Solar Turbines
A Caterpillar Company

Solar Turbines Creep Test Fixture

Design Report

Team: Eric Nelson
Rene Maciel
Chris Ewald

California Polytechnic State University (Cal Poly)
San Luis Obispo, CA, 93405
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Executive Summary

This report outlines the steps taken to arrive at a final product that satisfies Solar Turbines' need for a fixture that will induce pure bending and/or bending-shear within their current uniaxial creep test machines. The final product consists of two attachments that can be fixed to the tensioning bars of the creep test machine and convert the tension load into a bending load. Although the fixture is capable of being attached at both ends, it will likely be tested by only attaching the upper support and hanging a weight from the lower support. This is due to the small amount of force required to induce the necessary stress in the cross section of the specimen. Theoretically, it has been determined that the fixture will not itself undergo any noticeable creep during testing.

The fixture has been analyzed with thorough analysis, and in the testing stage (as of 12/05/2012). Geometric dimensioning and tolerancing of the final fixture has been completed and can be followed to ensure proper production of the final fixture design. One prototype is currently in testing to determine if the design is sufficient. Changes have been made since this prototype to further ensure alignment of all parts in the fixture. However, in testing this prototype, the extensometer used to measure the displacement of the specimen was used in place as an alignment mechanism. The prototype is made from 321 stainless steel with a specimen that is 4340 low alloy steel. The final specimen is to be machined from MAR-M-421 and the fixture will be machined from a nickel alloy, which is specially designed to improve creep rupture strength. The approximate cost of the material used in production of a single fixture is about $10,000. However, since the final fixture is hollowed out, much of this material will be available for use in other applications or possibly in the production of more parts such as the plunger or mandrel.

Due to the duration of a creep test, this fixture remains in the testing phase at this time. We have verified the design of this fixture. The design was thoroughly thought out and analyzed to ensure the fixture should perform as desired. Once the final fixture is made, it may be used to perform creep tests in bending, an area for metals in which little to no information is available currently. By performing these tests, it can be concluded whether a part experiencing multiple loading regimes during use will experience creep differently than a part in simple uniaxial tension. If so, this data will allow for more accurate determination of the life of parts in the future. For Solar Turbines, this is critical to better predict component failure risk and overhaul cycles for their gas turbines.

Introduction

Solar Turbines (a subsidiary of Caterpillar Inc.) is headquartered in San Diego, CA, and are a world leader in manufacturing industrial gas turbines. With a large product line, they heavily influence the oil, natural gas, and power generation industries. Their products consist of gas-turbine engines, gas compressors, gas turbine-powered compressor sets, mechanical-drive packages, and generator sets (Solar Turbines, mysolar.cat.com).

California Polytechnic State University (Cal Poly) is fortunate to have a strong working relationship with Solar Turbines, as well as many other leading engineering companies. The various Cal Poly engineering projects, specifically the mechanical engineering senior design series, provides companies a means of pursuing their own design interests while also enabling students to complete a thorough design project. Depending on the projects showcased by engineering firms, senior project groups may be coalesced from various engineering backgrounds (such as Electrical, Civil, Software, etc.).

Being one of the world's leading manufacturers of industrial gas turbines, Solar Turbines works with many components that operate under high stresses and temperatures over long periods of time. When a component experiences these types of conditions, creep becomes a critical issue that must be taken into account in engineering design. Creep is the tendency of a solid material to permanently deform when exposed to stresses below its yield strength over long periods of time. At temperatures greater than 40% of a materials melting point, the effects of creep, especially those near the material's melting point, become much more severe (J. Daniel Whittenberger). Creep is therefore a significant engineering factor that must be taken into account in gas turbine design. For this reason there is an interest in further investigating creep effects within critical components that include turbine blades, disks, nozzles, and dampers. In particular, a deeper understanding of creep would allow for a better prediction of service life and overhaul cycles of gas turbine and possibly help in the development of manufacturing processes that can help minimize creep.

The current standard for high temperature creep testing involves loading a specimen at a constant tensile load and temperature while the strain is recorded over time. Solar Turbines currently conducts creep tests in the same manner; however, they are interested in investigating whether the creep characteristics of an anisotropic material would change under different loading conditions. Understanding creep under these conditions would allow for better prediction of the life of gas turbine components. To do this Solar Turbines wants to modify one of their current creep test rigs to expand its loading capabilities beyond pure tension. Originally the project asked for loadings of bending, shear, torsion, and any combination of these; however, the scope of the project was narrowed to address only bending, which is of particular interest to Solar Turbines.

The creep test rig being modified is a Lever Arm Creep Testing System manufactured by Applied Test Systems, serial number B921373-1-11-92. Figure 1 is a photograph of the machine. There are older creep fixtures Solar Turbines is planning on using as well.

Additionally, a schematic demonstrating the loading mechanism used by the machine is given in Figure 2, and then a picture of the furnace and its critical dimensions are provided in Figure 3.

Figure 1. Lever arm creep testing system by Applied Test Systems

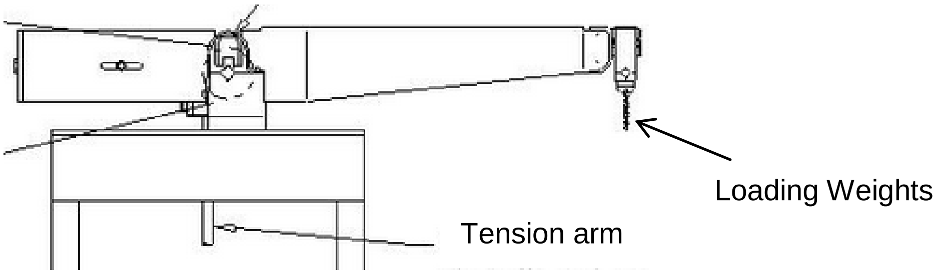


Figure 2. Lever arm testing system. Schematic of the standard loading. (Applied Test Systems, Inc.: http://www.atspa.com)

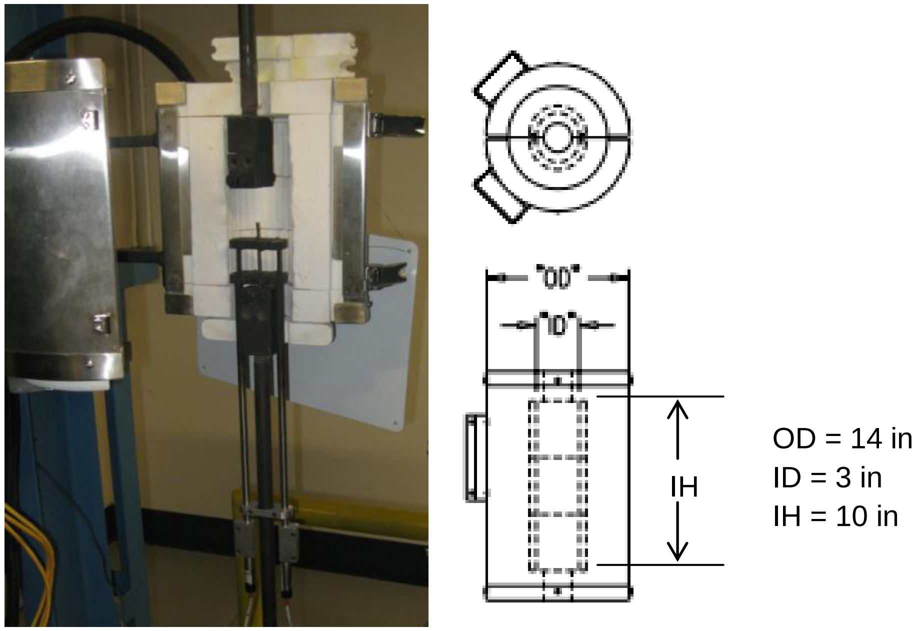


Figure 3. Creep furnace. Photograph and critical dimensions used in creep test machine

Problem Definition

Original:

Solar Turbines currently has machines to perform uniaxial (in-line tension) creep tests, but no method to perform creep tests under any other loading regimes. There are currently no resources for the effect of multi-axial loading on the creep characteristics of a material. For this reason, a fixture that can be attached to the creep test machine's tensioner bars is needed to induce loading on a specimen in ideally pure bending, pure shear, pure torsion, and in combination of any two loading regimes.

Final:

Solar Turbines currently has machines to perform uniaxial (in-line tension) creep tests but no method to perform creep tests under any other loading regimes. There are currently no resources for the effect of multi-axial loading on the creep characteristics of a material. Solar Turbines is most interested in the effects on creep properties resulting from loading a specimen in pure bending. For this reason, a fixture that can be attached to the creep test machine's tensioner bars is needed to induce loading on a specimen in three-point bending.

Background

Discussion of Existing Creep Information

Creep testing is generally done at high temperatures, in Solar Turbines' case up to 1900°F. This makes choices for measurement devices limited by accuracy and cost. High accuracy testing equipment for high temperature environments are expensive, so it would be ideal if the designs could be measured using Solar Turbines' current extensometers, which are used in uniaxial tensile loading.

Document searches performed on Google Scholar (http://scholar.google.com/), using the California Polytechnic State University library (Robert E. Kennedy Library) as a host, aided in viewing certain American Society of Testing and Materials (ASTM) standards. When searching for standards involving testing of materials under loading patterns other than pure tension, the only documentation found applicable to this project was under the designation of E 290-09, as of the date 2-28-2012. No documents concerning pure shear, pure torsion, or combined loading standards were found.

"Standard Test Methods for Bend Testing of Material for Ductility" , E 290-09, (ASTM)

The E 290-09 explains standard methods of testing materials under bending loads. Four types of tests are described: Guided Bend, Semi-guided Bend, Free Bend, and Bend and Flatten. Because a specimen will be tested for creep at elevated temperatures, the bending must take place over an extended period of time in a furnace, which means the duration of the test must commence and end over one loading cycle. This limits the possible bending methods to a guided bend, or semi-guided bend test. In addition, the there is a size constraint that eliminates any bend tests that would not be designed to fit within the critical dimensions of the creep test furnace.

Being that a creep test under bending is not a traditional bending test, i.e. the specimen does not need to complete an angle-of-bend; the specimen geometry does not need to meet current bending standards. See concept description below for further description of the bending test.

"Creep, Stress-Rupture, and Stress-Relaxation Testing" (J. Daniel Whittenberger)

Solar Turbines provided this document to inform the team about creep. The document describes the creep phenomenon of materials as being accentuated at elevated temperatures. When testing at elevated temperatures, three main phases occur: primary, secondary, and tertiary. Figure 4 shows the general behavior of creep in a material.

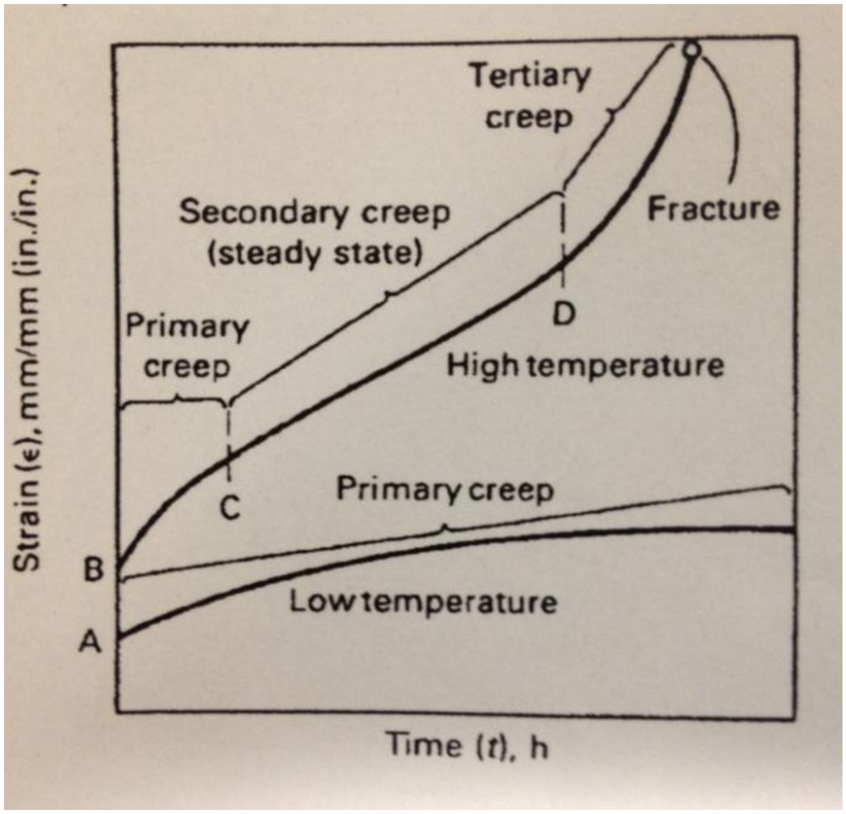


Figure 4. Common stages of creep. Low and high temperature creep of a material under a constant engineering stress (from "Creep, Stress-Rapture, and Stress-Relaxation Testing" by J. Daniel Whittenberger).

'Creep, Stress-Rupture, and Stress-Relaxation Testing,' by J. Daniel Whittenberger provided most of the background on creep test requirements. One requirement has a large bearing on the design considerations; loading at the gage section must remain constant. As the fixture is pulled in tension using the current creep test machine, it is necessary that the loading applied is constant. One problem when providing loading in bending, shear, or torsion is as the angle of the applied force changes the stress experienced by the specimen. Thus, fixtures where the applied load is dependent on an angle would not be ideal for testing creep (Many concepts were omitted due to this concern).

Because creep is dependent on stress, creep is typically measured under either of the two conditions: constant force applied at the cross section, or constant displacement of the specimen gage section. The best form of creep testing enables accurate strain measurement as a function of time. Other forms of creep testing exist, such as a creep-rupture (where deformation is recorded as a function of time to failure), and interrupted-creep (where strain as a function of time is measured, but the specimen is not loaded to failure). This project will focus on capturing strain measurements as a function of time, where the specimen will be loaded to various degrees of strain and even rupture. This will provide a means of collecting the most data possible.

In this document, J. Daniel Whittenberger emphasizes the importance of taking measurements only of the specimen, “Care must be taken to ensure that the measure deformation occurs only in the gage section. Thus measurements based on the relative motion of parts of the gripping system above and below the test specimen are generally inaccurate, because the site of deformation is unknown.” Careful design must ensure accurate measurements.

Existing products that solve similar problems

Currently, there are only creep test machines that apply a uniaxial load to the specimen. No information regarding machines with additional loading capabilities for creep testing at elevated temperatures were found.

Design Requirements and Specifications

1. Must convert uniaxial load applied by test rig to a bending load on the specimen
2. Must attach to the test rig threaded tensioner rods
3. Fixtures must fit within a cylindrical furnace with following inner dimensions
    a. 3 in diameter, 10 in height
4. Test specimen is a beam with rectangular cross-section and has gage dimensions
    a. 1.00 x 0.100 x 0.032 in (cross-section dimensions can change for other tests)
5. The fixture must be capable of applying 100 ksi at specimen test section
6. Fixture itself must not creep at temperatures up to 1900 °F
7. Fixture material: Nickel alloy
8. Test specimen material: Various alloys
9. Loading must be repeatable (fixture alignment, specimen placement, etc.)
10. A measurement method for strain must be provided (preferably creep test machine’s current extensometer)
11. Provide a fixture that may be modified for other loading conditions (desired but not critical)

Concept generation

Originally the project asked for the generation of ideas for all loading cases. This included bending, shear, torsion, and any combination thereof. In the ideation process we produced ideas for each of these loading cases before the scope of the project was narrowed to include only bending. Here discussion of the ideation process is provided for all loading cases.

The 6-3-5 Brainstorming Method

The 6-3-5 Method was used to help generate concepts for possible creep test fixtures and specimens. Initially everyone in the group was given five minutes to produce three ideas. After the five minutes, the ideas were explained with text or through a sketch. Each individual passed their lab notebook to the next person, and the process was repeated until everyone could not come up with anymore original ideas. This method is helpful in giving each person in the group some ideas to expand upon (One person can have a general idea and someone else can have an improvement to the idea). This was performed for each loading requirement.

General Brainstorming

While the 6-3-5 method is good for generating many ideas, the lack of discussion of ideas leads to less productive results. To aid in the ideation process, it was necessary to review the ideas from the 6-3-5 method and discuss all the possibilities for each loading case. Bouncing ideas off each other led to many new concepts, many of which were the most viable options for the specific loading case. The idea here was that the more possibilities that were explored, the more possible solutions that could be found.

Concept Selection Process

A Quality Functional Deployment (QFD) Matrix, Figure 5, was created and evaluated given the project requirements from Solar Turbines. Solar Turbines specified the importance of each requirement, and then the design team developed measures to quantify the requirements. The QFD matrix allows for a direct comparison of measures and requirements, thus allowing the determination of critical measures to focus on when brainstorming concepts. The most important measures, as highlighted by the QFD matrix, are: inline loading fixture, loads between 30-100 ksi, consistent loading and consistent results (repeatability).

Solar Turbines Requierments	Item No.	Importance	Loads between 30-100 ksi at specimen	Inline loading fixture	Threaded test attachments	Consistent Loading	Meet ASTM Standards	Consistent Results	Cost	Catastrophic Failure	Ease of prototyping	Ease of load isolation	Ability to measure strain	Adaptable
		◎○△□▽◇	B	C	D	E	F	G	H	I	J	K	L	M
Load in pure shear	1	3	9	9	9	9	3	9	9	9	9	9	1	9
Load in pure bending	2	5	9	9	9	9	9	9	9	9	9	9	9	9
Load in pure torsion	3	1	3	1	3	9	1	3	1	3	1	3	1	1
Bending + Shear	4	5	9	9	9	9	1	9	9	9	9	9	3	9
Bending + Torsion	5	1	1	1	1	1	1	1	1	1	1	1	1	1
Tension + Shear	6	4	9	9	9	9	1	9	3	1	3	9	1	1
Bending + Tension	7	4	9	9	3	3	1	3	9	9	3	3	3	3
Tension + Torsion	8	2	3	9	9	9	1	9	1	9	1	9	1	1
Shear + Torsion	9	1	1	1	1	1	1	1	1	1	1	1	1	1
		Units	ksi	mm	y/n	ksi	y/n		$	y/n	hours			y/n
		Difficulty	1	3	2	5	3	5	1	3	4	3		5
		Target Values	100	1	y	±0.05	y		<5000	n	15			y
N/A	Good	5												
		4												
	Company Ratings	3												
		2												
	Bad	1												
		Weighted Importance	200	210	188	194	72	188	170	180	146	188	84	138
		% Importance	10.215	10.725	9.602	9.908	3.677	9.602	8.682	9.193	7.457	9.602	4.290	7.048
		Ranking	2	1	4	3	10	4	6	5	7	4	9	8

Figure 5. QFD Matrix. For the "Importance" block, the number 5 signifies most important. Under the "Measures" block, the number 9 signifies the measure being compared strongly satisfies respective requirement.

Initially, Solar Turbine's problem statement asked for the development of fixtures that could apply pure bending, pure shear, pure torsion, and the combined loading of bending-tension, bending-shear, bending-torsion, tension-shear, tension-torsion, and shear-torsion. Given this requirement, our team brainstormed concepts for each of these loading cases and produced over 70 ideas. All these ideas can be found in the Appendix A as rough sketches accompanied by a brief description of the concept.

After producing a large quantity of concepts for all possible loading cases (pure bending, shear and torsion, as well as combined loadings) it was necessary to evaluate the concepts to eliminate the ones that would not work, and to determine which ones would give the best opportunity for success. Considering the many loading cases presented in the beginning, it would not have been possible to make a separate fixture for each case during the scope of this project. Since none of the ideas presented were adaptable to incorporate every loading case, it was decided that some of the loading cases should be discarded in order to narrow the project goals. This process was started by evaluating the concepts for each loading case for feasibility.

When producing concepts, many of the limitations on the project were not taken into account, so as to not limit the ideation process. From this, there were many concepts that were easy to disregard when considering the limitations. These limitations include the size of the fixture, the

need for constant loading, the complexity of the design, the ability to isolate loading cases, the ability to measure the gage section deflection, and the ability to adapt the fixture for other cases. When evaluating concepts, it became evident for many of the load cases that the concepts generated did not meet the requirements; all of those concepts were disregarded. This aided in narrowing down the project.

None of the concepts for loading cases involving torsion were found to have acceptable solutions. Since Solar Turbines is least concerned with torsional cases, they decided to discard the designing of a fixture to test torsional loading from this project. Since there were also no concepts that would satisfy the requirements for the combined shear and tension case, it was necessary to abandon this loading case and focus on the remaining. There were feasible concepts that would, or could be modified to, meet the requirements for the remaining cases (pure bending, pure shear, bending-shear, and bending-tension). These concepts can be seen in Figures 5 through 8. After presenting these concepts to Solar Turbines, the final scope of the project was determined to include three-point bending, and potentially bending-shear and bending-tension if able. Pure shear loading was eliminated from the focus of the project due to the difficulty in strain measurement. After the first design has been finished, the plan is to have a platform of which Solar can modify to accommodate other loading regimes.

Loading cases involving bending were now the focus of this project. With a much more narrow design goal, it was decided to attempt to solve all cases with a single fixture. This would be ideal because one of the requirements of Solar Turbines is the use of a single specimen in all loading cases, for ease of comparison of creep data. Since the concepts for the combined loading cases were designed specifically for those cases, they were found to not be easily adaptable to the other loading cases. Eventually it was found impractical to have only one fixture.

After further evaluation of the pure bending concept presented in Figure 6, it was evident that the fixture could likely be modified to test bending-shear, and potentially bending-tension cases as well. The analysis of this pure bending fixture became the focus for the design.

Top Concepts

The top concepts resulting from our first round of concept generation and evaluation are the following:

The initial concept for the pure bending fixture was developed using the ASTM E 290-09 standard for Pure Bending of Material for Ductility. A standard three point bend test forms the basis of this design, and it consists of a mandrel and plunger (shown in Figure 6). The mandrel and plunger will be attached to the tensioning rods so that their relative motion causes the desired bending load on the specimen. As this is drawn, the upper tension rod will be connected to the lower mandrel, and the plunger will be rigidly connected to the bottom tension rod.

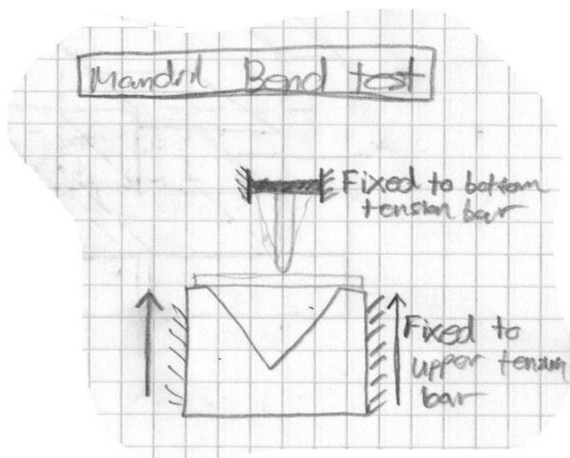


Figure 6. Sketch of initial concept for pure bending fixture

To apply a combined loading of bending and shear on the specimen, the concept in Figure 7 was developed. In this fixture a flat specimen is fixed at one end and a load is applied at the other end, mimicking a cantilever beam. The end where the specimen is fixed will be forced one way while the load at the end is forced in the opposite direction as shown by the two arrows.

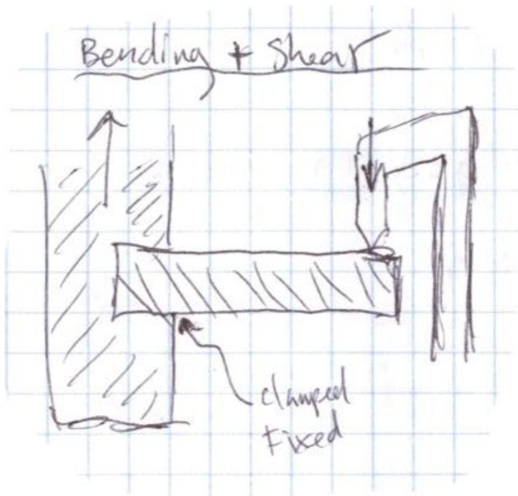


Figure 7. Sketch of initial concept for bending and shear combined loading fixture

A simple idea for a pure shear application is shown in Figure 8. The idea is to have two fixtures with through holes machined in each of them. One of these fixtures would be attached to the upper tensioning rod and the other to the lower tensioning rod. Each fixture has its hole that lines up with the opposite fixture. A specimen is placed inside the hole, and then the tension is applied. This will shear the specimen across its midsection. The specimen does not have to be cylindrical. It may be changed to a different shape if needed.

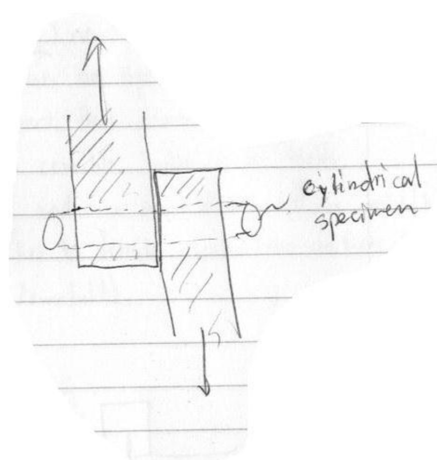


Figure 8. Sketch of initial concept for pure shear

For the combined loading of bending and tension the concept in Figure 9 resulted from our brainstorming. Here the ends of the specimen are connected to the fixtures, which are connected to the bottom tension bar. The circular plunger is connected to the upper tension bar. As the tension bars pull apart the specimen will bend as shown. The specimen will also undergo tensile loads as a result of the pin fixture connections.

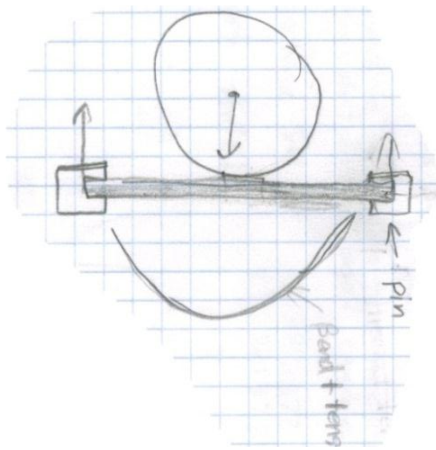


Figure 9. Sketch of initial concept for combined bending and tension

First Quarter Concept

This section details the concept developed at the end of the first quarter of the senior project series. After many iterations and discussions with Solar Turbines, a simple design was developed to primarily produce pure bending on the specimen. We found that this design may potentially be modified to accommodate, bending-shear, bending-tension, and pure shear loading regimes. The three point bend test concept described in Figure 6 formed the basis of this design.

Figure 10 through Figure 14 shows a solid model of our design and of all the components. A plunger and mandrel are incorporated into an assembly that attach to the upper and lower tensioning bars. A specimen with a rectangular cross section is placed between the plunger and mandrel. As the plunger is pulled upward, the mandrel is kept stationary, resulting in bending at the specimen's mid-length.

There are many appealing features in this particular design. For one, the creep test machine's current strain measurement instrumentation can be used. The machine's extensometer was incorporated in our design so that the linear displacement of the specimen's mid-section can measured. From this displacement, an angle of bend can be determined. Two, the compactness in of design may allow for the fixture to fit within the machine's current furnace, and three, it allows for the applied loading to remain inline.

The mandrel and plunger assemblies will be assembled with bolts and they will have threaded holes so that they can be fastened to the tensioning arms. The extensometer has a thin rod that is placed in contact with the specimen on the opposite side of the plunger, as can be seen in Figure 10. A groove in the specimen will provide a contact area for the extensometer. To ensure the proper placement of the specimen in each test, the mandrel has rectangular recessions (see Figure 12).

As can be seen in Figure 11 and Figure 13, the plunger is supported by four angled push rods. By making these push rods angled, a more robust design is accomplished. The push rods will experience a compressive load and minimal bending.

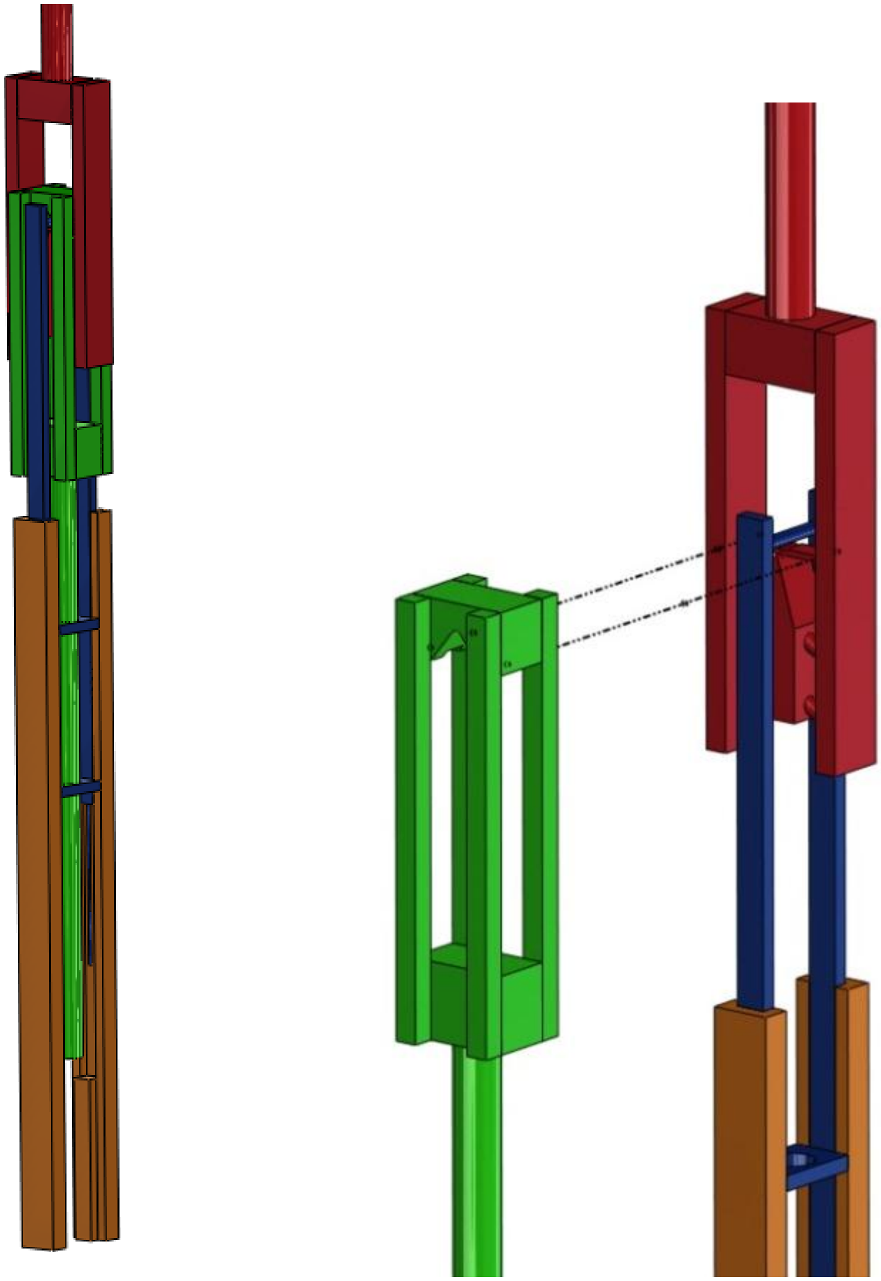


Figure 10. Completely assembled and semi-exploded view of bending fixture concept. The green subassembly is the mandrel, stationary. The red subassembly is the plunger, moves upward. The blue subassembly is the extensometer, measuring device. The orange subassembly is the extensometer guide. The largest diagonal width is 2.47 inches.

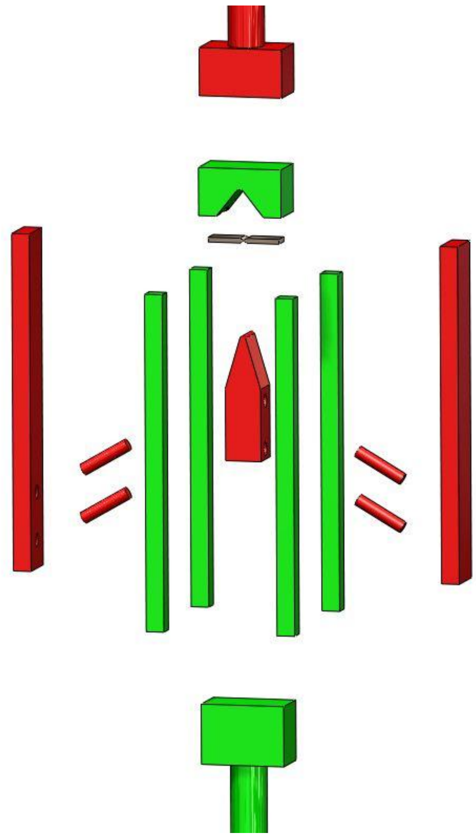


Figure 11. Completely exploded view of first concept without extensometer.

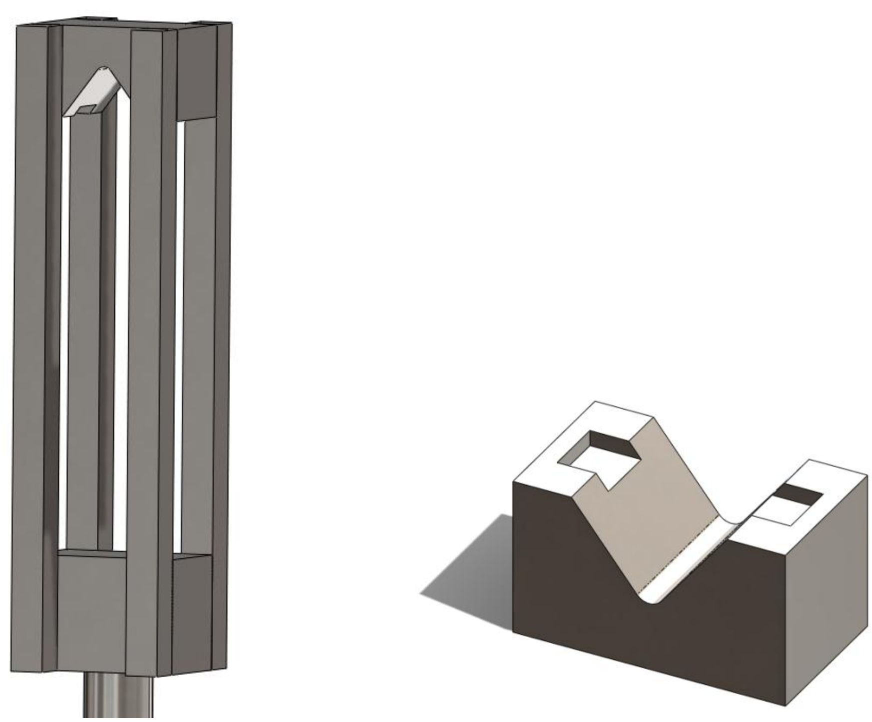


Figure 12. Mandrel subassembly and mandrel. Rectangular recession on top of mandrel is for proper positioning of specimen.

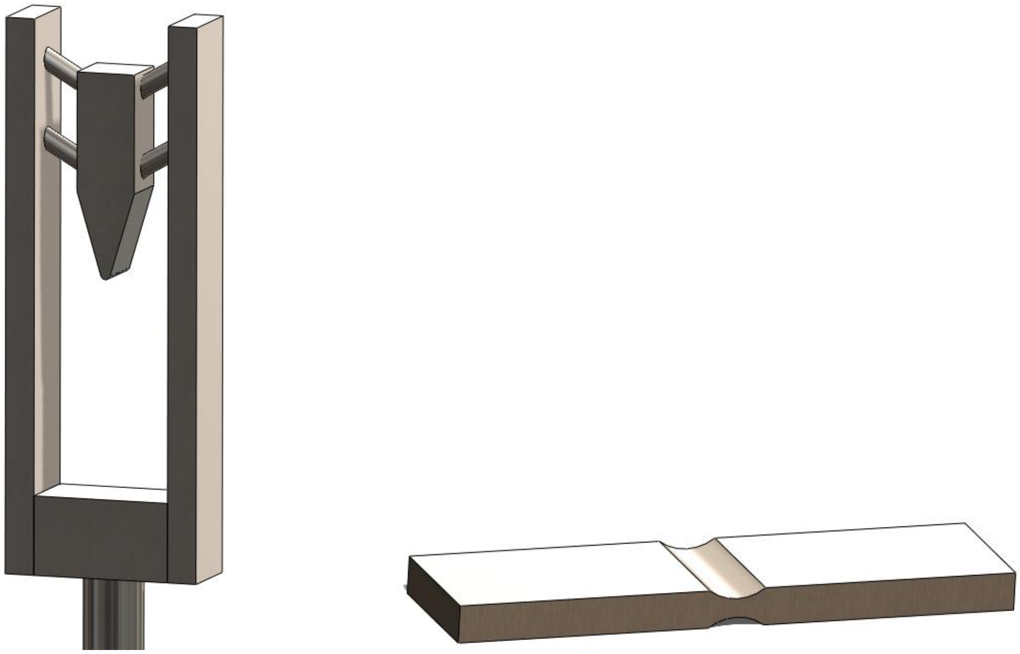


Figure 13. Plunger subassembly and original test specimen concept

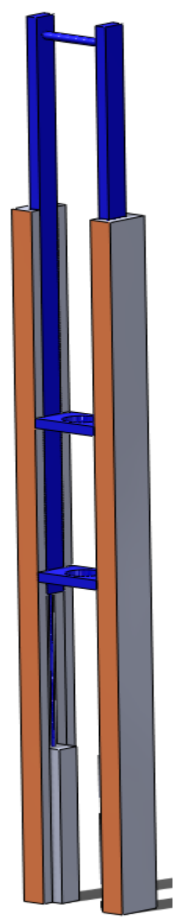


Figure 14. Extensometer and guide assembly

One of the major limitations on this design is the furnace size. As can be seen in Figure 3, our fixture must fit within a cylindrical space with a 3 inch diameter and a height of 10 inches. In order to determine how much the fixture could be scaled down, the specimen size limitations were necessary. The largest width of our concept is 2.55 inches, thus the concept will fit within the furnace. See Appendix B for detailed drawings of the bending fixture assembly and component concepts.

To determine specimen size, a MATLAB program was developed to investigate how the force applied to the specimen, and the initial specimen deflection, vary with specimen thickness for pure bending and bending-shear loading regimes.

The sizing of the specimen was done assuming MAR-M 247 as the specimen material. MAR-M 247 is a nickel-based super alloy specially designed to improve creep rupture strength; therefore, MAR-M 247 is commonly used for high temperature, high pressure applications. Based on data provided by Solar Turbines, MAR-M 247 at 1200 °F has a modulus of elasticity (E) and yield strength of 14500 ksi and 118.7 ksi, respectively. Following Solar Turbines' current testing protocol for MAR-M 247, a maximum normal stress of 73 ksi was the assumed normal stress at the critical element on the specimen cross-sectional area. The critical element is on the surface of the specimen at the gage section, and on the side of the specimen that is in tension.

Loading Conditions and Load Calculations

The dimensions of the specimen around which the fixture was designed were determined based on beam calculations to determine required force to produce the necessary stresses, as well as the static deflection in the beam. The equations, shown below, were written into MATLAB code in which thickness was varied to determine the optimum thickness for the design.

General Equations for Beam Calculations

Moment of Inertia: $$I = \frac{wt^3}{12}$$

Static Moment of Area: $$Q = \frac{wt^2}{4}$$

Max shear stress: $$\tau = \frac{VQ}{It}$$

Normal stress: $$\sigma = \frac{3FL}{2wt^2}$$

Where w is the specimen width, t is the specimen thickness, and V is shear force.

Simply Supported Beam (Simple Three Point Bend Test)

This is the loading case being utilized by our design. The force F is that being applied by the plunger and the F/2 forces are those applied by the mandrel. Using this loading condition, the stress being applied on the specimen gage section was determined.

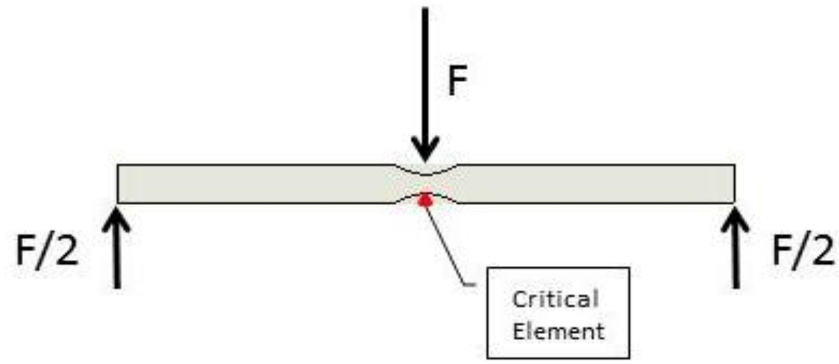


Figure 15. Critical element location. Force F is applied by the Plunger, and the Reaction Forces, F/2, are applied by the Mandrel. Because the ends of the specimen are not restrained from deflecting upward, the specimen will have the largest initial deflection; verified in Figure 15.

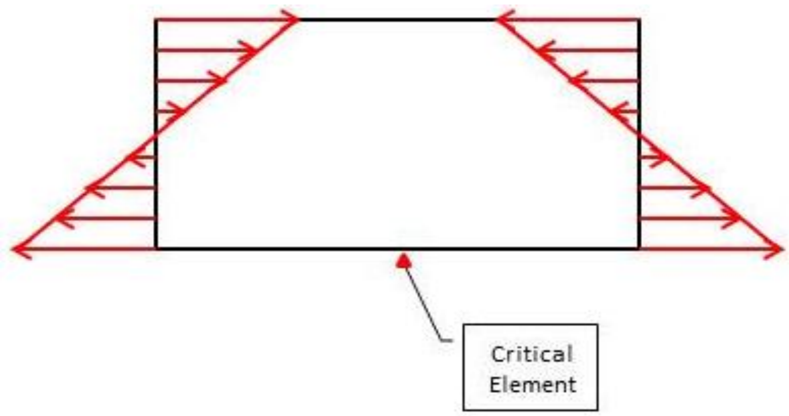


Figure 16. Stress distribution. Gage section of bending and bending plus shear loading regimes with critical element depicted as shown.

Deflection at center of beam – Simply Supported Beam:

$$y = \frac{FL^3}{48EI}$$

Max Shear in beam – simply supported (Three Point Bend):

$$V = \frac{F}{2}$$

The loading cases of the specimen provided below are those that our design may easily be expanded to apply. These can be accomplished by modifying the mandrel and plunger so that the conditions illustrated are achieved. This would allow for testing of bending and shear. We believe it is worth mentioning these two loading conditions in this report.

Fixed Ends Beam (Three Point Bend Test)

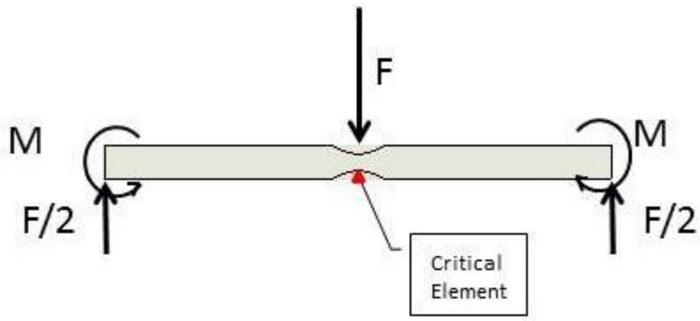


Figure 17. Critical element location for bending-shear. Force F is applied by the Plunger, and the Reaction Forces, F/2, are applied by the Mandrel. The moments are caused by restricting the ends of the specimen from translating in the vertical direction.

Deflection at center of beam – Fixed Ends:

$$y = \frac{FL^3}{192EI}$$

Five point bend test

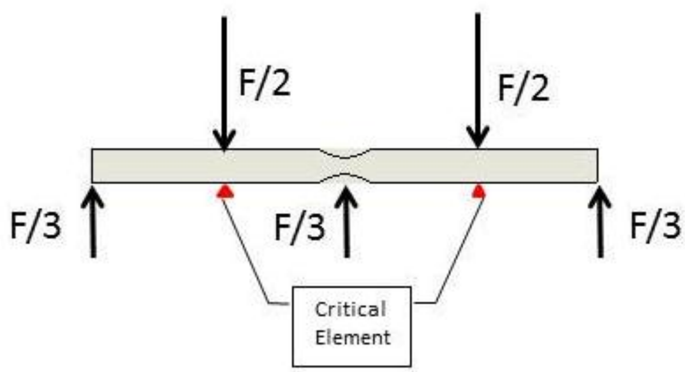


Figure 18. 5 point bend test. For a 5 point bend test, a new mandrel other than depicted in drawing B1 is necessary. The critical point is no longer in the center of the specimen. The extensometer would need to be modified to measure the critical points vertical displacement.

Deflection at center of beam – Five Point Bend:

$$y = \frac{\left(\frac{F}{2}\right)\left(\frac{L}{4}\right)^2}{96EI}\left(11\left(\frac{L}{4}\right) - 9\left(\frac{L}{2}\right)\right)$$

Max Shear in beam – simply supported (Five Point Bend):

$$V = \frac{F}{3}$$

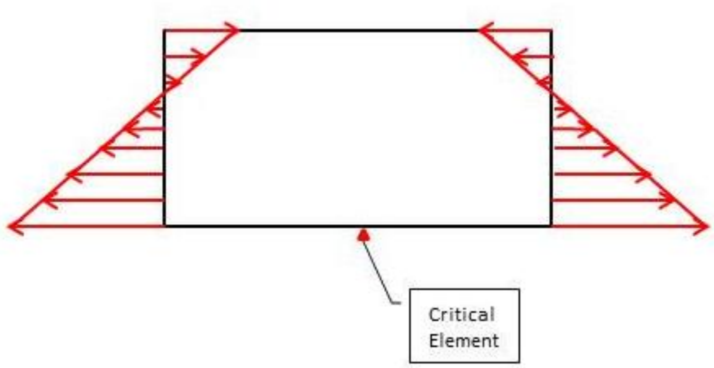


Figure 19. 5 point bend test stress distribution. Gage section of bending-tension loading regime with normal stress distribution depicted.

Specimen Sizing:

In the beginning of the project, the specimen sizing was determined based on a criteria for a three-point bend test with a width that is four times the thickness. From this criterion, we determined a size that would cause a small initial deflection given a loading that produces a stress that is half of the yield strength of the material.

Later in the design process, it was determined that it would be beneficial to use the same specimen shape that is used in typical tensile creep testing (shown in Figure 20). However, it was also determined that it would be acceptable to vary the thickness of this specimen to allow for use of a greater applied force. The dog-bone shape, as seen in the tensile testing specimens, is used. The gage section of our specimen can vary in width and thickness, but must maintain a constant gage length of 1 inch in order to fit within the mandrel.

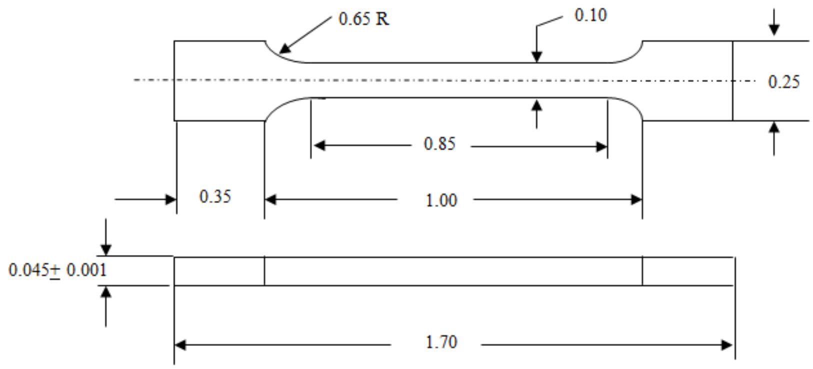


Figure 20. Specimen drawing

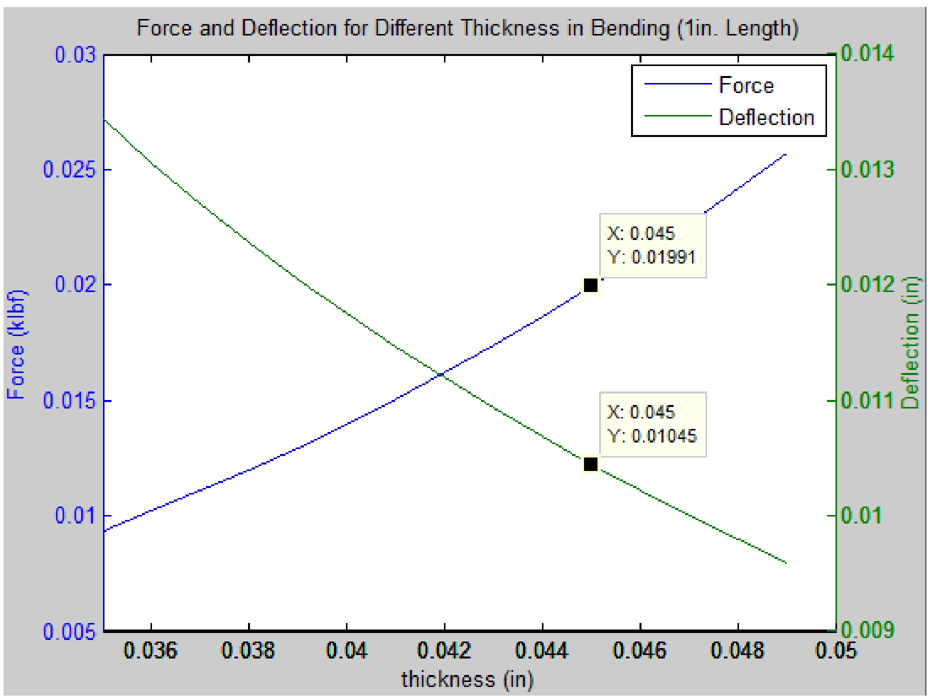


Figure 21. Force and deflection for different thickness in bending for 1 inch test length.

The Matlab model was initially designed such that the changes in required force and initial deflection for different sized specimens could be viewed. The required force is the force necessary to produce a maximum stress in the beam; that is, half of the yield strength of the specimen material. This force varies as the thickness and width are changed as seen above. The deflection is the maximum static deflection that is expected when the beam been is loaded to the required force. This program was determined to be unnecessary and size specifications were determined by other means. However, the same means by which force required is calculated in this program was followed in determining required forces for future tests.

Final Creep Fixture Design

After further discussion of our design with Solar Turbines, we found the fixture was still too complex in geometry and in assembly. We wanted to make the design as simple as possible by using the minimal amount of components needing assembly and keeping in mind their ease of machining. Since the fixture is being made from an expensive material, MAR-M 247, it is important that we use a minimal amount. Figure 22 shows a solid model of the assembled fixture design and Figure 23 provides an exploded view of the assembly. As seen in the figures, the use of fasteners was eliminated completely, which prevents galling from being a concern. Excessive dovetail connections were also reduced to just one for the connection of the plunger and plunger support. Additionally, the interchangeability of the plunger, mandrel, and specimen was simplified.

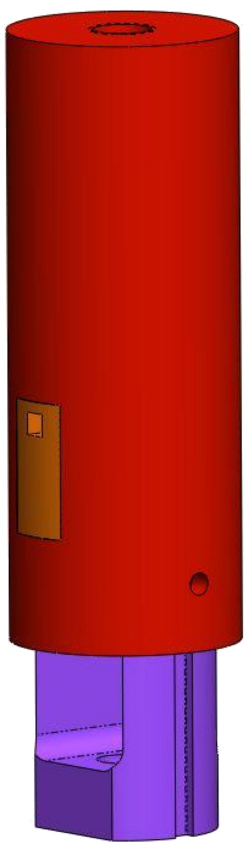


Figure 22. Final fixture design fully assembled.

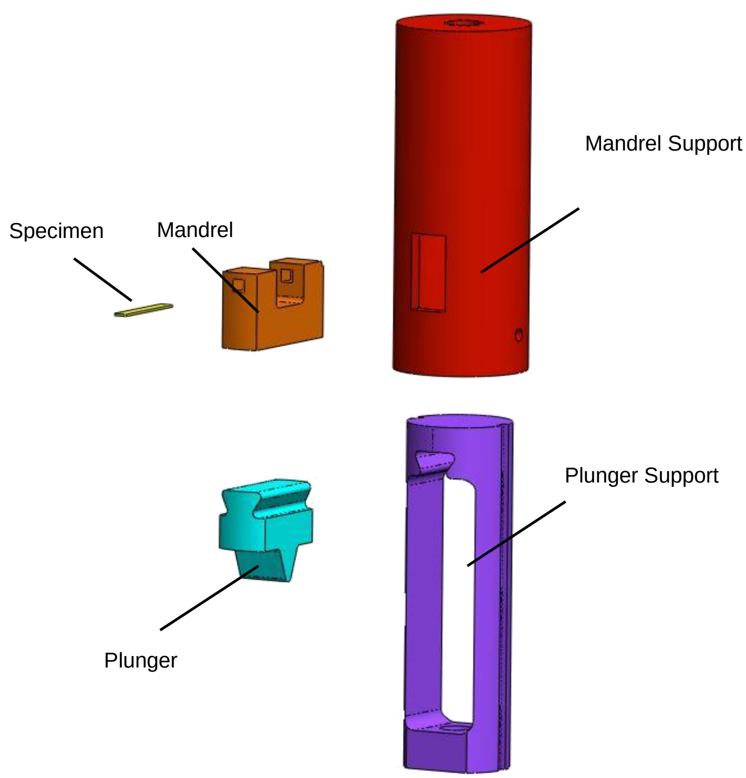


Figure 23. Exploded view of final fixture design

The fixture was simplified to two concentric cylinders, one holding the plunger and the other the mandrel. The fixture now consist of only four components as oppose to 14. A description of each component is given below:

Plunger Support

The plunger support, shown in Figure 23, is a cylinder with a rectangular hole and dovetail profile cut into it. The dovetail cut is where the plunger tip is slipped into place. There is a tapped hole, opposite the dovetail cut out, where the pull rod is to be connected. The benefit of this design is that it can be machined from one single peace of stock material and therefore eliminating the necessity of attaching multiple parts together like the previous design. This results in a more mechanically robust component. Guide rails are also inclued along the legs of the plunger support. These will interface with pins on the mandrel suppor to ensure consistant allignment.

Plunger

The plunger tip was simplified to one single piece with a dovetail profile cut out for it to attach to its support. This allows for easy plunger changes. The flat surfaces on either side of the tip is a new feature that prevents the tip from colliding with the mandrel. The flat surfaces will make contact with the mandrel before the tip does, preventing any damage.

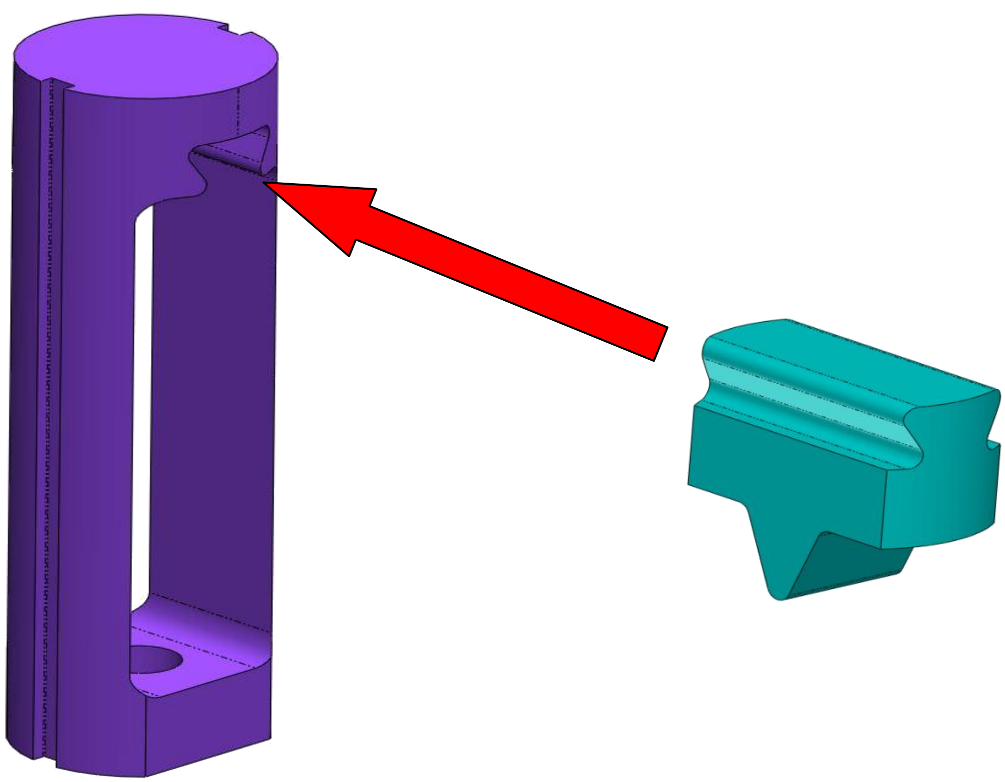


Figure 24. Solid model of plunger support **Figure 25. Solid Model of plunger**

Mandrel Support

The mandrel support is a cylinder that is hollowed out for the plunger support to slide within it (shown in Figure 26). The lower square hole is where the mandrel will slide in such that the cylinder walls support the mandrel at its ends. The section view shows the small hole where the pin will be placed that interfaces with the guide rails. As is shown in section view, there is a tab left where the mandrel will interface. The tab esures consistant allignment of the madrel. The threaded hole at the top of the mandrel support is where the pull rod will attach.

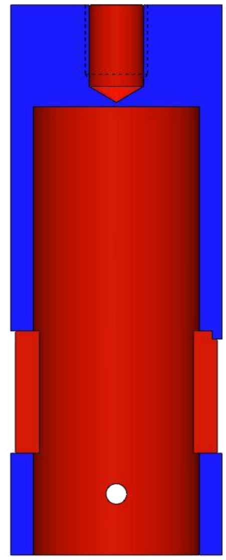


Figure 26. Solid Model of Mandrel Support (Section View)

Mandrel

The mandrel design was changed to accomidate a smaller specimen size. A hole was made to slide in the specimen for testing. The width of the hole makes a tight clearance fit with the specimen and, the back hole is not a through hole like the front hole. This helps ensure proper placement of the specimen for each test. The specimen is slid in until it makes contact with the back surface of the second hole. The height of the hole was made much larger than the specimen thickness to ensure the specimen ends are free to move in the vertical direction when experiencing bending to eliminate any shear affects. (This feature could be removed for a shear and bending loading) Additionally, the hole in the mandrel allows for the fixture to be used upside down with the mandrel moving down if need be. The tab cutout ensures alignment.

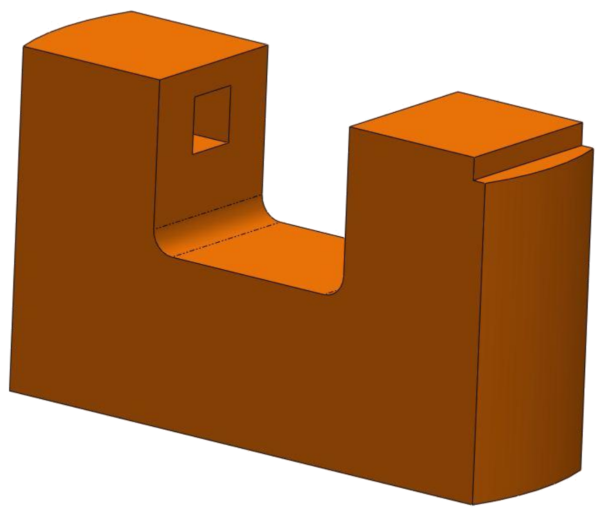


Figure 27. Solid model of mandrel

Assembly of Fixture

The steps of assembling the fixture are described below with figures demonstrating each step.

1. Slide plunger into the plunger support
2. Attach pull rod to plunger support
3. Slide specimen into mandrel until front end of specimen touches the back wall of the second hole in the mandrel
4. Slide plunger support (with plunger) into the mandrel support cylinder in the orientation shown in the figure below
5. Slide mandrel (with specimen) through the square slot in the mandrel support
6. Attach pull rod to mandrel support

Fixture Analysis

In running a creep test a desired stress within the specimen and a temperature are given as testing parameters. Given this information we needed to find a relationship that relates the stress in the specimen under bending to a force that is necessary to induce that stress. This was done for a simply supported beam specimen with a rectangular cross-sectional area.

Required Force: Worst case for MAR-M 241 specimen (1700°F, 80% yield stress)

Given the worst case for MAR-241 specimen test parameters of 1700°F and a stress equal to 80% of its yield stress, the required force to induce this worst case scenario was determined. This will provide us the maximum force that the fixture will experience in testing.

$$\sigma = -\frac{My}{I}$$

$$I = \frac{1}{12}bh^3$$

$$M = \frac{\sigma I}{y} = \frac{FL}{4}$$

$$F = \frac{4\sigma I}{yL} = \frac{4\sigma \frac{1}{12}bh^3}{\frac{t}{2}L}$$

$$F = \frac{2}{3}\frac{\sigma b h^2}{L}$$

Where b is width, h is thickness, L is length and σ is the yield strength (80% in our case)

σ = 77,740 psi at 1700°F

$$\sigma_{80\%} = 0.80 * 77740\, psi = 62192\, psi$$

Plugging in values into the force calculation, we get:

$$F = \frac{2}{3}\frac{62192psi(0.1in.)(0.032in.)^2}{1in.} = 4.24\ lb_f$$

This calculation can be varied for all tests to determine the required load at the center of the cross section of the specimen. This calculated force can now be used to conduct creep analysis in the fixture.

Fixture Creep Analysis

It is important to ensure the fixture will not itself creep under the testing conditions. A common method for determining the life of a creep resistant material such as Mar-M-247 is the Larsen-Miller parameter method. To use the Larsen-Miller parameter, one must know the stress and temperature the object experiences; the life expectancy can then be determined through a correlation. For the typical specimen without the dog-bone cutouts, 19.9 pounds of force is needed for an adequate test. The parts of the fixture that have the smallest cross-sectional area are the arms of the plunger support. The total cross-sectional area as seen in a plane orthogonal to the vertical orientation of the fixture is 0.46 inches squared. With this specified cross-section, there will be a stress of 43.3 psi in the arms of the plunger support. This stress is much lower than any stress used in previous tests of Mar-M-247. Large estimations would need to be made in order to determine the approximate life of the fixture under the bending creep test conditions. Instead, a comparison can be made to data that has already been collected for Mar-M-247 under more severe conditions. By realizing that Mar-M-247 has a generous life under these severe conditions, it is safe to say the material will have a long life under the testing specification for this bending creep test.

Analysis

We found the critical element in the fixture was the Plunger Support as it has the smallest cross-sectional area while still undergoing a force that is half of the applied force. This calculation is a determination of whether the fixture itself will creep during testing.

Using the maximum load that would be applied by the fixture, F=4.24 lb_f, a normal stress at the cross-section of the plunger support bars can be calculated (See Figure 24).

$$\sigma = \frac{P}{A} = \frac{4.24\ lb/2}{(0.23in.)^2} = 40\ psi$$, where P = F/2

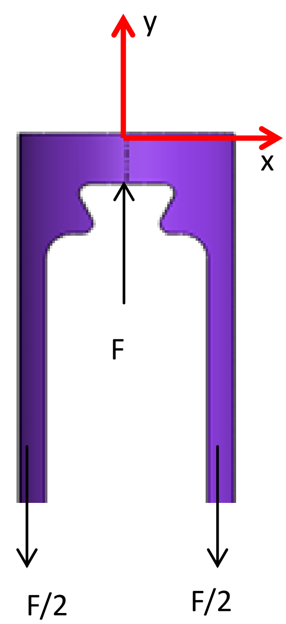


Figure 28. FBD of Plunger Support

- This value is based on the force required at a temperature of 1700°F.
- The lowest Larson-Miller parameter for which we have data is at a stress of 10,000 psi for 1700°F

At a stress of 10ksi, the LMP data gives a life of 71923.34 hours. This stress is orders of magnitude greater than the calculated stress of 20 psi. Thus, at our stress, we would expect no noticeable creep in the fixture over a large amount of tests.

Bending Stress and Normal Stress Correlation

In order to utilize current creep analysis tools that were developed based on uniaxial creep testing like the Larsen-Miller Parameter, a correlation between bending stress and normal stress needs to be formulated. A predictive calculation was developed; however, a more accurate and justifiable relationship cannot be created until test data is produced.

In order to use current Larsen-Miller Parameter data the normal stress being applied on a specimen in tension must be provided from this stress a corresponding LMP value can be deduced from the data. This LMP value can be used in the equation below to determine a time till rupture.

$$LMP = T(\log t + C)$$

Where,
LPM is the Larson-Miller Parameter
T is the absolute test temperature
C is a constant (usually 20), and
t is the time for rupture

To correlate bending stress to a normal stress an attempt was made to produce an average stress developed from bending that may be used in LMP calculations. This was done by taking the average tensile (or compressive) stress acting on the specimen when a bending load is applied (see Figure below).

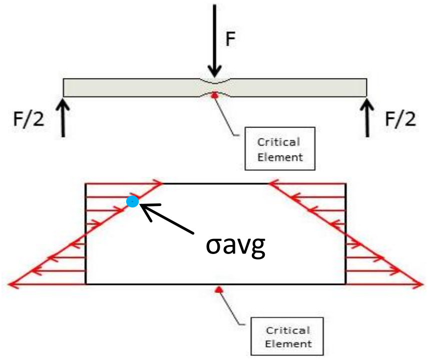


Figure 29. Location of average stress experienced at any cross section along beam

This average tensile/compressive stress was calculated by first determining the location where the average stress occurs from the neutral axis. This gives an average stress along the cross section for tension or compression.

In addition the moment is not constant along the length of the specimen since the internal moment is a function of the location along the specimen. As a result, an average moment needed to be calculated. The figure below demonstrates where the average moment occurs on a moment diagram.

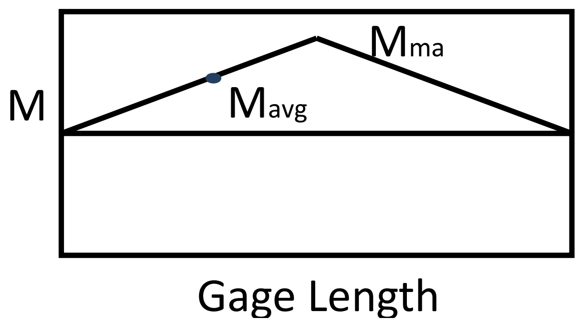


Figure 30. Location of average moment along specimen length in moment diagram

Using this information an average stress was calculated as follows:

A mean stress was calculated based on the average moment

$$\sigma_{mean} = \frac{\frac{1}{2}M_{max}(c)}{I}, \ where\ M_{max} = \frac{FL_g}{4}$$

Then an average stress was calculated using this mean stress and accounting for the average tension/compressive stress

$$\sigma_{avg} = \frac{1}{2}\sigma_{mean}$$

This gave an average stress experienced by the specimen on either the tension side or the compressive side

$$\sigma_{t,avg} = \sigma_{c,avg} = \sigma_{avg}$$

Now, to account for both tension and compression the root-sum-square of the two was taken

$$\sigma_{convert} = \sqrt{({\sigma_{c,avg}}^2) + ({\sigma_{t,avg}}^2)}$$

$$\sigma_{convert} = \frac{\sqrt{2}}{2}\sigma_{mean}$$

$$\sigma_{convert} = \frac{3\sqrt{2}FL_g}{8wt^2}$$

Where,

$\sigma_{convert}$ is the resulting or converted stress to be used in LMP calculations
F is the force applied by the plunger at the specimen mid-length
Lg is the gauge length of the specimen
w is the specimen width, and
t is the specimen thickness

This calculation is a best attempt at correlating the bending stress to a normal stress that would be experienced in tension. This lacks justification and cannot be validated until test data is available. Once multiple tests are done and sufficient data is available a better predictive method can be deduced.

It may turn out to be necessary for a new creep analysis method like the Larson-Miller Parameter that is based on bending creep data to be developed for better time to rupture predictions, as well as predictions for the amount of deformation a component has experienced.

Prototype

A preliminary prototype was manufactured out of stainless steel to verify proper machining and dimensioning of the fixture, and to ensure proper functionality. The final fixture will be made out of very expensive MAR-M 247, making this step critical to make sure manufacturing of the final design is done right. Below are some images of this prototype.

Figure 31. Stainless Steel Prototype

Testing

Currently testing is being done with the stainless steel prototype. This will provide better insight to the fixture’s functionality under testing conditions. In addition the repeatability of load application by the fixture will be investigated. For this test the extensometer ensured proper alignment of Plunger Support and Mandrel Support.

The test is being conducted at a temperature of 900°F. The required load on the specimen was calculated to be 11 lbf to produce a stress of 55 Ksi bending stress at its cross-section. A specimen thickness of 0.055 inches was used for this particular test. The duration of the test is still unknown. Below are some images of the fixture within the furnace while in testing.

Figure 32. Prototype in testing within Furnace

Future Plans for Fixture

Once the design is proved satisfactory Solar Turbines will proceed to manufacture the final fixture out of MAR-M 247 and conduct further validation of design. Finite element analysis will be conducted to simulate creep under the desired test condition.

If test results demonstrate a difference in creep characteristics under bending, the degree or magnitude of its affect will need to be determined to better life gas turbine components. An analytical model to correlate bending stress to current creep test done under tensile loading should be formulated and validated.

Other loading conditions will also be investigated once the bending condition is tested. The fixture can be modified to test for combined bending and shear loading by clamping the specimen ends in the mandrel. Also, new designs for the mandrel and plunger can be made to possible apply some of the other loading conditions.

Project Timeline, Gantt Chart

See Appendix D for the Gantt Chart, which provides a visualization of the project work flow. For a finished report, tasks 11, and 13 through 21 must be completed. Prototyping was successful; both the Cal Poly senior project team and Solar Turbines have a rapid prototyped version. The steel prototype has been machined and is in testing, as of 12/03/2012. Creep tests can take thousands of hours to complete. Being that this type of testing is new, no definite failure time can be established.

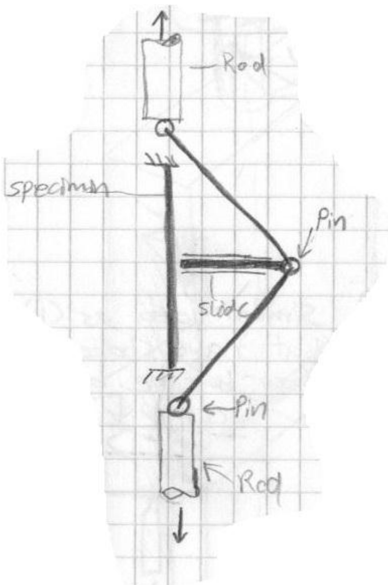
References

[1]ASTM Standard E 290, 2009, "Standard Test Methods for Bend Testing of Material for Ductility", ASTM International, West Conshohocken, PA, 2009, DOI: 10.1520/C0033-03, www.astm.org.

[2]Whittenberger, J. Daniel. " Creep, Stress-Rapture, and Stress-Relaxation Testing". NASA Lewis Research Center

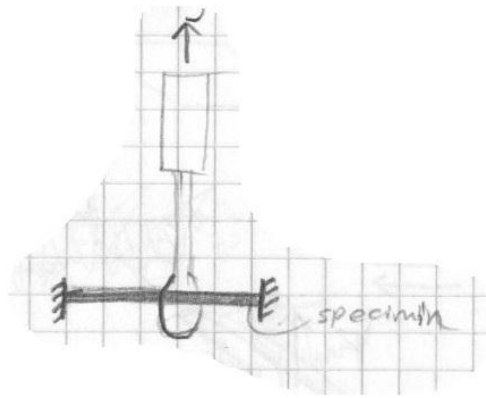
Appendix A – All Generated Concepts

Pure Bending Concepts



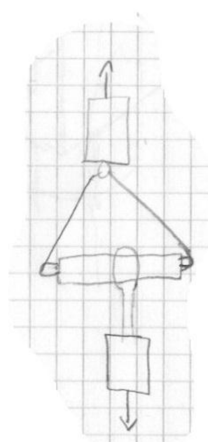
Concept B-1.

The specimen is the dark, vertical member with both ends held fixed. The two tension rods are connected to a ram rod by a pin as shown. The ram rod is constrained to move only in the horizontal direction. As the tension rods pull apart, the ram rod is applied to the specimen. This will experience tension, and possibly significant shear depending on the length of the specimen.



Concept B-2.

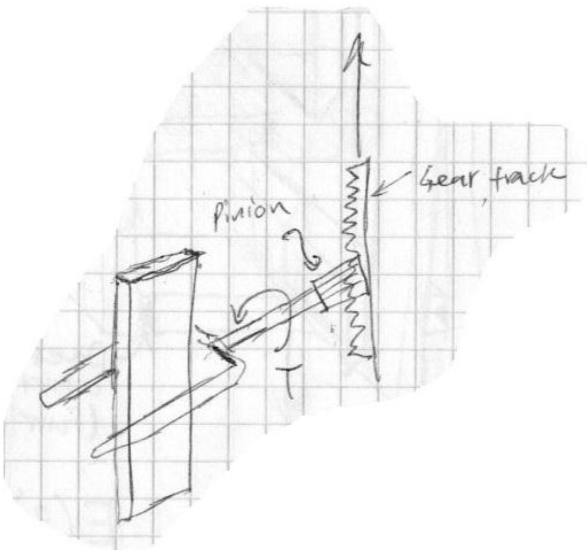
A horizontal specimen is held fixed (probably by the bottom tension rod). The top tension bar is connected to a device that has a hole for the specimen to slip through when being mounted. The tension bar applies the bending. Shear and tension will also be present because the ends of the specimen are held fixed.



Concept B-3.

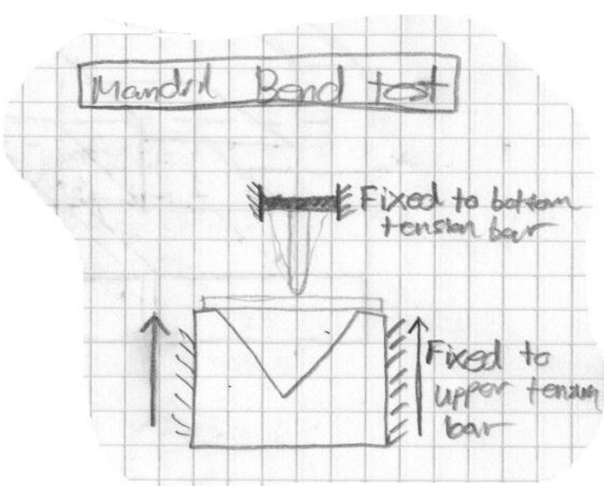
This is along the same lines as Concept B-2, but uses two rods with pin-to-pin ends to connect the specimen to the upper tension bar. Because the pins will allow the ends of the specimen to rotate as bending occurs, this concept

eliminates the shear that is induced in Concept-B2.



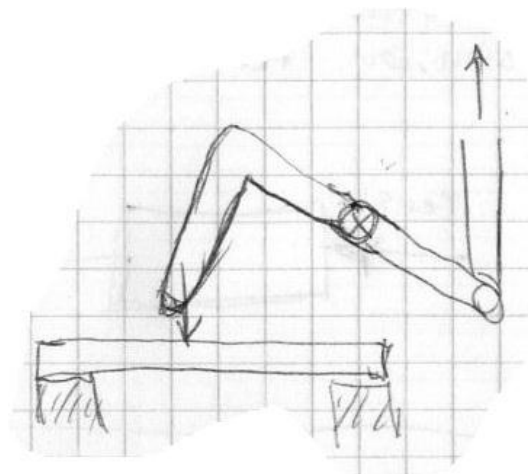
Concept B-4.

The upper tension bar is connected to a gear track. As the track is pulled upward, it spins a gear. The gear is connected to a prong that straddles the specimen, while the specimen is held fixed at one end. Bending will occur on specimen at about its midsection.



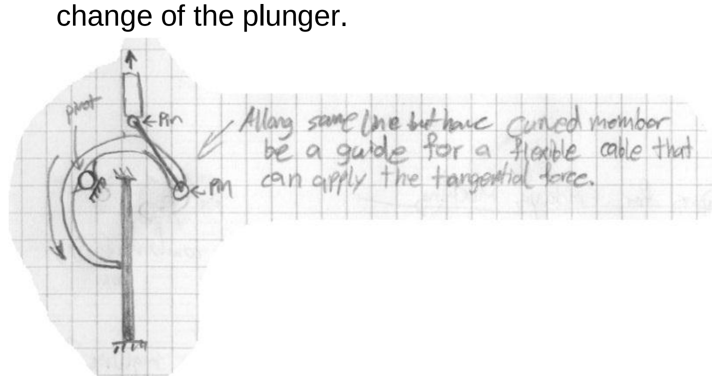
Concept B-5.

From the ASTM E 290-09 standard for Pure Bending of Material for Ductility, a mandrel bend test was developed. This set up can be rotated 180 degrees to make the load application easier. As this is drawn, the upper tension rod will be connected to the lower mandrel, and the plunger will be rigidly connected to the bottom tension rod. The benefit to this configuration is the specimen can lie on the mandrel while applying load.



Concept B-6.

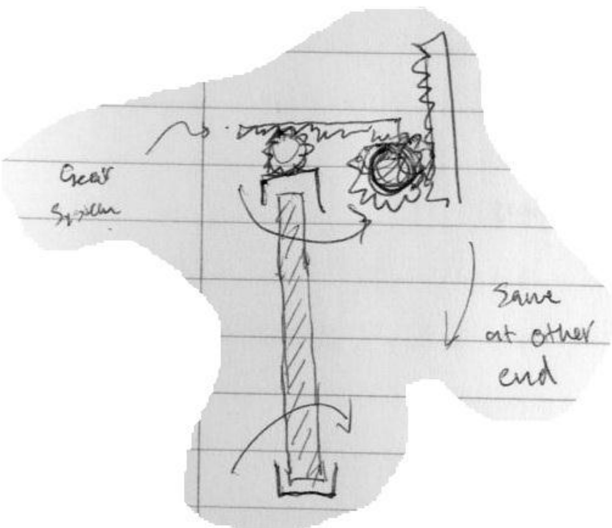
The specimen is resting on a surface with a gap (can be a mandrel such as the one in Concept B5) while a force is applied a pivoting plunger. The plunger lever arm is connected to the upper tension bar. A downside to this is inconsistent loading due to the angle change of the plunger.



Concept B-7.

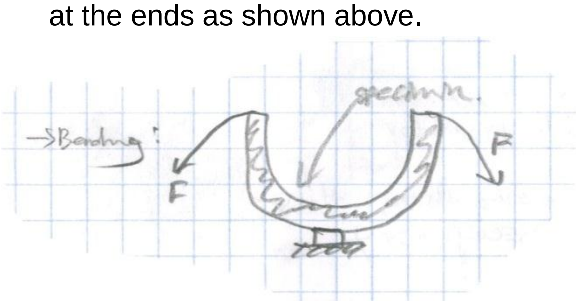
A circular guide path (maybe a tube) contains a strong cable that can bend to the meet the shape of the guide. The end of the cable that is exposed is connected to the upper tension rod. As

the tension rod pulls up, it forces the cable to move in the guide, ultimately applying a bending load on the vertical specimen, which is fixed in place. (Would need to make specimen free to obtain pure bending.)



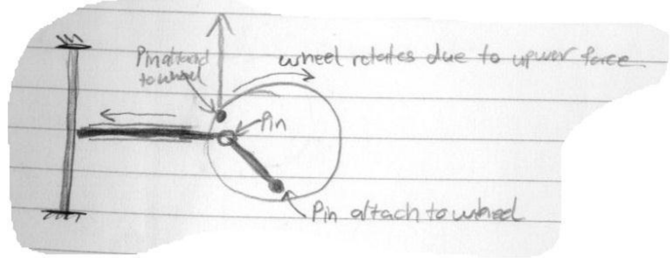
Concept B-8.

The specimen is held at its ends by a piece that has slots machined to it and an arced gear track opposite the slots. The bending on the specimen will be produced by a set of gears and gear tracks. The tensile load will pull on a vertical gear track that will cause a gear to rotate. This gear will than translate a horizontal gear track that then rotates another gear that is meshed with the arced gear track on the end pieces. The end pieces will result in bending forces at the ends as shown above.



Concept B-9.

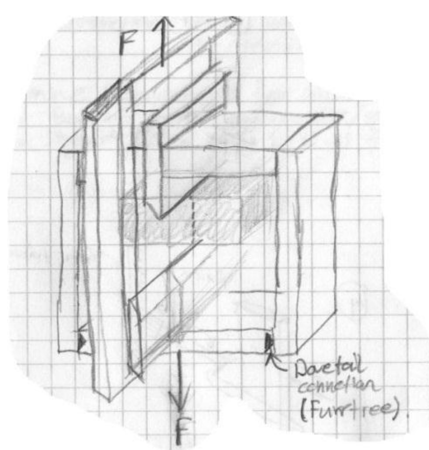
A "U" shaped specimen will be supported by the bottom tension bar and added fixture. The Force F will be applied equally on both sides, causing the ends to bend down. Developing the needed fixtures need to apply the loads to develop pure bending should be considered.



Concept B-10.

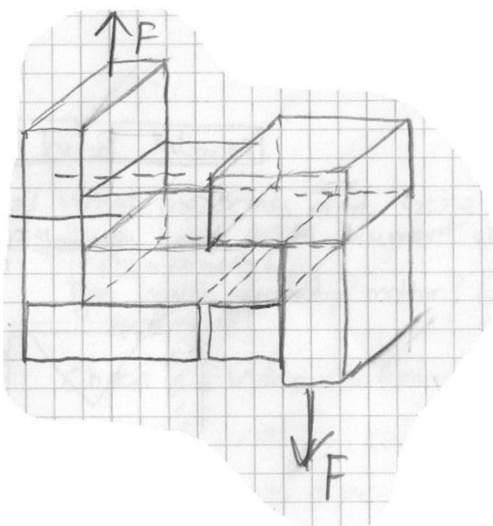
A vertical specimen undergoes a force applied to its midsection. The plunger is connected by a two bar linkage to a disk that is free to rotate as shown. The upper tension rod is connected to the disk, and as the tension rod is pulled upward, this causes the disk to rotate. The plunger advances on the specimen as a result of the disk rotation.

Pure Shear Concepts:



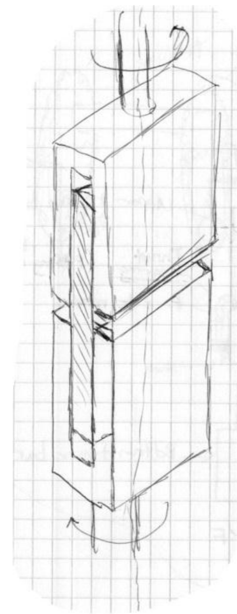
Concept S-1.

In this concept there are two shear blades that will cut the shaded square specimen as shown. As the upper tension rod is pulled upward, the bottom shear edge advances on the specimen. the top shear edge applies and equal and opposite force on the specimen. Dovetail grooves (or fur tree grooves) could be used in to construct this arrangement.



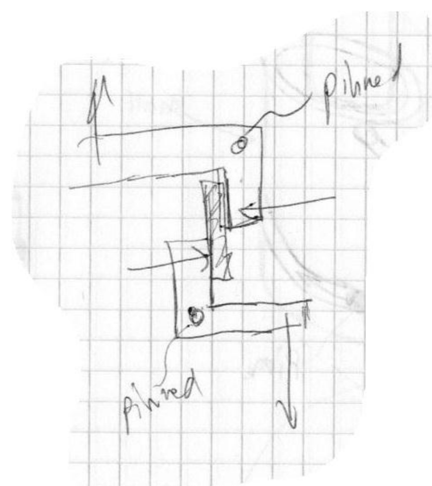
Concept S-2.

A square specimen is held between two fixtures as shown. As the forces (F) are applied by the tension rods, the specimen will be sheared across its midsection.



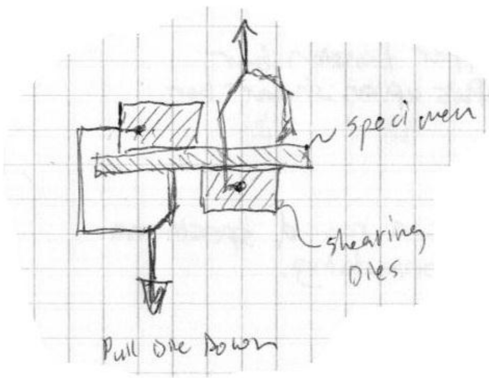
Concept S-3.

A specimen is gripped by two fixtures and a large torque is applied. The specimen will be sheared across its midsection. The shear applied is not consistent, because the distance from the torque center-line changes. How twisting will result from a tensile load is not explained not know.



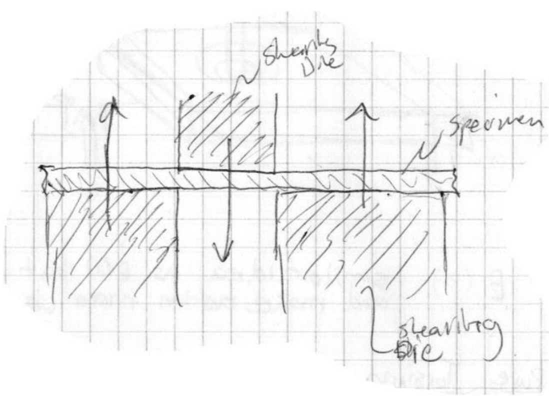
Concept S-4.

A specimen undergoes shear when two pivoting cutters are forced to rotate when pulled on by the tension bars. Shear will not be constant because the angle of the cutters is changing.



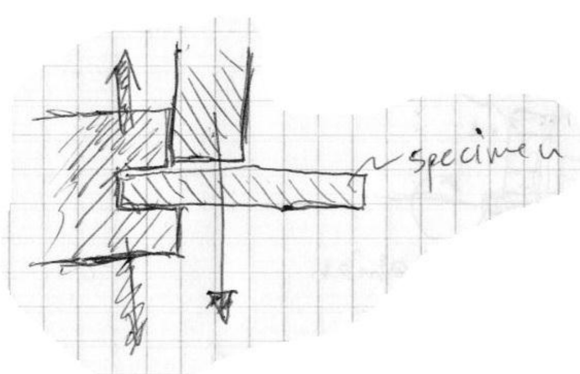
Concept S-5.

Shearing dies are used to cut the specimen along its midsection. Adapters will be added to allow for the tension forces to pull in an in-line motion.



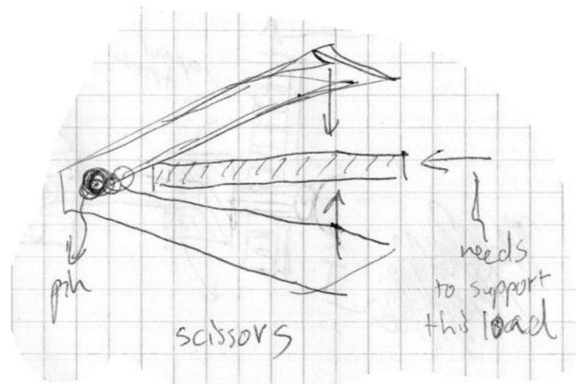
Concept S-6.

A specimen is set between a mandrel and a punch. The mandrel is connected to the upper tension bar, and the punch to the bottom tension bar. There are other test methods for shear the follow this same line of thought; hole punching.



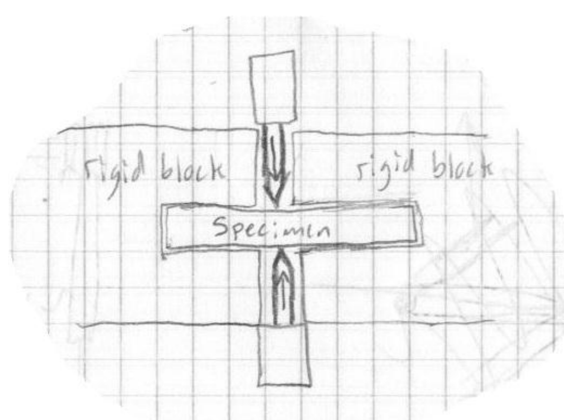
Concept S-7.

A specimen is treated as an overhang beam, while a cutter is applied at the surface of the clamp where the specimen is held. The tension forces are applied, and the cutter shears the specimen.



Concept S-8.

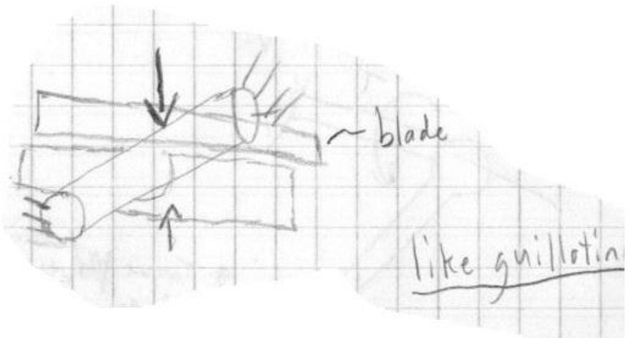
This concept is based on the same mechanism as a pair of scissors. Two shearing blades will be pinned together at one end and the other ends will be attached to the rig attachments. The tensile load will cause a shearing of the specimen.



Concept S-9.

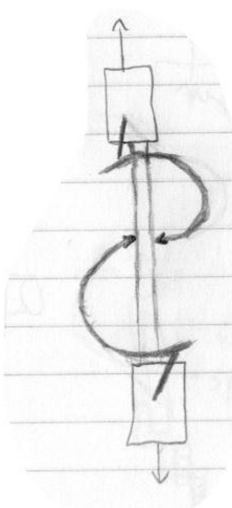
Two rigid blocks hold the specimen so as to minimize the effects of possible bending A sharp cutter is applied to

either side of the specimen so as to cause shear and not cause bending.



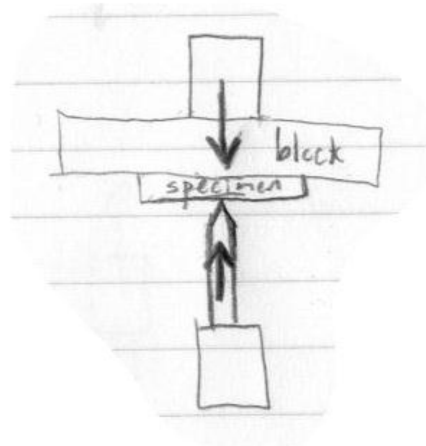
Concept S-10.

The specimen is rigidly attached at its sides. A sharp cutter is attached to the bottom with a cut out that fits around the specimen. A blade with a sharp edge is pulled down slightly offset from the cutter on the bottom so as to shear it. It is to function like a guillotine.



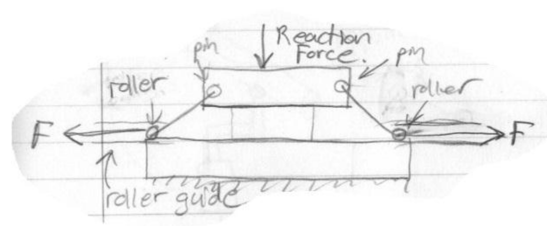
Concept S-11.

This is much like Concept S-7. This instead has two circular guide paths attached to the upper tension rod and lower tension rod. When the tension rod pulls up, both of the cables move within the guides and pull up causing a force to be applied at the center. These ends are both sharp so as to cause shear at the same height on opposite sides.



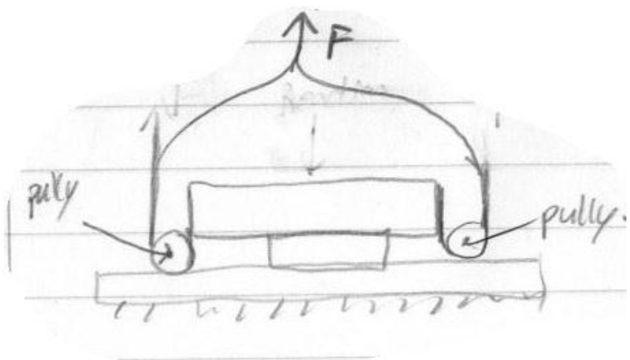
Concept S-12.

A specimen is held in place against a flat plate while a cutter is forced upon its midsection. The forces can be applied in-line with the tension bars to allow consistent loading.



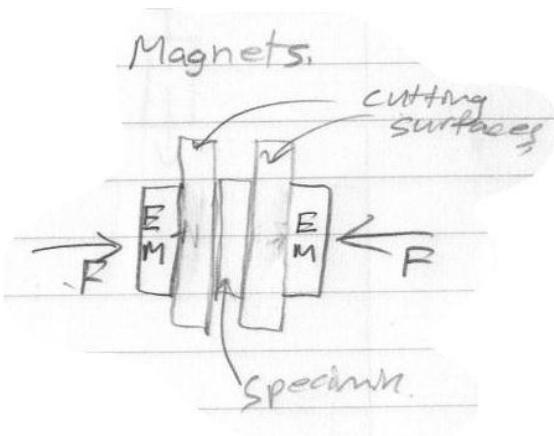
Concept S-13.

Visualize this setup as the forces are being applied in the vertical direction. There is on cutter that will be applied to the specimen as the tension is applied. The tension rods are connected to pin-to-pin members. The pin of each member that connects to the tension rods is held within guides. There will be a change in angle, so the shear applied will vary.



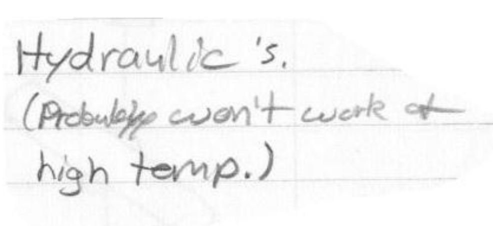
Concept S-14.

Much like in Concept S-12, a cutter is descended upon the specimen as the tension force is applied. Pulleys are used to enable a constant force applied to the cutters. The pulleys could just as easily be sprockets spun by chains.



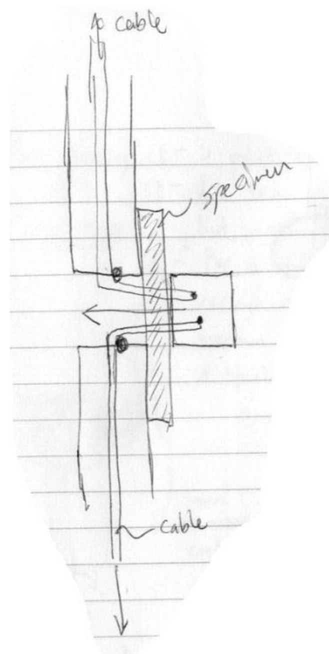
Concept S-15.

Magnets are used to apply constant shear applied to the specimen. Strong electromagnets will be needed. This could also be a Concept for pure bending.



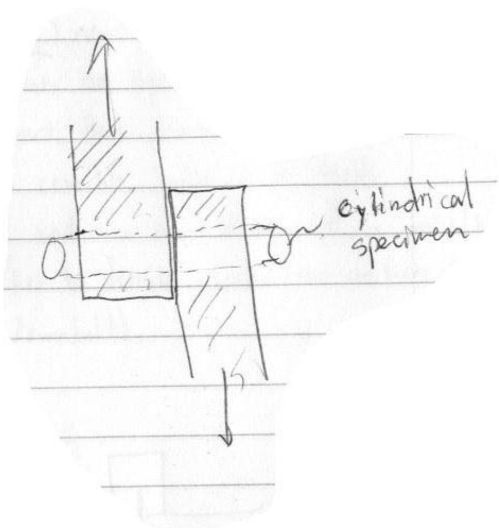
Concept S-16.

Considering using fluids to apply the necessary forces was considered, but finding a liquid that could be used at elevated temperatures is unlikely. The change in density or possible combustion (for oils) should be considered.



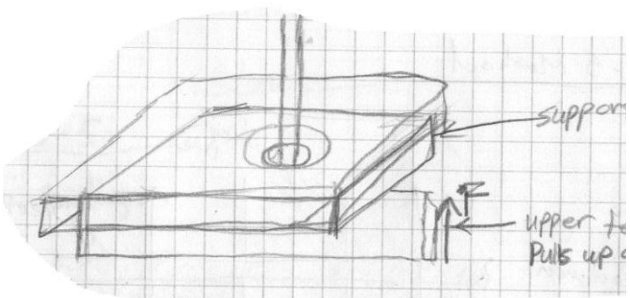
Concept S-17.

As the cable or chain is pulled on by the tension rods, the cutter is applied to the specimen. The cable or chain would need to pass through holes cut into the specimen, meaning special specimens will be needed.



Concept S-18.

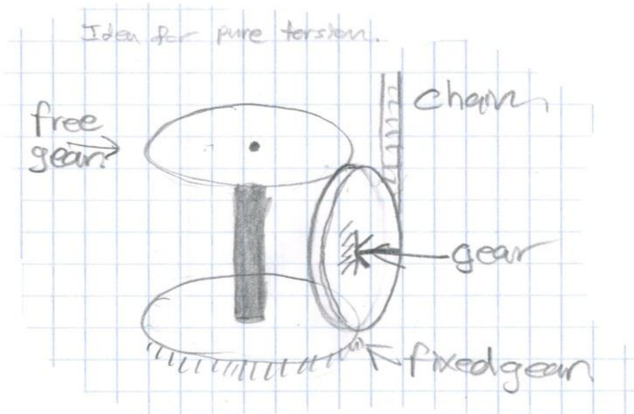
A simple idea for a pure shear application. The tension bars are connected to fixtures. Each fixture has a hole that lines up with the opposite fixture. A specimen is placed inside the hole, and then the tension is applied. This will shear the specimen across its midsection.



Concept S-19.

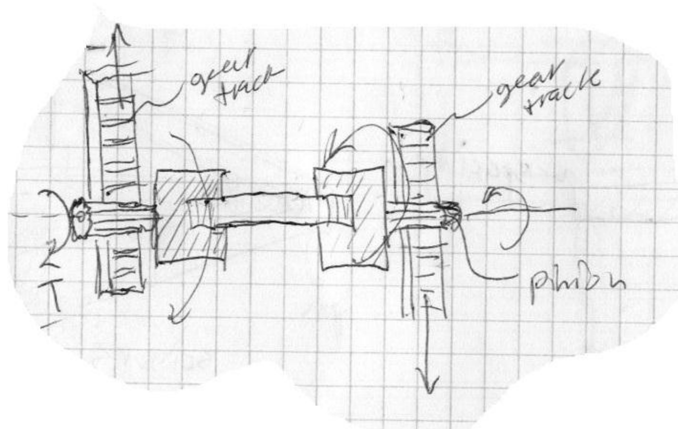
The backing plate is on top of the specimen and is supported by the lower tension rod. There is a hole through both the backing plate and the specimen, which connects to the cutter. The tension bars are pulled on, and the specimen will be sheared across its midsection. Special specimens will be needed.

Pure Torsion Concepts:



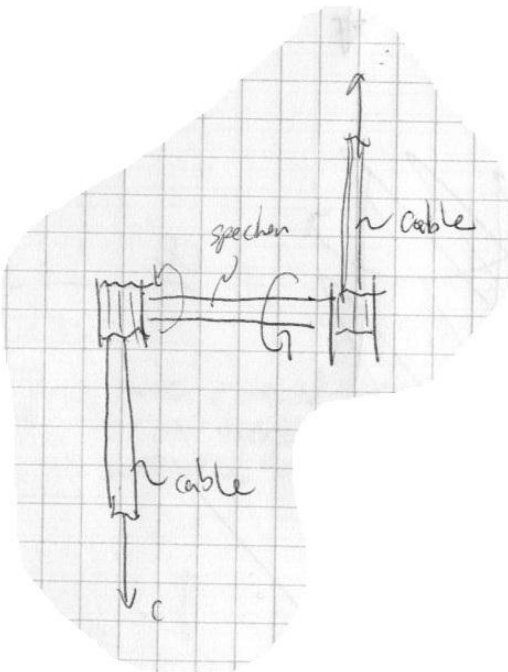
Concept T-1.

A gear and chain is used to apply torque to the specimen (shaded). The bottom gear is held fixed in place by the bottom tension rod. As a result, the bottom tension rod will experience torsion when the loads are applied.



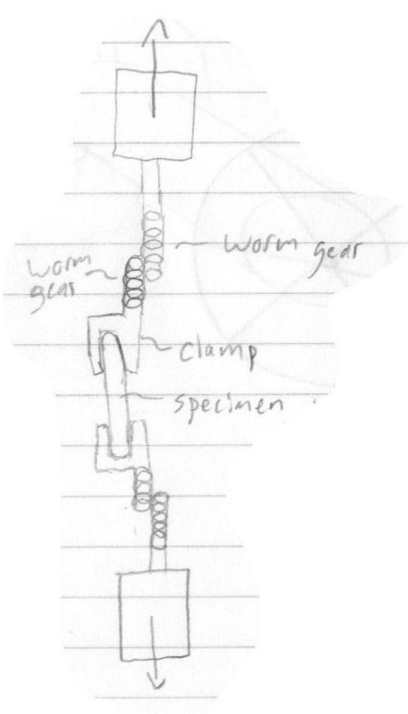
Concept T-2.

A cylindrical specimen is fixed to two end pieces that have a small gear attached to them. The gears will be meshed to gear tracks that are attached to the rig. The tensile load will thus result in a twisting of the specimen as shown above.



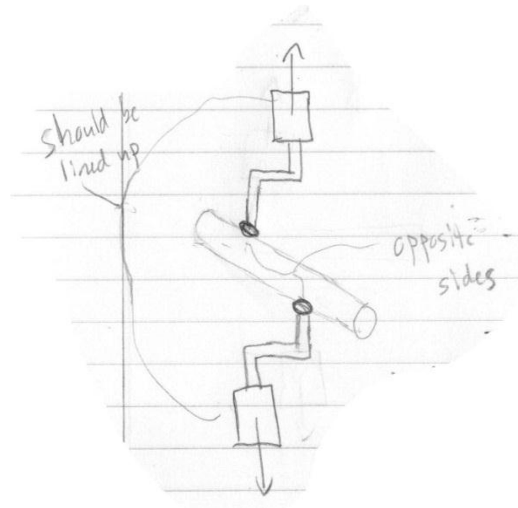
Concept T-3.

The specimen has two pulleys, one attached to each end. The specimen will be supported in the middle in some way. The pulleys rotate in opposite directions inducing torsion on the specimen.



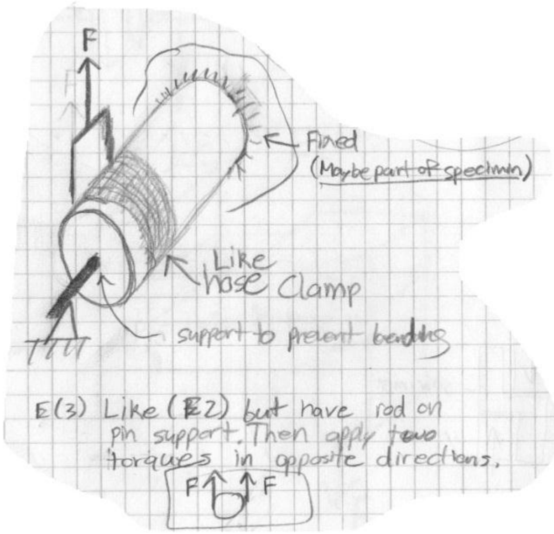
Concept T-4.

This concept is to use worm gears along with clamps on each side of the specimen (specimen could also screw into the clamps). As it is pulled in tension, the idea is that the worm gears will cause rotation in opposite directions and in turn load the specimen in torsion.



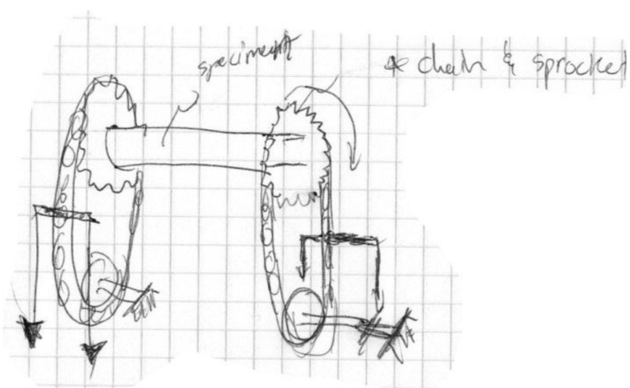
Concept T-5.

The specimen would be rigidly attached at its ends. When the specimen is viewed horizontally, there is an attachment on the front side near one end of the specimen and another attachment on the back side near the other end of the attachment. Bars, shaped like a z, attach to the tension rod and then to the attachments on the specimen. When loaded in tension this will cause torsion. This would likely cause bending as well and may be more appropriate under torsion-bending concepts.



Concept T-6.

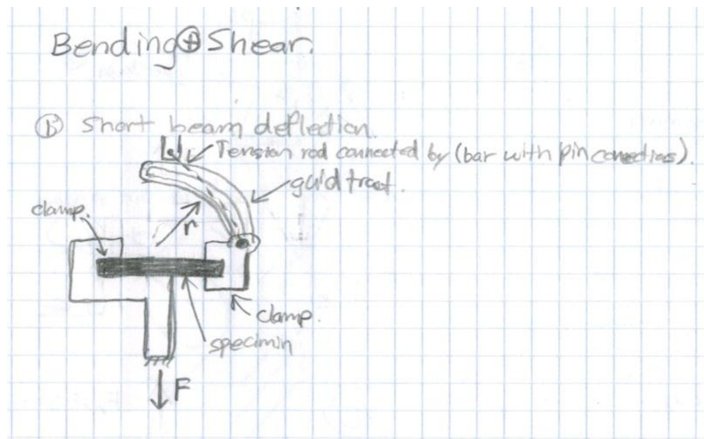
A specimen is held rigidly by a clamp on one end by the bottom tension bar, and then a strap is wrapped around the other end of the specimen. The strap is pulled upward by the upper tension bar and torque is induced. Ideally the end not held fixed by the bottom tension bar will also be supported in a bearing type housing; as a means to prevent bending.



Concept T-7.

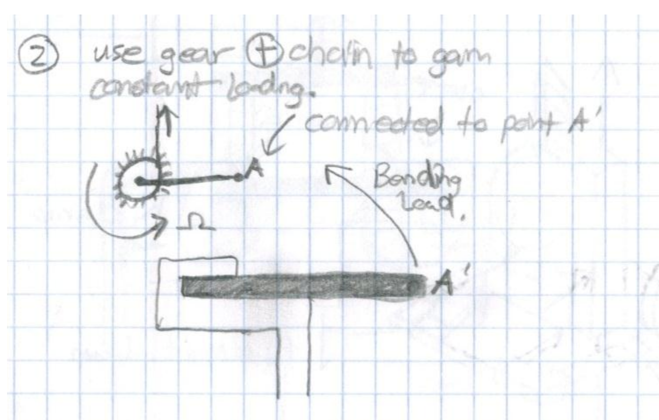
Chain and sprockets are implemented here. Similar to the gear and gear track idea, this concept has two sprockets attached to the ends of the specimen and chains twist the ends in opposite directions as they are pulled apart by the rig attachments.

Bending + Shear Concepts:



Concept BS-1.

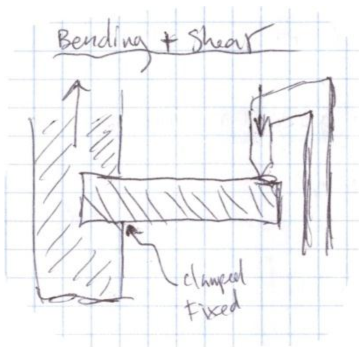
Here, a specimen (shaded) is held on the left by a fixture that attaches to the bottom tension bar. A clamp grabs the other end. The clamp is connected to the upper tension bar by means of a pin-to-pin member. As tension is applied, the pin-to-pin member is guided along a path with a constant radius; this would be designed to minimize shear at the clamp.



Concept BS-2.

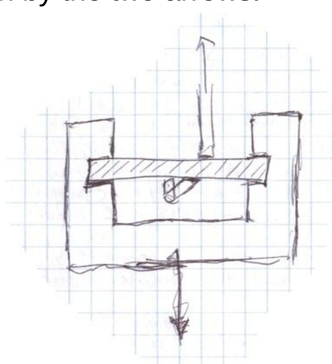
Same fixture as in Concept BS-1, but instead of using a guided pin-to-pin

member, use a gear connected to a rigid beam to apply force in a constant radius.



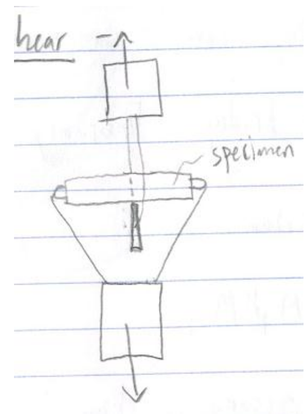
Concept BS-2.

A flat specimen is fixed at one end and a load is applied at the other end, mimicking a cantilever beam. The end where the specimen is fixed will be forced one way while the load at the end is forced in the opposite direction as shown by the two arrows.



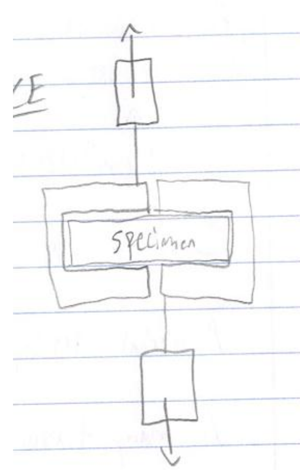
Concept BS-3.

The specimen is fixed at both ends by one attachment while a load is applied mid-length by the other attachment. The tensile load applied to the attachments will produce the bending and shear loading on the specimen.



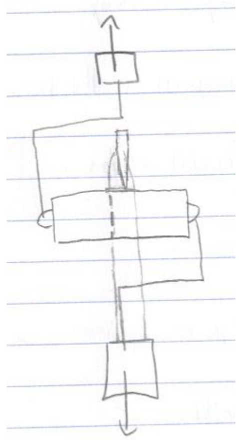
Concept BS-4.

A cutting edge is also attached to the fixture connected to the upper tension bar. As the upper tension bar is pulled upward, the device bends and cuts the specimen.



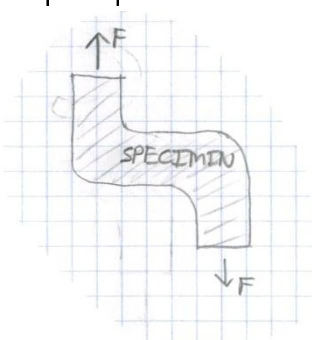
Concept BS-5.

The specimen is held by two clamps, and the clamps are connected to the tension bars. As the tension force is applied, bending and shear will cause the specimen to rotate slightly, which will induce a bending action. The amount of shear is controlled by the gap between the clamps.



Concept BS-6.

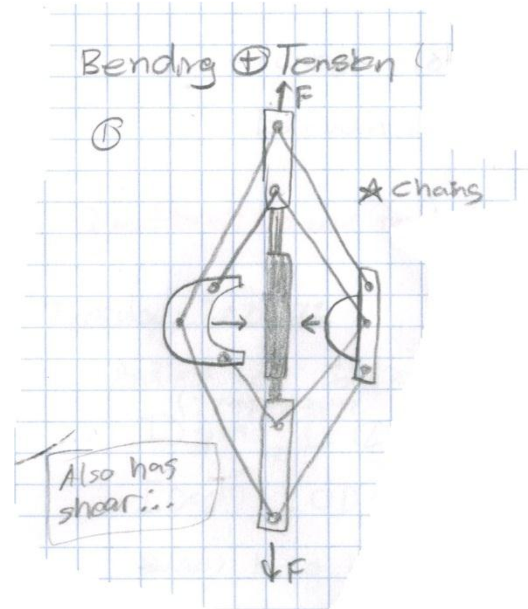
The specimen has an attachment at each end and is held horizontal. Attachments shaped like a ‘Z’ are attached to each of the tension rods to cause a bending moment when pulled in tension. There is also a cutter that attaches to the bottom tension rod that causes shear as it is pulled down and acts as a pivot point for the bending.



Concept BS-8.

The specimen is in an “S” shape. Each end of the “S” is connected to the tension bar with a type of fixture. When the tension is applied, the specimen’s midsection will be put under shear and bending, and also tension.

Bending + Tension Concepts:

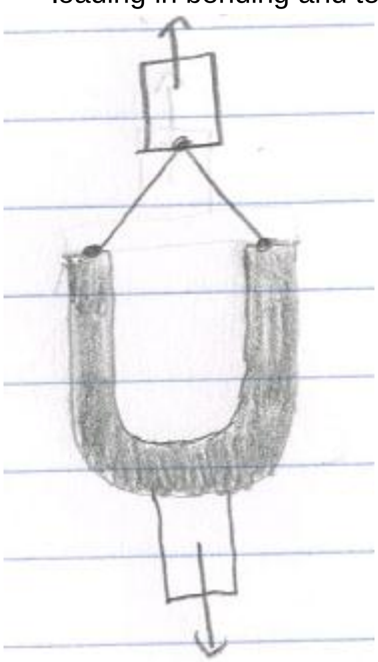


Concept BT-1.

The specimen is connected to the tension bars both on top and bottom. The upper and lower tension bars are also connected to a plunger and mandrel. As the tension bars are pulled apart, they cause direct tension in the specimen, while the mandrel and plunger induce bending on the specimen.

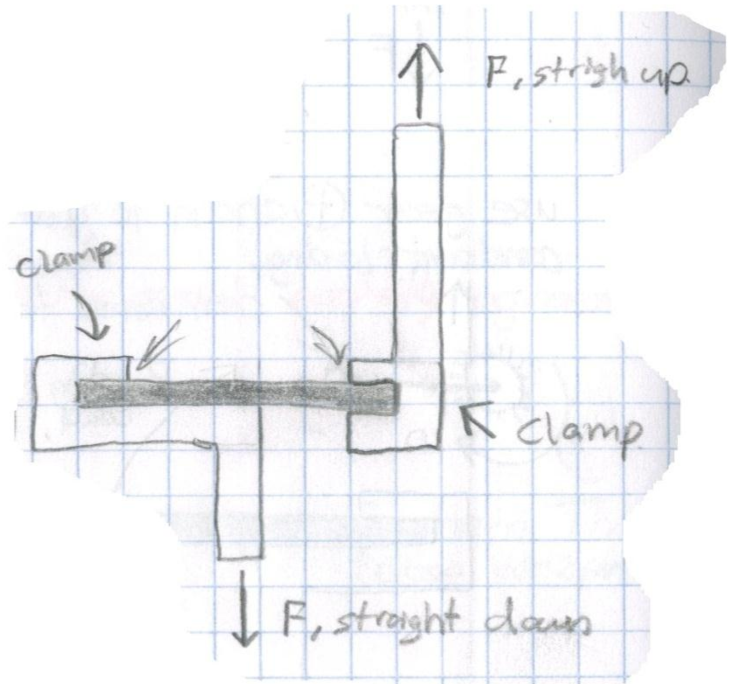
Concept BT-2.

This concept is a new specimen design. By simply creating a ‘C’ shaped specimen and pulling it in tension as shown, the expectation is that it will be loading in bending and tension.



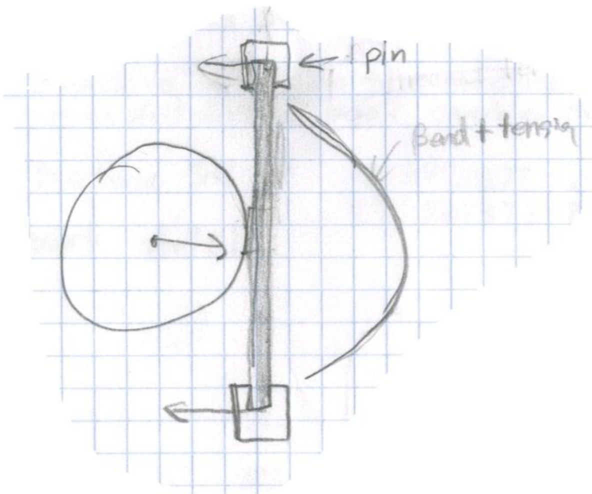
Concept BT-3.

This is another possible use of the new specimen design with attachments at different spots. Using the cables to pull up as shown, the two sides of the specimen will be pulled together and cause bending while the opposing pull downward should cause tension.



Concept BT-4.

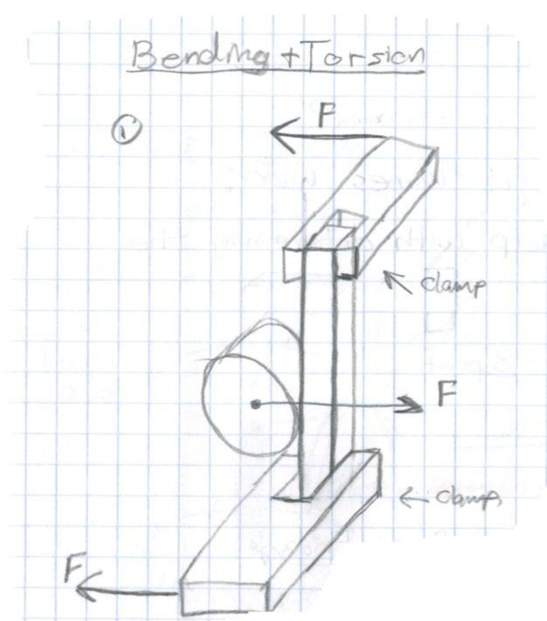
The upper tension bar is connected to the fixture holding the right side of the specimen (shaded). The bottom tension bar is connected to a fixture that supports the left side of the specimen. As the tension bars are pulled apart, bending will occur at the locations in proximity to the clamped ends, while tension will be applied throughout the specimen. Tension and bending will not be constant, because the specimen will rotate as the tension bars pull apart. The rotation will change the angles, thus preventing constant loads at critical cross sections.



Concept BT-5.

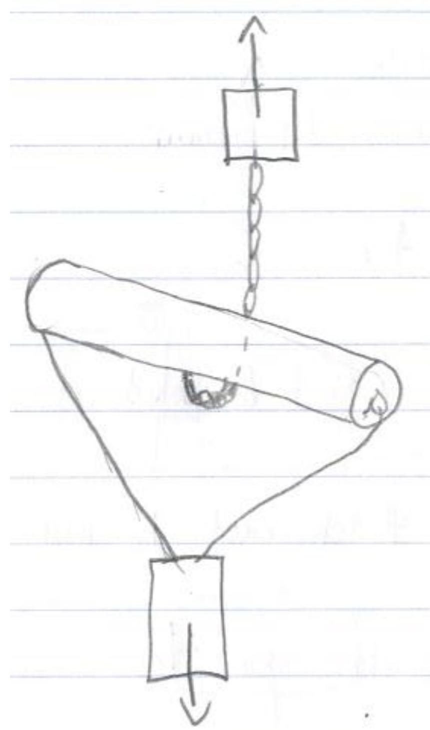
This can be viewed as though the specimen (shaded) is horizontal. The ends of the specimen are connected to the fixtures, which are connected to the bottom tension bar. The circular plunger is connected to the upper tension bar. As the tension bars pull apart the specimen will bend as shown. The specimen will also undergo tensile loads as a result of the pin fixture connections.

Bending + Torsion Concepts:



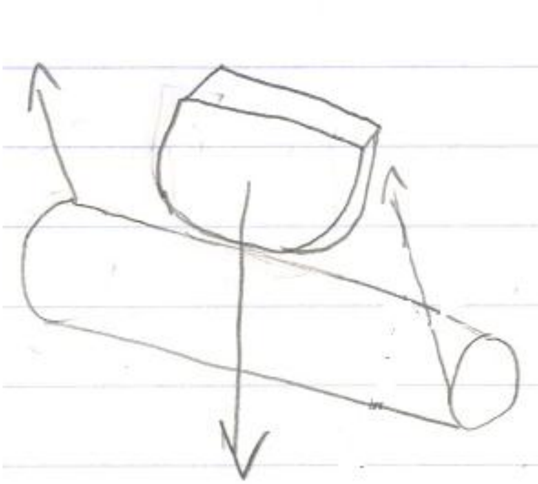
Concept BTO-1.

The specimen (vertical) has its ends connected to torque bars. The torque bars will rotate in opposite directions as the force F is applied. The circular plunger will provide bending while the torque bars apply torque. Tension will also be noticeable as the bend angle increases.



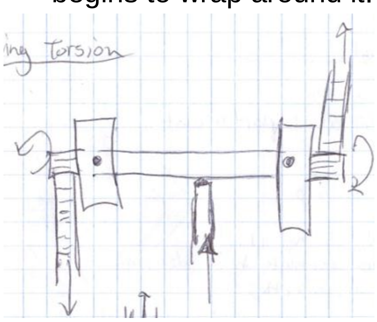
Concept BTO-2.

The attachments at the end of the specimen are connected to cables that pull them downward together with the chain pulling upward, acting as a pivot point and allowing for bending. Torsion occurs as the chain pulls up because it is attached beneath the specimen. Tension will also be present once significant bend has been achieved.



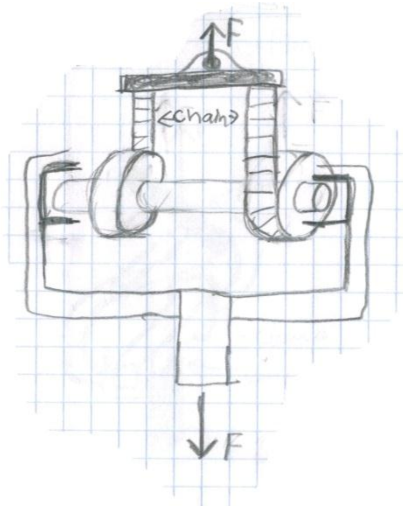
Concept BTO-3.

The ends of the specimen are attached to the upper tension rod. One end has the attachment on the front side of the specimen and the other end has the attachment on the back side of the specimen which will cause torsion. It is possible to add a rigid pulley system on the ends of the specimen if this doesn’t work well. Also, as the specimen is pulled up, a curved block that is attached to the bottom tension rod is used to cause bending as the specimen begins to wrap around it.



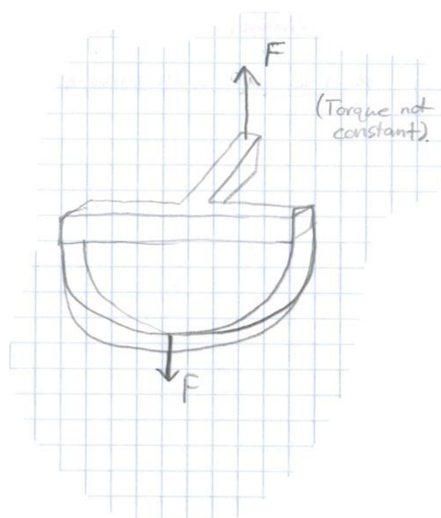
Concept BTO-4.

A cylindrical specimen will be fixed at its ends where the two dots are. There are pinions at each end that are engaged by a gear tracks that will produce torsion in the specimen while a load is applied mid-length of the specimen.



Concept BTO-5.

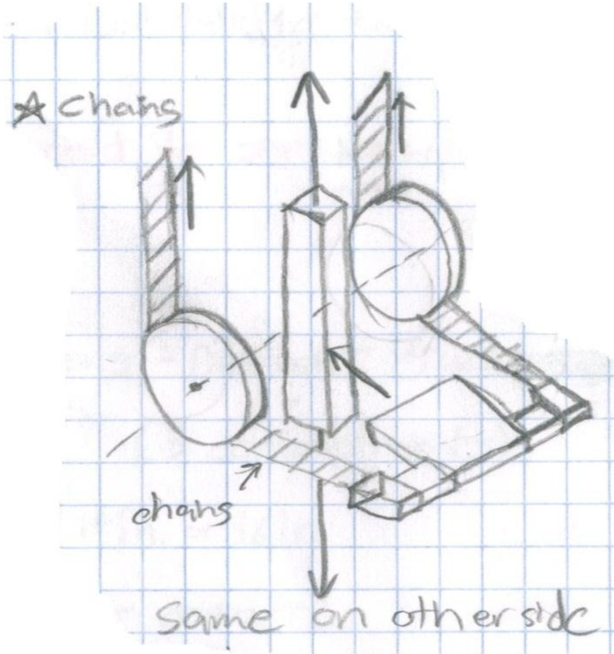
A cylindrical specimen is fixed at its ends by one of the rig attachments. A chain will be attached near each of the end so that a twisting of a specimen can be produces as the chains are pulled



Concept BTO-6.

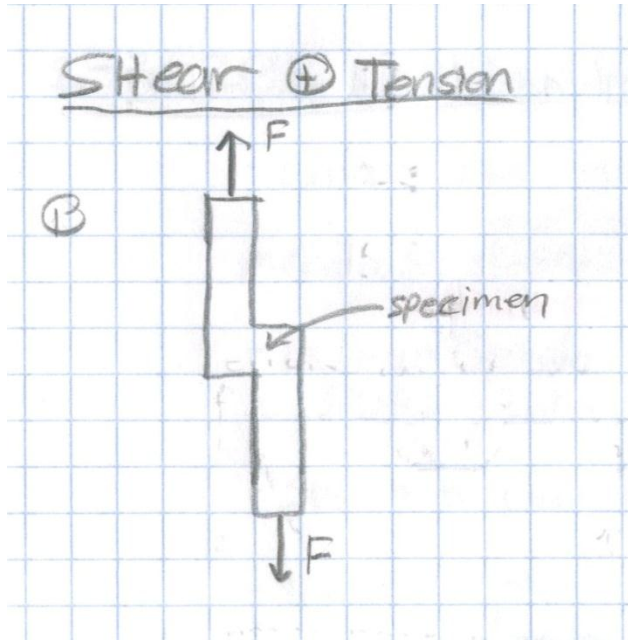
Pulling up on the overhang arm of the specimen will cause the specimen to load in torsion. The overhang is connected to the upper tension bar while the “U” shaped fixture is supported by the bottom tension bar. The specimen will want to bend outward away from the “U.”

Shear + Tension Concepts:



Concept ST-1.

The specimen (vertical) is pulled in tension by the tension bars, while also experiencing shear from the cutters. The cutters are connected to chains which are connected to the upper and lower tension bars. As the tension bars are pulled apart, the chains will travel along the gears allowing constant shear application.

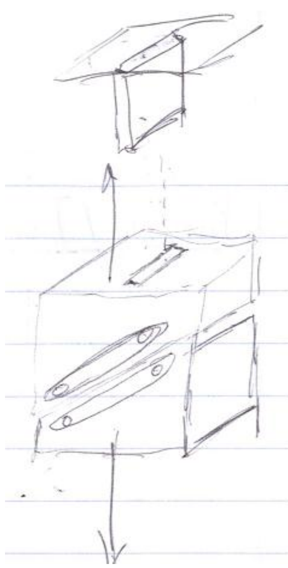


Concept ST-2.

Because of the specimen shape, the midsection will undergo tension and shear when the ends are pulled on. The geometry can be designed in such a way to minimize bending, hopefully.

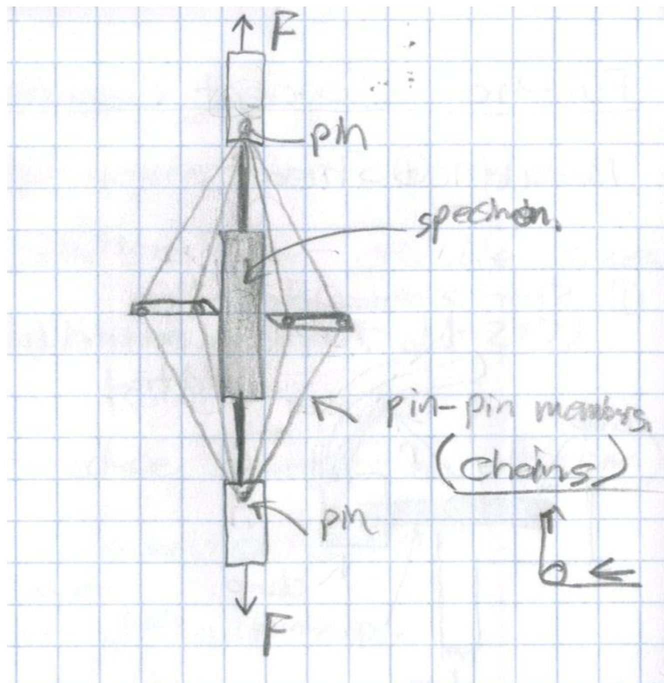
Concept ST-3.

This concept is exactly like Concept S-11 as seen in the section for pure shear. The only difference is that the specimen is rigidly attached to the tension rods to cause tension also.



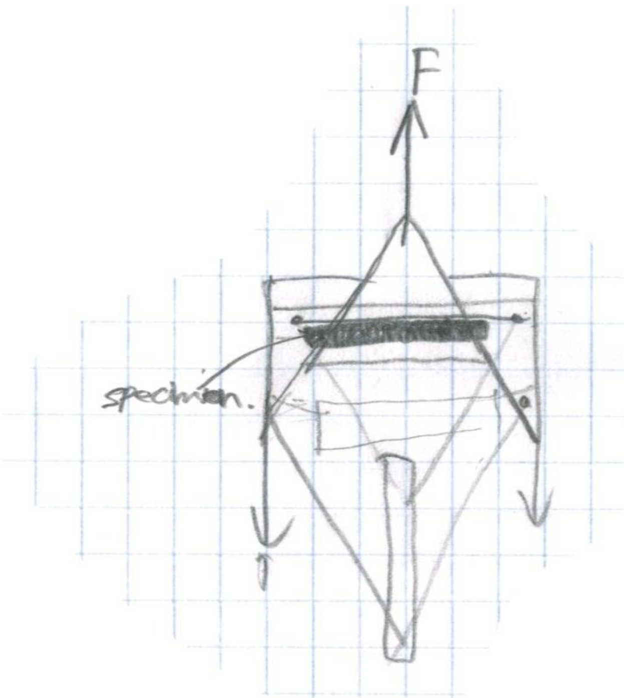
Concept ST-4.

The sliding motion of the two blocks as they are pulled apart will be used to shear a specimen that is contained within a slot in the interior. The specimen will have a plate-like end so when placed it is in the slot and the blocks are pulled apart the specimen will also experience tension.



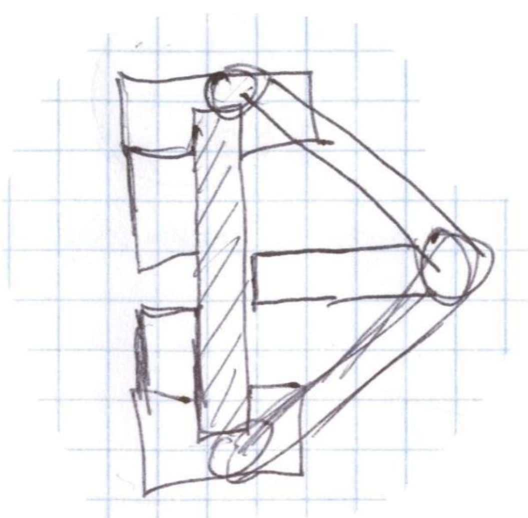
Concept ST-5.

This concept is along the same lines as Concept BT-1. Instead of a plunger and mandrel, this concept employs two shearing edges.



Concept ST-6.

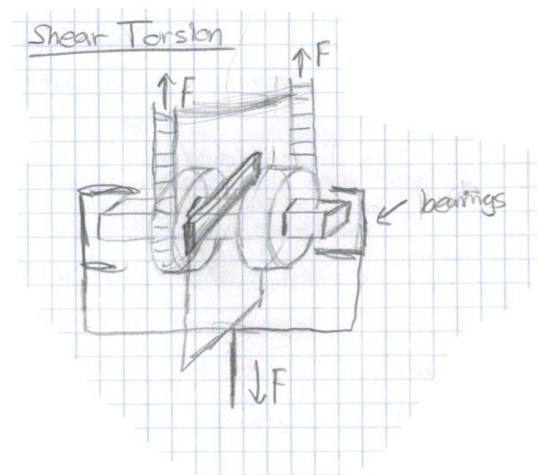
The specimen (shaded) is contained within a slot that spans three separate triangular blocks, which will act as shears. The two outer triangles are pulled downward while the center triangle is pulled upward. If the specimen's ends are both fixed to the outer triangles, then as the triangles are forced apart, they will induce tension on the specimen in conjunction with shear. The loads should be constant.



Concept ST-7.

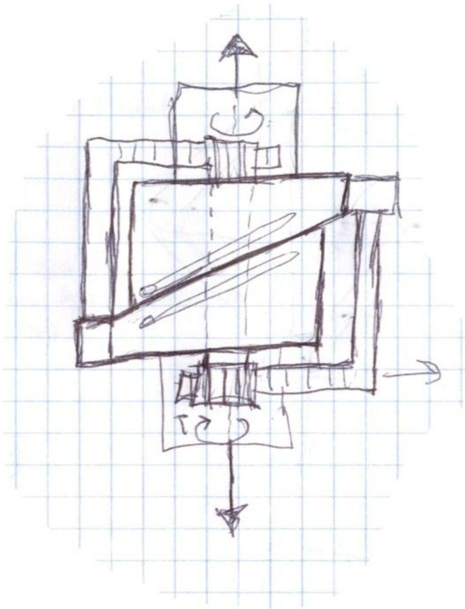
As the tension bars pull upward, the specimen undergoes tension. There is a plunger attached to the tension rods as well, and when the rods pull apart, the plunger acts as a hole punch of sorts, on the specimen.

Shear + Torsion Concepts:



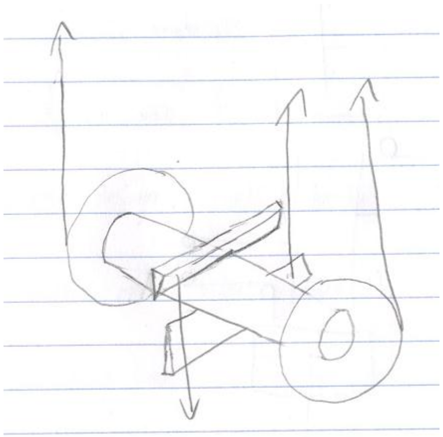
Concept STO-1.

The specimen (horizontal and square) has two gears fit onto it. The specimen sits within bearings that are supported by the bottom tension member. Chains being pulled upwards by the upper tension bar cause the specimen to twist under torsion. There is also a cutting bar that is rigidly connected to the bearing fixture. This cutter imparts shear on the specimen. Different bearing considerations will need to be considered to enable the specimen to move in the vertical direction so shear can be applied.



Concept STO-2.

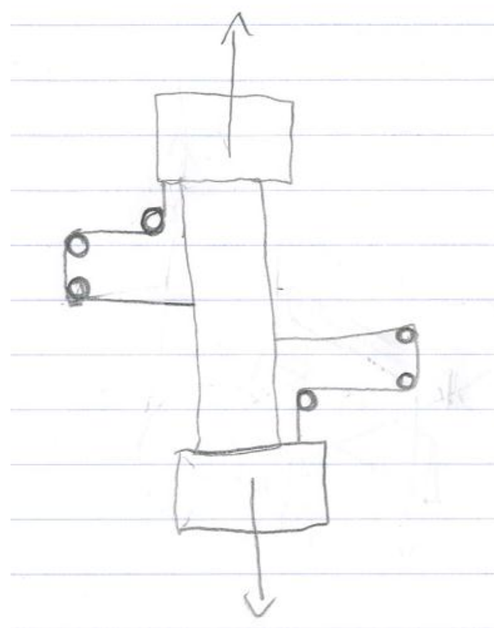
This concept has two sliding blocks that produce shearing of a specimen that is located in a machined hole (shown in dashed lines). As the blocks are pulled apart they slide on the angled cut. Movement in the horizontal direction by the blocks will be used to rotate two gears attached to the ends of the specimen to produce torsion as it is sheared. An issue with this concept is that the tensile load will become misaligned as the blocks slide apart.



Concept STO-3.

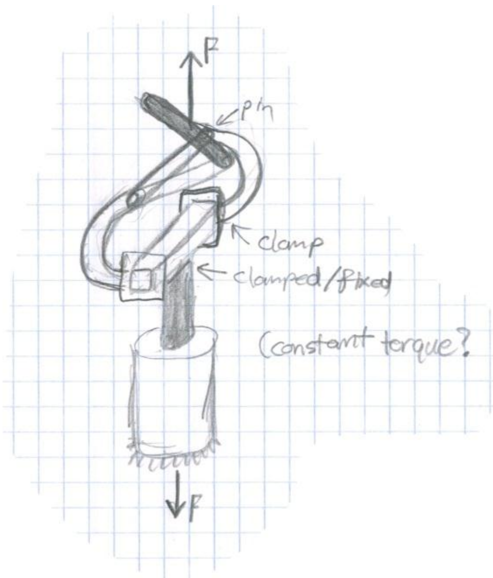
The top tension rod will pull up on both pulleys, on opposite sides, to cause torsion. The top and bottom torsion rods will also pull up and down on sharp cutters to cause shear.

Tension + Torsion Concepts:



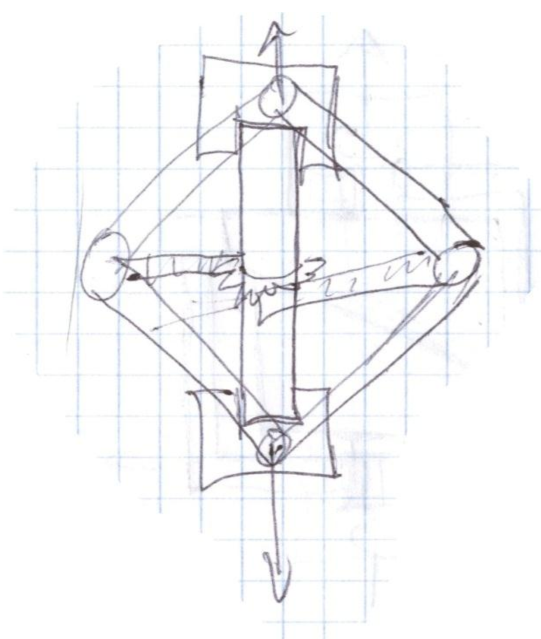
Concept TT-1.

The specimen is rigidly attached to the torsion rods to cause tension. There is a pulley system on either side of the specimen around which a cable is attached to the specimen. One cable is attached to the front side of the specimen in the drawing and the other cable is attached to the back so as to cause torsion when the cable is pulled in tension.



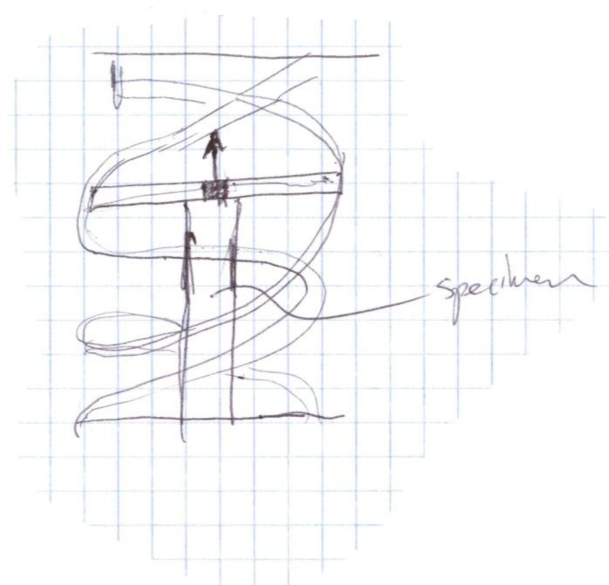
Concept TT-2.

The specimen (vertical and shaded) is connected to the bottom tension member. The specimen's top end is connected to a horizontal bar. Two cured beams are connected to the horizontal bar and are also joined in their middle by a pin. The pin is pulled upward, allowing the horizontal bar to twist while being pulled upward. This imparts tension and torsion on the specimen.



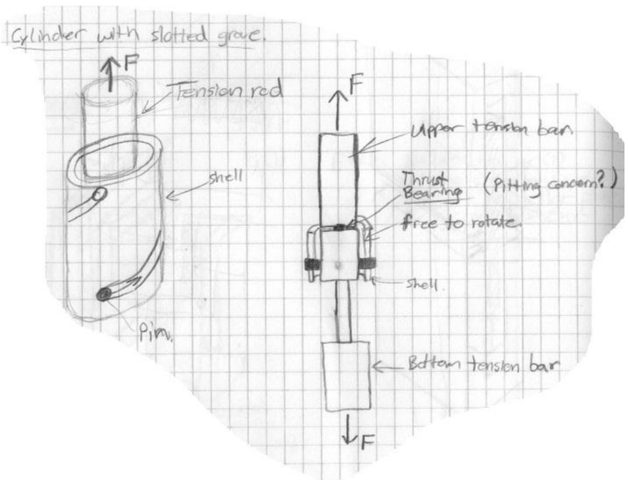
Concept TT-3.

The ends of a cylindrical specimen are fixed to two end-pieces that are attached to the rig. The two-bar linkages will produce torsion in the specimen through a gear (attached to specimen) and gear tracks as shown in the figure.



Concept TT-4.

Spiral guide tracks will guide a bar that is attached to the specimen. When the specimen is pulled in tension the bar will be forced to follow the guide track causing a twisting of the specimen. Machining the spiral guide track and its rigidity may be problems for this concept.



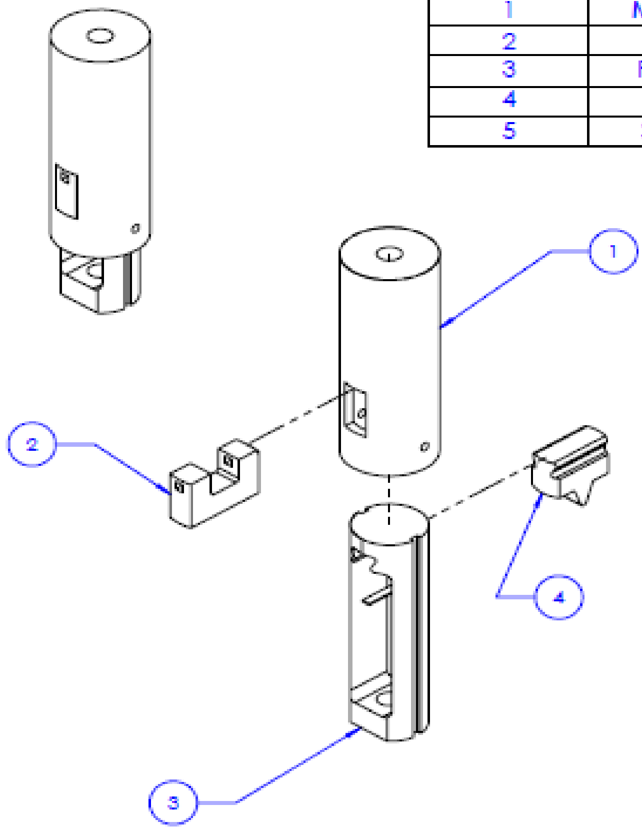
Concept TT-5.

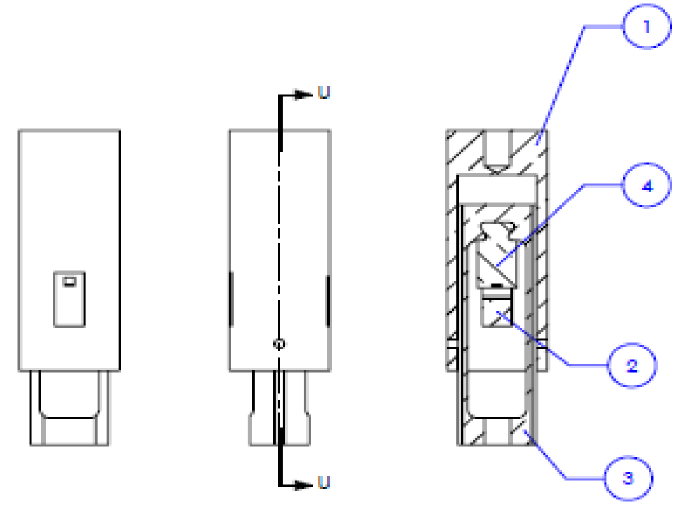
A shell with spiral guides cut into its sides enables tension and torsion for only a pure tensile load. There are four main parts to this concept. The upper tension rod is connected to another rod that is allowed to rotate freely due to some bearing design (see thrust bearing). The rod that is free to rotate is connected the specimen, which is then connected to the bottom tension bar. The free-to-rotate rod has pins that protrude from each side, mirrored. The pins fit into the slots of the shell. As the tension is applied, the free-to-rotate rod will be pulled upward along the path defined by the guides in the shell, thus applying a torque to the specimen as well as tension.

Appendix B

Detailed Engineering Drawings of Final Design

ITEM NO.	PART NAME	DRAWING NUMBER	QTY.
1	MandrelSupport	B2	1
2	Mandrel	B3	1
3	PlungerSupport	B4	1
4	PlungerTip	B5	1
5	SpecimenNEW		1



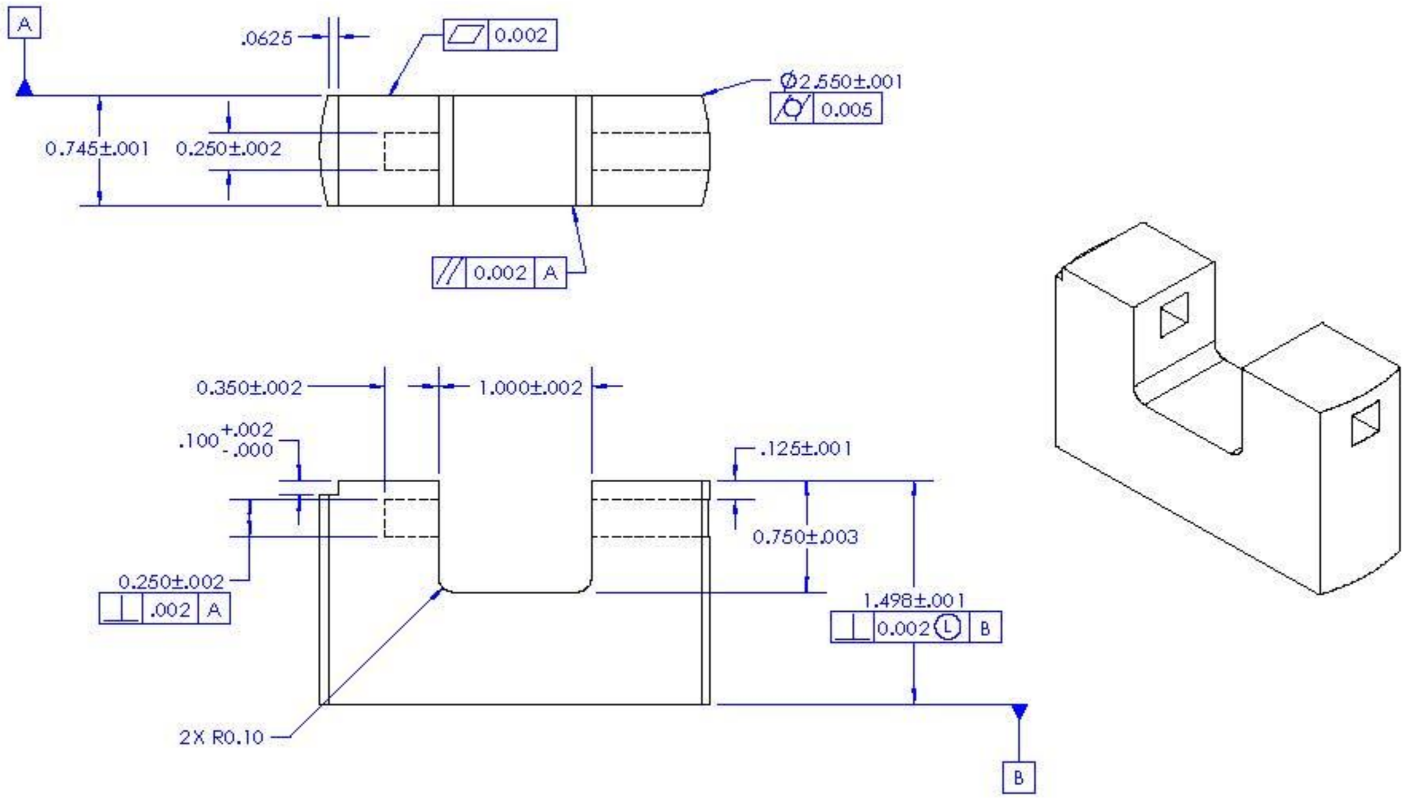


SECTION U-U
SCALE 1 : 4

THE CREEPS

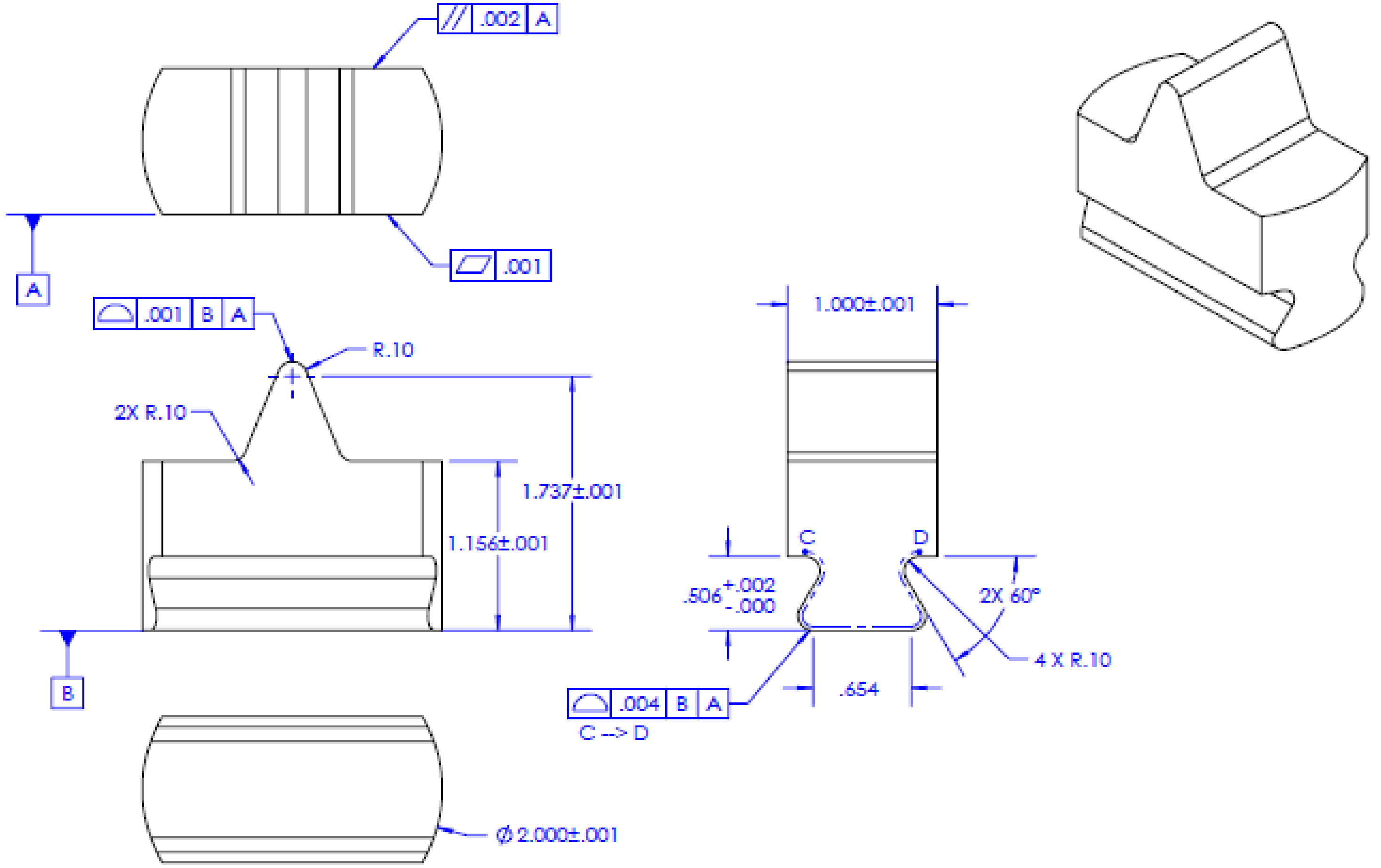
SCALE: 1: 8	CREEP TEST FIXTURE
UNITS:INCHES	MATERIAL: MAR-M 247
DWG #: CBA1	NAME: Eric Nelson, Rene Maciel, Chris Ewald
DATE: 07/24/2012	SIGNATURE:

5 4 3 2 1



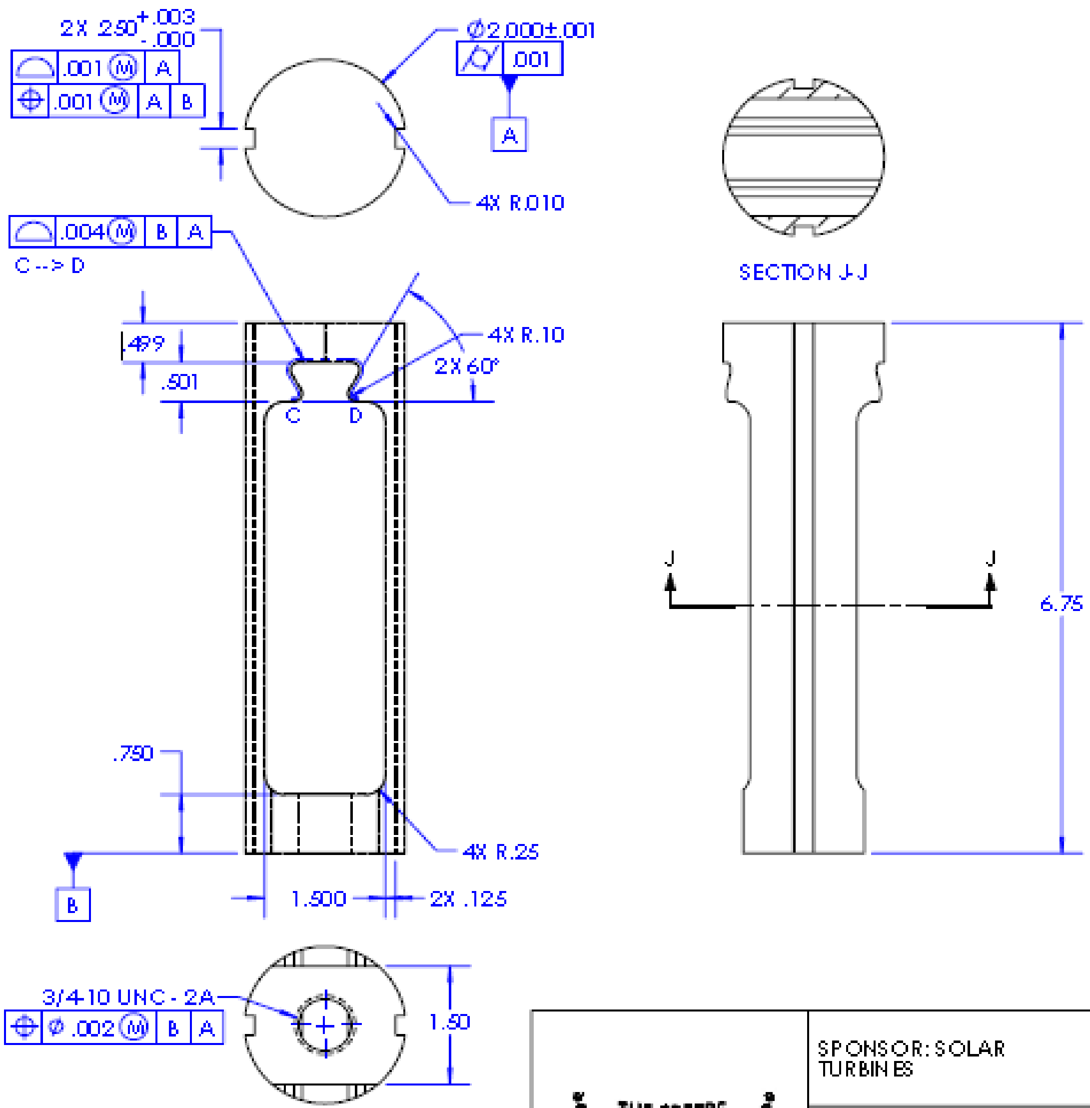
THE CREEPS	SPONSOR: SOLAR TURBINES	SCALE: 1: 1	MANDREL
		UNITS:INCHES	MATERIAL: MAR-M 247
	NEXT ASSY:CBA1	TOLERANCE: ±0.01	ERIC NELSON, RENE MACIEL, CHRIS EWALD
	DWG #: B3	DATE: 11/13/2012	SIGNATURE:

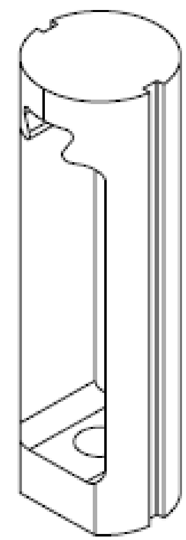
5 4 3 2 1



THE CREEPS	SPONSOR: SOLAR TURBINES	SCALE: 1: 1	PLUNGER TIP
		UNITS:INCHES	MATERIAL: MAR-M 247
	NEXT ASSY:CBA1	TOLERANCE: ±0.01	ERIC NELSON, RENE MACIEL, CHRIS EWALD
	DWG #: B5	DATE: 11/09/2012	SIGNATURE:

5 4 3 2 1

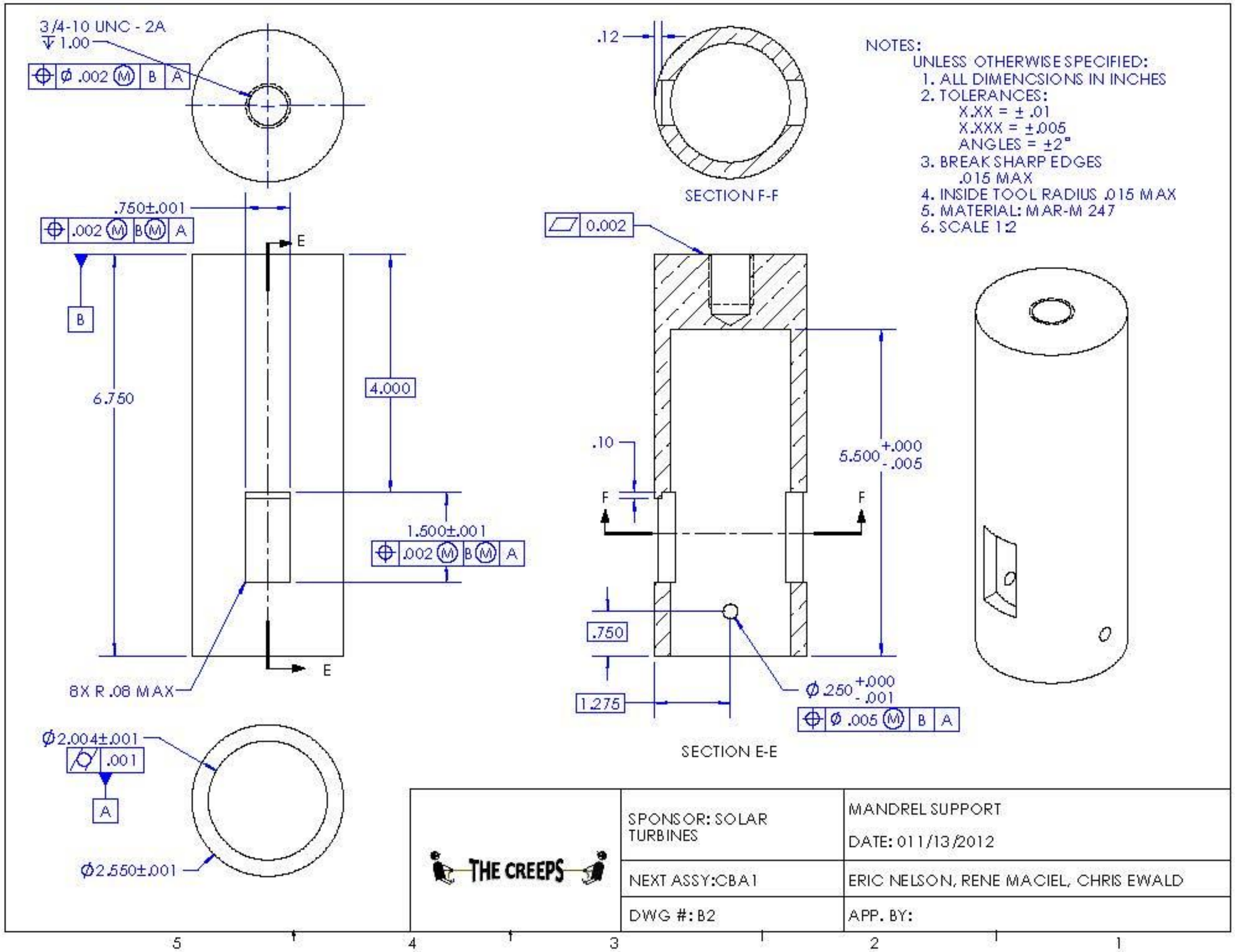




NOTES:
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES:
X.XX = ± .01
X.XXX = ± .005
ANGLES = ±2°
3. BREAK SHARP EDGES .015 MAX
4. INSIDE TOOL RADIUS .015 MAX
5. MATERIAL: MAR-M247
6. SCALE 1:2

THE CREEPS	SPONSOR: SOLAR TURBINES	PLUNGER SUPPORT
		DATE: 11/09/2012
	NEXT ASSY: CBA1	ERIC NELSON, RENE MACIEL, CHRIS EWALD
	DWG #: B4	APP. BY:

5 4 3 2 1


3/4-10 UNC - 2A
↧ 1.00
Ø .002 Ⓜ B A
.750±.001
.002 Ⓜ B Ⓜ A
B
6.750
4.000
1.500±.001
.002 Ⓜ B Ⓜ A
8X R .08 MAX
E
Ø2.004±.001
.001
A
Ø2.550±.001
.12
SECTION F-F
0.002
.10
F
5.500 +.000 -.005
.750
1.275
Ø .250 +.000 -.001
Ø .005 Ⓜ B A
SECTION E-E
NOTES:
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENCSIONS IN INCHES
2. TOLERANCES:
X.XX = ± .01
X.XXX = ±.005
ANGLES = ±2°
3. BREAK SHARP EDGES .015 MAX
4. INSIDE TOOL RADIUS .015 MAX
5. MATERIAL: MAR-M 247
6. SCALE 1:2
THE CREEPS
SPONSOR: SOLAR TURBINES
MANDREL SUPPORT
DATE: 011/13/2012
NEXT ASSY:CBA1
ERIC NELSON, RENE MACIEL, CHRIS EWALD
DWG #: B2
APP. BY:
5
4
3
2
1

Appendix C – Preliminary Analysis for Final Design

MATLAB code developed to determine specimen size

```
% Determination of Specimen Cross Section based on initial loading
% conditions of sig = 0.5Sig_yield.

Sig_y = 118.7; %ksi (Maximum tensile yield strength, at 1200 degrees F, as
                provided by Solar Turbines in 'MARM247_YIELDvsTEMP' excel
                sheet)
Sig_max = 73; % ksi (applied load for yield strength around 114ksi as
                provided in e-mail by Estevan Negrete)
I = 0;        % in^4
L = 1;        % in
sig = 0;
n=0;
to=1/32;      % in
E = 14500;    % ksi (Youngs modulus for MAR-M 247 at 1200 degrees F as
                provided by Solar Turbines in 'MAR-M247_E_Modulus' excel
                sheet)


for n= 1:1:15
      t(n)= to+(1/64)*n-(1/64) %increase thickness by 1/64 inch each run
      w(n) = 4*t(n) %width is 4 times the thickness from ASTM specs

      % Deflection, 3 point bend, free supports model (bending)

      I(n) = w(n)*(t(n)^3)/12 %moment of inertia calculation
      Q(n) = w(n)*(t(n))^2/4 %static moment of area
      F_b(n) = Sig_max*2*w(n)*t(n)^2/(3*L) %required force to cause necessary
      stress
      Def_b(n) = (F_b(n)*L^3)/(48*E*I(n)) %deflection at center of beam
      V_b(n) = F_b(n)/2 %max shear in beam
      tau_max_b(n) = V_b(n)*Q(n)/(I(n)*t(n)) %max shear stress in beam

      % Deflection, 3 point bend, fixed supports model (bending+shear)

      F_bs(n) = Sig_max*16*I(n)/(3*L*t(n))
      Def_bs(n) = (F_bs(n)*L^3)/(192*E*I(n))
      V_bs(n) = F_bs(n)/2
      tau_max_bs(n) = V_b(n)*Q(n)/(I(n)*t(n))

      % Deflection, 5 point bend, fixed free supports model (bending)

      F_b5(n) = Sig_max*I(n)*24/(L*t(n))
      Def_b5(n) = (((F_b5(n)/2)*(L/4)^2)/(96*E*I(n)))*(11*(L/4)-9*(L/2))
      V_b5(n) = F_b5(n)/3
      tau_max_b5(n) = V_b5(n)*Q(n)/(I(n)*t(n))
end

Plot functions are omitted.
```

Appendix D – Gantt Chart

	Task Name	Duration	Start	Finish
1	Problem Definition	4 days	Mon 1/9/12	Thu 1/12/12
2	Engineering requirements	10 days	Fri 1/13/12	Thu 1/26/12
3	Preliminary Research	11 days	Thu 1/26/12	Thu 2/9/12
4	Concept Generation	11 days	Thu 2/2/12	Thu 2/16/12
5	Concept Evaluation	5 days	Thu 2/16/12	Wed 2/22/12
6	Final Concept Selection	4 days	Wed 2/22/12	Sun 2/26/12
7	Preliminary Analysis	5 days	Mon 2/27/12	Fri 3/2/12
8	Detailed Analysis (Including Creep)	16 days	Mon 3/26/12	Mon 4/16/12
9	~~FEA on Specimen~~	~~11 days~~	~~Wed 3/28/12~~	~~Wed 4/11/12~~
10	Managerial Info (Cost)	3 days	Thu 4/19/12	Sat 4/21/12
11	Final Solid Model & GDT Drawings	4 days	Tue 4/17/12	Fri 4/20/12
12	Prototyping (Physical Model Rapid Prototyped)	11 days	Sat 4/21/12	Fri 5/4/12
13	Conceptualize Extensometer Attachment	10 days	Mon 5/14/12	Fri 5/25/12
14	Finalized GDT drawings	5 days	Mon 5/14/12	Fri 5/18/12
15	Second Draft Design Report	98 days	Tue 1/3/12	Thu 5/17/12
16	Final Design Built	47 days	Fri 6/1/12	Sat 8/4/12
17	Design Testing (Creep test at Solar)	60 days	Mon 6/25/12	Fri 9/14/12
18	Design Iteration (If needed)	15 days	Mon 10/8/12	Fri 10/26/12
19	Final Design Report	22 days	Mon 9/24/12	Tue 10/23/12
20	Create Senior Design Expo	15 days	Mon 10/22/12	Fri 11/9/12
21	Senior Design Expo	3 days	Wed 11/28/12	Fri 11/30/12