the samples do not slip or break at the clamped point, and instead fail at the expected point of failure, the middle of the sample. This fixture will be used for the unstitched 1” and 2” pieces as part of the “Webbing Failure” test and for a stitched 1” piece as part of the “Stitched Webbing Failure” test discussed in Chapter 5. A few of our concepts are based off of existing designs for fabric strap holders, primarily ratchet straps and machine webbing grips. The main requirements for the design are to be compatible with our testing requirements, be compatible with the sample material, be compatible with the Instron machine, be simple to manufacture, and be easy to setup and use.

Each concept is based off the same basic structure and includes similar elements. This basic structure is shown in Figure 30. The strap is set up the same way for each design; the main difference is in how the rod is secured during testing. These concepts can potentially fulfill the above requirements, in addition to two design-specific goals: the ability to rotate what the material is wrapped around during setup and to prevent that rotation during testing. After one end of the material is secured, it is impossible to wrap the loose end around the other fixture rod without rotation of the rod.

Figure 30. Basic Structure of Custom Fixture
Five concepts are shown in Figure 31 below. The first concept uses a screw to secure the rod to the side plate on each end. One of the screws is reverse-threaded so that when the shaft attempts to rotate under loading, each screw tightens instead of one tightening while the other loosens. The screws compress the rod ends against the plate to prevent rotation and can be removed for strap setup. The next concept is similar, except that the rod is set into the side plate so that the plate can take some of the loading off of the bolt during testing. The third concept builds off of the last. Since concepts 1 and 2 rely heavily on the screws being tightened down enough, concept 3 includes a failsafe; a set screw is used on the top of the side plate to help keep the rod from rotating. Concept 4 is the first of the concepts where the shaft extends all the way through the side plates. It uses a screw on the top of the side plate to stop the rotation, threading into a specific location on the shaft. Concept 5 is similar, except a bolt or pin (shown as 5A and 5B, respectively) goes all the way through the side of the plate and shaft to prevent the rotation. A side view of this concept is also included. We also considered using a key between the shaft and side plate to prevent rotation, but eliminated the idea since keys are not designed to be removed easily or often.

Concept 5 was selected. See decision matrix in Appendix A for detailed comparison and analysis of each concept. Our top design considerations were machinability, testing compatibility, and ease of setup and use. This design does not rely on anything being threaded through the shaft so we do not
have to worry about it coming undone during testing. It also seems like the least likely to fail under max loading (6000 lbf for the 2” strap) since the force will be distributed through the side plate and the pin. It does, like the other designs, rely on precise machining with the right amount of clearance between components. A more detailed description of our selected concept is discussed in the next section.

II. Final Design

We will be making two custom fixtures, one for each clamp of the Instron machine. The assembly layout is shown below in Figure 32. The labeled parts in the assembly with basic descriptions are included in Table 4. This design allows for us to insert one end of our sample piece through the slot in the shaft and rotate the shaft to wrap the sample around, similar to a ratchet strap. This shaft is 2 inches in diameter with a 2.5-inch-long slot that goes all the way through. The reason the diameter is so large is to decrease the stress concentration on the shaft. Two Grade 8 bolts go through the side plates and the ends of the shaft. During testing, these bolts will withstand the moment caused by the loaded fabric sample trying to rotate the shaft, locking the shaft in place. The mini plate attached to the bottom plate is what the Instron clamps to.

![Figure 32. Custom Fixture Assembly for Fixture A](image)

Note that the actual welds will be much bigger for complete penetration. The fixture structure will be stick welded with size 7018 electrode.
Since only one in the pair of fixtures needs to be able to rotate, Fixture B will have the shaft welded to the side plates to prevent rotation. The model is shown above in Figure 33 and also displays how the fabric is wrapped in the fixture. It will not include the bolts or nuts listed in the Bill of Materials.

Table 4. Bill of Materials per Fixture A

<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>PART NO.</th>
<th>DESCRIPTION</th>
<th>QTY.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Side Plate</td>
<td>4.25&quot;x4&quot;x1&quot; 1018 Steel</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Shaft</td>
<td>2&quot; diam Chrome-Plated Steel</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>7/16&quot; Bolt</td>
<td>Grade 8, 7/16-14, 5&quot; long Bolt</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>7/16&quot; Nut</td>
<td>Grade 8 7/16-14 Hex Nut</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>Bottom Plate</td>
<td>4.25&quot;x5&quot;x1&quot; 1018 Steel</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>Mini Plate</td>
<td>1.5&quot;x1.5&quot;x0.375&quot; 1018 Steel</td>
<td>1</td>
</tr>
</tbody>
</table>

The materials chosen for the fixture are based on the ability to machine and weld and the strength to withstand our maximum loading. Grade 8 bolts and nuts were chosen to lock the shaft in place since they can withstand the loading from the shaft. Since each plate will be welded and machined to size and other part-specific details, a low-carbon steel was chosen - 1018 steel plate. We also chose the 1045 steel shaft for similar reasons since the stock piece will have to be modified. Refer to Appendix B for detailed part drawings.
Resources for machining and welding are available in both machining labs on campus. First, we will machine each plate to the specified dimensions, not including any holes in the part, such as for the side plate. We will also machine out the 2.5-inch long slot in the shaft. The side plates will be welded to the bottom plate, followed by the mini plate, as depicted in Figures 32 and 33. Welding is done before the next machining steps because of how welding and heat affects metal. Heat can change how pre-machined parts line up, even if perfect part orientation and setup was attained. By machining after the pieces are set in their final positions, any parts that go through the holes will not need to be forced through and be under any unexpected internal loading.

After welding, the 2-inch diameter hole in the side plate will be bored out, either with an end mill or drill bit, depending on what is available. It will be cut such that there is clearance for the shaft, since we want it to be easy to rotate. The shaft will then be placed through the side plates and clamped with the slot located in between the two plates. Then the 7/16-inch holes will be bored out, all the way through the side plate and shaft. It will be cut such that there is clearance for the bolts so that they are easy to remove and reset. Because our design relies on the bolt holes lining up, one side of the shaft and its side plate will be marked so the orientation of the shaft will be the same with each use. This will allow the user to be able to slip in the bolt and lock the shaft in place efficiently. The cost analysis for each part needed is listed in Table 5.

<table>
<thead>
<tr>
<th>PART</th>
<th>DETAIL</th>
<th>SUPPLIER</th>
<th>QTY.</th>
<th>COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt</td>
<td>Grade 8 7/16-14, 5&quot; long, pack of 5</td>
<td>McMaster-Carr</td>
<td>1</td>
<td>10.03</td>
</tr>
<tr>
<td>Nut</td>
<td>Grade 8 7/16-14 hex nut, pack of 50</td>
<td>McMaster-Carr</td>
<td>1</td>
<td>7.33</td>
</tr>
<tr>
<td>Plate</td>
<td>1x4.5x36 1018 steel bar (3 ft long)</td>
<td>McMaster-Carr</td>
<td>1</td>
<td>115.39</td>
</tr>
<tr>
<td>Shaft</td>
<td>2 OD, 12 length steel shaft</td>
<td>McMaster-Carr</td>
<td>1</td>
<td>60.18</td>
</tr>
<tr>
<td>Washer</td>
<td>7/16 lock washer, pack of 50</td>
<td>McMaster-Carr</td>
<td>1</td>
<td>6.17</td>
</tr>
<tr>
<td>Drill Bit</td>
<td>2&quot;, Morse Taper 4, 7.6&quot; Drill Depth</td>
<td>McMaster-Carr</td>
<td>1</td>
<td>452.72</td>
</tr>
</tbody>
</table>

Total: $651.82

Each part of the assembly was analyzed under maximum loading conditions - a 2-inch strap under 6000 lbf in tension. Table 6 contains the analysis results for each piece of the assembly. All of the calculated safety factors are well over 1.0. This is due primarily to the chosen plate thickness; the design calls for a bolt that will go through the side of the plate, so the thickness is dependent upon the minimum possible bolt diameter. The bolt was analyzed as a beam with a high stress concentration at the edge between the shaft and the side plate. The maximum allowable stress is due to the moment created by maximum distributed load caused by the pins’ reaction to the side plate and twisting of the shaft. The chosen Grade 8 bolt can withstand this loading with a safety factor of 1.27. Originally, we planned to use a 18-8 stainless steel clevis pin in place of the bolt, but the material could not withstand that loading. Refer to Appendix E for detailed supporting analysis of the fixture.
Table 6. Fixture Analysis Results

<table>
<thead>
<tr>
<th>PART</th>
<th>MATERIAL</th>
<th>YIELD STRENGTH (ksi)</th>
<th>ULTIMATE STRENGTH (ksi)</th>
<th>MAXIMUM STRESS (ksi)</th>
<th>SAFETY FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaft</td>
<td>1045 Steel</td>
<td>45.0</td>
<td></td>
<td>9.50</td>
<td>4.74</td>
</tr>
<tr>
<td>Bottom Plate</td>
<td>1018 Steel</td>
<td>53.7</td>
<td></td>
<td>24.35</td>
<td>2.21</td>
</tr>
<tr>
<td>Side Plate</td>
<td>1018 Steel</td>
<td>53.7</td>
<td></td>
<td>21.10</td>
<td>2.55</td>
</tr>
<tr>
<td>Bolt</td>
<td>Grade 8 Steel</td>
<td>130.0</td>
<td></td>
<td>102.76</td>
<td>1.27</td>
</tr>
<tr>
<td>Welding</td>
<td>E80 Electrode</td>
<td>(0.3)(80)</td>
<td></td>
<td>16.30</td>
<td>1.47</td>
</tr>
</tbody>
</table>

Safety considerations for this fixture include good machining and welding practices; no processes will be done alone and all machine and welding setups will be checked before operation. Not only will this guarantee the user’s safety, but also that the fixture will be manufactured as intended. In terms of the use of our fixture, the biggest safety concern is that the nuts on the bolts are tightened. If a nut is loose, the bolt has the potential to slip out of the assembly. If one bolt slips out during testing, the other bolt will be under all the loading and has the potential to fail. It is really important to verify that all bolts and nuts are tightened before testing and that each fixture is secured in the clamps of the Instron. It is also important that the Instron load does not exceed 6000 lbf since anything greater will approach failure of the bolts. If the bolt, or any other part of the fixture, does begin to fail, the user will notice any deformation during testing so they can pause the test. More safety considerations and failure analysis are included at the end of Appendix E.

In terms of maintenance, if a bolt does break, it can be easily replaced. If, however, the bolt failure causes irreparable damage to the side plate or shaft, that part of the assembly may have to be rebuilt, depending on the severity of the damage, i.e. a bent shaft.

III. Product Realization

Both fixtures were manufactured on Cal Poly’s campus, utilizing the tooling and machines in Mustang 60, the Rose Float lab, and the BRAE lab. First both shafts were cut to size on the band saw and the edges gridned down. Then, the slot in each shaft for the fabric to wrap through was milled out. The process and final product are pictured below in Figure 34a. and Figure 34b.
Following the completion of the shafts, the main structure of the fixture was manufactured. The 1-inch side plates and bottom plates were cut to size with a band saw, and all sharp edges were grinded down. The pieces were then welded as displayed below in Figure 35.

Each fixture then had the main hole for the shaft drilled out on the Carlton Drill Press, starting with a pilot hole as a guide for the drilling of the 2-inch hole. This hole went through both sides of the plate,
using supports between each side to prevent any bending of the plates. Progress pictures for the drilling of the pilot hole and completion of the 2-inch hole are shown below in Figure 36a. and Figure 36b.

![Figure 36a. Pilot hole drilled in fixture](image1)

![Figure 36b. 2-inch hole drilled in fixture](image2)

Once the 2 inch holes were completed, Fixture A was turned on its side to drill the holes for the bolts. Additionally, matching holes were drilled for the shaft. Because the sides were not perfectly square with the base of the fixture, the bolts only fit in the shaft in one specific orientation. Since Fixture B did not have to be adjustable, one shaft was welded in place. Lastly, the tabs that are clamped in the Instron were welded to the bottom of each fixture. Below are the completed fixtures, Fixture A in Figure 37a and Fixture B in Figure 37b.

![Figure 37a. Completed Fixture A](image3)

![Figure 37b. Completed Fixture B](image4)
IV. Design Verification and Recommendations

For the testing of the base material, our Instron testing procedures were followed. However, rather than clamping the webbing sample directly into the Instron, we clamped in each fixture. First, the welded fixture was secured in the lower clamp, followed by the adjustable fixture in the upper clamp. The webbing material was cut and first wrapped through and around the lower fixture. While keeping the first wrap secure, the loose end of the strap is then wrapped through the upper fixture slot. The shaft is rotated by hand to wrap that end of the webbing material. When the strap is tight, the bolts are inserted through the side plates and tightened. The complete Instron setup with the fixtures and webbing material is shown in Figure 38.

![Figure 38. Fixtures setup in Instron during testing](image)

During our initial testing with the fixtures, not only were we limited by the stroke of the Instron, but after multiple tests, Fixture A began to fail at tabs because of unexpected moment. As can be seen in the Solidworks drawings above in Figure 38 the tab that is gripped in the Instron was welded in the center of the fixture, which is subjected to a moment since the force on the straps is not in line with the force transmitted through the tabs from the Instron machine. Before reaching complete failure, the fixtures were safely removed and modified. The tabs were recreated and welded in line with the
In order to successfully perform the testing for material strength verification, the fixtures need to be improved or replaced. Ideally, the fixtures would be ratcheting so that the straps were better secured and could be pretensioned. The pretensioning is key since the straps material stretches so much before reaching a significant load.
Chapter 7: Conclusions and Recommendations

I. Additional Testing & Analysis

For the scope of our project, we were able to run multiple iterations of testing different patterns, as well as a range of different stitching densities. We have concluded that the circle pattern with a 0.75mm stitch length and 2.5mm stitch width performed the best when subject to our tests. Though, we believe additional testing iterations could prove beneficial in further optimizing stitch density and pattern design.

Beyond the scope of our project, there are a few different failure modes and additional analysis that can be run to further improve the effectiveness of this design. First, taking a more detailed look at the full net catch system’s loading scenario (not only the net and stitching, but the full system) could help provide insight into modeling the system as well.

Other parameters of the net can be varied as well, including:
- Webbing material
- Webbing size
- Center distance of webbing intersections

There also exists other forms of failure that we did not study in great detail, some being harder to quantify, including:
- Fatigue failure
- Complex real system loading of 1 or multiple intersections
- UV damage over time
- Airplane on fire, fire resistance
- Propeller cutting material
- Plane impacting faster than 100mph
- Abrasion failure, net being dragged, or plane rubbing on net

Peel failure and shear failure, as tested in detail in our project, are the primary forms of failure our sponsors wished to investigate according to their analysis of failed nets. Yet, these other forms of failure need to be considered in design of these nets as well, to address all possible failure scenarios.

II. Testing standards for general textile tensile testing

Our testing procedure Instron Tensile Testing of Textiles shown below in Appendix G is specific to our testing setup and specimens. This testing procedure can be generalized and expanded upon to create an applicable ASTM standard for tensile testing of all high-strain textile/webbing materials. Additionally, a template for the analysis we performed on our data is included in Appendix H, which includes some sample data and Stress vs. Log Strain graph.
References

Appendix A. Design Requirements and Related Material
   A1. Requirements and Standards for Testing and Sewing Pattern
   A2. Custom Fixture Decision Matrix

Appendix B. Drawing Packet
   B1. Custom Fixture Assembly with Bill of Materials
   B2. Side Plate Detail Drawing
   B3. Bottom Plate Detail Drawing
   B4. Shaft Detail Drawing

Appendix C. Vendor Information
   C1. List of Vendors
   C2. Contact Information
   C3. Pricing

Appendix D. Vendor Supplied Component Specifications and Data Sheets
   D1. Material Data Sheet, 1” Webbing
   D2. 7/16 Bolt Data Sheet and Drawing
   D3. 7/16 Nut Data Sheet and Drawing
   D4. 7/16 Lock Washer Data Sheet and Drawing
   D5. 2” Diam Shaft Data Sheet and Drawing
   D6. 1018 Steel Bar Data Sheet

Appendix E. Supporting Analysis and FMEA

Appendix F. Gantt Chart

Appendix G. Test Procedures

Appendix H. Testing Data Analysis

Appendix I. Sources
Appendix A:

A1.

Table A1. Requirements for Testing Procedures

<table>
<thead>
<tr>
<th>Spec #</th>
<th>Parameter Description</th>
<th>Requirement/Target</th>
<th>Tolerance</th>
<th>Risk</th>
<th>Compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Standardization</td>
<td>written procedure, compliance with ASTM</td>
<td>Min</td>
<td>H</td>
<td>A, S</td>
</tr>
<tr>
<td>2</td>
<td>Repeatability</td>
<td>standard procedure, universal test machine</td>
<td>Min</td>
<td>H</td>
<td>S, T</td>
</tr>
<tr>
<td>3</td>
<td>Safety</td>
<td>lab and machine safety training</td>
<td>Min</td>
<td>H</td>
<td>S, I, T</td>
</tr>
<tr>
<td>4</td>
<td>Validity</td>
<td>documentation and model</td>
<td>Min</td>
<td>H</td>
<td>A, T</td>
</tr>
<tr>
<td>5</td>
<td>Hydraulic Instron Machine: Max Load</td>
<td>22000 lbf</td>
<td>Max</td>
<td>M</td>
<td>T, S</td>
</tr>
<tr>
<td>6</td>
<td>Hydraulic Instron Machine: Max Elongation</td>
<td>4 in</td>
<td>Max</td>
<td>M</td>
<td>T, I</td>
</tr>
<tr>
<td>7</td>
<td>Hydraulic Instron Machine: Fatigue Cycles</td>
<td>1000 cycles</td>
<td>Max</td>
<td>M</td>
<td>T, I</td>
</tr>
<tr>
<td>8</td>
<td>Width of Clamps</td>
<td>2 in and 1 in</td>
<td>Min</td>
<td>H</td>
<td>T, S</td>
</tr>
<tr>
<td>9</td>
<td>Abrasion Failure Test</td>
<td>200 cycles</td>
<td>Max</td>
<td>L</td>
<td>T, S, I</td>
</tr>
<tr>
<td>10</td>
<td>Testing Material Cost</td>
<td>$1000</td>
<td>Max</td>
<td>M</td>
<td>A, S</td>
</tr>
</tbody>
</table>

Table A2. Requirements for New Sewing Pattern

<table>
<thead>
<tr>
<th>Spec #</th>
<th>Parameter Description</th>
<th>Requirement/Target</th>
<th>Tolerance</th>
<th>Risk</th>
<th>Compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Life Cycle</td>
<td>100 cycles</td>
<td>Min</td>
<td>L</td>
<td>A, T, I</td>
</tr>
<tr>
<td>2</td>
<td>Webbing Strength</td>
<td>2 in: 6000 lbf 1 in: 4200 lbf</td>
<td>Min</td>
<td>H</td>
<td>A, T, I</td>
</tr>
</tbody>
</table>

1 High (H) • Medium (M) • Low (L)
2 Analysis (A) • Test (T) • Similarity to Existing Designs (S) • Inspection (I)
3 Target values expected to change in accordance with our initial tests of the current sewing pattern. Our goals are to improve the current design, and we will not know its capabilities until testing.
<table>
<thead>
<tr>
<th></th>
<th>Peel Strength</th>
<th>1000 lbf/in</th>
<th>Min</th>
<th>H</th>
<th>A, T, I</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Shear Strength</td>
<td>1000 lbf/in</td>
<td>Min</td>
<td>M</td>
<td>A, T, I</td>
</tr>
<tr>
<td>5</td>
<td>Abrasion Resistance</td>
<td>50 cycles</td>
<td>Min</td>
<td>M</td>
<td>A, T, S, I</td>
</tr>
<tr>
<td>6</td>
<td>Stiffness</td>
<td>2000 lbf/in</td>
<td>Min</td>
<td>L</td>
<td>A, T</td>
</tr>
<tr>
<td>7</td>
<td>Manufacturing Cycle Time</td>
<td>60 sec/joint</td>
<td>Max</td>
<td>M</td>
<td>T, S</td>
</tr>
</tbody>
</table>

A2.

Table A3. Decision Matrix for Custom Fixture Concepts

<table>
<thead>
<tr>
<th>CONCEPT</th>
<th>TEST COMPATIBILITY</th>
<th>FABRIC SAMPLE COMPATIBILITY</th>
<th>INSTRON COMPATIBILITY</th>
<th>EASE OF MANUFACTURING</th>
<th>SETUP AND USE</th>
<th>SCORE</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>C2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>C3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>C4</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>C5</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>11</td>
</tr>
</tbody>
</table>

All concepts had the same score for Fabric Sample Compatibility and Instron Compatibility; this is because they will all be clamped in the Instron the same way and the fabric will attach to the fixture in the same way. Alternatives for the fabric attachment were considered, but were prematurely eliminated because they added unnecessary complexity to the setup and did not follow the typical way of securing fabric straps under loading. The concepts also had close Test Compatibility rankings since their ideation was based off of our already developed procedures. C4 and C5 were ranked higher only because the rotation prevention method matched the typical design for fabric strap fixtures. C4 and C5 were ranked the highest for Setup and Use because the two bolts don’t need to be tightened to a specified degree, in comparison to C1 and C2. C1, C2, C4, and C5 all have has less pieces to setup than C3, which requires the set screws to be tightened enough. C5 was ranked the highest for Ease of Manufacturing because no internal threading is necessary and the length of shaft does not have to be exact. Only 3 bores need to be made since our manufacturing plan accounts for keeping everything lined up by assembling the fixture as it is manufactured.
Appendix B. Drawing Packet

B1. Custom Fixture Assembly with Bill of Materials
B2. Side Plate Detail Drawing
B3. Bottom Plate Detail Drawing
B4. Shaft Detail Drawing
Appendix C. Vendor Information

**Stitching Pattern:** SLO Sail and Canvas
- All material and sewing machines required are available through our sponsor.
- All testing of the stitching will be performed in Cal Poly’s composite lab with the Instron Tensile Machine.

**Custom Fixture:** McMaster Carr
- All prices listed in the Cost Analysis table in Chapter 7.
- All custom pieces will be machined in Cal Poly’s labs.
- Website: [http://www.mcmaster.com/](http://www.mcmaster.com/)
Subject: Webbing details
From: Madrano, Humberto (HMedrano@trivantage.com)
To: SLOsailandcanvas@yahoo.com;
Date: Friday, November 6, 2015 9:17 AM

Sorry for the delay but just got it in. hope it still helps.

Product: N0095-1"

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Unit</th>
<th>Target</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>Inch</td>
<td>1&quot;</td>
<td>±1/32</td>
</tr>
<tr>
<td>Thickness</td>
<td>Inch</td>
<td>.073</td>
<td>±.005</td>
</tr>
<tr>
<td>Weight</td>
<td>lb</td>
<td>74.57</td>
<td>±10%</td>
</tr>
</tbody>
</table>

Weaving Information

<table>
<thead>
<tr>
<th>Sley</th>
<th>Descr</th>
<th>End</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td></td>
<td>240 (G) &amp; (G)</td>
<td>Nylon</td>
</tr>
<tr>
<td>210</td>
<td></td>
<td>21 ppm</td>
<td>Nylon</td>
</tr>
<tr>
<td>210</td>
<td></td>
<td>1</td>
<td>Nylon</td>
</tr>
<tr>
<td>N/A</td>
<td></td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Physical Characteristics:

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension Strength</td>
<td>Lbf</td>
<td>0/8 average</td>
</tr>
</tbody>
</table>

Humberto Medrano | Sales Representative
Southern California | Trivantage, LLC
www.trivantage.com ph: 704.236.5281

Attachments
- image001.png (25.31KB)
High-Strength Grade 8 Steel Cap Screw
7/16"-14 Thread, 5" Long, Zinc-Plated

Material: Steel
Grade: 8
Finish: Zinc-Yellow-Chromate Plated
Thread Size: 7/16"-14
Head Width: 5/8"
Head Height: 19/64"
Screw Size: 7/16" (0.437"
Length: 5"
Thread Length: 1 1/8" to 1 1/2"
RoHS: Not Compliant

The standard for high-strength cap screws, these are made from alloy steel and have a minimum tensile strength of 150,000 psi. Length is measured from under the head.

Inch screws are marked on the head with six radial lines to indicate Grade 8. Screws have a minimum Rockwell hardness of C33 and a Class 2A thread fit. They also meet ASME B18.2.1 and SAE J429.

Zinc-Yellow-Chromate Plated—Screws are rust resistant.
D3. 7/16 Nut Data Sheet and Drawing

Zinc Yellow-Chromate Plated Steel Hex Nut
Grade 8, 7/16"-14 Thread Size, 11/16" Wide, 3/8" High

Packs of 50
In stock
$7.33 per pack of 50
94895A817

1 added to your order 01/28/18.

Material Steel
Grade 8
Finish Zinc Yellow-Chromate Plated
Thread Direction Right Hand
Thread Size 7/16"-14
Width 11/16"
Height 3/8"

Use these hex nuts for general purpose fastening applications.

Inch sizes have a Class 2B thread fit. Nuts with 1/4" screw size and larger are known as full or finished hex nuts.

D4. 7/16 Lock Washer Data Sheet and Drawing
Type 18-8 Stainless Steel Split Lock Washer
7/16" Screw Size, 0.450" ID, 0.776" OD

Material: 18-8 Stainless Steel
Screw Size: 7/16"
ID: 0.450"
OD: 0.776"
Thickness: 0.109"
RoHS: Compliant

Split lock washers prevent bolted joints from loosening under small amounts of vibration. As a screw is tightened, these washers are forced into a flat shape, which adds tension to your joint for a tight hold.
Chrome-Plated Steel Shaft
2" OD, 12" Length

<table>
<thead>
<tr>
<th>Material</th>
<th>1045 Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finish</td>
<td>Chrome Plated</td>
</tr>
<tr>
<td>Diameter</td>
<td>2&quot;</td>
</tr>
<tr>
<td>Diameter Tolerance</td>
<td>-0.0015&quot; to 0&quot;</td>
</tr>
<tr>
<td>Length</td>
<td>12&quot;</td>
</tr>
<tr>
<td>Straightness Tolerance</td>
<td>1/8&quot; per 10 ft.</td>
</tr>
<tr>
<td>RoHS</td>
<td>Compliant</td>
</tr>
</tbody>
</table>

In stock
930.18 Each
5947K22

Straightness Tolerance is 1/8" per 10 Feet
### D6. 1018 Steel Bar Data Sheet

**Low-Carbon Steel Rectangular Bar**

1" Thick, 4-1/2" Width

<table>
<thead>
<tr>
<th>Length</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2 ft.</td>
<td></td>
</tr>
<tr>
<td>1 ft.</td>
<td></td>
</tr>
<tr>
<td>2 ft.</td>
<td></td>
</tr>
<tr>
<td>3 ft.</td>
<td></td>
</tr>
<tr>
<td>6 ft.</td>
<td></td>
</tr>
</tbody>
</table>

### Specifications

- **Grade**: 1018
- **Shape**: Rectangular Bar
- **Finish**: Unpolished
- **Thickness**: 1"
- **Thickness Tolerance**: -0.010"
- **Width**: 4 1/2"
- **Width Tolerance**: -0.010"
- **Yield Strength**: 54,000 psi
- **Hardness**: Medium (Rockwell B70)
- **Specification**: ASTM A108
- **Construction**: Cold Drawn

### Material Composition

- **Carbon**: 0.13-0.20%
- **Manganese**: 0.30-0.90%
- **Silicon**: 0.15-0.30%
- **Phosphorus**: 0.04% Max.
- **Sulfur**: 0.05% Max.
- **Iron**: 96.06-99.42%

- **Nominal Density**: 0.283 lbs./cu. in.
- **Electrical Resistivity**: 15.9 microhm-cm @ 32°F
- **Thermal Conductivity**: 29.4 Btu/sq. ft./hr./°F @ 212°F
- **Coefficient of Thermal Expansion**: $6.7-7.5 \times 10^{-5}$
- **Elongation Range**: 10-36%
- **RoHS**: Compliant

### Notes

One of the most widely used types of steel, low-carbon steel is weldable, machinable, and can be surface hardened by heat treating. It is suitable for a variety of applications, such as structural and power transmission components.

**Warning**: Physical, mechanical, and chemical properties are not guaranteed and are intended only as a basis for comparison.

Material is 1018 carbon steel. Thickness and width tolerances are -0.006" for 1/8" to 4" wide bars; they are -0.010" for 4 1/2" to 6" wide bars; and they are -0.013" for bars 7" and wider. Length tolerance is ±1/8" for 1/2-ft. lengths, ±1" for 1-ft. lengths, ±2" for 2-ft. lengths, ±3" for 3-ft. lengths, and ±5" for 6-ft. lengths.
\[ \sigma' = \frac{1}{2} \left\{ (G_1-a_1)^2 + (G_2-a_2)^2 + \left( \frac{a_1-a_2}{2} \right)^2 + \frac{G_1+G_2}{4} \right\}^{\frac{1}{2}} \]

\[ \sigma'' = \left( G_{yy} - 2o_{xy} + 3\zeta_{yy}^2 \right)^{\frac{1}{2}} \]

\[ \sum M_1 = 0 \quad \sum V = 0 \quad \frac{V}{a} = 30,000 \, \text{lb} \]

\[ M = 10,500 \, \text{in.-lb} \]

\[ F = 3,000 \, \text{lb} \]

\[ \tau = \frac{\sqrt{\left( \frac{G_{yy}}{2} \right)^2 + 126.9^2}}{126} \]

\[ \tau = \frac{G_{yy}}{2} < \frac{600}{2} \]

\[ \sqrt{\sigma} = 24.35 \, \text{ksi} < S_y (551 \, \text{ksi}) (n = 2.2) \]

\[ \frac{M}{h} = \frac{(17,250 \, \text{lb}) (1.5 \, \text{in})}{126} \]

\[ \frac{f}{h} = \frac{(14,250) (1 \, \text{in})^3}{126} \]

\[ \sigma = \frac{M}{h} \]

\[ \tau = \frac{4087.2}{h} < \frac{30,000}{20} \, \text{ksi} \]

\[ \rightarrow h = 0.126 \, \text{in} \]

\[ \tau \text{ must be increased} \]

\[ \delta \text{unchanged} = 0.25 \, \text{in} \]

\[ \sigma = 163 \, \text{ksi} \]

\[ \frac{h}{w} = 1.855 \]
\[ EF = 0 \]
\[ A = B \]
\[ EM_0 = 0 \]
\[ -T_f z + 2.125 A + 2.125 B = 0 \]
\[ T_f z = 4.25 A \]
\[ r = 6000 \text{ in.-lb} \]
\[ A = 705.88 \text{ lb} \]
\[ B = 705.88 \text{ lb} \]

\[ A + B \text{ due to pin reaction} \]
\[ C + D \text{ due to shear force} \]
\[ A + C = R \]
\[ B + D = S \]

\[ \frac{D}{1} \]
\[ T_f z = 3000 \text{ in.-lb} \]

\[ \text{model} \]
\[ I = 2.34 \times 10^6 \]
\[ A = 2.32 \times 10^4 \]
\[ G = \frac{M}{A} \]
\[ G = (46.75 \times 0.25)(1.5) \]
\[ G = 2.32 \times 10^4 \]
\[ T_f = 2) \text{ ksi} \]
\[ n = 2.5 \]
\[ S_Y = 65 \text{ ksi} \]

\[ \text{pin} \quad F = 25 \rightarrow \sigma = 122.2 \text{ ksi} \quad \checkmark \]

\[ (-9.25 \quad r = 3.75) \quad \sigma = 36.2 \text{ ksi} \quad \checkmark \]

\[ (-5.15 \quad v = 3.166) \quad \sigma = 62.1 \text{ ksi} \]

\[ \rightarrow S_Y = 65 \text{ ksi} \]

**Changes?**

- Pin usable length: 4.25 in.
- Pin: \( d = 0.75 \text{ in.} \)

Problem: modeling as beam, when actually it's pin surrounded on all sides.

So stress concentration at cylinder shaft and side plates.

\[ M \]

\[ \text{check for} \quad d = 0.15 \text{ in.} \]

\[ M = (50 \times 80) \cdot \left( \frac{4.25}{8} - 1 \right) \text{ ft-lb} \]

\[ M = 837.1 \text{ ft-lb} \]

\[ \sigma = \frac{837.1}{\pi \left( \frac{0.25}{2} \right)^2} \]

\[ \sigma = 62.84 \text{ ksi} \quad \checkmark < 65 \text{ ksi} \]

\[ \text{So pin and is diam. per} \]

\[ \sigma = \frac{844.77}{\pi \cdot d^2} \]

\[ S_Y = 65 \text{ ksi} \quad n = 1.4 \quad \sigma = 46.42 \text{ ksi} \]

\[ R = \frac{844.77}{4 \cdot 0.25^2} \]

\[ R = 685 \text{ in.} \]

\[ \rightarrow r = 0.285 \text{ in.} \quad \rightarrow d = 0.59 \text{ in.} \]

\[ n = 1.2, \quad \sigma = 54.16 \text{ ksi} \]

\[ \rightarrow r = 0.27 \text{ in.} \quad \rightarrow d = 0.54 \text{ in.} \]

\[ \rightarrow \text{diam pin too small} \]

For this length & load.

If less conservative, use 2/3 load.

\[ n = 1.2, \quad \text{min} = 0.23 \text{ in.} \]

\[ \text{2nd attempt} \]

\[ \text{Final} \]
Pipe or solid shaft

\[ \frac{v_0}{v} = 1.035 \]

\[ \rho = \frac{v_0}{v} = 1.035 \]

\[ M = 5230 \text{ in-lb} \]

\[ \sigma = \frac{5230}{(1.1975 + 1.0355)} \]

\[ \text{Carbon Steel} \]

\[ S_y = 30 \text{ ksi} \]

Shear stress problems

Grade B bolt in pin \( \rightarrow S_y = 130 \text{ ksi} \)

\[ n = 1.2 \]

\[ \sigma_{\text{max}} = 108.3 \text{ ksi} \]

\[ \frac{P}{A} = 108.3 \text{ ksi} \]

\[ P = 0.275 \text{ M} \]

\[ d = 0.43 \text{ in} \]

\[ A = \frac{1}{4} \pi r^2 \]

\[ r = 0.275 \text{ in} \]

\[ d = 0.43 \text{ in} \]

Limiting bolt plate: \( 2 \times 5 \times 4.25 = 42.5 \text{ in}^2 \)

Side plate: \( 4 \times 4.25 \times 4 = 68 \text{ in}^2 \)

Total area: \( 110.5 \text{ in}^2 \)

\[ 4 + 4 = 8 \text{ in} \]

\[ 4.25 \times 2 + 1 \]

Can only get \( 4.25 \times 2 \text{ in} \times 1 \)

Pipe or solid shaft

\[ v_0 = 1.035 \]

\[ v = 1.035 \]

\[ M = 5230 \text{ in-lb} \]

\[ \sigma = \frac{5230}{(1.1975 + 1.0355)} \]

\[ \text{Carbon Steel} \]

\[ S_y = 30 \text{ ksi} \]

Shear stress problems

Grade B bolt in pin \( \rightarrow S_y = 130 \text{ ksi} \)

\[ n = 1.2 \]

\[ \sigma_{\text{max}} = 108.3 \text{ ksi} \]

\[ \frac{P}{A} = 108.3 \text{ ksi} \]

\[ P = 0.275 \text{ M} \]

\[ d = 0.43 \text{ in} \]

\[ A = \frac{1}{4} \pi r^2 \]

\[ r = 0.275 \text{ in} \]

\[ d = 0.43 \text{ in} \]

Limiting bolt plate: \( 2 \times 5 \times 4.25 = 42.5 \text{ in}^2 \)

Side plate: \( 4 \times 4.25 \times 4 = 68 \text{ in}^2 \)

Total area: \( 110.5 \text{ in}^2 \)

\[ 4 + 4 = 8 \text{ in} \]

\[ 4.25 \times 2 + 1 \]

Can only get \( 4.25 \times 2 \text{ in} \times 1 \)
<table>
<thead>
<tr>
<th>Severity</th>
<th>Occurrence</th>
<th>Detection</th>
<th>Risk Priority Number</th>
<th>Potential Failure Mode</th>
<th>Potential Failure Effects</th>
<th>Potential Failure Causes</th>
<th>Recommended Actions</th>
<th>Current Design Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>6</td>
<td>Worn out of alignment</td>
<td>Misalignment or failure</td>
<td>Wear and tear</td>
<td>Worn out of alignment</td>
<td>Misalignment or failure</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>1</td>
<td>6</td>
<td>Binding</td>
<td>Misalignment or failure</td>
<td>Wear and tear</td>
<td>Binding</td>
<td>Misalignment or failure</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>2</td>
<td>6</td>
<td>Loosen nut</td>
<td>Misalignment or failure</td>
<td>Wear and tear</td>
<td>Loosen nut</td>
<td>Misalignment or failure</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>2</td>
<td>6</td>
<td>Release</td>
<td>Misalignment or failure</td>
<td>Wear and tear</td>
<td>Release</td>
<td>Misalignment or failure</td>
</tr>
</tbody>
</table>

**Recommended Actions:**
- Regular maintenance
- Replace worn parts
- Tighten loose connections
Appendix G. Test Procedures

1. Grip Test

Purpose:
To determine if the use of a customized fixture that will secure the textile pieces to the Instron test machine is necessary, as compared to using the current grips on the machine. This will be determined by the location of the failure on the textile sample: if the failure is at the location of the grips, a customized fixture is necessary; if the failure is at the predicted point (the sewing at the textile overlap), the current method is acceptable.

Materials:
1”x1” textile samples, overlapped and sewn together
Instron test machine

Procedure:
1. Follow all safety and setup procedures of “Instron Tensile Testing of Textiles Procedure” for the initial machine setup.
2. At step 7, prepare the sample in the following ways for each run through:
   a. Unmodified sample
   b. Fabric ends doubled up, small pieces are sewn on the end
3. Continue following the steps outlined in the above procedure.
4. Observe where the sample fails.
5. Remove the sample from the machine following the safety guidelines in the above procedure.
6. Repeat, preparing the sample as specified in 2.b.
2. Instron Tensile Testing of Textiles Procedure

Instron Tensile Test Procedure for Joined Textiles

This procedure outlines the steps for testing materials and small structures using the Instron servo-hydraulic load frame and associated NI/LabView data acquisition system (DAS).

**Basic Safety Requirements:**

- *NEVER* operate this machine alone and without having been trained or under direct supervision your lab instructor, advisor or trained lab assistant.
- Safety glasses and appropriate clothing and shoes must be worn at all times in the composites and structures lab.
- All student-built tooling and test plans must be inspected and reviewed by the student’s project advisor or lab coordinator.
- No food in the composites and structures lab.

Note: Instron Manual should be consulted with questions to the load frame and 8500 controllers. The 8500 front panel controls all the test parameters. DAS and Labview questions can be answered via the on-line help menus associated with the software.

**TENSILE TESTING OF TEXTILES**
The procedure outline that follows is a tensile test that involves reading the load and displacement from the test machine. This could be using a ASTM D5034 textile fabric specimen as sketched below.

![Diagram of Instron Tensile Test Procedure](image)
Strain data will be generated using actuator position data, and the standard definition of logarithmic strain.

\[ \varepsilon = \ln \left( \frac{L}{L_0} \right) \]

Log strain is used because the strains found in textile systems are very high even for low loading conditions. Log strain is recommended for systems where normal engineering strain is above 5%, which is true for the vast majority of textiles.

There will be three main tests run on our given strap material, meant to model the three main types of failure:

1. Webbing failure
2. Stitching shear failure
3. Stitching peel failure

A. Webbing failure
Four independent tests, with two different setups as shown in figures 3 and 4, will be run.

These two tests will then be repeated again for 2” width strap.
B. Stitching Shear failure
For shear failure, 1” webbing will be used, with a test setup as shown in figure 5.

Figure 5. Shear failure testing

C. Stitching Peel failure
For peel failure, 1” webbing will be used, with a test setup as shown in figure 6.

Figure 6. Peel failure testing

Instron Machine Set-up

Safety reminders and tips:
A) Safety Glasses must be on before starting the hydraulic system.
B) One person only must load the specimens and operate the test machine and run tests. This will preclude starting a test while hands or any other body part are in the test area where grip clamps and crosshead can exert large dangerous forces.
C) Be careful with manual actuator up and down buttons. Remember it is the bottom grip or crosshead that moves up and down. Make sure no one is near the crosshead area when moving the actuator ram manually. Also take great care when clamping specimens with the hydraulic grip clamps. Keep your fingers far away from the grip area of the specimen you are holding.
D) If you need to adjust crosshead height using the two side rams get help from your instructor or advisor.
E) Never operate the equipment while alone in the lab.
*Textiles cannot be clamped directly into the jaw clamps of the Instron tensile tester, as the abrasive forces resultant on the strap can cause damage to the material and skew test results. Thus, it is necessary to use an alternative clamping fixture.

1. Make sure that the water line to the hydraulic pump is open. It should be opened about ¾ of a turn for cooling the heat exchanger. Failure to provide the cooling water will result in excess temperature and damage to the pump system. There is a temperature limit shutdown circuit which will automatically turn off the system to prevent damage in the case of lack of coolant or valve failure.

2. Turn on the Instron Controller. (May have to “unlatch” the oil light safety)

3. Using the OUTPUTS button on the front panel make sure the following:

   - Load is going out channel A.
   - Position is going out B.

Then select each (load, position) and note the data/voltage relationship, e.g. load channel may output 2.0kips/volt. The DAS must have corresponding relationships to convert the voltage into appropriate units. Make sure each channel is in the track mode as well.

4. Calibrate the load cell. The setup light is flashing. Press this then CAL, CAL, AUTO, GO. The cell is calibrated when the light stops flashing.

5. Turn on the hydraulic pump. Turn on pressure to the actuator press low pressure first then high. Note the system will displace with this process make sure the one of the grips is not closed or there is a gap of 0.05in on flex test for the system to move as position control is able to hold its position after the pressure transient.

The following directions are split to account for the different types of testing:

A. Webbing Failure Test

   1. Insure that there is enough room in between the clamp jaws for the clamping fixtures to fit. If there isn’t, raise the upper crosshead.
      *ensure that the lower cross head is fully raised, to allows for enough stroke when tensioning the strap and running the test.
   2. Install the testing fixtures into the upper and lower clamp jaws, starting with the upper clamp jaw. Keep fingers away from the hydraulic jaws during this procedure. Orientation of the clamp fixtures does not matter; they are symmetrical.
   3. Once the fixtures are installed, cut a sample piece approximately 16 inches long.
   4. Place the specimen into the upper clamp first by feeding it through the slot in the center, and wrapping it around at least 2 full rotations.
   5. Repeated with the other end of the strap. It will be necessary to remove the two pins from the fixture to allow the center bar to rotate. Thread the strap through the center slot, and rotate the piece to ensure at least 2 full wraps on the bar. Place the pins back in to lock it into place.
6. Lower the lower cross head just enough to ensure that there is tension in the strap, so that there is enough friction to keep the straps securely in the fixtures.
7. Measure the initial length of the strap from center to center of the shafts.
8. **Install the plastic shield for safety, as failure may result in specimen fracture and rapid strain energy release.**
9. Continue to Step 6 under “LabView DAS Setup” and repeat this setup for each sample.

**B. & C. Stitching Shear and Peel Failure Test**

1. Install each end of the stitched samples into the upper and lower clamp jaws, starting with the upper clamp jaw. Keep fingers away from the hydraulic jaws during this procedure.
2. Lower the lower cross head just enough to ensure there is some tension in the strap before beginning the test.
3. Measure the initial length of the strap from clamp to clamp of exposed material.
4. **Install the plastic shield for safety, as failure may result in specimen fracture and rapid strain energy release.**
5. Continue to Step 6 under “LabView DAS Setup” and repeat this setup for each sample.

**LabView DAS Setup**

6. Double-Click the Labview VI file *Disp.vi*. This file acquires load and displacement data from the test machine.
7. Check that the voltage relationships correspond with the Instron outputs.
8. Note the ASCII data file name and folder or location. This file should be saved after each test.

**Run Test**

9. Before beginning the test, measure the nominal gage length of the strap, taken from center to center of the round portion of each clamp fixture, as pictured below. This should be around 8 inches. This will be used to normalize the deformation data to strain.
10. Press WAVEFORM corresponding to position control on the Instron front panel. Lower display entries should be:

   \[
   \begin{align*}
   \text{RAMPS } &= 3.5\text{in} \\
   \text{S RAMP } &= 0.030\text{in/sec}
   \end{align*}
   \]

   (i.e. the actuator will move down 3.5in at a rate of 0.030in/sec).
11. Start the data acquisition process by clicking the start arrow on the labview VI.
12. **Make sure that no persons or body parts are near the test setup.** Press START on the Instron controller to start the test, the lower grip will move down.
13. **To stop the actuator for any reason, press HOLD on the controller. Press START to resume the test waveform.**
14. After failure of the specimen press HOLD.
15. The lower portion of the fractured specimen may be removed by opening the lower grip.
16. End the test by pressing RESET which will move the actuator to its position at the start of the test.
17. Remove the upper portion of the specimen from the upper grip.

**System Shut Down**

18. The system may be shut down as follows:

   A) turn off actuator by pressing LOW, then OFF,
   B) turn off hydraulics,
   C) turn off controller,
   D) Exit VI and shutdown the DAS computer. Turn of the manual water valve.
Table A4. Data Analysis Template and Example

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>Position</td>
<td>Length</td>
<td>Log strain</td>
<td>Stress</td>
<td>Initial Length</td>
<td>Max Load</td>
<td>Max Stress</td>
<td>Strain</td>
</tr>
<tr>
<td>(from DAQ)</td>
<td>(from DAQ)</td>
<td></td>
<td></td>
<td></td>
<td>(recorded after setup)</td>
<td></td>
<td></td>
<td>strain at max stress</td>
</tr>
<tr>
<td>3.662</td>
<td>-1.966</td>
<td>5.125</td>
<td>0</td>
<td>3.73673469</td>
<td>5.125</td>
<td>631.104</td>
<td>643.9836735</td>
<td>0.23</td>
</tr>
<tr>
<td>3.662</td>
<td>-1.966</td>
<td>5.125</td>
<td>0</td>
<td>3.73673469</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.052</td>
<td>-1.966</td>
<td>5.125</td>
<td>0</td>
<td>3.11428571</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.662</td>
<td>-1.966</td>
<td>5.125</td>
<td>0</td>
<td>3.73673469</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.662</td>
<td>-1.966</td>
<td>5.125</td>
<td>0</td>
<td>3.73673469</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.662</td>
<td>-1.966</td>
<td>5.125</td>
<td>0</td>
<td>3.73673469</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.662</td>
<td>-1.954</td>
<td>5.137</td>
<td>0.002338726</td>
<td>3.73673469</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.104</td>
<td>-1.942</td>
<td>5.149</td>
<td>0.004671996</td>
<td>6.22857143</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.662</td>
<td>-1.953</td>
<td>5.161</td>
<td>0.006999834</td>
<td>3.73673469</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.104</td>
<td>-1.918</td>
<td>5.173</td>
<td>0.009322266</td>
<td>6.22857143</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.104</td>
<td>-1.906</td>
<td>5.185</td>
<td>0.011639317</td>
<td>6.22857143</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.104</td>
<td>-1.894</td>
<td>5.197</td>
<td>0.013951011</td>
<td>6.22857143</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.104</td>
<td>-1.882</td>
<td>5.209</td>
<td>0.016257374</td>
<td>6.22857143</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.545</td>
<td>-1.87</td>
<td>5.221</td>
<td>0.018558429</td>
<td>8.7198776</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.155</td>
<td>-1.858</td>
<td>5.233</td>
<td>0.020854202</td>
<td>9.34183673</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.597</td>
<td>-1.846</td>
<td>5.245</td>
<td>0.023144717</td>
<td>11.836735</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.207</td>
<td>-1.834</td>
<td>5.257</td>
<td>0.025429957</td>
<td>12.4561224</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.597</td>
<td>-1.822</td>
<td>5.269</td>
<td>0.027710066</td>
<td>11.836735</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.648</td>
<td>-1.81</td>
<td>5.281</td>
<td>0.029984949</td>
<td>14.9469388</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.038</td>
<td>-1.798</td>
<td>5.293</td>
<td>0.032254688</td>
<td>14.3244898</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.038</td>
<td>-1.786</td>
<td>5.305</td>
<td>0.034519247</td>
<td>14.9469388</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.7</td>
<td>-1.774</td>
<td>5.317</td>
<td>0.036778709</td>
<td>18.0612245</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.752</td>
<td>-1.762</td>
<td>5.329</td>
<td>0.039030378</td>
<td>21.1755102</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.752</td>
<td>-1.75</td>
<td>5.341</td>
<td>0.041282376</td>
<td>21.1755102</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23.004</td>
<td>-1.738</td>
<td>5.352</td>
<td>0.043526626</td>
<td>24.2897599</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28.855</td>
<td>-1.728</td>
<td>5.365</td>
<td>0.045765851</td>
<td>27.4030612</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29.297</td>
<td>-1.714</td>
<td>5.377</td>
<td>0.046000073</td>
<td>28.8948858</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29.507</td>
<td>-1.702</td>
<td>5.385</td>
<td>0.050229314</td>
<td>30.5173469</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Max Stress: 643.98 lbf/in
Max Force: 631.1 lbf
Log Strain: 0.23

X-axis: Column D
Y-axis: Column E
Appendix I: Sources


