MET 494

Final Report

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Engineering Technology
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Shear Strength Testing Fixture

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EXECUTIVE SUMMARY

This report presents the complete design process for a shear strength testing device created for Indiana University – Purdue University of Fort Wayne (IPFW). Values for shear strength are often estimated using data from tensile tests. The goal of the design has been to give IPFW the ability to measure these exact values rather than estimating them as they currently do. The shear strength testing fixture developed throughout the course of this senior design project was engineered as an attachment for an existing tensile testing machine. Designing it to mount to existing equipment saves the university money by eliminating the need for additional machinery to be purchased.

Design

The design of this two component fixture allows for the standing machine to serve a dual purpose, thus broadening the functionality of the existing equipment. Each component of the fixture device threads into the existing crosshead supported nuts on the tensile testing machine in place of a tensile test specimen. A shear test specimen can then be loaded into the fixture, and the machine is operated in the same manner as it is for a tensile test. The data gathered after the procedure has been completed exhibits the shear specimen's exact shear strength values.

Development

During the developmental phase of the device, finite element analysis and calculations were performed for all possible modes of failure to ensure none of these modes would occur in any component of the fixture before the desired shear failure mode would occur in the specimen. The concepts of shear and tensile strength and their relationships were investigated and became key in creating the device. Using the information gathered, materials and dimensions were then decided and the device was fabricated by Industrial Engineering Inc. Upon receiving the completed fixture, shear and tensile tests were performed and all of the data gathered from these tests confirmed that the design phase calculations were accurate. Proposed deadlines throughout the development process of the project were all met, and the team was able to remain within budget while successfully completing the project.

Utilization

The mechanism is capable of testing all of the material types that are used in other IPFW courses and labs today. It is also capable of testing stronger materials that are not currently used in these courses. Values found from estimation equations and the values found from the shear testing procedures show the percentage of error between the two methods of finding this data. We recommend that IPFW include new lab courses or procedures in current courses that will utilize this fixture in future demonstrations to expand the range of engineering material taught; Furthermore, this new capability will dramatically improve upcoming IPFW student's understanding of the shear strength concept.

INTRODUCTION

Shear strength is the maximum load a material can withstand before fracturing when another surface applies force perpendicularly against it. Every material has a different shear strength value, and these values are most often estimated using various equations in conjunction with tensile test data. Along with these equations, there are predetermined tables that are also used to estimate these values, however the Engineering Department at Indiana University – Purdue University of Fort Wayne (IPFW) does not have any means of measuring the exact values.

The fixture developed throughout the course of this IPFW Senior Design Project is intended to be used as a tool to test and determine a material's exact shear strength value. The fixture was manufactured in a manner that allows it to be mounted on the existing 60,000 pound Tinius Olsen tensile testing machine to keep costs as low as possible for the university by eliminating the need for additional equipment to be purchased in order to utilize the device. The following content of this report details designing, developing, testing, results, and intended future uses of the device.

KEY CONCEPTS

Strength of Materials

Strength is a mechanical property of materials including metals, polymers, and ceramics, which is directly related to how the material reacts when it experiences an applied load. The main types of strength include torsion, impact, shear, tensile, compression, fatigue, and bending strengths. These properties of strength are established by the atomic structure and grain sizes of the material and can be measured using various test procedures. Determining the correct test method required to gage this value depends on the desired type of strength the material should possess to ensure optimal performance.

It is possible to calculate strength values based on the atomic structure and grain size of a metal or alloy, but any imperfections resulting from the development of the material can dramatically change these values. If this property is essential to the integrity of the product it will be used to manufacture, each batch of the material should be tested before being used to ensure the product will perform as expected.

What is Shear Strength?

When the surfaces of the two blades on a pair of scissors slide against each other while cutting a piece of paper, the paper is known to be under shear stress. The two metal blades of the scissors are made of the same kind of material, while the paper is made of a different type of material. For the scissors to cut through the paper, the blades must be stronger than the paper. If the paper were the stronger material of the two, then the scissor blades would deform before the paper would shear. The measure of this type of strength for any material is called *shear strength*.

Shear strength is defined as the maximum load, applied perpendicularly, that a material can withstand before fracture [1]. This means that shear strength values represent the maximum shear stress that can be sustained by a material before rupture, which is equivalent to the ultimate strength of a material subjected to shear loading. When two pieces of metal are held together with a bolt as shown in Figure 1, the bolt is loaded in single shear across its cross-section. The shear plane passes through the bolt where the two pieces of metal meet. If three pieces of metal are held together with a bolt as shown in Figure 2, then the bolt experiences double shear across its cross-section. Single and double shear test methods produce similar values, but double shear is most commonly preferred in industry. This is because single shear involves some bending and is not pure shear.

Figure 1: Single Shear [2]

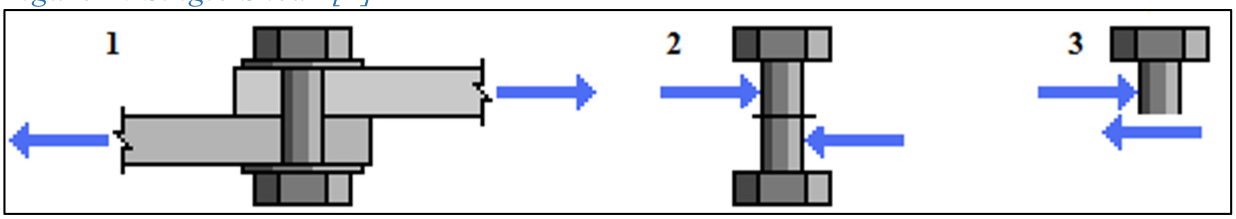
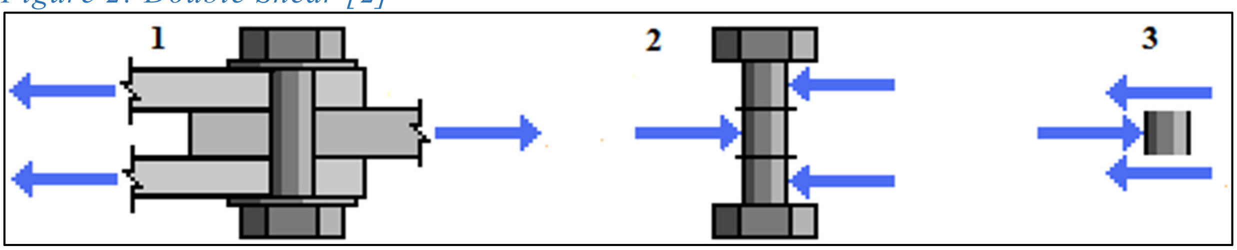


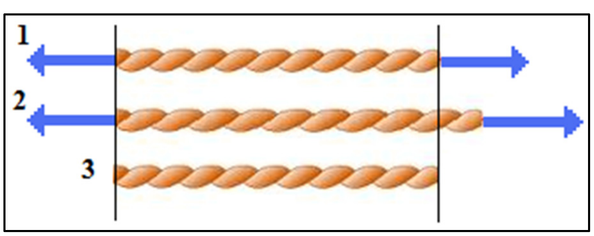
Figure 2: Double Shear [2]



What is Tensile Strength?

When two people pull on a single piece of rope in opposite directions, the rope is known to be under *tensile stress.* The force applied by the people on the rope is known as a *tensile load*. The magnitude, or size, of the tensile load can have three possible effects on the rope. These three cases are necessary in understanding tensile strength and are discussed next.

Figure 3, Elastic Tensile Stress



The first situation that can occur is when the rope temporarily becomes longer than its original length as shown in Figure 3. This happens if the rope is pulled with enough force to cause it to stretch, but it returns to its original length when released. In this case, the rope has undergone what is known as temporary, or *elastic*, deformation which is similar to stretching and releasing a rubber band. The greatest magnitude of a tensile load that a material can handle before the deformation type is no longer temporary is called the *yield strength* value of the material.

The second case occurs if the rope is pulled with enough force to cause it to stretch beyond its yield strength value as shown in Figure 4. When this happens, the rope has undergone what is known as permanent, or *plastic*, deformation, and the rope will not return to its original length after it is released. Instead, the rope will be permanently longer than its original length. The largest tensile load a material can withstand before breaking after passing the yield strength limit is known as the *ultimate tensile strength*, sometimes referred to as just *tensile strength*, value of the material. The last possibility is when the rope can breaks which is called *fracture* or *rupture* and is shown in Figure 5.

Figure 4, Plastic Tensile Stress

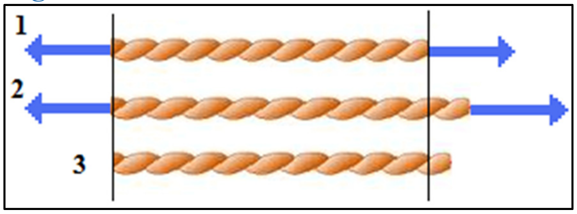
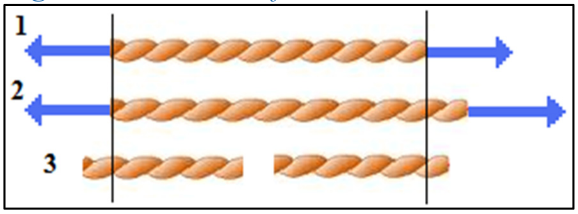


Figure 5, Fracture from Tensile Stress

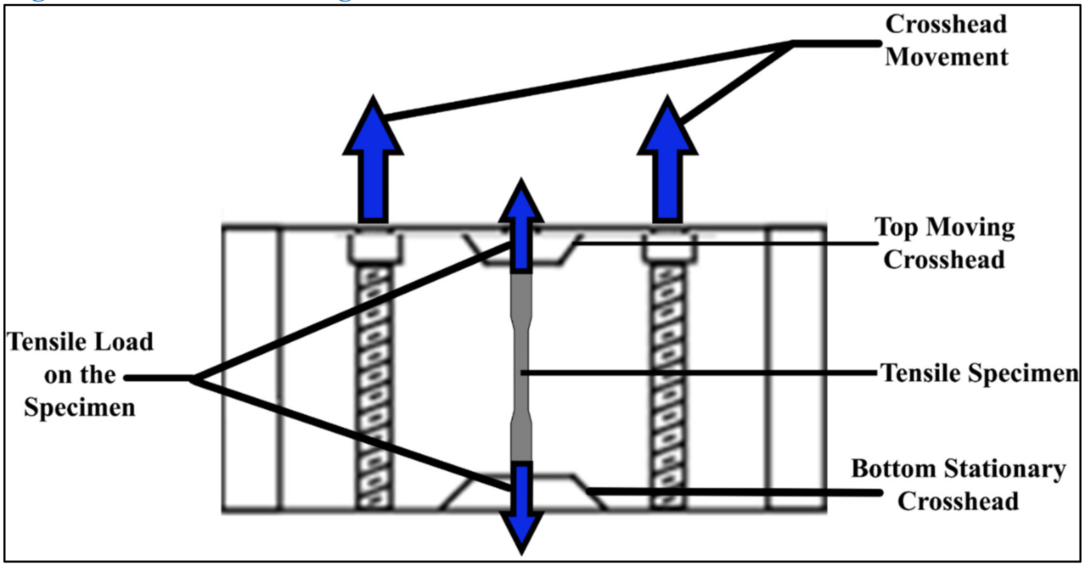


How Are Tensile Tests Performed?

The Tinius Olsen tensile test machine is designed with an upper and a lower crosshead. The bottom crosshead is stationary while the top crosshead can be hydraulically moved up or down. To test a sample of material for tensile strength, the upper crosshead is lowered, and a tensile specimen is threaded into the nuts in each crosshead.

Once everything is in place and the machine is started, the top crosshead moves upward vertically as shown in Figure 6. As this movement occurs, the specimen experiences a tensile load parallel to its axis. The magnitudes of the load and the deflection, which is the degree that the specimen has changed in length, are recorded until the specimen breaks. This information can then be analyzed to determine the material's tensile strength values.

Figure 6, Tensile Testing



THE CURRENT SITUATION

Shear strength data can already be derived in a few different ways. There are obtainable equations used to estimate this value as well as tables of predetermined values for various materials. There are also machines used to test this exact value, but IPFW does not have this equipment or a mountable fixture required for the existing tensile testing machine to perform or demonstrate these exact measurements. These tools can be very costly and regarded as an unnecessary expense for a nonprofit organization, when there are equations that could be used to estimate the data.

There are times in industry when an estimation is not precise enough to ensure the design will operate as needed. If an engineer were assigned the task of designing a machine with the requirement that it must have a fail-safe device to protect the machine or operator, how would the engineer know how strong or weak the fail-safe device should be? When it comes to protecting expensive equipment or an operator for harm, an estimation should not be used in some cases. Instead, exact values may need to be found to prevent the user from experiencing harm or even death. One example of such a design is the shear pin in a snow blower. If the impeller on the snow blower becomes clogged or hits a solid object, the shear pin will break before the auger in the machine. This small pin is much cheaper to replace than the entire auger system, and the user is much safer than they would be if the machine failed instead of the pin.

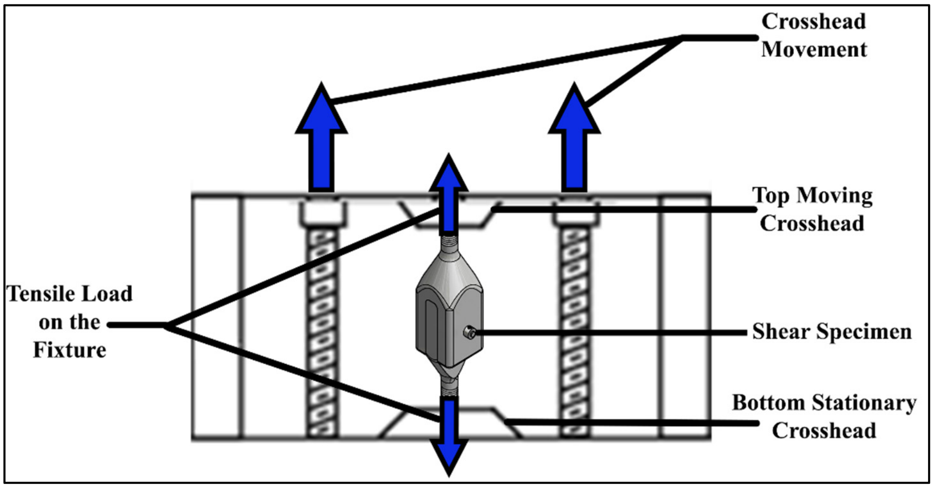
The existing tensile testing machine at IPFW is only used at this time to determine the tensile strength and related data of various materials by pulling a specimen in opposite directions until it breaks. The machine has a dial indicator that measures the change in the distance between two crossheads which are fixed to the machine. A prepared sample of material is threaded into nuts which are supported by these crossheads. As the tensile test is in progress, the force applied to the specimen is measured in pounds and can be read off of a dial throughout the procedure. The measured force can then be used in various equations to calculate related sets of data values.

DESIGNING THE SHEAR STRENGTH TESTING FIXTURE

The Design Concept

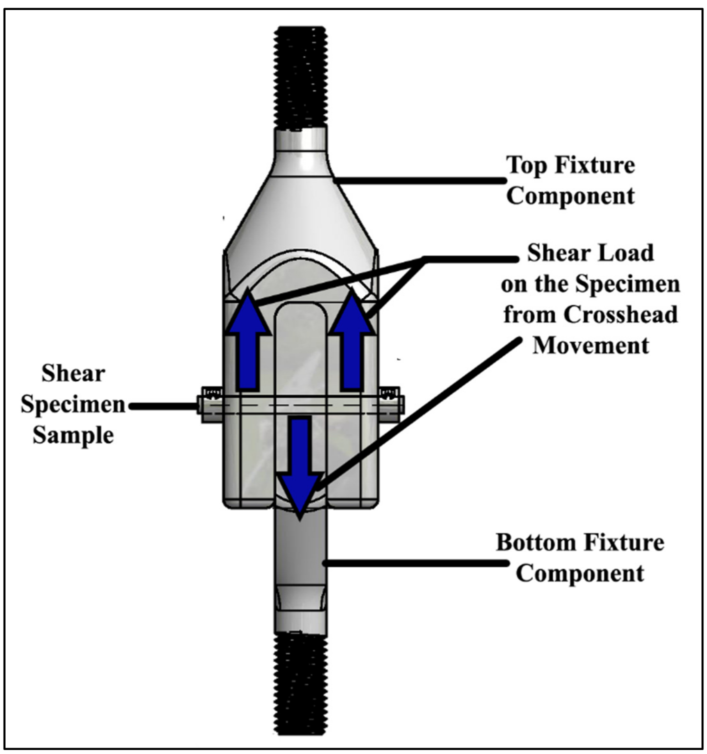
The shear strength testing fixture developed throughout this project was chosen to supply the university with a tool which is currently unavailable to them. It was decided to design the device specifically for the tensile testing machine at IPFW to utilize and broaden the functionality of the existing equipment. Since the tensile test applies a load parallel to the specimen's axis, the team had to find a way to apply a load perpendicularly to a specimen's axis without altering the machine.

Figure 7, Shear Testing



Based on these facts, the preferred design concept was to create a fixture consisting of two separate pieces. Each component was designed to thread into the existing threaded nuts supported by the crossheads of the test machine in place of a tensile test specimen. When the two parts are aligned, the holes in the fixture will become a single hole through which the shear strength test specimen can be loaded normal to the fixture as shown in Figure 7.

Figure 8, Shear Load on the Specimen



The specimen is placed through the aligned holes and secured with a collar on each side to hold everything in place while the fixture is being mounted to the machine. After the two fixture parts, the specimen, and the two collars are in place, the fixture is screwed into the threaded nuts of the machine's crosshead plates. While the plate and the top piece of the fixture, moves upward at a gradually increasing load, a shear force is created on the specimen.

This design allows the load from the machine on the specimen to be applied perpendicular instead of parallel causing the specimen to fail in shear rather than tension as shown in Figure 8. The increasing load amount can be read from a dial indicator on the machine and used to determine the shear force. Data will be gathered until the specimen reaches shear failure. From this data, calculations can then be made to determine the shear strength of the material.

The Design Specifications

Once the team had confirmed that this was the optimal design concept for the project, the mechanical and physical specifications were the next items to be determined. This included selecting materials, dimensions, performing failure calculations, and analyzing the design data.

Materials

The first step in defining these details was to decide what materials that the device would be used to test. The team referred to the lab manual for the Materials and Processes (MET 180) required course for the Mechanical Engineering and Technology major at IPFW. It was found that the tensile testing lab portion of this course uses the machine to test the following materials.

- 1020 grade cold drawn low carbon steel with a tensile strength of 65,000 psi [3]
- C26000 annealed cartridge brass with a tensile strength of 48,000 psi [3]
- 2024-T4 grade aluminum with a tensile strength of 68,000 psi [3]

After speaking with John Mitchell, who machines the specimens to be tested in the tensile lab, the team found that the course no longer uses the 1020 grade steel. Mr. Mitchell advised the team to use ASTM A36 steel with a tensile strength of 58,000 psi [3] instead. The team planned to test both a tensile and a shear specimen of each of the three materials and discussed this with Mr. Mitchell as well. It was desired that both specimen types be made from the same batch of material to prevent inconsistency in the data. After taking the amount of material Mr. Mitchell had on hand to create the specimens, the team was advised to once again change this steel specimen to 12L14 cold drawn steel with a tensile strength of 78,000 psi [4] to ensure there was enough material to make both specimens from the same lot.

After the decision on the specimen material was finalized, the team began researching materials to use for the fixture and for a facility who supplied it for the cheapest cost. Valbruna Slater Stainless Inc. graciously offered to donate the fixture material to the team at no charge. The fixture needed to be capable of testing these three types of materials repeatedly without failing, so the initial consideration was to use heat treated 630 HH1150 stainless steel to fabricate the fixture. It was also considered to heat treat it again to H900 hardness either before or after fabrication. The team chose to use this heat treated material that exceeds the current needs due to the possibility that the educational courses, thus the materials being tested, could change in the future and may require a higher strength from the fixture.

Mike Rodenbeck, Vice President of Sales at Industrial Engineering, the machine shop chosen to manufacture the two main components of the fixture, contacted the team with concerns that heat treating the material to H900 prior to machining could cause many difficulties during fabrication. The additional heat treatment to H900 after fabrication would increase the hardness of the material to a point that any corrective machining would be very difficult if not relatively impossible. After investigating how the heat treatment would possibly affect the part after it was machined, it was found that there would likely be some distortion of the part and loss of crucial tolerances caused by the treatment.

Valbruna tested the 630 HH1150 material without the additional H900 heat treatment to find and report its properties. The results of this testing are shown in Table 1. It was decided after consulting this data in conjunction with ASTM specifications A-479 [5] and A-564 [6] that the material alone is more than strong enough to perform the required tests without additional heat treatment.

Table 1, Data of Pre-Machined Fixture Material

Valbruna 630 HH1150 Material Testing Results	
Test and Units of Measure	**Measurement**
Ultimate Tensile Strength, σ_{UTS} (psi)	142700
Yield Strength with 0.2% Offset, σ_{YS} (psi)	123300
Elongation (in 2 Inches)	21.10
Reduction of Area (%)	58.90
Rockwell (HRWC)	32.00
Charpy V Notch Impact Energy Average (ft-lb)	77.67
Charpy V Notch Lateral Expansion Average (%)	48.33
Charpy V Notch Shear Resistance Average (%)	75.00

Dimensions

Originally, the team wanted to explore the possibility of using spacers to hold the specimens internally. The spacers would have been used to reduce the inner diameter of the hole to allow for testing of a range of specimen sizes from 0.25 inch to 0.5 inch diameters.
The spacers were ordered from McMaster-Carr [7], but upon arrival the spacers had unexpected small chamfers on their inner and outer diameters which raised the concern that these chamfers would affect the resulting data gathered from shear tests. It was decided not to use the spacer components which resulted in altering the dimensions to only allow for a specimen of 0.25 inch diameter in the fixture and specimen specifications.

The initial design called for the shear test specimens to be threaded on both ends so they could be held in place with nuts on each side of the fixture. It was later decided that using collars would allow for a simpler prepping method of the test specimens. By using a collar that can be attached to each end and tightened to the same diameter as the specimen to hold it in place, this eliminates the need for threading the ends of the specimens and using nuts to hold them into place. The collars were ordered and received from McMaster-Carr [8].

Upon receiving the parts, the team did further investigation on incorporating them into the overall design. The team decided that using the collars was a needed change to the design and will be used in place of the nuts. The collars would be added at the beginning of each shear test and remain in place throughout the testing process to hold the specimen ends once it breaks. All of the force of the test procedure will be absorbed by the fixture, so the strength of the collars is not a concern. The specimen should not move in the fixture after the test begins other than along the shear planes. Drawings were created specifying all dimensions of both components of the fixture as well as the specimens and are available in Appendix A.

Calculations

All preliminary calculations for the design were performed to ensure that the device would function as anticipated. All of the data computed has indicated that the fixture will not fail in any manner before the shear specimen fails. The design calculations, values used, and results are further detailed in Appendix B and include the following:

- Shear failure to find the point where the specimen should fail in the desired mode
- Bearing failure to ensure none of the specimens could cause crushing damage to the fixture
- Gross tensile failure to determine if tearing would occur across the fixture plates
- Minimum length of thread engagement to ensure the fixture's threads will not fail
- Tensile failure at the thread pitch diameter to confirm the fixture will not fail at its weakest point
- Design factor of safety

All of the calculations were performed for each of the three materials that will realistically be tested in the future on the fixture. When the specimen material for steel changed, the calculations including that material were repeated. In addition to the calculations, finite element analysis (FEA) reports were performed on three of the specimen types and the fixture. All four reports have been included in Appendices C, D, E, and F. The calculations and FEA reports indicated that the fixture would not fail in any manner before the shear specimen fails as desired.

TESTING THE SHEAR STRENGTH FIXTURE

Once Industrial Engineering completed the device, and it was received by the team, it was visually inspected and compared to the design specifications. Based on the visual analysis, no issues or concerns were found. Soon after, the shear and tensile test specimens were ready. After receiving them, the team made arrangements to test the device on the tensile testing machine with assistance from Dr. Barry Dupen. All three tensile specimens and all three shear specimens were tested through the procedure outlined in Appendix G. There were no unexpected issues experienced during either test procedure. The data from testing was gathered and processed in Excel with comparison charts. This information is available in Appendix H as well as shear and tensile stress-strain curves that were created to visually demonstrate the data.

Post-Testing Calculations

The idea of the project from the beginning was to compare the actual values from the testing results to general estimation formula values commonly used in industry and academics. Each type of material has its own estimation method and all were retrieved from the same source [9]. Each set of methods involves yield strength and tensile strength.

Steel Estimation

12L14 cold drawn carbon steel is an alloy. There are two known estimation methods used for an alloy steel. The first is based on the material's yield strength in tension, and states that the shear yield strength should be equivalent to approximately 58% of the tensile yield strength. The second is based on the material's ultimate tensile strength and states that the shear strength should be equivalent to 75% of the tensile strength.

Yield Strength Estimation Method

The yield strength found during tensile testing for the steel specimen was 75,000 psi. 58% of this value is 43,500 psi, thus the shear yield strength should also be 43,500 psi. The actual data shows this value to be 36,500 psi.

Ultimate Tensile Strength Method

The ultimate tensile strength found during testing for the steel specimen was 79,600 psi. 75% of this value is 59,700 psi. The actual value was found to be 43,900 psi.

Aluminum Estimation

2024-T4 is also an alloy. There are two known estimation methods used for an aluminum alloy. The first is based on the material's yield strength in tension, and states that the shear yield strength should be equivalent to approximately 55% of the tensile yield strength. The second is based on the material's ultimate tensile strength and states that the shear strength should be equivalent to 65% of the tensile strength.

Yield Strength Estimation Method

The yield strength found during tensile testing for the aluminum specimen was 43,400 psi. 55% of this value is 23,900 psi, thus the shear yield strength should also be 23,900 psi. The actual data shows this value to be 27,700 psi.

Ultimate Tensile Strength Method

The ultimate tensile strength found during testing for the aluminum specimen was 52,600 psi. 65% of this value is 34,200 psi. The actual value was found to be 30,600 psi.

Brass Estimation

Annealed cartridge brass is a copper alloy. Copper alloys have two estimation methods as well. The first is based on the material's yield strength in tension, and states that the shear yield strength should be equivalent to approximately 58% of the tensile yield strength. The second is based on the material's ultimate tenile strength and states that the shear strength should be equivalent to 65% of the tensile strength.

Yield Strength Estimation Method

The yield strength found during tensile testing for the aluminum specimen was 43,900 psi. 58% of this value is 25,500 psi, thus the shear yield strength should also be 25,500 psi. The actual data shows this value to be 28,200 psi.

Ultimate Tensile Strength Method

The ultimate tensile strength found during testing for the aluminum specimen was 51,000 psi. 65% of this value is 33,150 psi. The actual value was found to 38,700 psi.

Conclusion of the Testing Results

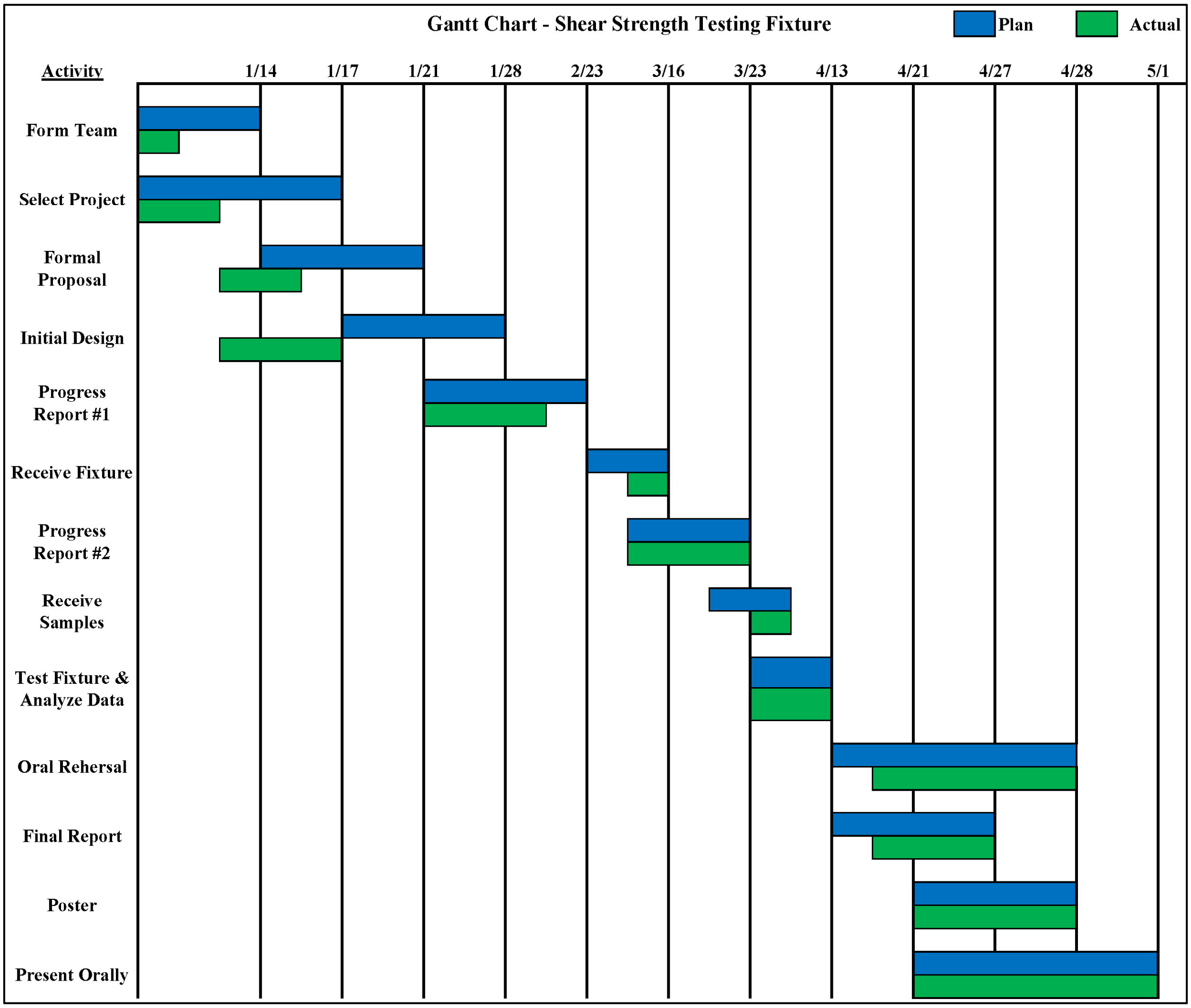
Both of these methods of estimation show that the actual values are very close to the estimated values for all three materials. The FEA reports were also compared to the actual results of the data. The shear stresses in the FEA for aluminum and brass were extremely close to the actual values from testing. The FEA report for steel was ran under the assumption that the specimen would be made of A36, but the actual sample was made of 12L14. Comparing the FEA report for steel to actual data does not give any helpful information. It was not expected that any forms of comparison to the actual data would be exact, but it was anticipated that they would be close. All values that were estimated in any manner and compared show that the device is functioning properly. This information also shows how far from the real value an estimate can be.

SCHEDULES AND BUDGETS

Schedules

The project was completed within the time frames the team had set in the beginning. A Gantt chart was created with the desired deadlines for certain portions of the project when the project began. It has been continually updated throughout the process to show the planned completion dates compared to the actual completion dates. Now that the project is complete, the Gantt chart has been updated to reflect completion and is shown in Table 2.

Table 2, Gantt Chart



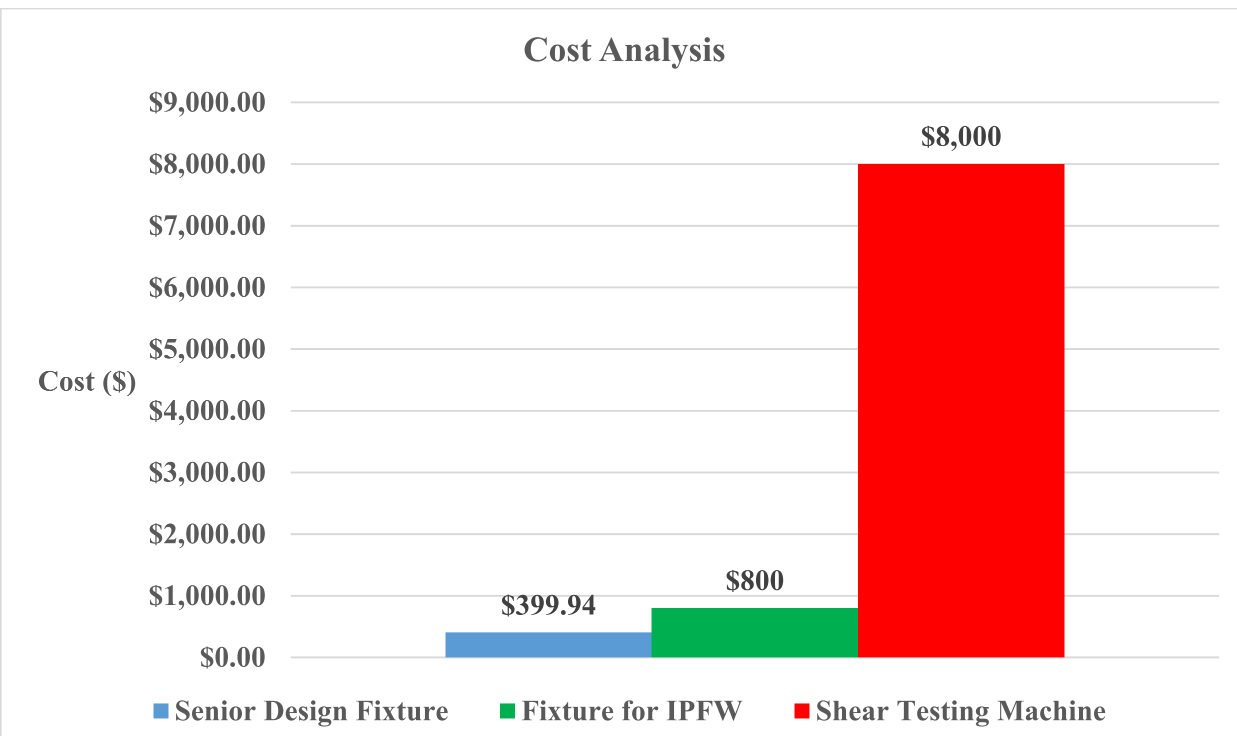
Budget

The total budget in addition to the fixture material, donated to the team by Valbruna Slater Stainless Inc., was $500. The team was able to design and create this device successfully while staying under this budget. A cost analysis, shown in Table 3 and Figure 9, was done to show how much money the team saved the university by creating and donating this device to them. To show the immense gratitude to the sponsors, the logos of Valbruna Slater Stainless and Industrial Engineering were engraved on the completed fixture.

Table 3, Cost Analysis

Cost Analysis					
Individual Actual Costs for Team		**IPFW's Theoretical Cost for Equivalent**		**Benefits for IPFW**	
Component	**Cost**	Cost of Shear Machine	$8,000	Cost Benefits	$420.00
Top Component	$250.00	Cost of Shear Fixture	$800	Cost Benefit Ratio	1.0502
Bottom Component	$130.00				
Shaft Collars (4)	$8.36				
Spacers (3)	$11.58				
Specimen #1	$0.00				
Specimen #2	$0.00				
Specimen #3	$0.00				
Total	**$399.94**				

Figure 9, Cost Analysis



CONCLUSION

The device performed exactly as hoped and planned. This fixture will contribute to IPFW because the university currently teaches multiple courses involving shear strength of various materials, but has no way to demonstrate the measurement process of this exact data to students. Other testing procedures are commonly demonstrated in various lab portions of certain courses, but only the concept and mathematics of shear strength are taught at the present time.The team recommends that IPFW modify current courses to include this device to demonstrate this concept to future students.

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APPENDIX A: FINAL SPECIFICATION FIGURES

Figure A-1, Top Component of Fixture

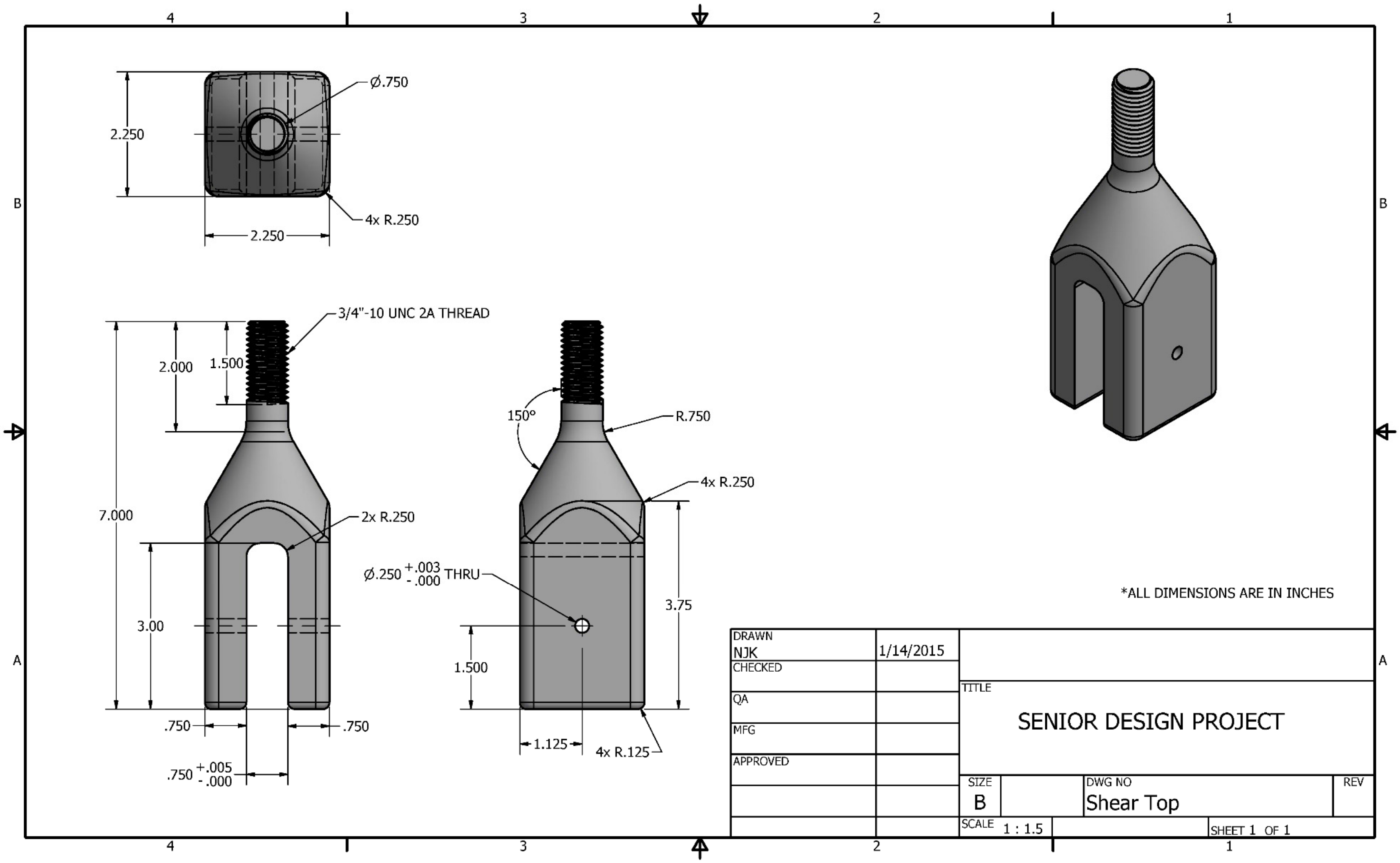


Figure A-2, Bottom Component of Fixture

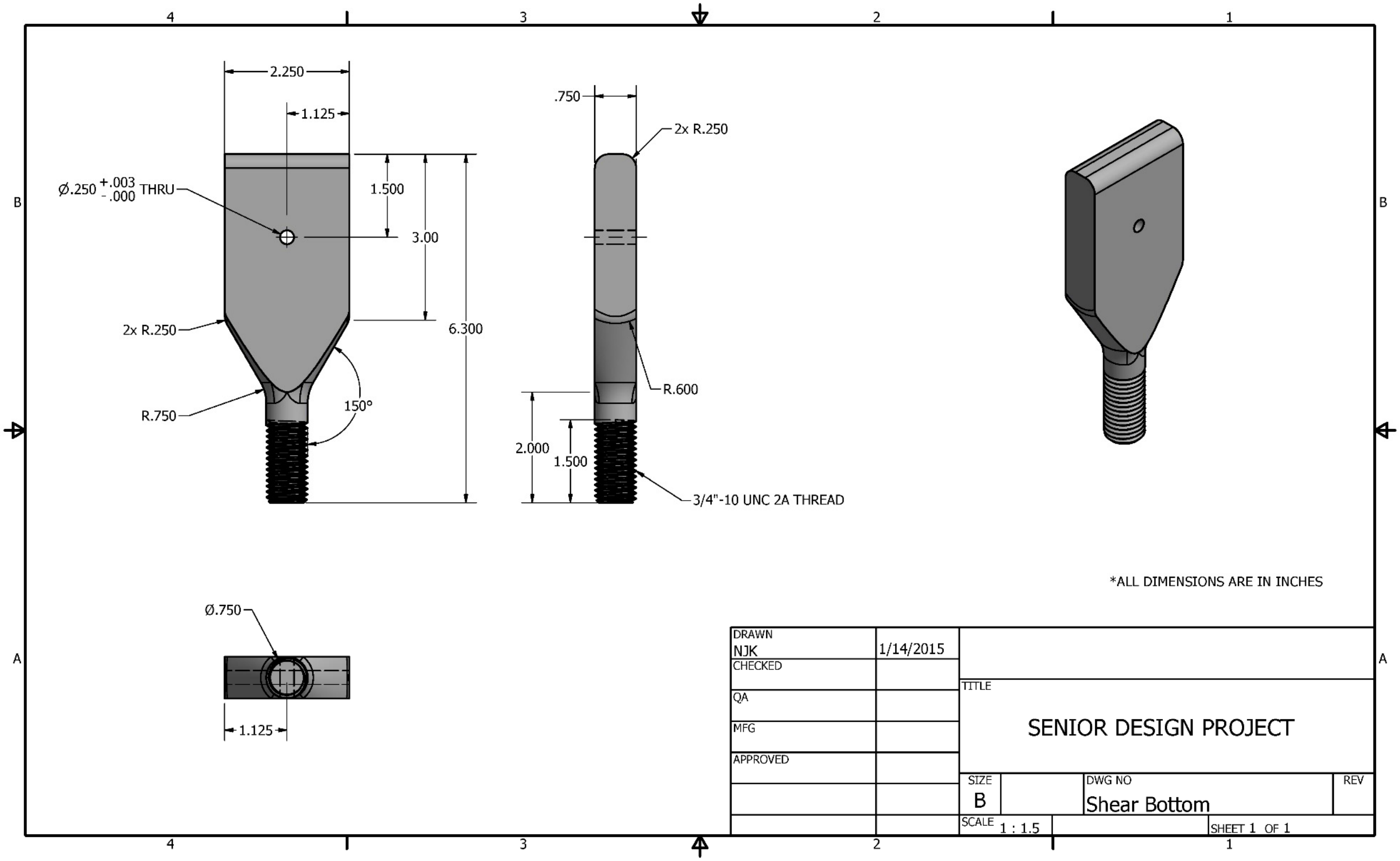


Figure A-3, Shear Specimen

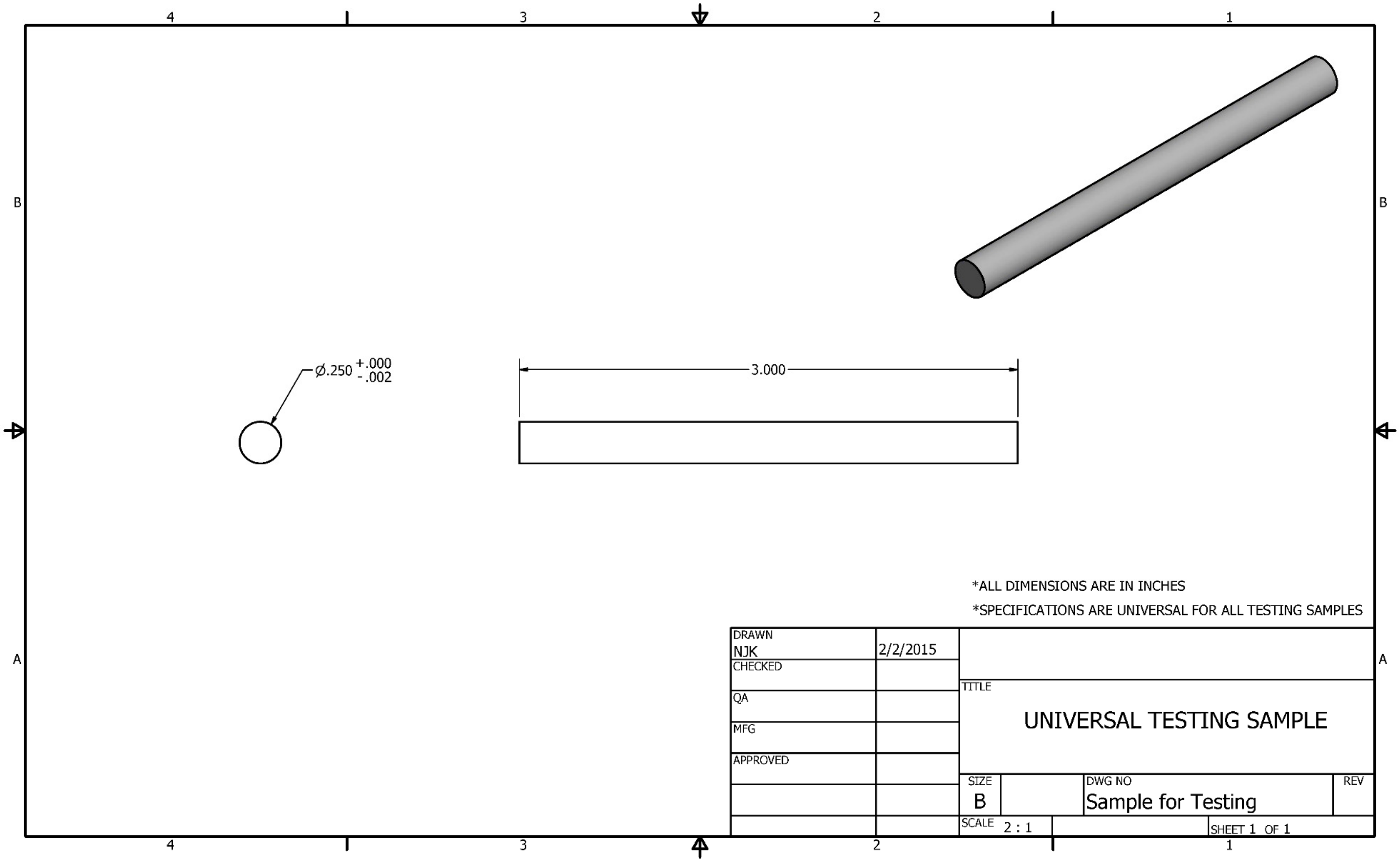


Figure A-4, Collar

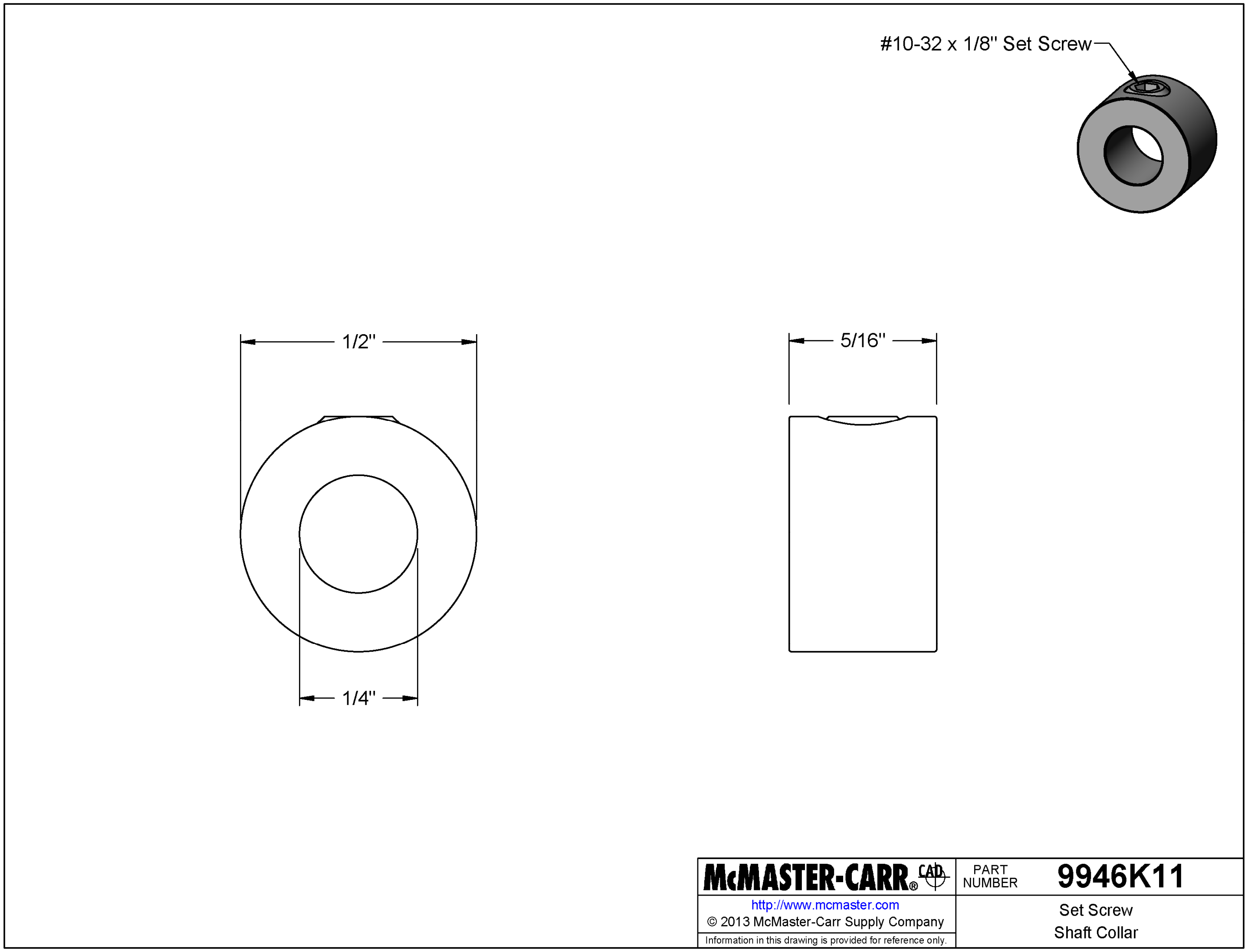
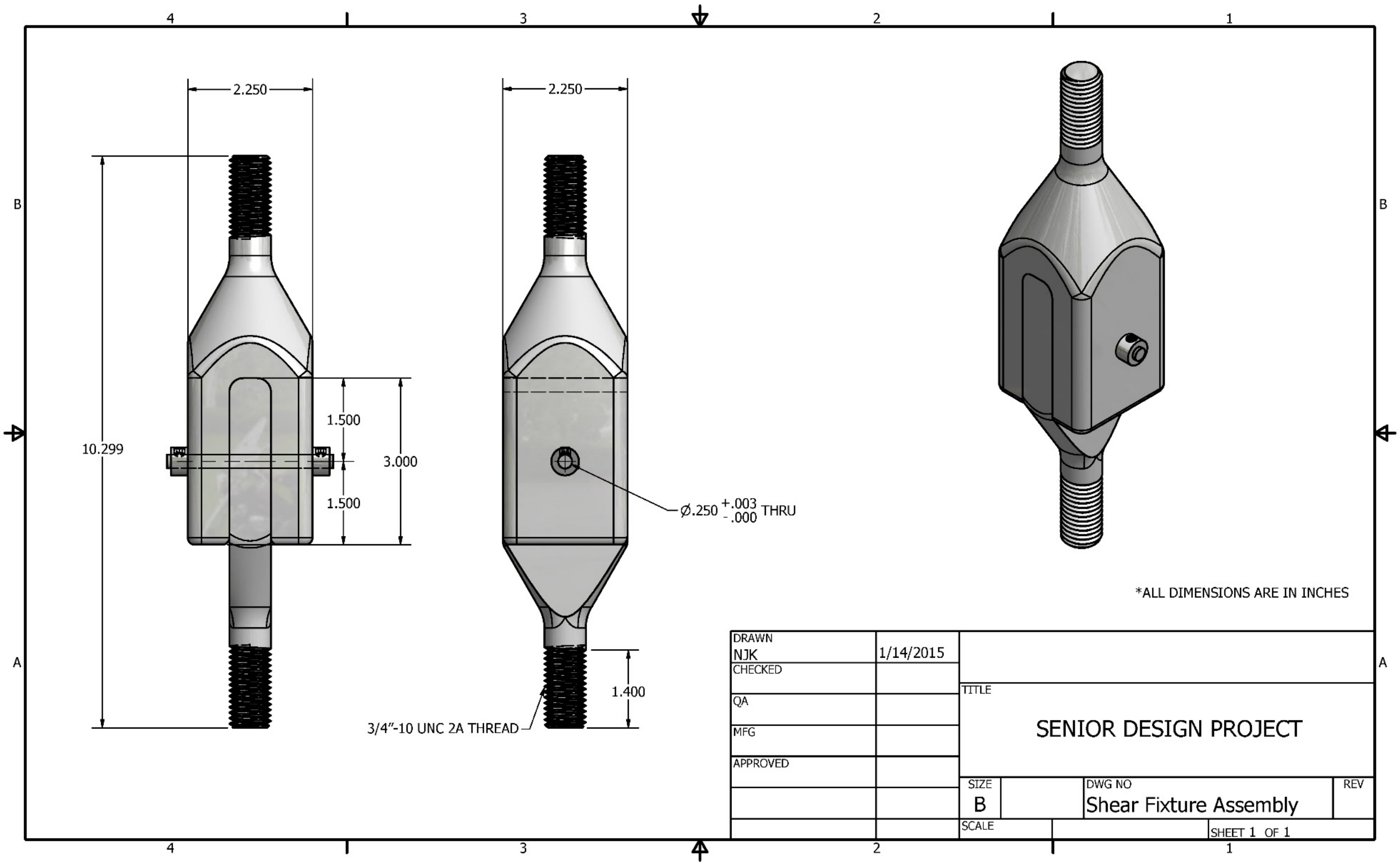


Figure A-5, Fixture and All Components Assembled



APPENDIX B: DESIGN CALCULATIONS AND DATA

Equation B-1, Shear Failure

The equation $P_s = n \times A_b \times \tau$ [1] was used to determine the point where the specimen should fail in shear, which is the desired mode of failure. In this equation, the variables used are,

- $n = 2$, and is defined as the number of shear planes in this design.
- $A_b = \frac{\pi \times d^2}{4} = 0.0491 in^2$, and is defined as the maximum cross-sectional area of the shear test specimen, where the diameter of the specimen is $d = 0.25$ inches.
- "τ" is the allowable shear strength of the test specimen material based on the estimation that the highest value this could be is approximately 70% of the material's ultimate tensile strength (σ_{UTS}). The ultimate tensile strength value for the fixture material was taken from the data test ran by Valbruna, and the values for the five specimen materials were found in existing tables [3] and [4] of materials properties at room temperature.

The values for "τ", "σ_{UTS}", and "P_s" are all available in Table 1, Design Failure Calculation Results. This value needs to be the lowest value compared to the following bearing or gross tensile failure calculation values to ensure that the specimen will fail before any other component of the fixture.

Equation B-2, Bearing Failure

The equation $P_p = d \times t \times \sigma_P$ [1] was used to determine if any of the specimens could cause crushing damage to the fixture at the specimen hole. In this equation, the variables used are,

- $d = 0.25$ inches, and is the maximum diameter of the specimen.
- $t = 0.75$ inches, and is the smallest thickness of the fixture plates which is the required value to be used in this equation. The bottom component has a total thickness of 0.75 inches, and the top component has a combined thickness of 1.5 inches.
- $\sigma_p = 1.5 \times \sigma_{UTS}$, and is defined at the allowable bearing stress. These values are in Table 1, Design Failure Calculation Results.

These final bearing failure values were all approximately 75% greater than the shear failure values as hoped, and can be seen in Table 1, Design Failure Calculation Results. This ensures that the specimen will fail before it damages the plates of the fixture in all four cases.

Equation B-3, Gross Tensile Failure

The equation $P_g = \sigma_g \times A_g$ [1] was calculated to determine if tearing across the fixture plate's gross cross-sectional area at any distance from the aligned specimen hole could occur before shear failure. In this equation, the variables used are,

- $A_g = t \times w = 1.6875 in^2$, and is defined as the smallest cross-sectional area of the fixture, where the thickness of the plate is the same value used in bearing failure and the width of the plate is w = 2.25 inches.
- σ_g is defined as the allowable gross tensile strength and is 60% of the material's yield strength (σ_{ys}). The yield strength value for the fixture material was taken from the data test ran by Valbruna, and the values for the three specimen materials were found in existing tables [3] and [4] of materials properties at room temperature.

The values for "σ_g", "σ_{ys}", and "P_g" are all available in Table 1, Design Failure Calculation Results. These final gross tensile failure values were all approximately 70% greater than the bearing failure values, thus extremely greater than shear failure values. This ensures that the specimen will fail in shear before the plates of the fixture experience tensile failure in all four cases. So for all calculated failure modes, the desired mode of shear failure will occur before any of the other modes.

Equation B-4, Minimum Length of Thread Engagement

This was calculated to ensure the fixture material would be substantially strong enough to endure the shear testing, so that gross tensile failure of the fixture plates will occur before stripping the fixture threads while it is mounted in the tensile testing machine using the equation, $L_e = \frac{2 \times A_t}{K_{n,MAX} \times \pi \times [\frac{1}{2} + 0.57735 \times n \times (E_{s,MIN} - K_{n,MAX})]}$ [10]. In the equation, the unknown variables are,

- $A_t = 0.7854 \times (D - \frac{0.9743}{S})^2 = 0.33446 in^2$, and is defined as the tensile stress area where the diameter of the threaded area in question D = 0.75 inches and the number of threads per inch S = 10 [11].
- $K_{n,MAX}$ = 0.6630 inches, and is defined as the maximum minor internal thread diameter [11].
- $E_{s,MIN}$ = 0.6773 inches, and is defined as the minimum external thread pitch diameter [11].

The result of the thread fastener length of engagement calculation was that L_e = 0.55128 inches. This means that the minimum thread length of the fixture are required to be at least 0.55128 inches long to ensure they do not fail. The threads in this design significantly exceed this minimum requirement since they are 1.5 inches in length.

Equation B-5, Tensile Failure at Minor Thread Diameter

This calculation was done to ensure that the fixture would not fail at the smallest cross-sectional area of the fixture, which would be the thread pitch diameter. It was determined that the equation $P_{CR} = \frac{\sigma_{UTS} \times \pi \times E_{SMIN}^2}{4} = 53{,}034\ pounds$ defines the point of loading that this type of failure would occur. The maximum load that could be applied to this design is 30,000 psi and well below this load needed to cause tensile failure in this location.

Equation B-6, Design Factor of Safety

The factor of safety was then determined for the design by dividing the load found that would cause tensile failure at the minor diameter by the maximum load to be applied. This resulted in a factor of safety of $F.S. = \frac{50{,}800lb}{30{,}000lb} = 1.69$.

Table 1, Design Failure Calculation Results

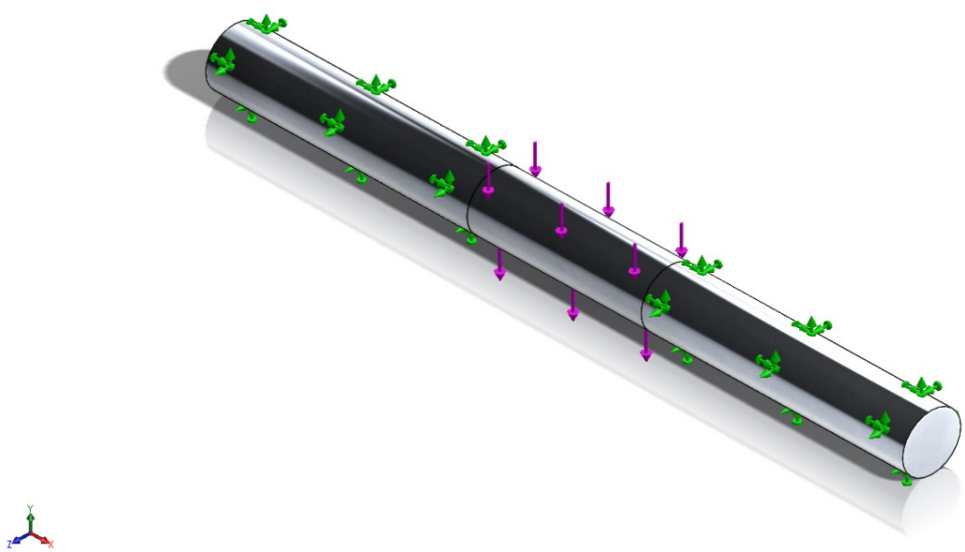
Material	**Ultimate Tensile Strength, σ_{UTS} (psi)**	**Yield Strength, σ_{YS} (psi)**	**Estimated Shear Strength, τ (psi)**	**Allowable Bearing Stress, σ_p, (psi)**	**Allowable Gross Tensile Stress, σ_g, (psi)**	**Specimen Shear Failure, P_s, (lbf)**	**Bearing Failure, P_p, (lbf)**	**Gross Tensile Failure (P_g) (lbf)**
Fixture Material (17-4 HH1150)	142,700	123,300	99,890	214,050	74,000	9,800	40,100	124,900
Aluminum (2024-T4)	68,000	47,000	47,600	--	--	4,700	--	--
Annealed Cartridge	48,000	16,000	33,600	--	--	3,300	--	--
1020 CD Steel	65,000	48,000	45,500	--	--	4,500	--	--
Low Carbon Steel (A36	58,000	36,000	40,600	--	--	4,000	--	--
12L14 CD Steel	78,000	60,000	54,600	--	--	5,400	--	--

APPENDIX C: FEA OF THE ALUMINUM SHEAR SPECIMEN

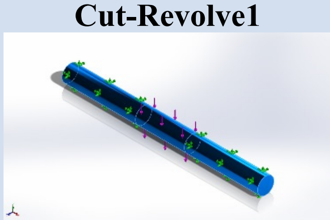
Introduction

The purpose of this simulation is to verify calculated values of shear failure in a 0.249 inch diameter specimen of 2024-T4 aluminum by means of a shear test. It is assumed that the material is homogenous and without defect.

Model Information



Model name: Shear Test Specimen
Current Configuration: Default

Solid Bodies			
Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
Cut-Revolve1 	Solid Body	Mass:0.014759 lb Volume:0.146952 in^3 Density:0.100434 lb/in^3 Weight:0.014749 lbf	C:\Users\eblack\Desktop\senior design\solid models\simulations\Shear Test Specimen.SLDPRT Apr 20 14:30:14 2015

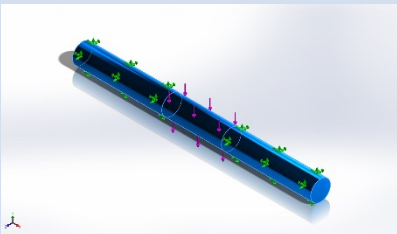
Study Properties

Study name	2024-T4 Shear Test
Analysis type	Static
Mesh type	Solid Mesh
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin
Include fluid pressure effects from SOLIDWORKS Flow Simulation	Off
Solver type	FFEPlus
In-plane Effect:	Off
Soft Spring:	Off
Inertial Relief:	Off
Incompatible bonding options	Automatic
Large displacement	Off
Compute free body forces	On
Friction	Off
Use Adaptive Method:	Off

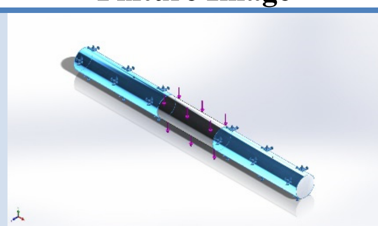
Units

Unit system:	English (IPS)
Length/Displacement	in
Temperature	Fahrenheit
Angular velocity	Rad/sec
Pressure/Stress	psi

Material Properties

Model Reference	Properties		Components
	Name: Model type: Default failure criterion: Yield strength: Tensile strength: Elastic modulus: Poisson's ratio: Mass density: Shear modulus: Thermal expansion coefficient:	2024-T4 Linear Elastic Isotropic Max von Mises Stress 47137.3 psi 68167.7 psi 1.05007e+007 psi 0.33 0.100434 lb/in^3 4.06106e+006 psi 1.28889e-005 /Fahrenheit	SolidBody 1 (Cut-Revolve1) (sample shear simulation)
Curve Data:N/A			

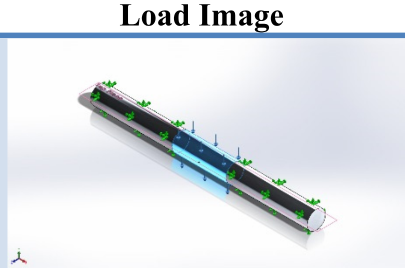
Fixtures

Fixture name	Fixture Image	Fixture Details	
Fixed-1		Entities: Type:	2 face(s) Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(lbf)	-0.0531236	4673.95	-0.0260979	4673.95
Reaction Moment(lbf.in)	0	0	0	0

Loads

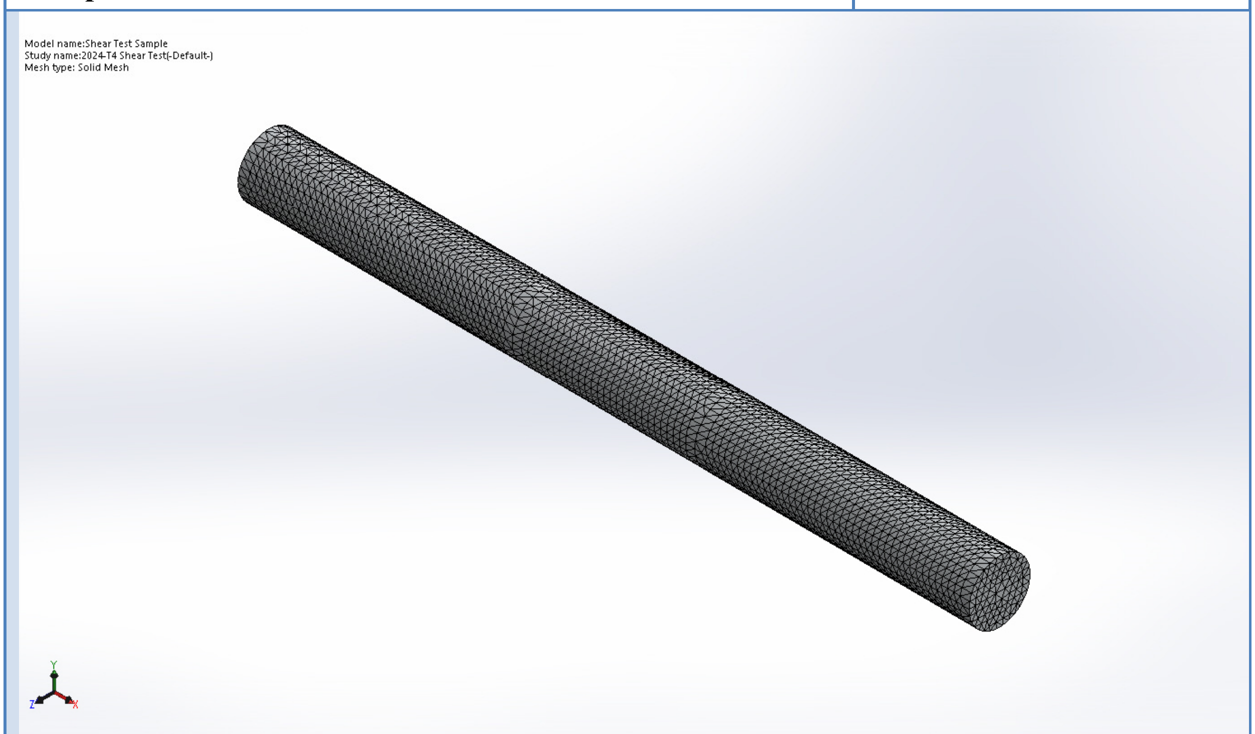
Load Name	Load Image	Load Details	
Force-1		Entities: Reference: Type: Values:	1 face(s), 1 plane(s) Top Plane Apply force ---, ---, -4674 lbf

Mesh Information

Mesh type	Solid Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points	4 Points
Element Size	0.0263792 in
Tolerance	0.00131896 in
Mesh Quality	High

Mesh Details

Total Nodes	71157
Total Elements	48027
Maximum Aspect Ratio	4.4012
% of elements with Aspect Ratio < 3	99.9
% of elements with Aspect Ratio > 10	0
% of distorted elements(Jacobian)	0
Time to complete mesh(hh;mm;ss):	00:00:01
Computer name:	FTW-ENGR-D3



Resultant Forces

Reaction Forces

Selection Set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	lbf	-0.0531236	4673.95	-0.0260979	4673.95

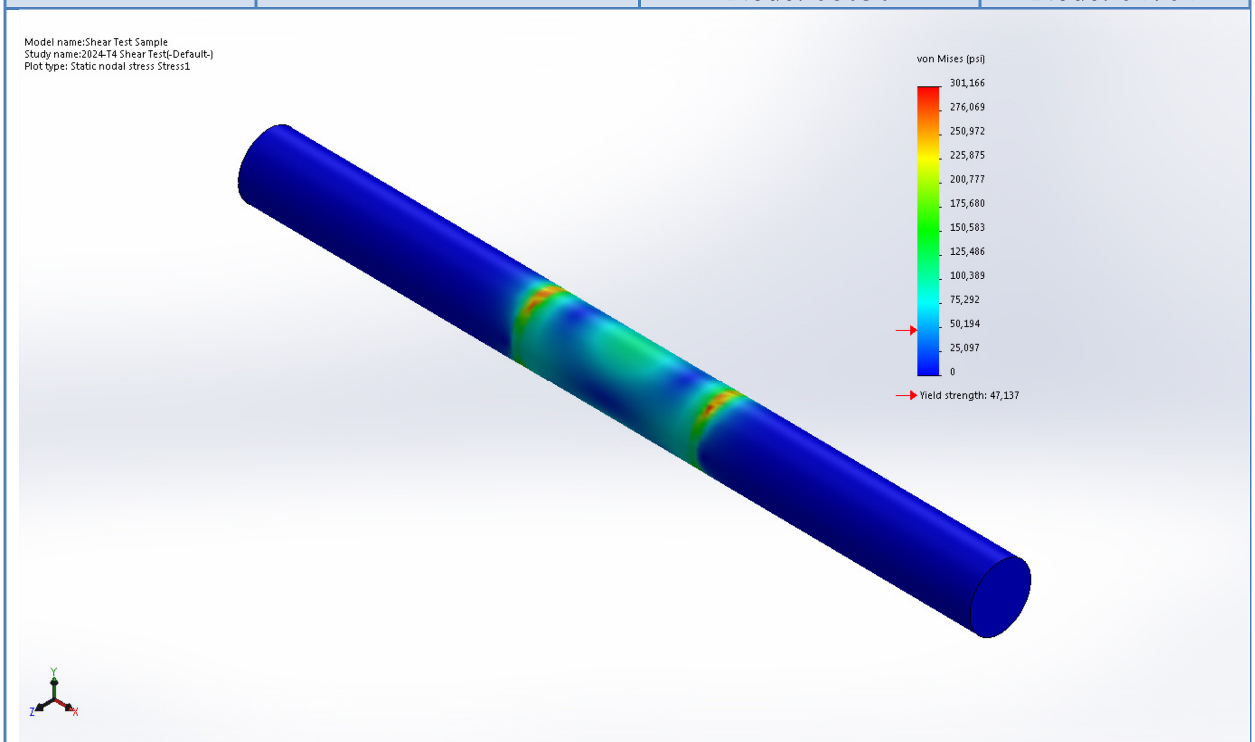
Reaction Moments

Selection Set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	lbf.in	0	0	0	0

Study Results

Stress

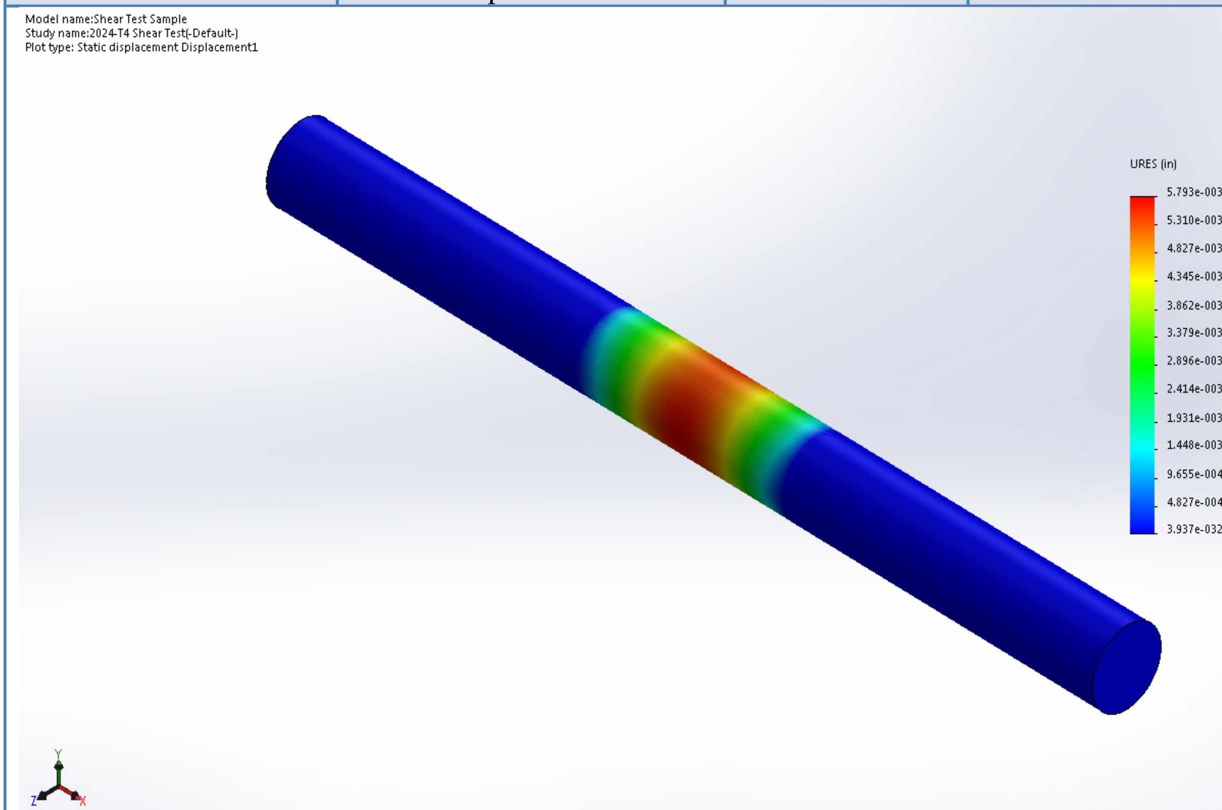
Name	Type	Min	Max
Stress1	VON: von Mises Stress	0.000183934 psi Node: 68030	301166 psi Node: 64764



Shear Test Specimen-2024-T4 Shear Test-Stress-Stress1

Displacement

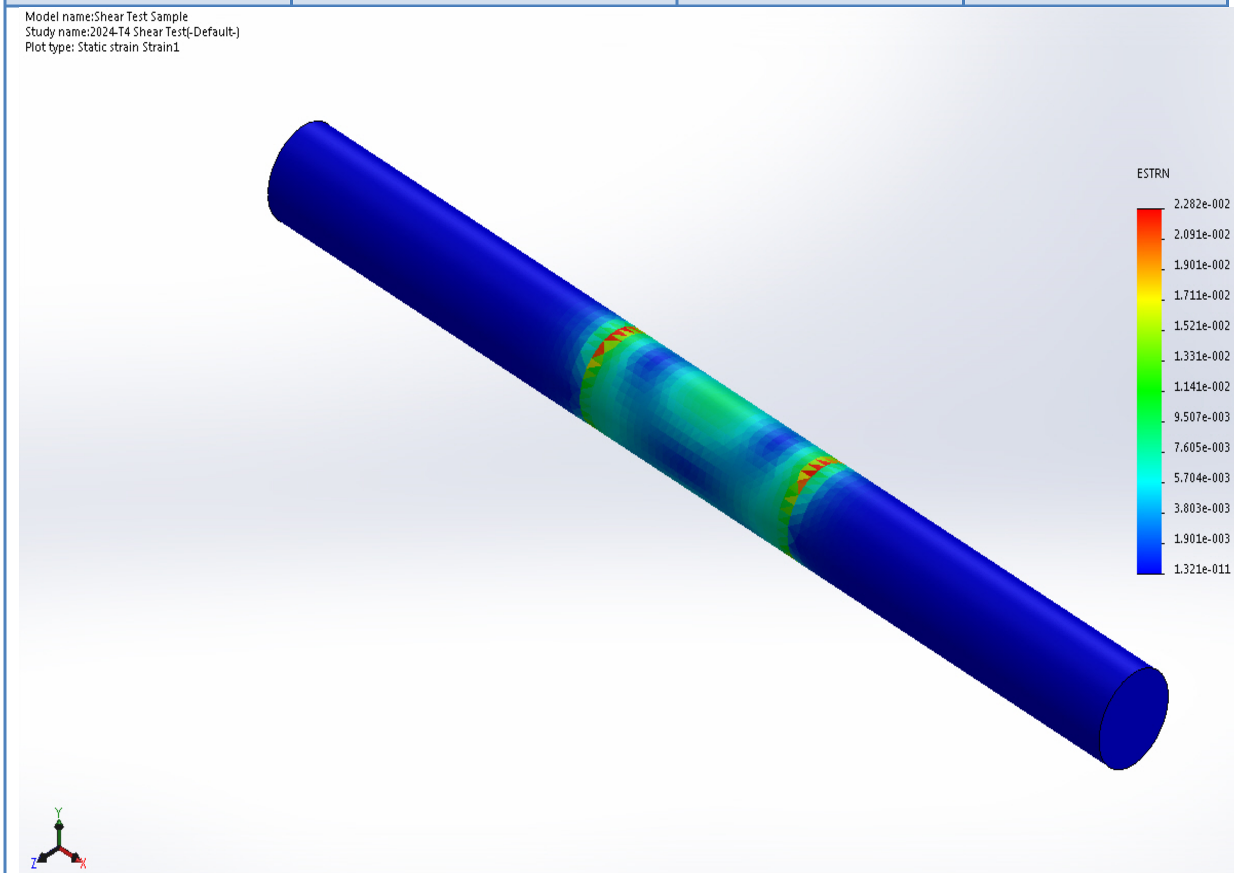
Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0 in Node: 1	0.00579286 in Node: 987



Shear Test Specimen-2024-T4 Shear Test-Displacement-Displacement1

Strain

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	1.32083e-011 Element: 21212	0.0228163 Element: 12204



Shear Test Specimen-2024-T4 Shear Test-Strain-Strain1

Conclusion

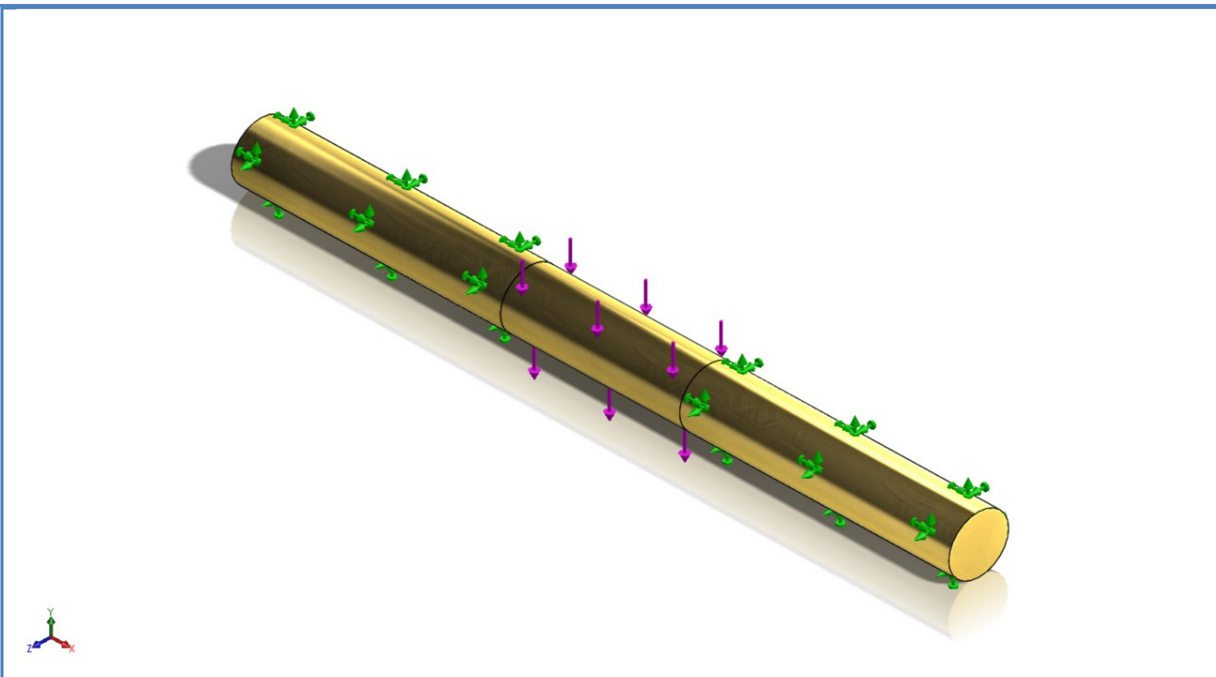
This is a static study and does not calculate any failure of material beyond normal displacement. The resulting stresses that come from shear and tensile failure will be reported as irregularly high values. In the case of this study, these high values verify that the specimen will shear at the applied load.

APPENDIX D: FEA OF BRASS SHEAR SPECIMEN

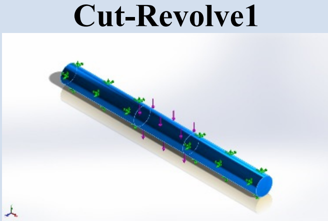
Introduction

The purpose of this simulation is to verify calculated values of shear failure in a 0.249 inch diameter specimen of annealed cartridge brass by means of a shear test. It is assumed that the material is homogenous and without defect.

Model Information



Model name: Shear Test Specimen
Current Configuration: Default

Solid Bodies			
Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
Cut-Revolve1 	**Solid Body**	Mass:0.0452613 lb Volume:0.146952 in^3 Density:0.308 lb/in^3 Weight:0.0452307 lbf	C:\Users\eblack\Desktop\senior design\solid models\simulations\Shear Test Specimen.SLDPRT **Apr 20 14:30:14 2015**

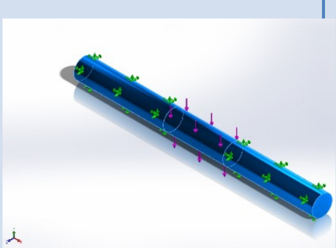
Study Properties

Study name	Cartridge Brass Shear Test
Analysis type	Static
Mesh type	Solid Mesh
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin
Include fluid pressure effects from Flow Simulation	Off
Solver type	FFEPlus
In-plane Effect:	Off
Soft Spring:	Off
Inertial Relief:	Off
Incompatible bonding options	Automatic
Large displacement	Off
Compute free body forces	Off
Friction	Off
Use Adaptive Method:	Off

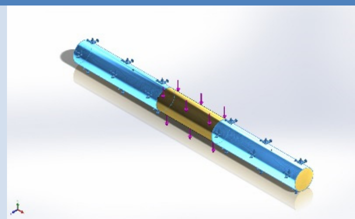
Units

Unit system:	English (IPS)
Length/Displacement	in
Temperature	Fahrenheit
Angular velocity	Rad/sec
Pressure/Stress	psi

Material Properties

Model Reference	Properties		Components
	Name:	Annealed Cartridge Brass	SolidBody 1(Cut-Revolve1)(sample shear simulation)
	Model type:	Linear Elastic Isotropic	
	Default failure criterion:	Max von Mises Stress	
	Yield strength:	16000 psi	
	Tensile strength:	48000 psi	
	Elastic modulus:	16969 psi	
	Poisson's ratio:	0.34	
	Mass density:	0.308 lb/in^3	
	Thermal exp. coeff:	11.1 /Fahrenheit	

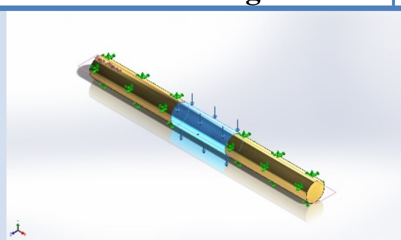
Fixtures

Fixture Name	Fixture Image	Fixture Details	
Fixed-1		Entities: Type:	2 face(s) Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(lbf)	0.0606387	3300	-0.0102784	3300
Reaction Moment(lbf.in)	0	0	0	0

Loads

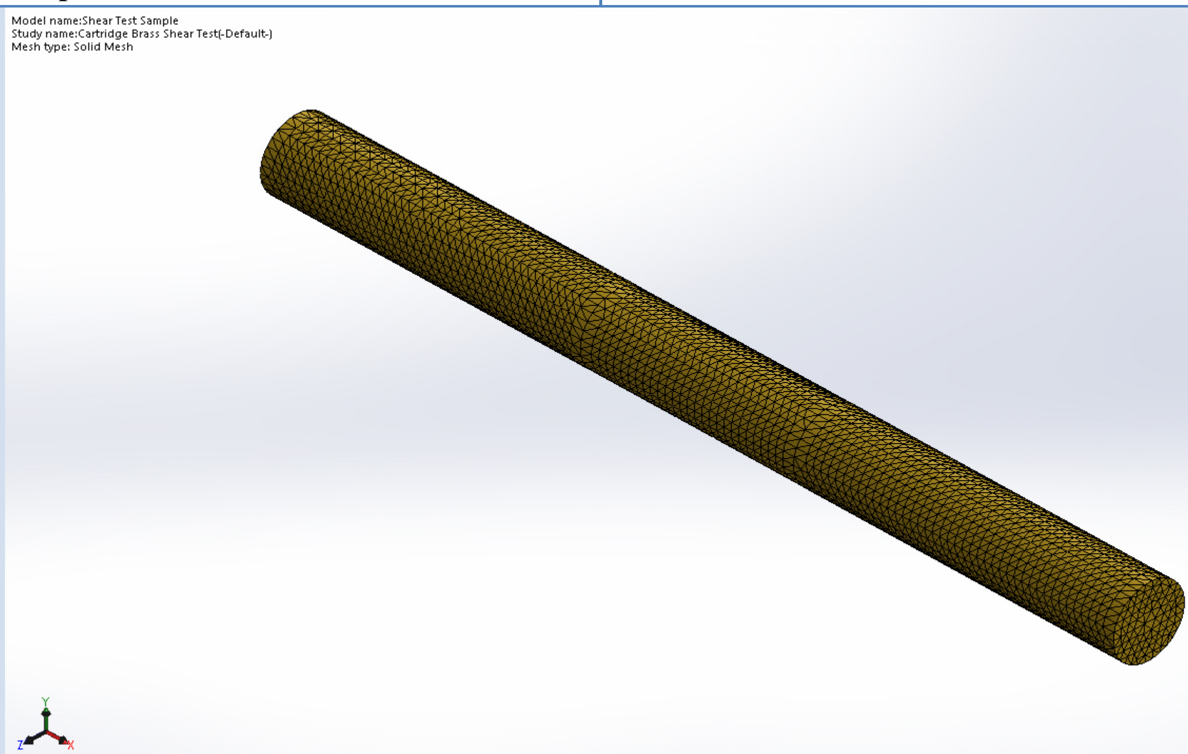
Load Name	Load Image	Load Details	
Force-1		Entities: Reference: Type: Values:	1 face(s), 1 plane(s) Top Plane Apply force ---, ---, -3300 lbf

Mesh Information

Mesh type	Solid Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points	4 Points
Element Size	0.0263792 in
Tolerance	0.00131896 in
Mesh Quality	High

Mesh Details

Total Nodes	71157
Total Elements	48027
Maximum Aspect Ratio	4.4012
% of elements with Aspect Ratio < 3	99.9
% of elements with Aspect Ratio > 10	0
% of distorted elements(Jacobian)	0
Time to complete mesh(hh;mm;ss):	00:00:02
Computer name:	FTW-ENGR-D3



Resultant Forces

Reaction Forces

Selection Set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	lbf	0.0606387	3300	-0.0102784	3300

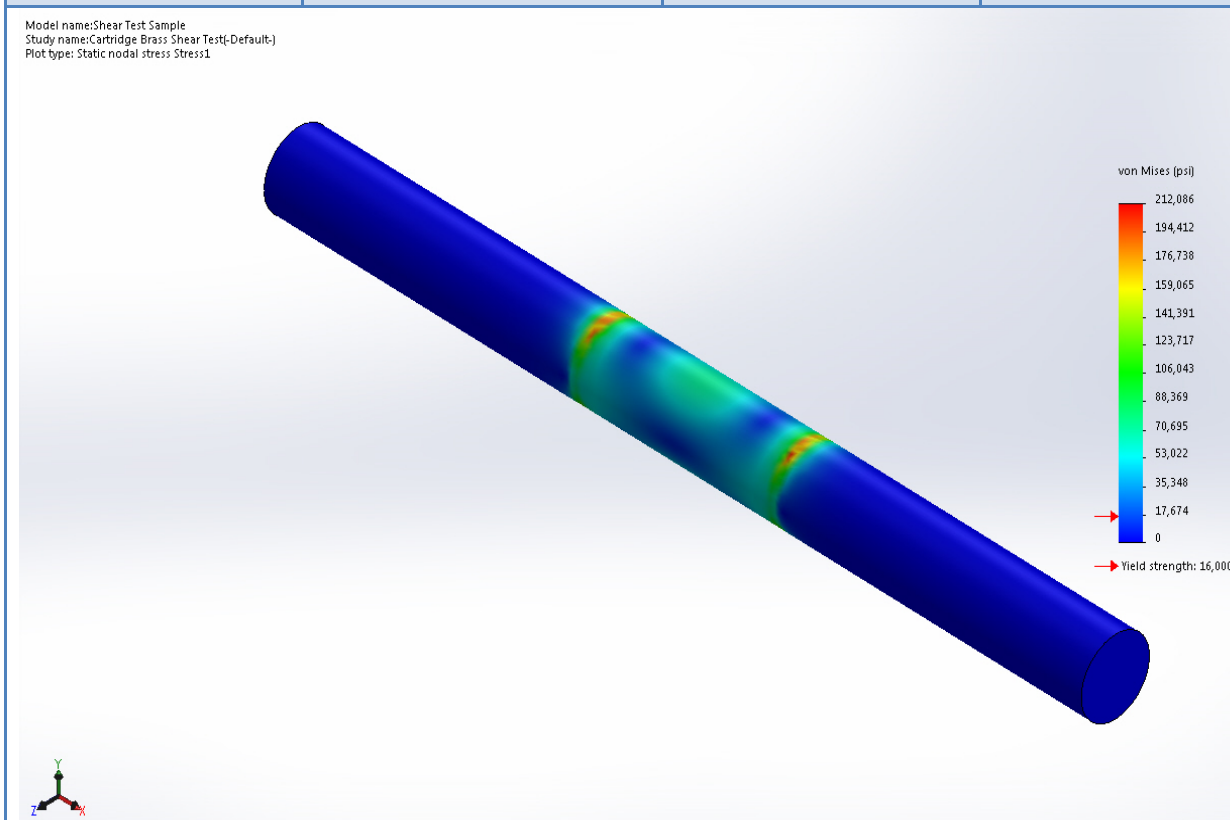
Reaction Moments

Selection Set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	lbf.in	0	0	0	0

Study Results

Stress

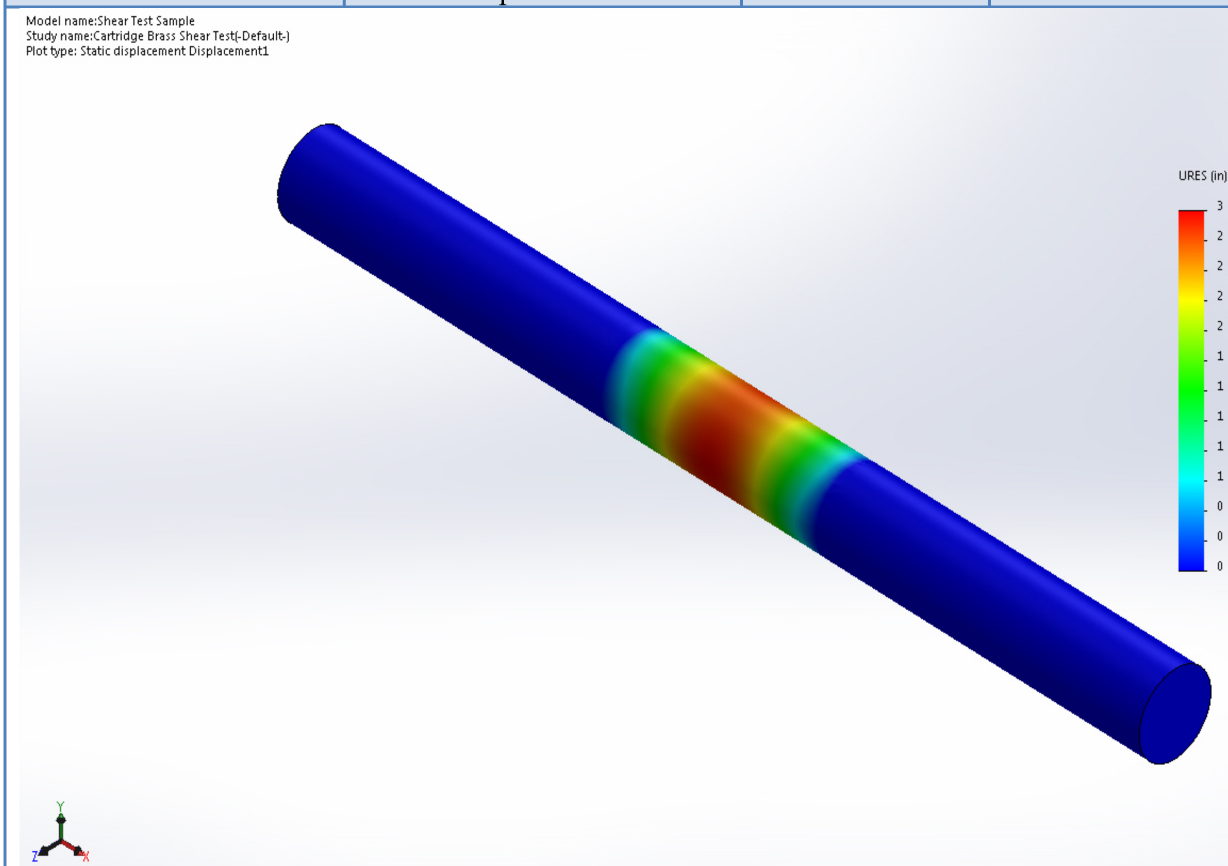
Name	Type	Min	Max
Stress1	VON: von Mises Stress	0.000119334 psi Node: 25776	212086 psi Node: 64764



Shear Test Specimen-Cartridge Brass Shear Test-Stress-Stress1

Displacement

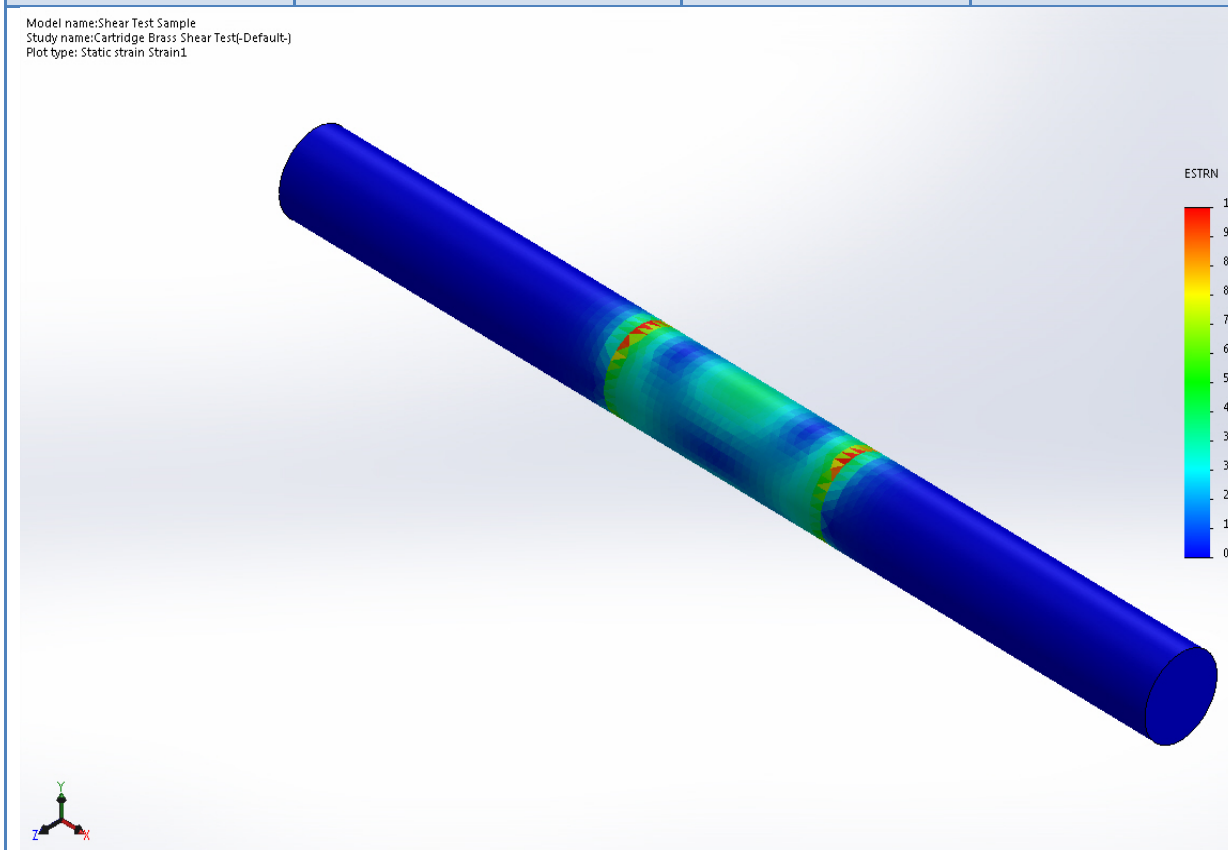
Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0 in Node: 1	2.53197 in Node: 987



Shear Test Specimen-Cartridge Brass Shear Test-Displacement-Displacement1

Strain

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	8.56383e-009 Element: 22243	10.0007 Element: 12853



Shear Test Specimen-Cartridge Brass Shear Test-Strain-Strain1

Conclusion

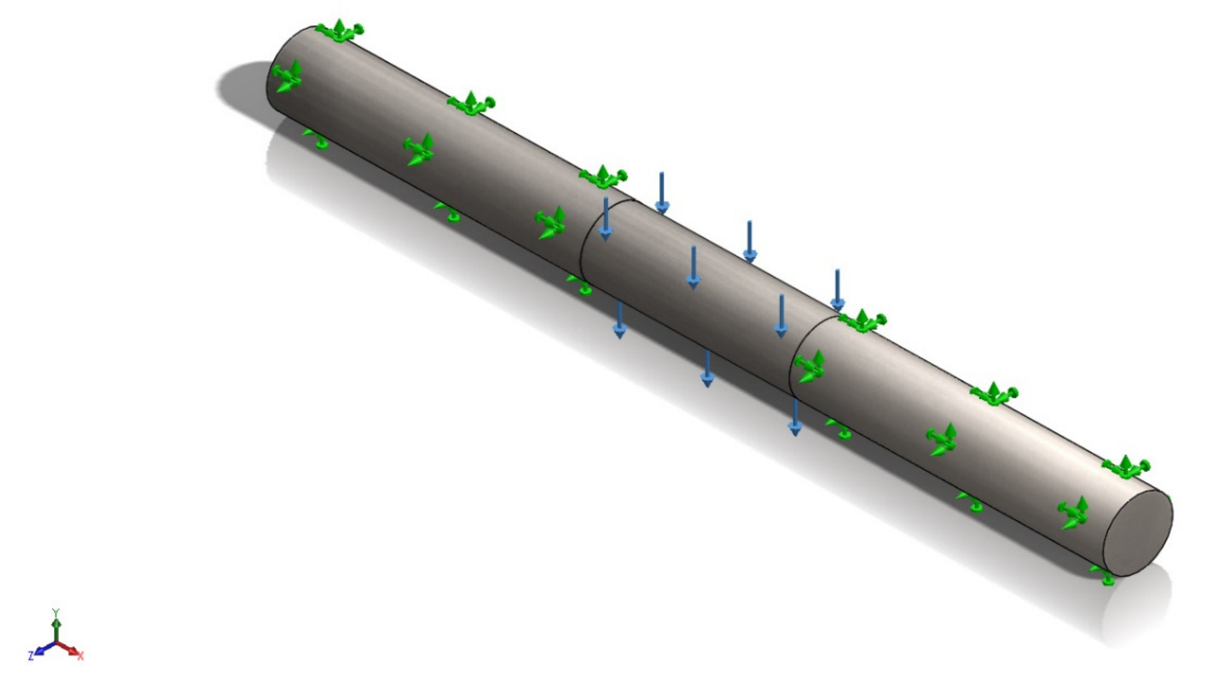
This is a static study and does not calculate any failure of material beyond normal displacement. The resulting stresses that come from shear and tensile failure will be reported as irregularly high values. In the case of this study, these high values verify that the specimen will shear at the applied load.

APPENDIX E: FEA OF A36 STEEL SHEAR SPECIMEN

Introduction

The purpose of this simulation is to verify calculated values of shear failure in a 0.249 inch diameter specimen of A36 steel by means of a shear test. It is assumed that the material is homogenous and without defect.

Model Information



Model name: Shear Test Specimen
Current Configuration: Default

Solid Bodies			
Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
Cut-Revolve1 	**Solid Body**	Mass:0.0416756 lb Volume:0.146952 in^3 Density:0.283599 lb/in^3 Weight:0.0416473 lbf	C:\Users\eblack\Desktop\senior design\solid models\simulations\Shear Test Specimen.SLDPRT **Apr 20 14:30:14 2015**

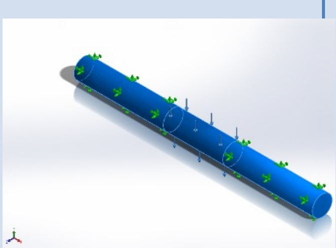
Study Properties

Study name	A36 Shear Test
Analysis type	Static
Mesh type	Solid Mesh
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin
Include fluid pressure effects from Flow Simulation	Off
Solver type	FFEPlus
In-plane Effect:	Off
Soft Spring:	Off
Inertial Relief:	Off
Incompatible bonding options	Automatic
Large displacement	Off
Compute free body forces	On
Friction	Off
Use Adaptive Method:	Off

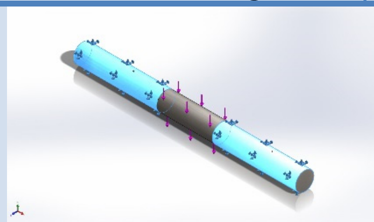
Units

Unit system:	English (IPS)
Length/Displacement	in
Temperature	Fahrenheit
Angular velocity	Rad/sec
Pressure/Stress	psi

Material Properties

Model Reference	Properties	Components
	Name: ASTM A36 Steel Model type: Linear Elastic Isotropic Default failure criterion: Unknown Yield strength: 36259.4 psi Tensile strength: 58015.1 psi Elastic modulus: 2.90075e+007 psi Poisson's ratio: 0.26 Mass density: 0.283599 lb/in^3 Shear modulus: 1.15015e+007 psi	SolidBody 1(Cut-Revolve1)(sample shear simulation)

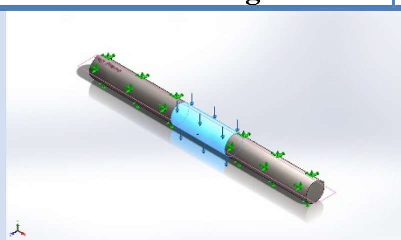
Fixtures

Fixture Name	Fixture Image	Fixture Details
Fixed-1		Entities: 2 face(s) Type: Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(lbf)	-0.0158854	3987	0.00649495	3987
Reaction Moment(lbf.in)	0	0	0	0

Loads

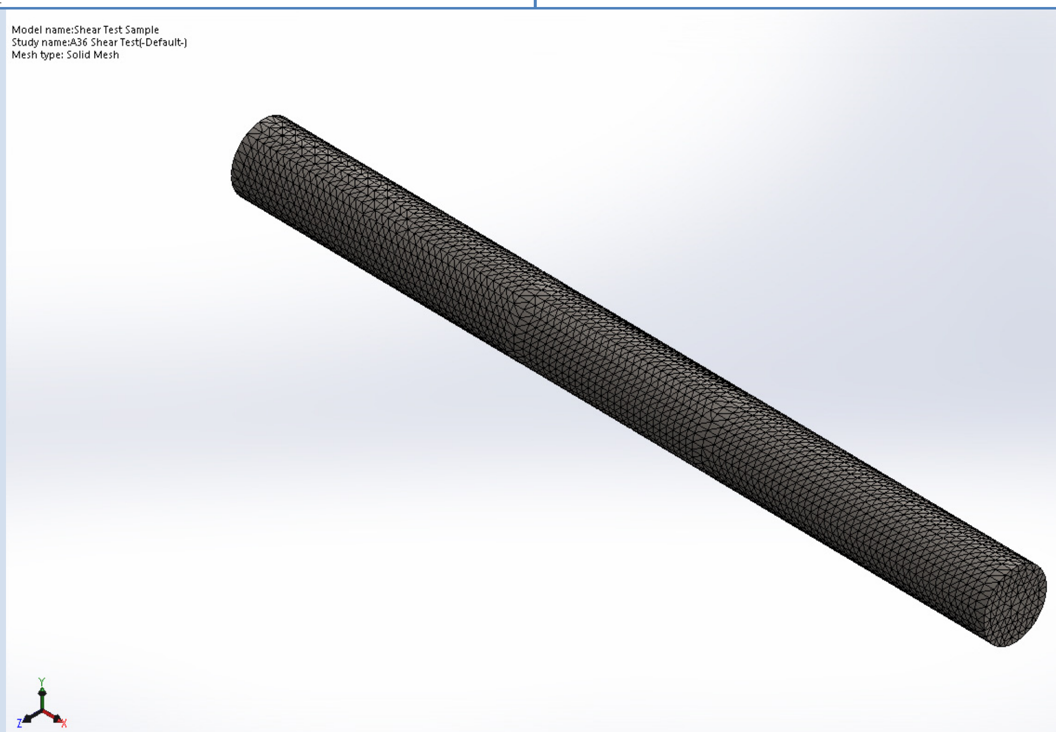
Load Name	Load Image	Load Details
Force-1		Entities: 1 face(s), 1 plane(s) Reference: Top Plane Type: Apply force Values: ---, ---, -3987 lbf

Mesh Information

Mesh type	Solid Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points	4 Points
Element Size	0.0263792 in
Tolerance	0.00131896 in
Mesh Quality	High

Mesh Details

Total Nodes	71157
Total Elements	48027
Maximum Aspect Ratio	4.4012
% of elements with Aspect Ratio < 3	99.9
% of elements with Aspect Ratio > 10	0
% of distorted elements(Jacobian)	0
Time to complete mesh(hh;mm;ss):	00:00:02
Computer name:	FTW-ENGR-D3



Resultant Forces

Reaction Forces

Selection Set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	lbf	-0.0158854	3987	0.00649495	3987

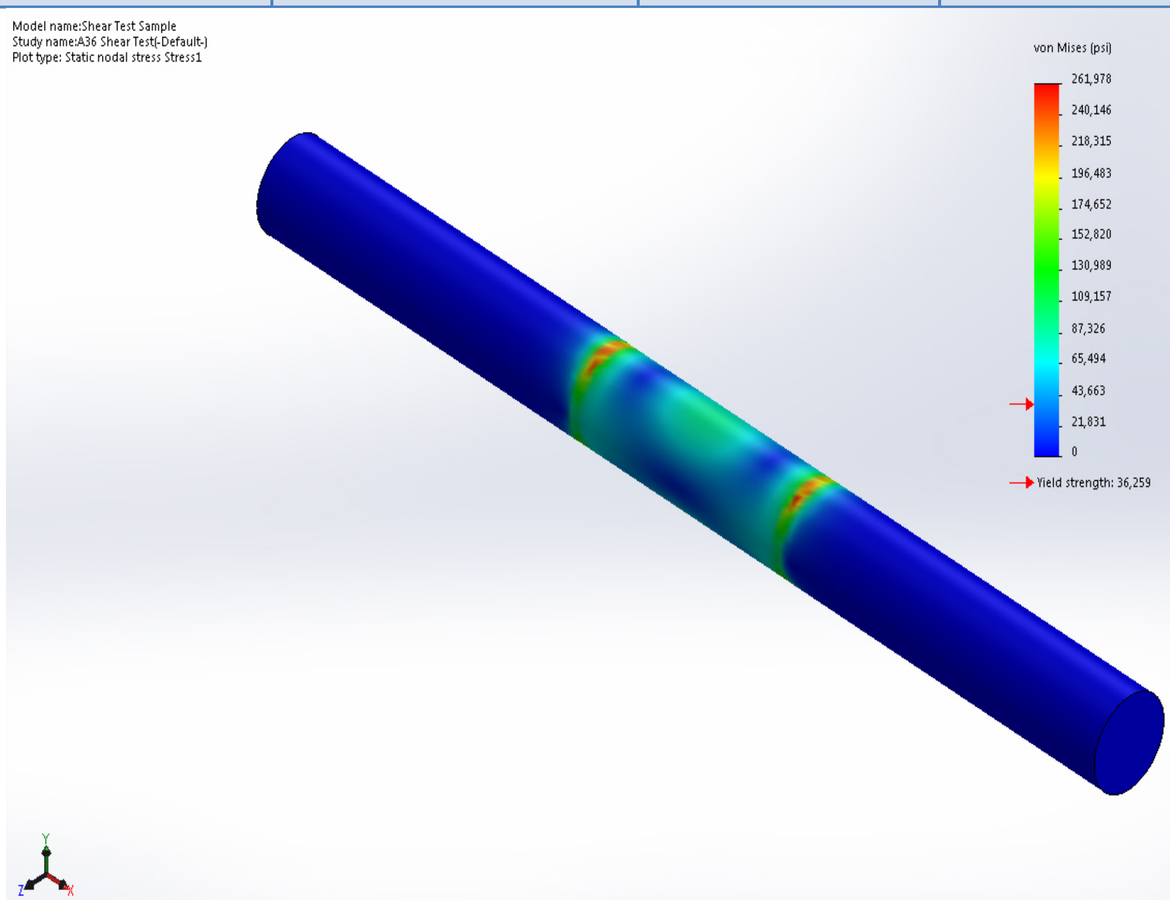
Reaction Moments

Selection Set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	lbf.in	0	0	0	0

Study Results

Stress

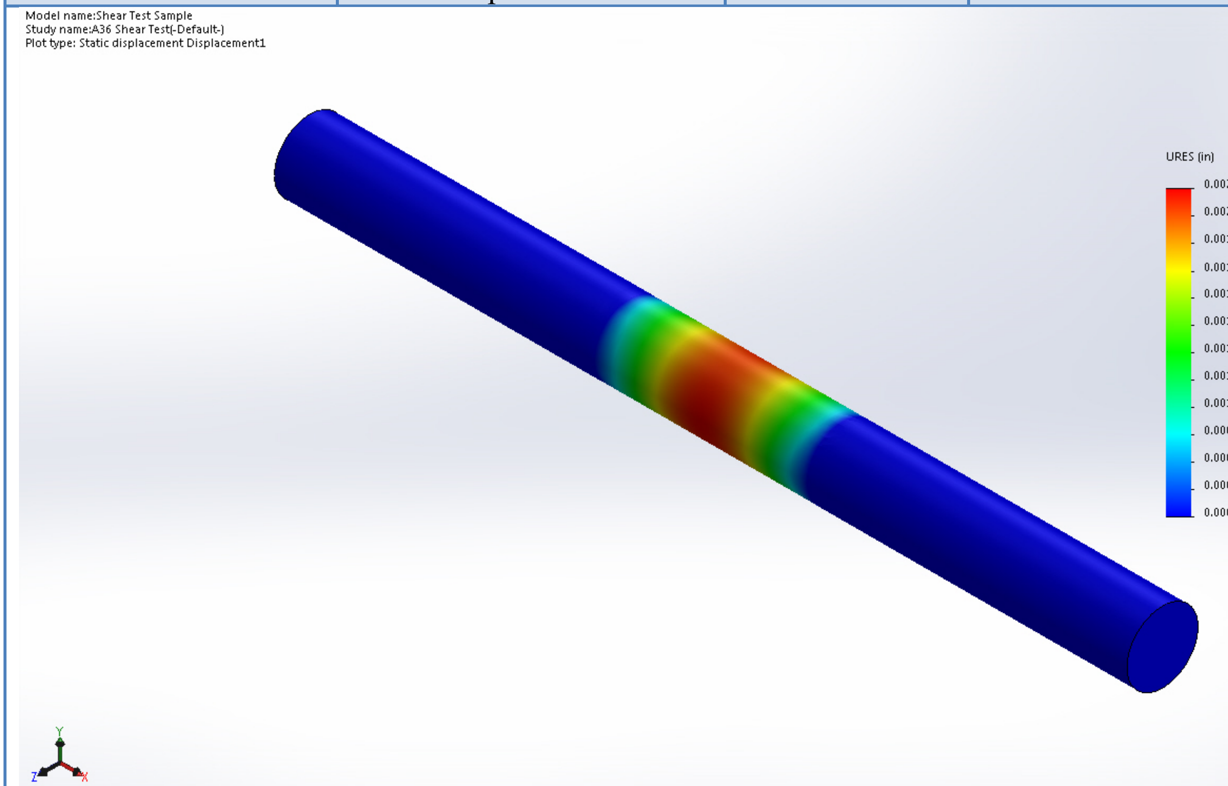
Name	Type	Min	Max
Stress1	VON: von Mises Stress	8.37421e-005 psi Node: 23724	261978 psi Node: 64764



Shear Test Specimen-A36 Shear Test-Stress-Stress1

Displacement

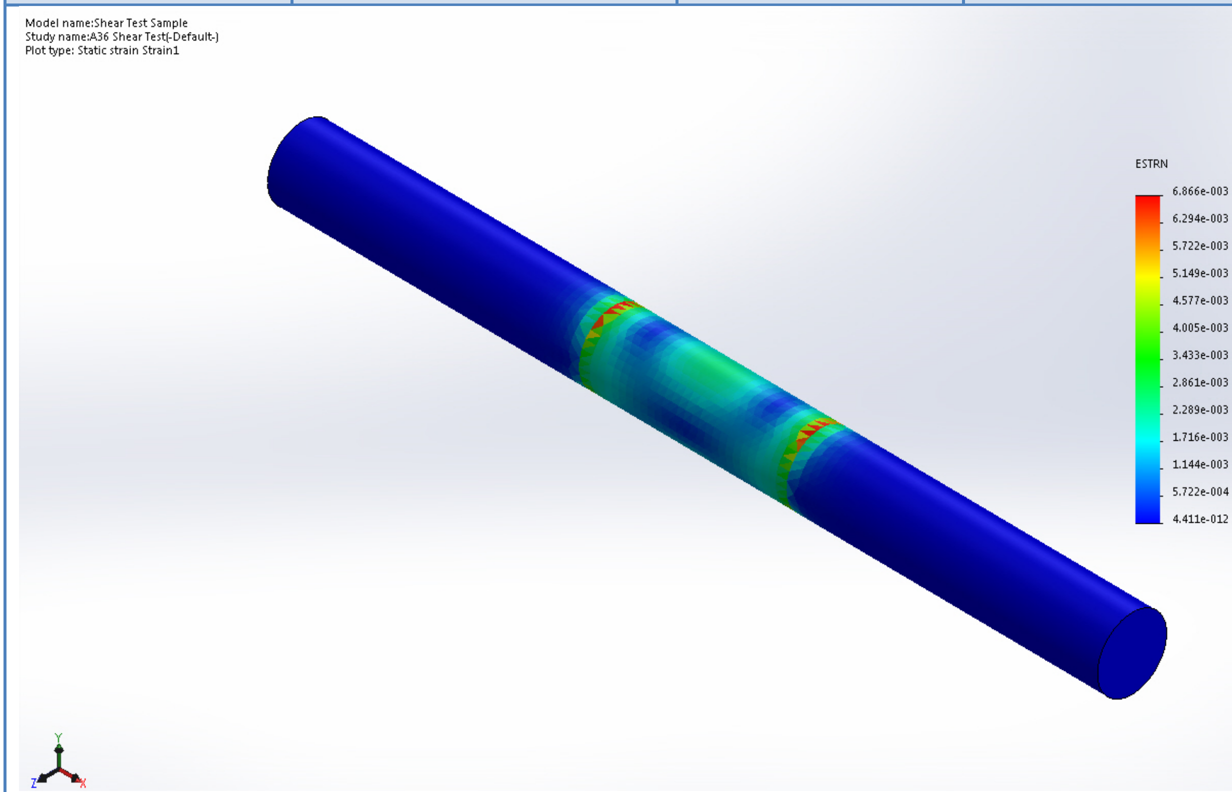
Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0 in Node: 1	0.00177684 in Node: 987



Shear Test Specimen-A36 Shear Test-Displacement-Displacement1

Strain

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	4.41141e-012 Element: 9009	0.0068658 Element: 12204



Shear Test Specimen-A36 Shear Test-Strain-Strain1

Conclusion

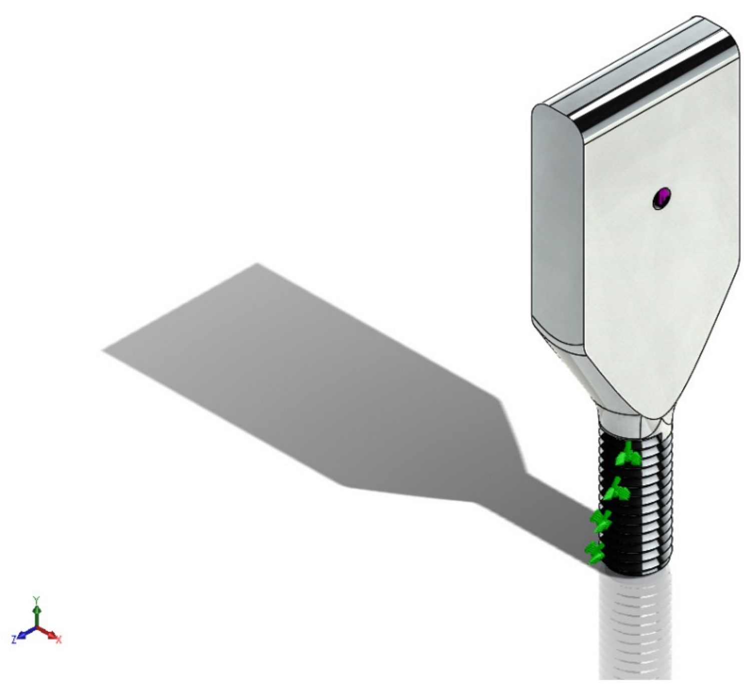
This is a static study and does not calculate any failure of material beyond normal displacement. The resulting stresses that come from shear and tensile failure will be reported as irregularly high values. In the case of this study, these high values verify that the specimen will shear at the applied load.

APPENDIX F: FEA OF SHEAR FIXTURE BOTTOM

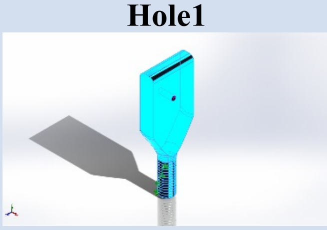
Introduction

The purpose of this simulation is to verify calculations of the gross tensile failure at the base of the threaded body of the fixture. It is assumed that the material is homogenous and without defect.

Model Information



Model name: Shear Fixture Bottom
Current Configuration: Default

Solid Bodies			
Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
Hole1 	**Solid Body**	Mass:1.99391 lb Volume:7.12143 in^3 Density:0.279987 lb/in^3 Weight:1.99255 lbf	C:\Users\eblack\Desktop\senior design\solid models\Shear Fixture Bottom.SLDPRT **Apr 20 17:07:46 2015**

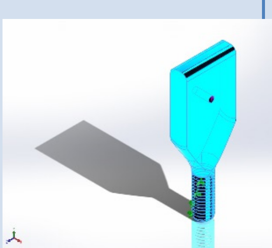
Study Properties

Study name	Tensile Failure
Analysis type	Static
Mesh type	Solid Mesh
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	77 Fahrenheit
Include fluid pressure effects from SOLIDWORKS Flow Simulation	Off
Solver type	FFEPlus
In-plane Effect:	Off
Soft Spring:	Off
Inertial Relief:	Off
Incompatible bonding options	Automatic
Large displacement	Off
Compute free body forces	On
Friction	Off
Use Adaptive Method:	Off

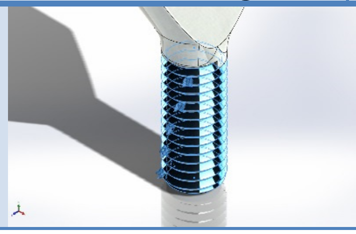
Units

Unit system:	English (IPS)
Length/Displacement	in
Temperature	Fahrenheit
Angular velocity	Rad/sec
Pressure/Stress	psi

Material Properties

Model Reference	Properties	Components
	**Name:** 630 HH1150 **Model type:** Linear Elastic Isotropic **Default failure criterion:** Unknown **Yield strength:** 123300 psi **Tensile strength:** 142700 psi **Elastic modulus:** 2.85724e+007 psi **Poisson's ratio:** 0.28 **Mass density:** 0.279987 lb/in^3	SolidBody 1(Hole1)(Shear Fixture Bottom)

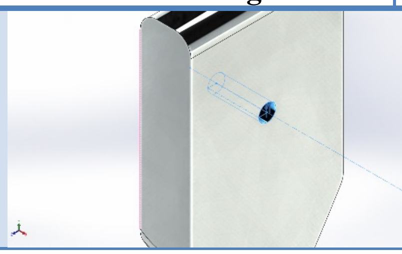
Fixtures

Fixture Name	Fixture Image	Fixture Details
Fixed-1		**Entities:** 1 face(s) **Type:** Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(lbf)	-2.60609	-53039.3	1.73468	53039.3
Reaction Moment(lbf.in)	0	0	0	0

Loads

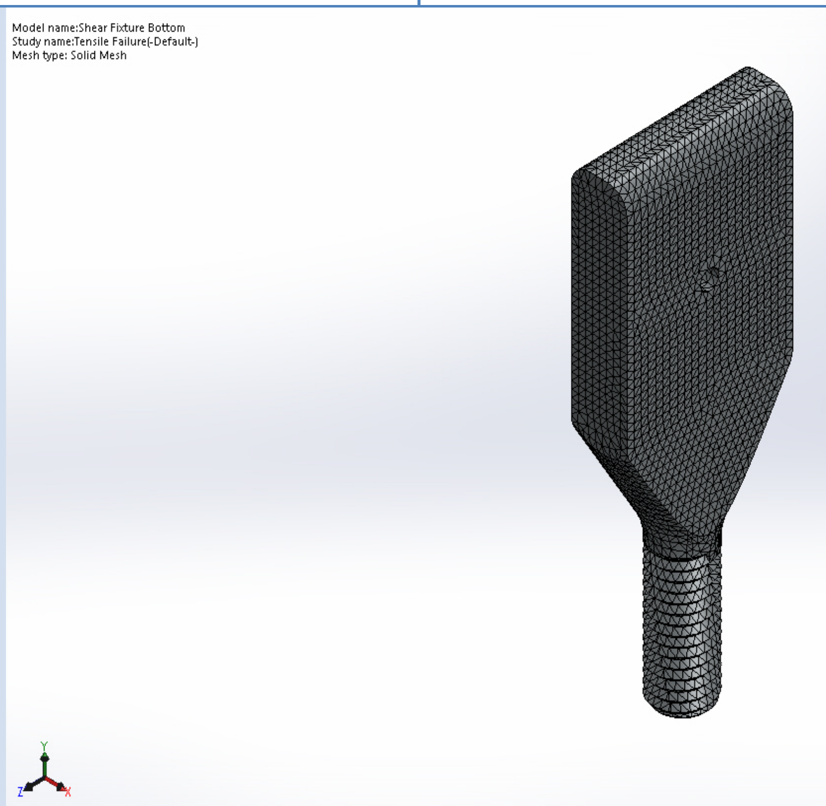
Load Name	Load Image	Load Details
Force-1		**Entities:** 1 face(s) **Reference:** Edge< 1 > **Type:** Apply force **Values:** ---, ---, -53035 lbf

Mesh Information

Mesh type	Solid Mesh
Mesher Used:	Curvature based mesh
Jacobian points	4 Points
Maximum element size	0 in
Minimum element size	0 in
Mesh Quality	High

Mesh Details

Total Nodes	79940
Total Elements	54507
Maximum Aspect Ratio	57.234
% of elements with Aspect Ratio < 3	99.7
% of elements with Aspect Ratio > 10	0.0312
% of distorted elements(Jacobian)	0
Time to complete mesh(hh;mm;ss):	00:00:05
Computer name:	FTW-ENGR-D3



Resultant Forces

Reaction Forces

Selection Set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	lbf	-2.60609	-53039.3	1.73468	53039.3

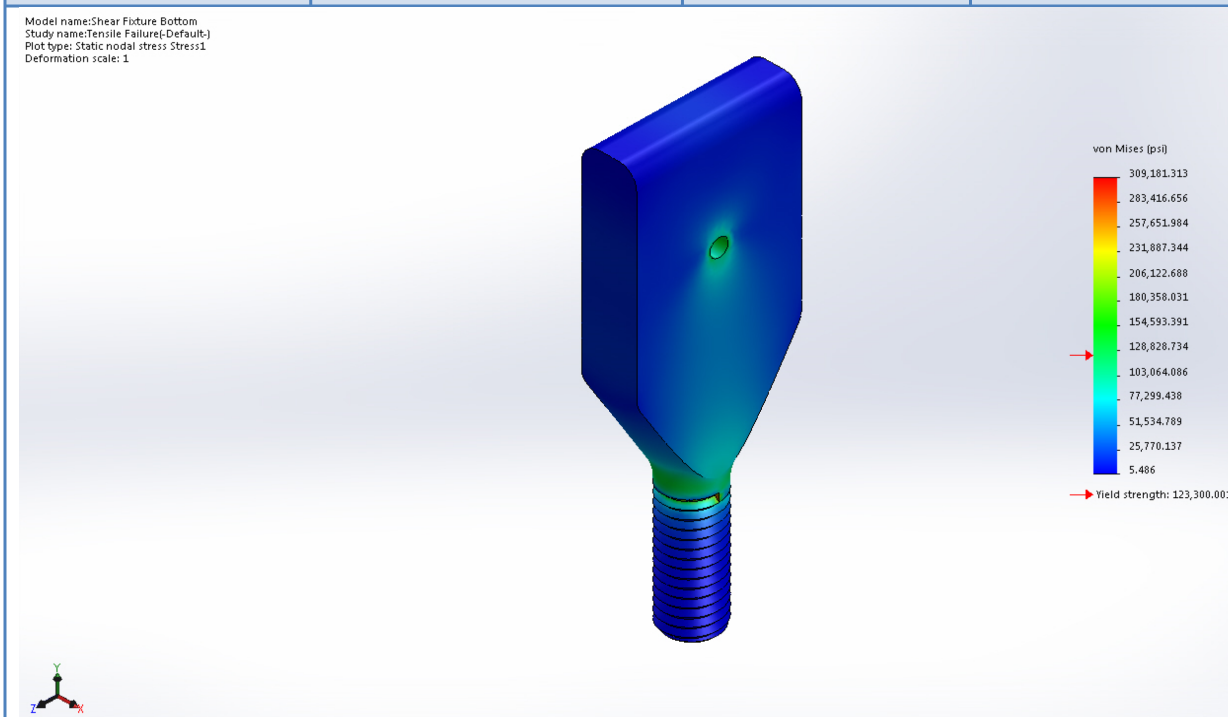
Reaction Moments

Selection Set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	lbf.in	0	0	0	0

Study Results

Stress

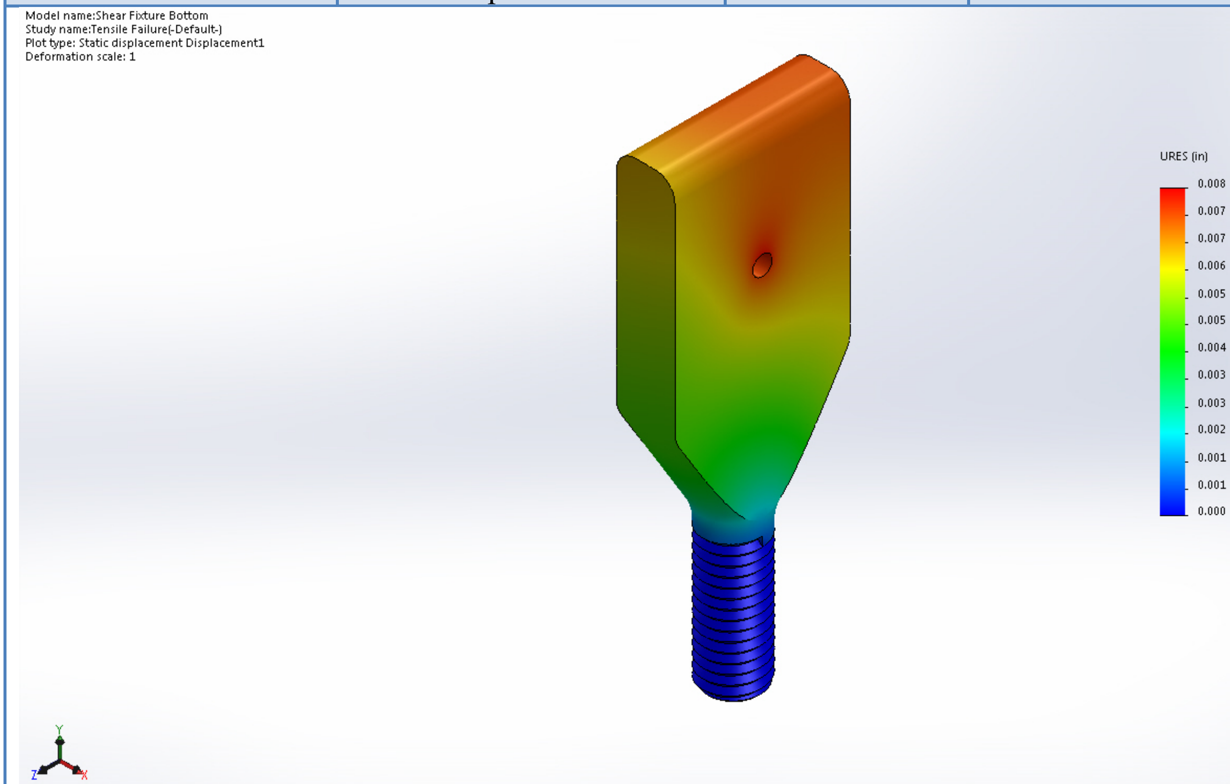
Name	Type	Min	Max
Stress1	VON: von Mises Stress	5.48646 psi Node: 75740	309181 psi Node: 79736



Shear Fixture Bottom-Tensile Failure-Stress-Stress1

Displacement

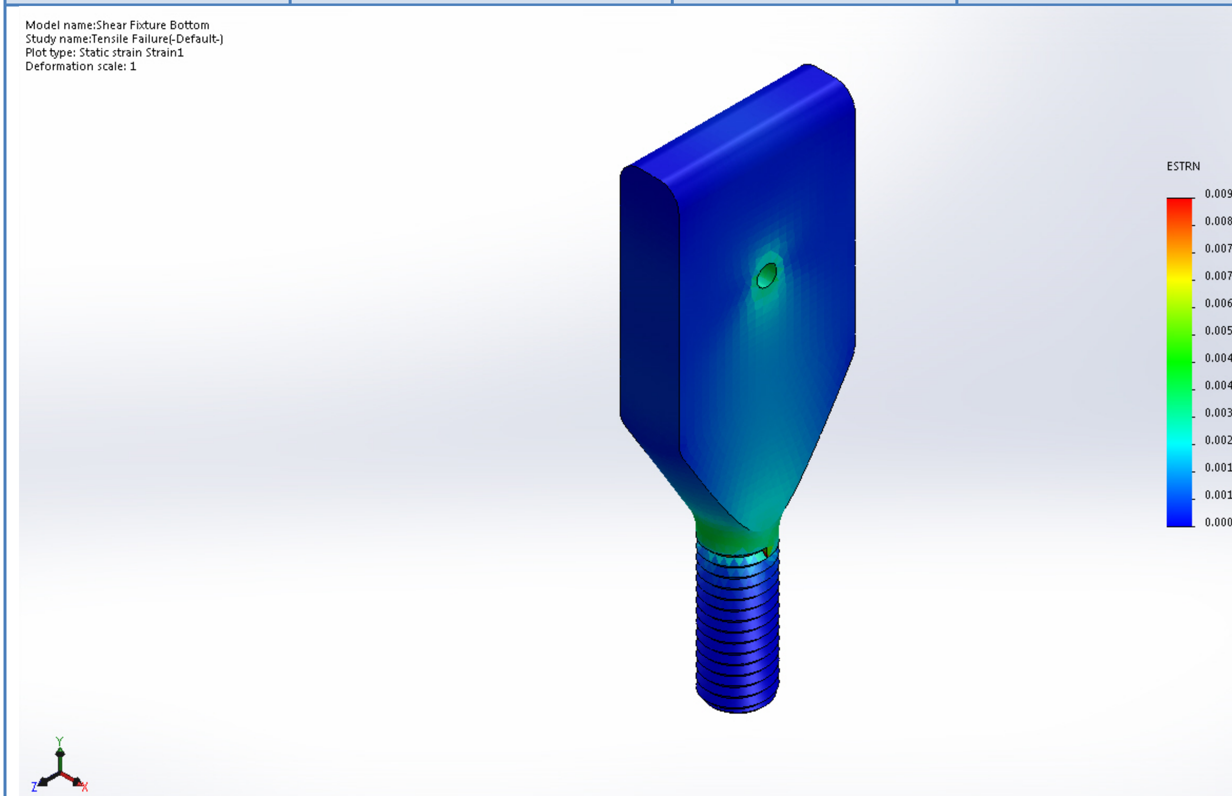
Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0 in Node: 2	0.00800013 in Node: 75001



Shear Fixture Bottom-Tensile Failure-Displacement-Displacement1

Strain

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	3.96717e-007 Element: 6747	0.00898262 Element: 5248



Shear Fixture Bottom-Tensile Failure-Strain-Strain1

Conclusion

The results of the simulation verify that gross tensile failure will occur at the base of the thread under the specified load.

APPENDIX G: TEST PROCEDURES

Table G-1, Tensile Testing Procedure

Tensile Test Methodology	
Step No.	***Description***
1	Measure and record the diameter of the specimen using the provided micrometer.
2	Secure the tensile specimen into the crosshead nuts on the tensile test equipment.
3	Clip the extensometer to the specimen for extension readings up until yielding.
4	Start the test by opening the "Load" valve on the machine. This begins to move the crossheads away from each other subsequently applying force to the test specimen.
5	Three readings need to be recorded until the extensometer is removed. When a group member reads off the extensometer reading (every 5x.0001"), another will read the dial indicator followed by the force reading.
6	The extensometer is removed when the samples begin to permanently deform. Once the extensometer is removed, the test may resume.
7	Read off every major 10x.001" hash mark on the dial indicator. A group member will read off the force reading at the same time. This will be repeated
8	After the test, the group will record the final diameter of the specimen, for reduction of area calculations, and the total elongation.
9	The group will then analyze the data of each sample and will adjust the change in length column based on the readings read off during the test.

Table G-2, Shear Testing Procedure

Shear Test Methodology	
Step No.	***Description***
1	Measure and record the each specimen’s diameter using the provided micrometers.
2	Align the specimen holes of the fixture by carefully bringing the upper and lower components of the fixture together.
3	Insert the test specimen through the aligned holes. Secure the sample specimen in the fixture by tightening the collars' set screw with the appropriate allen wrench.
4	Secure the fixture into each of the machines crossheads. Tighten each crosshead nut to ensure stability.
5	Set up the dial indicator and zero the dial before starting the test. The dial indicator will be used to measure the distance the crossheads move away from each other.
6	Start the test by opening the "Load" valve on the machine. This begins to move the crossheads away from each other subsequently applying force to the test specimen.
7	A group member will read off the dial indicator reading every 5x.001". Subsequently, a second group member will read off the applied force. This will be repeated until the sample reaches failure and breaks cleanly at the shear planes.
8	Group members will then analyze the data and compare the measured ultimate shear strength with the estimated values.

APPENDIX H: TESTING DATA

Aluminum

Table H-1, Aluminum Tensile Test Data

Aluminum Tensile Test								
Initial Diameter	**0.505** in.		Elongation **19%**			Area Reduction	45%	
Final Diameter	**0.374** in.					UTS	52,672 psi	
Extensometer (0.0001")	Dial indicator (0.001")	Extensometer (in.)	Dial Indicator (in.)	Adjusted Dial Indicator (in.)	Change in Length (in.)	Strain (in./in.)	Force (lb.)	Stress (psi)
5	3	0.0005			0.0005	0.00025	550	2,746
10	7	0.0010			0.0010	0.00050	1,200	5,991
15	10	0.0015			0.0015	0.00075	1,600	7,988
20	12	0.0020			0.0020	0.00100	2,250	11,233
25	14	0.0025			0.0025	0.00125	2,750	13,730
30	16	0.0030			0.0030	0.00150	3,250	16,226
35	18	0.0035			0.0035	0.00175	3,750	18,722
40	20	0.0040			0.0040	0.00200	4,250	21,219
45	21.5	0.0045			0.0045	0.00225	4,750	23,715
50	23	0.0050			0.0050	0.00250	5,250	26,211
55	25.5	0.0055			0.0055	0.00275	5,500	27,459
60	27	0.0060			0.0060	0.00300	6,200	30,954
65	29	0.0065			0.0065	0.00325	6,500	32,452
70	30	0.0070			0.0070	0.00350	7,050	35,198
75	32	0.0075			0.0075	0.00375	7,500	37,445
80	33.5	0.0080			0.0080	0.00400	7,900	39,442
85	34	0.0085			0.0085	0.00425	8,250	41,189
90	36	0.0090			0.0090	0.00450	8,550	42,687
95	37	0.0095	0.037	0.010	0.0095	0.00475	9,000	44,933
	40		0.040	0.013	0.0125	0.00625	9,300	46,431
	50		0.050	0.023	0.0225	0.01125	9,500	47,430
	60		0.060	0.033	0.0325	0.01625	9,600	47,929
	70		0.070	0.043	0.0425	0.02125	9,750	48,678
	80		0.080	0.053	0.0525	0.02625	9,800	48,928
	90		0.090	0.063	0.0625	0.03125	9,950	49,676
	100		0.100	0.073	0.0725	0.03625	10,050	50,176
	110		0.110	0.083	0.0825	0.04125	10,150	50,675
	120		0.120	0.093	0.0925	0.04625	10,200	50,925
	130		0.130	0.103	0.1025	0.05125	10,250	51,174
	140		0.140	0.113	0.1125	0.05625	10,300	51,424
	150		0.150	0.123	0.1225	0.06125	10,350	51,673
	160		0.160	0.133	0.1325	0.06625	10,450	52,173
	170		0.170	0.143	0.1425	0.07125	10,500	52,422
	180		0.180	0.153	0.1525	0.07625	10,550	52,672
	190		0.190	0.163	0.1625	0.08125	10,550	52,672
	200		0.200	0.173	0.1725	0.08625	10,550	52,672
	210		0.210	0.183	0.1825	0.09125	10,550	52,672
	220		0.220	0.193	0.1925	0.09625	10,550	52,672
	230		0.230	0.203	0.2025	0.10125	10,550	52,672
	240		0.240	0.213	0.2125	0.10625	10,550	52,672
	250		0.250	0.223	0.2225	0.11125	10,550	52,672
	260		0.260	0.233	0.2325	0.11625	10,550	52,672
	270		0.270	0.243	0.2425	0.12125	10,500	52,422
	280		0.280	0.253	0.2525	0.12625	10,450	52,173
	290		0.290	0.263	0.2625	0.13125	10,400	51,923
	300		0.300	0.273	0.2725	0.13625	10,350	51,673
	310		0.310	0.283	0.2825	0.14125	10,200	50,925
	320		0.320	0.293	0.2925	0.14625	10,100	50,425
	330		0.330	0.303	0.3025	0.15125	9,950	49,676
	340		0.340	0.313	0.3125	0.15625	9,700	48,428
	350		0.350	0.323	0.3225	0.16125	9,650	48,179
	360		0.360	0.333	0.3325	0.16625	9,400	46,931
	370		0.370	0.343	0.3425	0.17125	9,200	45,932
	380		0.380	0.353	0.3525	0.17625	8,950	44,684
	390		0.390	0.363	0.3625	0.18125	8,750	43,685
	400		0.400	0.373	0.3725	0.18625	8,400	41,938
	410		0.410	0.383	0.3825	0.19125	8,100	40,440

Figure H-1, Aluminum Tensile Stress-Strain Curve

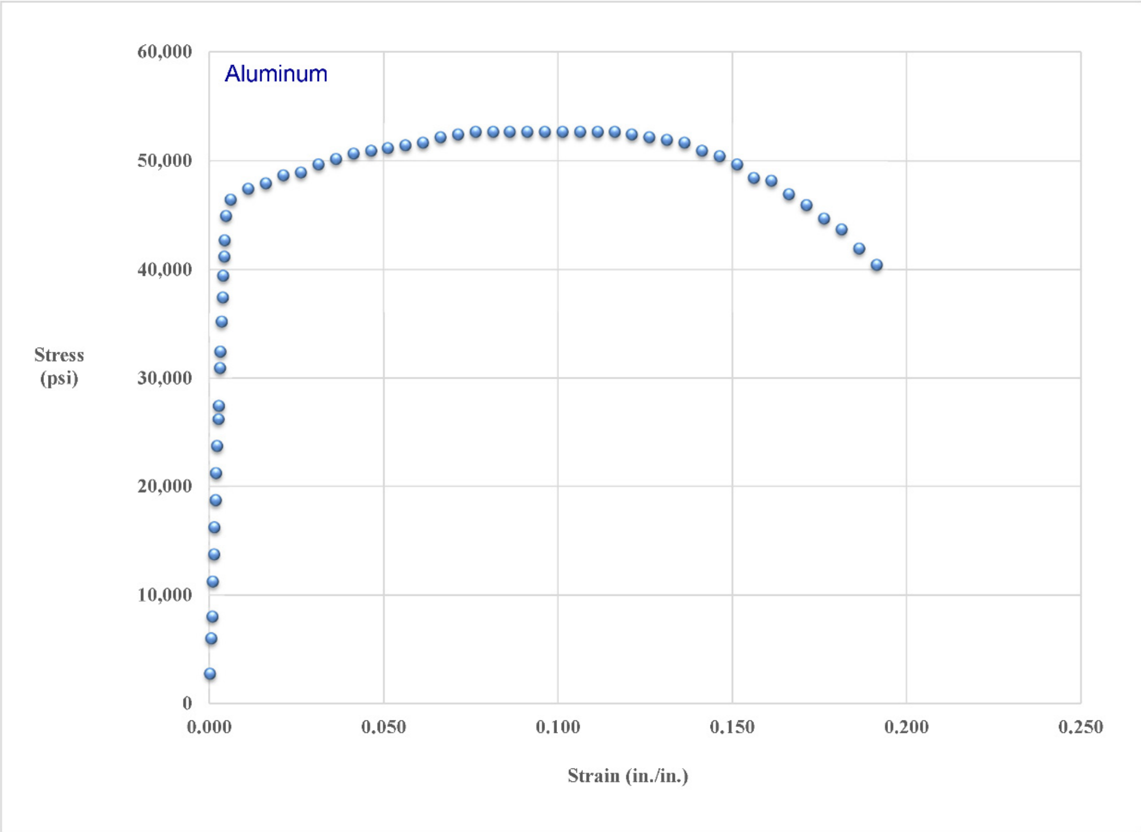


Figure H-2, Aluminum Tensile Young's Modulus

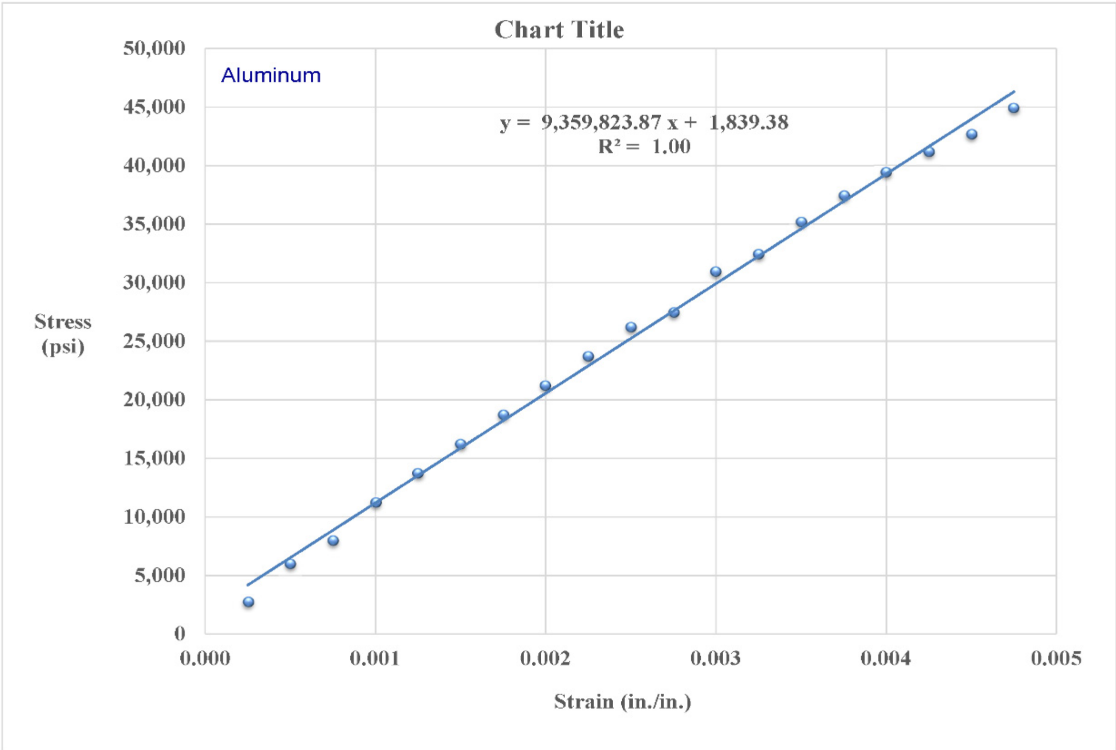
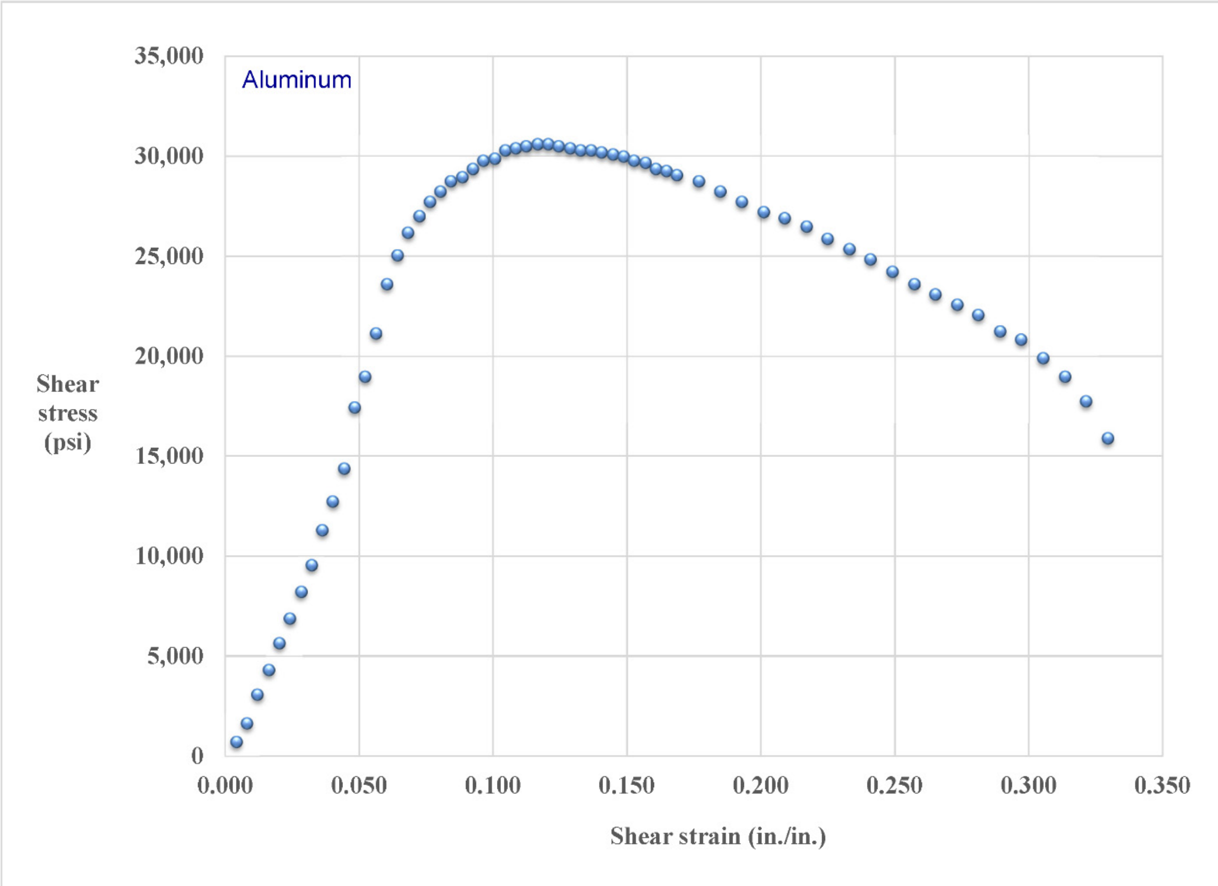


Table H-2, Aluminum Shear Test Data

Aluminum Shear Test				
Initial Diameter (in.)	0.249	Ultimate Shear Strength	30,598	psi
Dial indicator (0.001")	Dial indicator (in.)	Strain (in./in.)	Force (lb.)	Shear stress (psi)
1	0.001	0.004	70	719
2	0.002	0.008	160	1,643
3	0.003	0.012	300	3,080
4	0.004	0.016	420	4,313
5	0.005	0.020	550	5,647
6	0.006	0.024	670	6,879
7	0.007	0.028	800	8,214
8	0.008	0.032	930	9,549
9	0.009	0.036	1100	11,295
10	0.010	0.040	1240	12,732
11	0.011	0.044	1400	14,375
12	0.012	0.048	1700	17,455
13	0.013	0.052	1850	18,996
14	0.014	0.056	2060	21,152
15	0.015	0.060	2300	23,616
16	0.016	0.064	2440	25,054
17	0.017	0.068	2550	26,183
18	0.018	0.072	2630	27,005
19	0.019	0.076	2700	27,723
20	0.020	0.080	2750	28,237
21	0.021	0.084	2800	28,750
22	0.022	0.088	2820	28,955
23	0.023	0.092	2860	29,366
24	0.024	0.096	2900	29,777
25	0.025	0.100	2910	29,880
26	0.026	0.104	2950	30,290
27	0.027	0.108	2960	30,393
28	0.028	0.112	2970	30,496
29	0.029	0.116	2980	30,598
30	0.030	0.120	2980	30,598
31	0.031	0.124	2970	30,496
32	0.032	0.129	2960	30,393
33	0.033	0.133	2950	30,290
34	0.034	0.137	2950	30,290
35	0.035	0.141	2940	30,188
36	0.036	0.145	2930	30,085
37	0.037	0.149	2920	29,982
38	0.038	0.153	2900	29,777
39	0.039	0.157	2890	29,674
40	0.040	0.161	2860	29,366
41	0.041	0.165	2850	29,264
42	0.042	0.169	2830	29,058
44	0.044	0.177	2800	28,750
46	0.046	0.185	2750	28,237
48	0.048	0.193	2700	27,723
50	0.050	0.201	2650	27,210
52	0.052	0.209	2620	26,902
54	0.054	0.217	2580	26,491
56	0.056	0.225	2520	25,875
58	0.058	0.233	2470	25,362
60	0.060	0.241	2420	24,848
62	0.062	0.249	2360	24,232
64	0.064	0.257	2300	23,616
66	0.066	0.265	2250	23,103
68	0.068	0.273	2200	22,589
70	0.070	0.281	2150	22,076
72	0.072	0.289	2070	21,255
74	0.074	0.297	2030	20,844
76	0.076	0.305	1940	19,920
78	0.078	0.313	1850	18,996
80	0.080	0.321	1730	17,763
82	0.082	0.329	1550	15,915

Figure H-3, Aluminum Shear Stress-Strain Curve



Brass

Table H-3, Brass Tensile Test Data

Brass Tensile Test								
Initial Diameter: **0.504** in. Final Diameter: **0.295** in.			Elongation **29%**			Area Reduction 66% UTS 51,127 psi		
Extensometer (0.0001")	Dial indicator (0.001")	Extensometer (in.)	Dial Indicator (in.)	Adjusted Dial Indicator (in.)	Change in Length (in.)	Strain (in./in.)	Force (lb.)	Stress (psi)
5	2	0.0005			0.0005	0.00025	300	1,504
10	6	0.0010			0.0010	0.00050	750	3,759
15	8.5	0.0015			0.0015	0.00075	1,000	5,012
20	11	0.0020			0.0020	0.00100	1,750	8,772
25	12	0.0025			0.0025	0.00125	1,850	9,273
30	15	0.0030			0.0030	0.00150	2,000	10,025
35	16	0.0035			0.0035	0.00175	2,200	11,027
40	17.5	0.0040			0.0040	0.00200	2,500	12,531
45	19	0.0045			0.0045	0.00225	3,100	15,539
50	21	0.0050			0.0050	0.00250	3,500	17,544
55	22.5	0.0055			0.0055	0.00275	3,850	19,298
60	24	0.0060			0.0060	0.00300	4,000	20,050
65	25.5	0.0065			0.0065	0.00325	4,500	22,556
70	27	0.0070			0.0070	0.00350	4,750	23,809
75	28.5	0.0075			0.0075	0.00375	5,100	25,563
80	30	0.0080			0.0080	0.00400	5,250	26,315
85	31	0.0085			0.0085	0.00425	5,800	29,072
90	32.5	0.0090			0.0090	0.00450	6,000	30,075
95	33	0.0095			0.0095	0.00475	6,500	32,581
100	33.5	0.0100			0.0100	0.00500	6,750	33,834
105	34.5	0.0105	0.035	0.011	0.0105	0.00525	7,000	35,087
	40		0.040	0.016	0.0160	0.00800	8,000	40,100
	50		0.050	0.026	0.0260	0.01300	8,750	43,859
	60		0.060	0.036	0.0360	0.01800	8,800	44,109
	70		0.070	0.046	0.0460	0.02300	9,050	45,363
	80		0.080	0.056	0.0560	0.02800	9,150	45,864
	90		0.090	0.066	0.0660	0.03300	9,250	46,365
	100		0.100	0.076	0.0760	0.03800	9,300	46,616
	110		0.110	0.086	0.0860	0.04300	9,400	47,117
	120		0.120	0.096	0.0960	0.04800	9,450	47,368
	130		0.130	0.106	0.1060	0.05300	9,500	47,618
	140		0.140	0.116	0.1160	0.05800	9,600	48,119
	150		0.150	0.126	0.1260	0.06300	9,650	48,370
	160		0.160	0.136	0.1360	0.06800	9,700	48,621
	170		0.170	0.146	0.1460	0.07300	9,750	48,871
	180		0.180	0.156	0.1560	0.07800	9,750	48,871
	190		0.190	0.166	0.1660	0.08300	9,800	49,122
	200		0.200	0.176	0.1760	0.08800	9,800	49,122
	210		0.210	0.186	0.1860	0.09300	9,800	49,122
	220		0.220	0.196	0.1960	0.09800	9,900	49,623
	230		0.230	0.206	0.2060	0.10300	9,900	49,623
	240		0.240	0.216	0.2160	0.10800	9,900	49,623
	250		0.250	0.226	0.2260	0.11300	10,000	50,124
	260		0.260	0.236	0.2360	0.11800	10,000	50,124
	270		0.270	0.246	0.2460	0.12300	10,000	50,124
	280		0.280	0.256	0.2560	0.12800	10,100	50,626
	290		0.290	0.266	0.2660	0.13300	10,100	50,626
	300		0.300	0.276	0.2760	0.13800	10,100	50,626
	310		0.310	0.286	0.2860	0.14300	10,150	50,876
	320		0.320	0.296	0.2960	0.14800	10,150	50,876
	330		0.330	0.306	0.3060	0.15300	10,150	50,876
	340		0.340	0.316	0.3160	0.15800	10,150	50,876
	350		0.350	0.326	0.3260	0.16300	10,150	50,876
	360		0.360	0.336	0.3360	0.16800	10,150	50,876
	370		0.370	0.346	0.3460	0.17300	10,150	50,876
	380		0.380	0.356	0.3560	0.17800	10,150	50,876
	390		0.390	0.366	0.3660	0.18300	10,150	50,876
	400		0.400	0.376	0.3760	0.18800	10,200	51,127
	410		0.410	0.386	0.3860	0.19300	10,200	51,127
	420		0.420	0.396	0.3960	0.19800	10,150	50,876
	430		0.430	0.406	0.4060	0.20300	10,150	50,876
	440		0.440	0.416	0.4160	0.20800	10,150	50,876
	450		0.450	0.426	0.4260	0.21300	10,150	50,876
	460		0.460	0.436	0.4360	0.21800	10,000	50,124
	470		0.470	0.446	0.4460	0.22300	10,000	50,124
	480		0.480	0.456	0.4560	0.22800	9,900	49,623
	490		0.490	0.466	0.4660	0.23300	9,800	49,122
	500		0.500	0.476	0.4760	0.23800	9,800	49,122
	510		0.510	0.486	0.4860	0.24300	9,750	48,871
	520		0.520	0.496	0.4960	0.24800	9,500	47,618
	530		0.530	0.506	0.5060	0.25300	9,400	47,117
	540		0.540	0.516	0.5160	0.25800	9,250	46,365
	550		0.550	0.526	0.5260	0.26300	9,100	45,613
	560		0.560	0.536	0.5360	0.26800	9,000	45,112
	570		0.570	0.546	0.5460	0.27300	8,750	43,859
	580		0.580	0.556	0.5560	0.27800	8,600	43,107
	590		0.590	0.566	0.5660	0.28300	8,250	41,353
	600		0.600	0.576	0.5760	0.28800	8,150	40,851
	610		0.610	0.586	0.5860	0.29300	7,900	39,598
	620		0.620	0.596	0.5960	0.29800	7,500	37,593
	630		0.630	0.606	0.6060	0.30300	7,250	36,340

Figure H-4, Brass Tensile Stress-Strain Curve

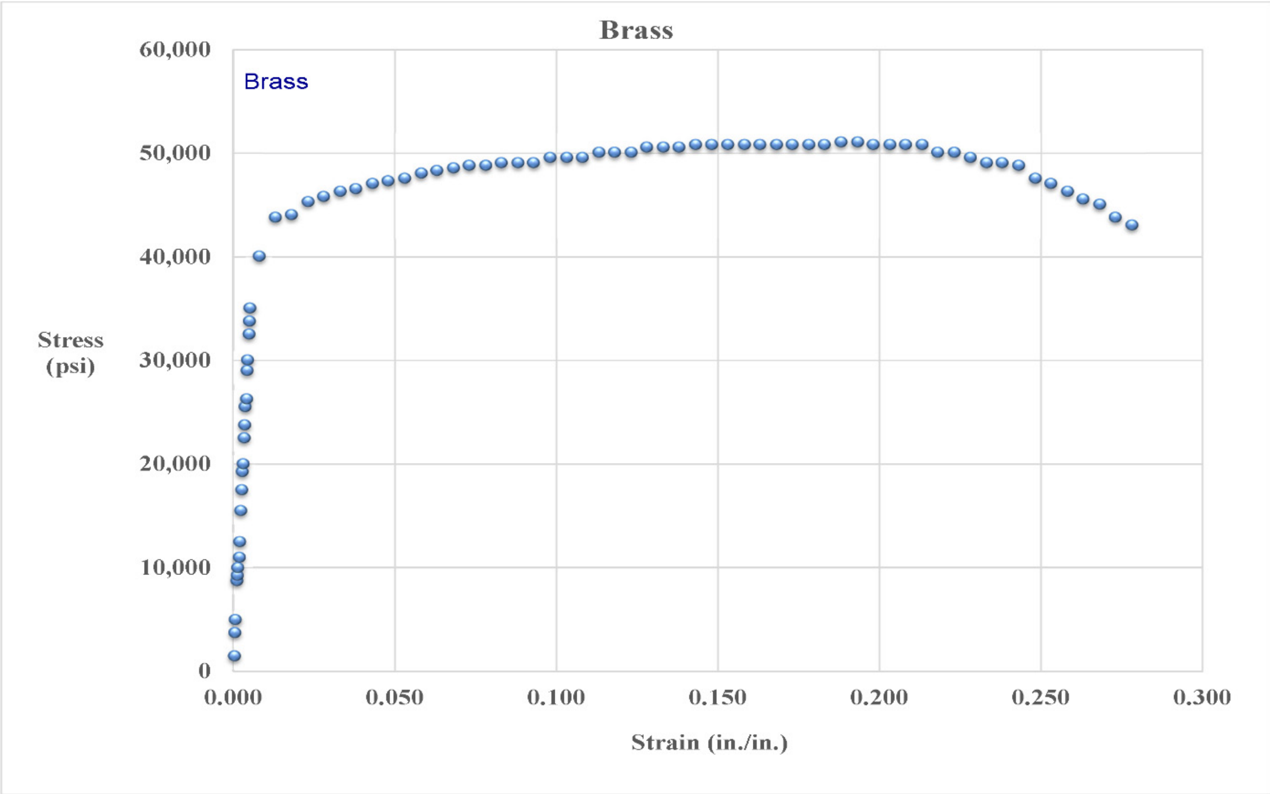


Figure H-5, Brass Tensile Young's Modulus

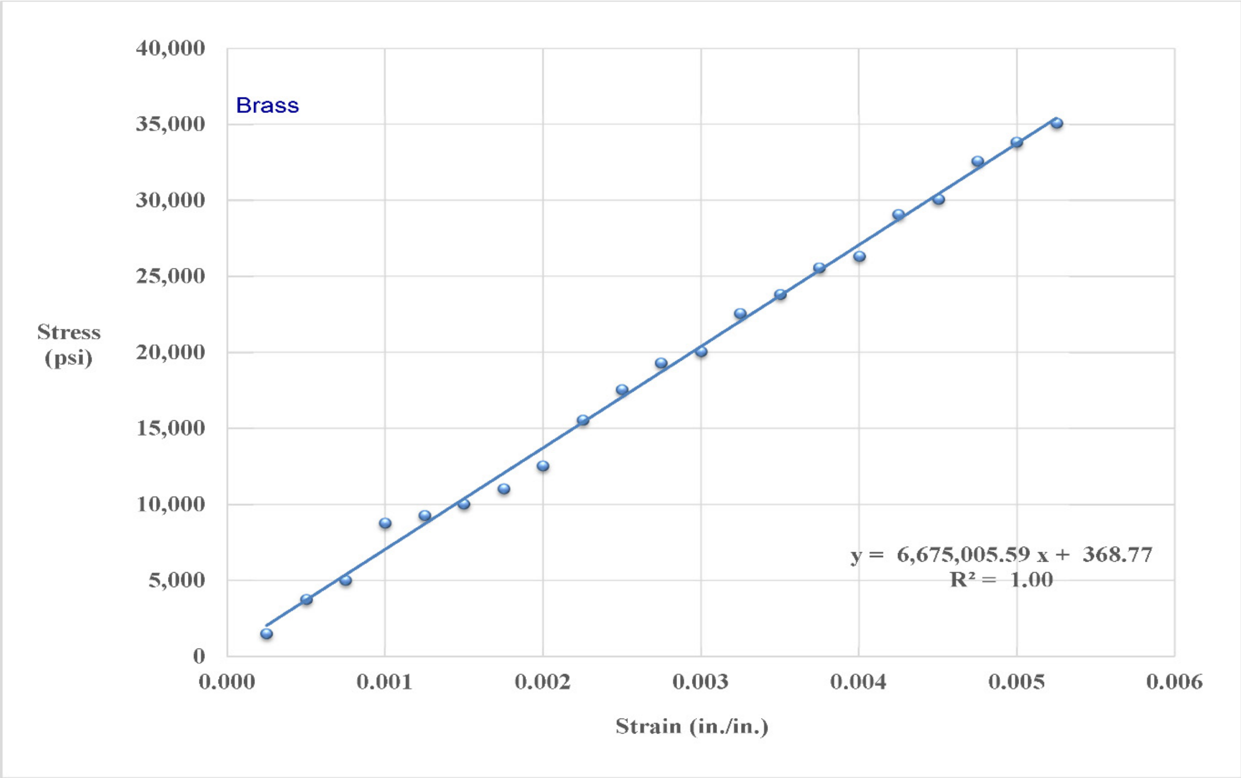
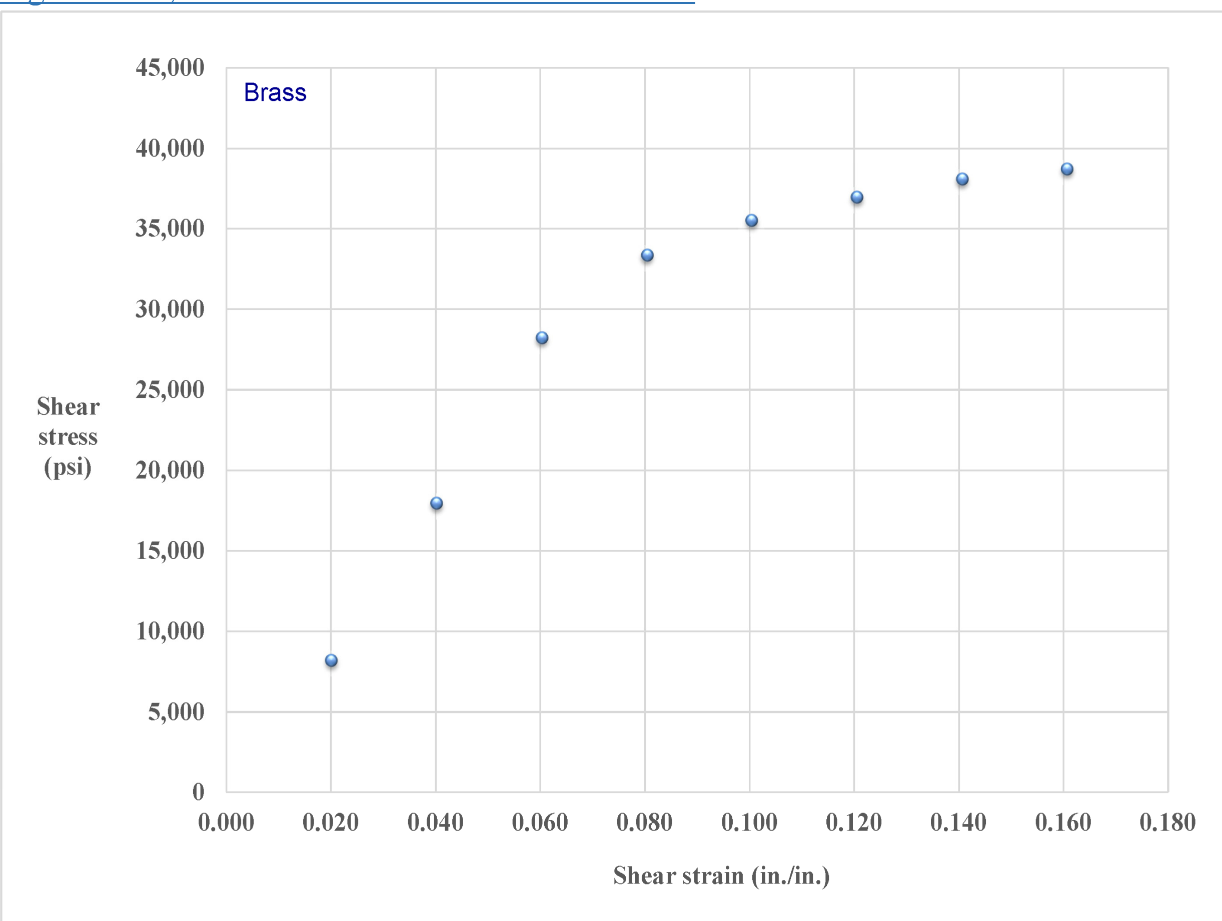


Table H-4, Brass Shear Test Data

Brass Shear Test				
Initial Diameter (in.)	0.249	Ultimate Shear Strength	38,710	psi
Dial indicator (0.001")	Dial indicator (in.)	Strain (in./in.)	Force (lb.)	Shear stress (psi)
5	0.005	0.020	800	8,214
10	0.010	0.040	1750	17,969
15	0.015	0.060	2750	28,237
20	0.020	0.080	3250	33,371
25	0.025	0.100	3460	35,527
30	0.030	0.120	3600	36,964
35	0.035	0.141	3710	38,094
40	0.040	0.161	3770	38,710

Figure H-6, Brass Shear Stress-Strain Curve



Steel

Table H-5, Steel Tensile Test Data

Steel Tensile Test									
Initial Diameter: **0.508** in. Final Diameter: **0.456** in.			Elongation **17%**			Area Reduction 19% UTS 79,681 psi			
Extensometer (0.0001")	Dial indicator (0.001")	Extensometer (in.)	Dial Indicator (in.)	Adjusted Dial Indicator (in.)	Change in Length (in.)	Strain (in./in.)	Force (lb.)	Stress (psi)	
5	8.5	0.0005			0.0005	0.00025	2,200	10,854	
10	13	0.0010			0.0010	0.00050	3,500	17,268	
15	16	0.0015			0.0015	0.00075	5,100	25,162	
20	20	0.0020			0.0020	0.00100	6,500	32,070	
25	23	0.0025			0.0025	0.00125	7,800	38,484	
30	26.5	0.0030			0.0030	0.00150	9,500	46,871	
35	29	0.0035			0.0035	0.00175	10,800	53,285	
40	32	0.0040			0.0040	0.00200	12,200	60,193	
45	35	0.0045			0.0045	0.00225	13,250	65,373	
50	36	0.0050			0.0050	0.00250	14,200	70,060	
55	38	0.0055			0.0055	0.00275	14,650	72,280	
60	39	0.0060	0.039	0.006	0.0060	0.00300	15,000	74,007	
	40		0.040	0.007	0.0070	0.00350	15,200	74,994	
	50		0.050	0.017	0.0170	0.00850	15,550	76,721	
	60		0.060	0.027	0.0270	0.01350	15,650	77,214	
	70		0.070	0.037	0.0370	0.01850	15,750	77,708	
	80		0.080	0.047	0.0470	0.02350	15,850	78,201	
	90		0.090	0.057	0.0570	0.02850	15,950	78,694	
	100		0.100	0.067	0.0670	0.03350	16,050	79,188	
	110		0.110	0.077	0.0770	0.03850	16,100	79,434	
	120		0.120	0.087	0.0870	0.04350	16,150	79,681	
	130		0.130	0.097	0.0970	0.04850	16,150	79,681	
	140		0.140	0.107	0.1070	0.05350	16,150	79,681	
	150		0.150	0.117	0.1170	0.05850	16,100	79,434	
	160		0.160	0.127	0.1270	0.06350	16,050	79,188	
	170		0.170	0.137	0.1370	0.06850	16,000	78,941	
	180		0.180	0.147	0.1470	0.07350	15,900	78,448	
	190		0.190	0.157	0.1570	0.07850	15,700	77,461	
	200		0.200	0.167	0.1670	0.08350	15,550	76,721	
	210		0.210	0.177	0.1770	0.08850	15,400	75,981	
	220		0.220	0.187	0.1870	0.09350	15,250	75,241	
	230		0.230	0.197	0.1970	0.09850	15,050	74,254	
	240		0.240	0.207	0.2070	0.10350	14,900	73,514	
	250		0.250	0.217	0.2170	0.10850	14,750	72,774	
	260		0.260	0.227	0.2270	0.11350	14,600	72,034	
	270		0.270	0.237	0.2370	0.11850	14,300	70,554	
	280		0.280	0.247	0.2470	0.12350	14,200	70,060	
	290		0.290	0.257	0.2570	0.12850	13,950	68,827	
	300		0.300	0.267	0.2670	0.13350	13,700	67,593	
	310		0.310	0.277	0.2770	0.13850	13,500	66,606	
	320		0.320	0.287	0.2870	0.14350	13,200	65,126	
	330		0.330	0.297	0.2970	0.14850	12,950	63,893	
	340		0.340	0.307	0.3070	0.15350	12,650	62,413	
	350		0.350	0.317	0.3170	0.15850	12,250	60,439	

Figure H-7, Steel Tensile Stress-Strain Curve

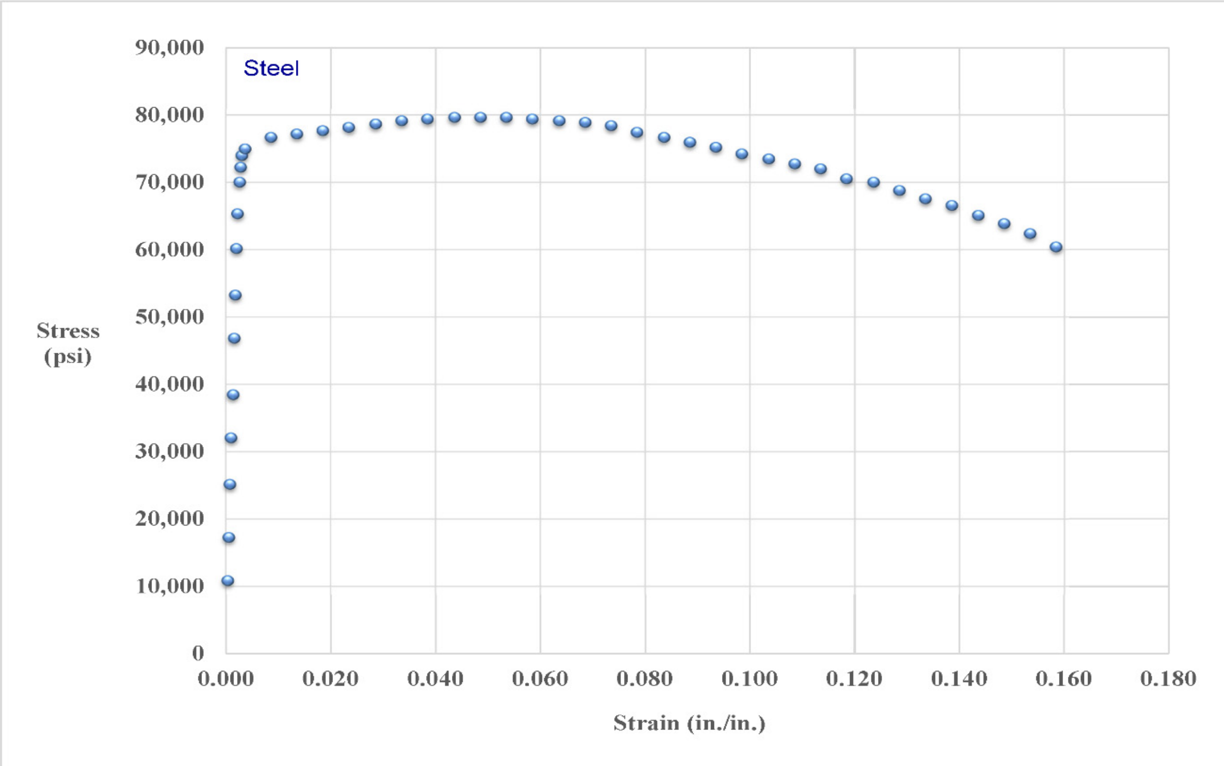


Figure H-8, Steel Tensile Young's Modulus

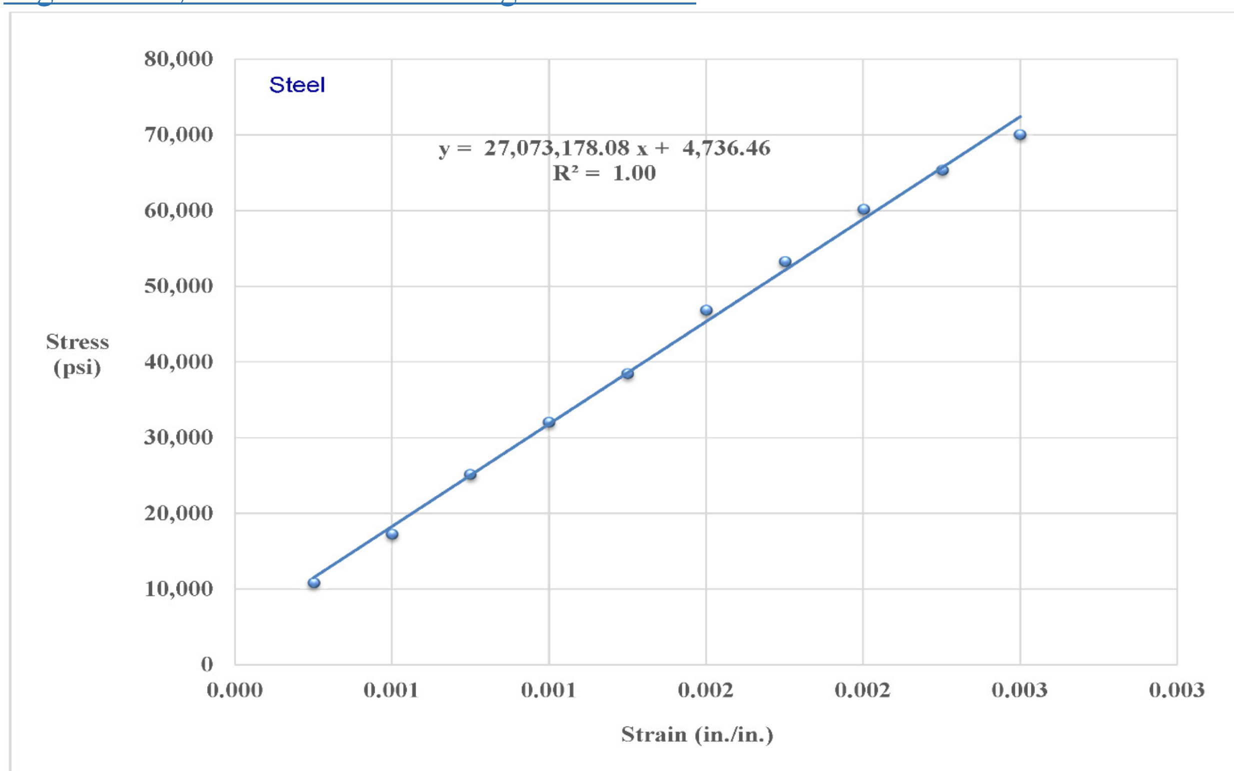


Table H-6, Steel Shear Test Data

Steel Shear Test				
Initial Diameter (in.) 0.249		Ultimate Shear Strength: 43,947 psi		
Dial indicator (0.001")	Dial indicator (in.)	Strain (in./in.)	Force (lb.)	Shear stress (psi)
5	0.005	0.020	950	9,755
10	0.010	0.040	2,300	23,616
15	0.015	0.060	3,550	36,451
20	0.020	0.080	3,960	40,661
25	0.025	0.100	4,150	42,612
30	0.030	0.120	4,250	43,639
35	0.035	0.141	4,280	43,947
40	0.040	0.161	4,150	42,612
45	0.045	0.181	3,850	39,531
50	0.050	0.201	3,500	35,938
55	0.055	0.221	3,200	32,857
60	0.060	0.241	2,750	28,237
65	0.065	0.261	2,300	23,616
70	0.070	0.281	1,700	17,455

Figure H-9, Steel Shear Stress-Strain Curve