# Truss Project - Final Design Report
GEEN 2581 - Fall 2021

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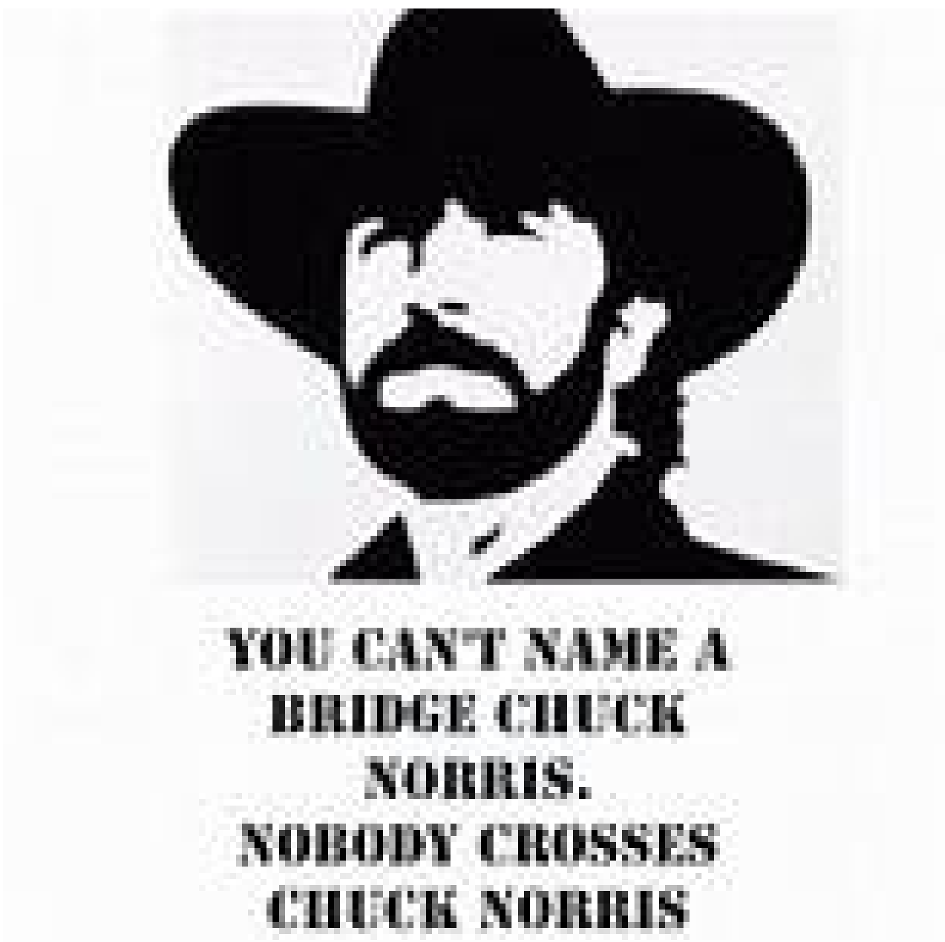

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## Summary of Scope

The purpose of this group project was to demonstrate knowledge gained throughout the course of the semester by applying it in the real world. To do this we designed and built a truss with the goal of withstanding 1200 lbs of force. We worked towards this goal by testing and calculating stresses and shear forces in different truss designs. During the design phase we decided that a simple truss would leave less room for error during the manufacturing process. So we decided on a basic Warren truss consisting of five triangles where the point load would act in the middle. When building our truss, we had to follow some assumptions in order to meet the requirements of a truss. None of the members could touch and all members had to be cut at a 90° angle. Some other requirements consisted of a size constraint of 22 - 23" in length, and a max height of 7". Each member specifically had to be greater than 3" and the truss had to consist of more than 6 members.

The first thing we tested was the shear strength of the glue and the bending strength in the wood. We used the machines in the ITLL to test the failure load of our components. In both the shear test and bending test, our materials broke right down the middle of the member. The stress in our wood was about 1.5 ksi and the shear stress was about 1.3 ksi. We predicted the shear stress to be 1252.64 psi and the maximum beam stress to be 14.29 ksi. This data allowed us to analyze the numbers and calculate our max load and strength to weight ratio. Our predicted maximum load was 2658 lbs and our predicted strength to weight ratio was 4437.

# Background and Theory

**Four Point Bending**

The four point bending test is a method to test the strength of the wood being used. The test is done by placing a beam of wood under a single force that increases until the beam breaks. The selected material is pine wood with dimensions of 12x.75x.5 inches. The wood is placed on two rollers, with 0.5 inches over each roller. The loading apparatus above the sample will apply two point forces (P/2) that are 4 inches from the bottom rollers (see Figure 1).

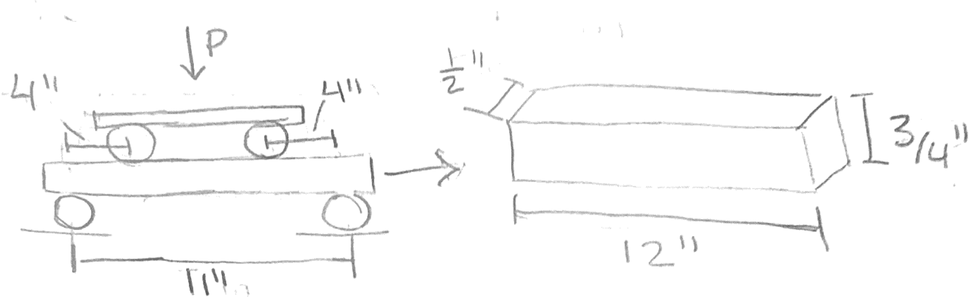



*Figure 1: On the left is the wooden beam in the bending test with two point forces downward and two point forces upward. On the right is the dimensions of the wooden beam.*

These results will allow us to determine (1) the bending stress:

$$(1) \quad \sigma = \frac{Mc}{I} = \frac{3Pl}{bh^2}$$

In equation (1) the values are: P=the force applied to the beam, l=4 inches (the length between the top rollers), b=0.75 inches and h=0.5 inches (the base and height of the wood).

**Shear Test**

The shear test will be used to test the maximum shear strength of the Titebond lll Wood Glue. The test specimen will be two pieces of pine wood 0.25x0.75x3 inches that are glued together by birch plywood plates that are 0.125x0.75x1.25 inches. The glue will cover 0.5 inch of each piece of wood on one side. The material is glued and then clamped for 24 hours to ensure a stronger hold (Figure 2).

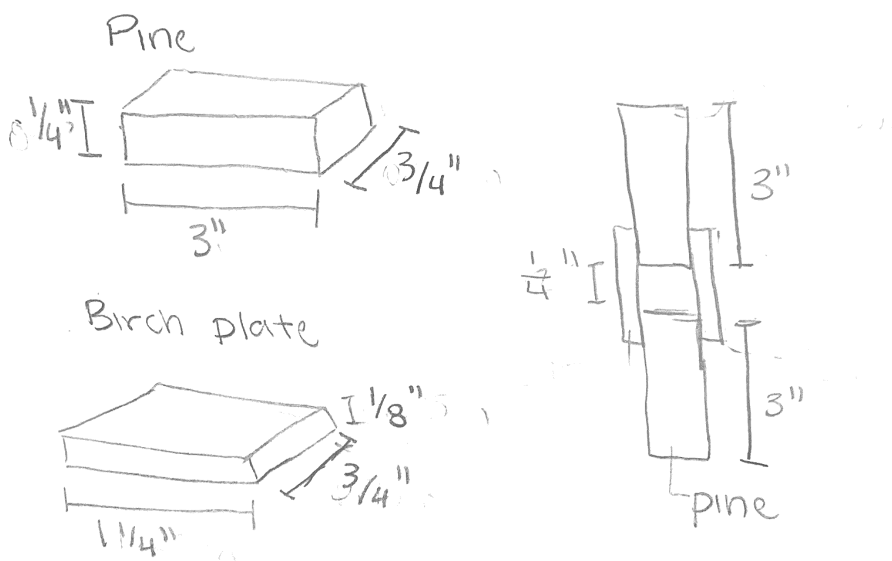



*Figure 2: On the top left is the pine wood that was glued together. The bottom left is the birch plate that was used as a gusset for the pine wood. On the right is the diagram of how the birch plates were used to glue the pine together.*

The test will be done by clamping the edges of the pine pieces and measuring the tension force and distance as they are pulled apart until the glue fails. The shear failure stress can be calculated by using:

$$(2) \quad \tau = \frac{F}{2A}$$

In equation (2) the variables F will be the tension force from the test and A is the area of the portion of wood covered by glue.

# Test Results

**Four Point Bending Test**

The strength of the pine wood was tested using the MTS machine. The force on the wood was recorded as it slowly increased until the specimen failed. The first specimen (Figure 3) broke at a force of 201.98 lbs and the second specimen (Figure 4) broke at a force of 190.709 lbs. The first beam broke at the midpoint and the second beam did not break fully but it bent at the midpoint. The bending stress for the first specimen was 16.12 ksi and the second was 14.29 ksi. Test 1 was the stronger, more resistant test. Table 1 shows the results from the test and Graph 1 and Graph 2 show the load versus deflection curve from the tests.

*Table 1: Four Point Bending*

| | Test 1 | Test 2 | Measurement Device |
|---|---|---|---|
| Failure Load P (lbs) | 201.98 | 190.709 | MTS Machine |
| Length (in) | 4 | 4 | Ruler |
| Base (in) | 0.717 | 0.719 | Calipers |
| Height (in) | 0.458 | 0.472 | Calipers |
| Stress σ (ksi) | 16.12 | 14.29 | Calculate (Figure 10) |

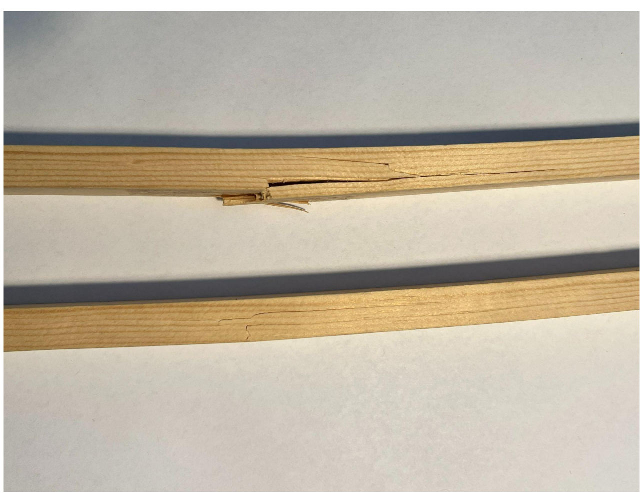


*Figure 3: Specimen after the bending test 1 (left) and 2 (right).*

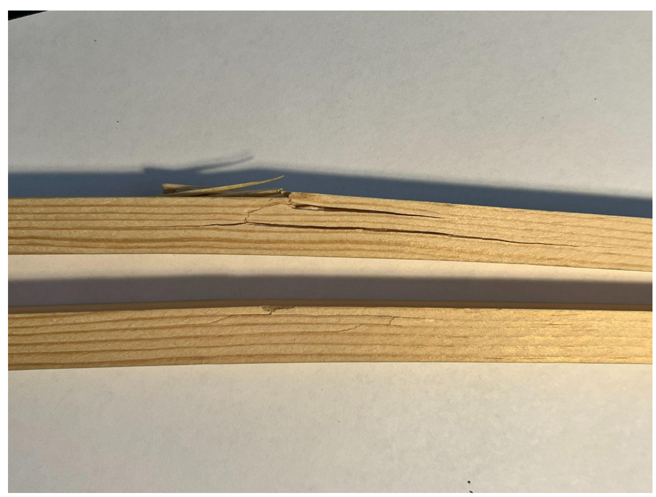
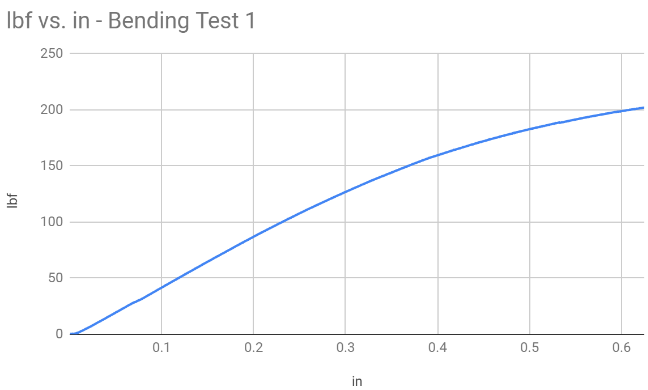
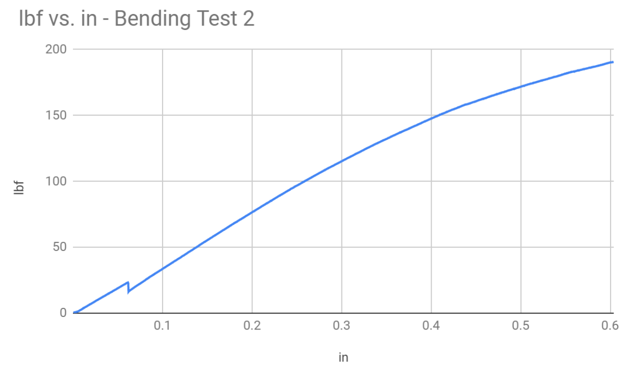


*Figure 4: Specimen after the bending test 1 (left) and 2 (right).*

*Graph 1 - Bending Test 1*




*Graph 2 - Bending test 2*




**Shear Test**

The shear test was used to determine the strength of the Titebond III Wood Glue. The shear force was recorded as two pieces of pine wood held together by birch plates glued to them were slowly pulled apart. The first test (Figure 6 and 8) failed at a force of 949.77 lbs and the second test (Figure 7 and 9) failed at a force of 1119.94 lbs. The shear stress for the first specimen was 1252.5 psi and the second was 1544.4 psi. The glue in test 2 was stronger than our second test. Both specimens broke the same way with one plate breaking off completely along with taking some of the pine wood with it while the other plate remained attached to one piece of pine. Table 2 shows the results of the test and Graph 3 and Graph 4 show the time versus load curve.

*Table 2: Shear Test Results*

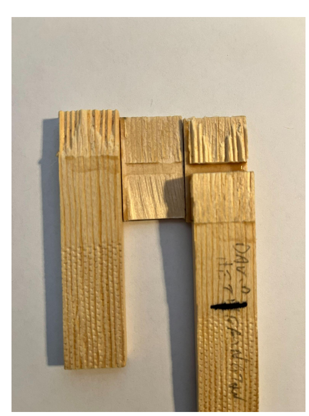
| | Test 1 | Test 2 | Measuring Device |
|---|---|---|---|
| Width (in) | 0.742 | 0.731 | Shear Machine |
| Length (in) | 0.511 | 0.496 | Calipers |
| Failure Load (lbs) | 949.77 | 1119.94 | Calipers |
| Shear Stress (psi) | 1252.46 | 1544.42 | Calculated by hand |

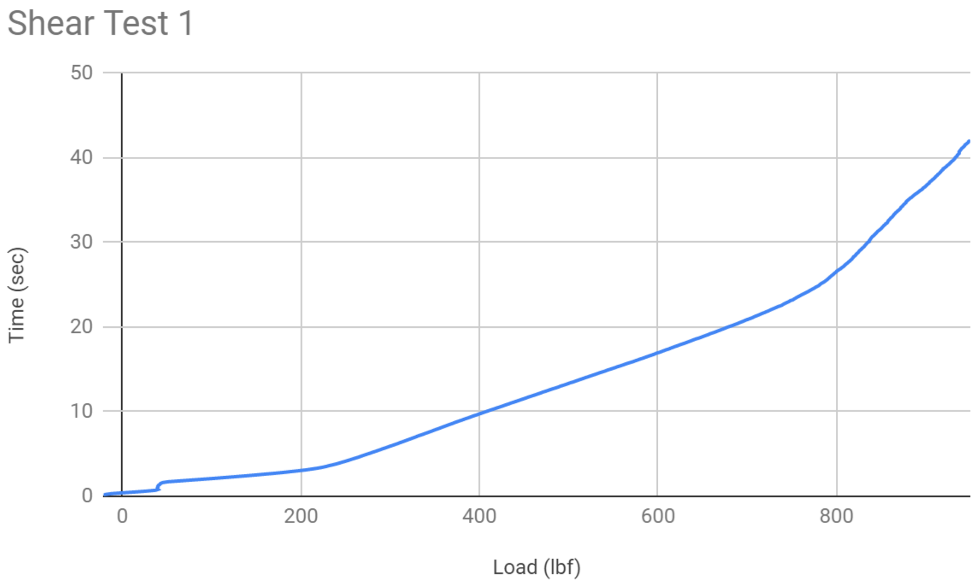
*Figure 5: Shear test 1*

*Figure 6: Shear test 2*

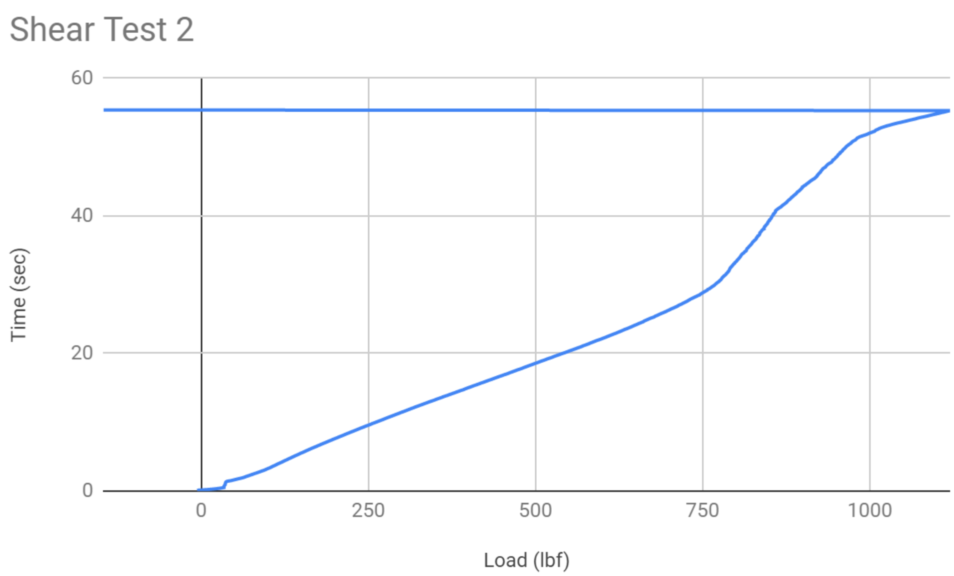
*Figure 7: Shear test 1*

*Figure 8: Shear test 2*






*Graph 3 - Shear Test 1*




*Graph 4 - Shear Test 2*

## Materials Testing Conclusion

In conclusion, the failure load for pine wood under the four point bending test was 201.9 lbs for test one and190.7 lbs for test two. The failure load of Titebond III Glue was 949.7 lbs for test one and 1120 lbs for test two. The failure loads for both the four point bending test and the shear test vary between tests because of possible errors. With the four point bending test, the failure load varied due to using different wood beams and a small uncertainty with the measurement. The bending stress for the first specimen was 16.12 ksi and the second was 14.29 ksi (Table 3). The shear stress for the first specimen was 1252.5 psi and the second was 1544.4 psi (Table 3). The test failure loads for each test were different due to the way the glue dried and how it bonded to the wood.

| *Calculations* | *Bending Stress* | *Shear Stress* |
|---|---|---|
| *Test 1* | *16.12 ksi* | *1252.5 psi* |
| *Test 2* | *14.29 ksi* | *1544.7 psi* |

*Table 3 - Bending stress and shear stress calculations*

## Dimensions and Analysis of Final Truss Design

When deciding on what type of truss to create we thought the simpler the better. We designed this 5 triangle truss similar to the Warren Truss. The final dimensions for our truss differ from what is used to calculate the normal stress, shear stress, and bending moment as those do not take into account real world factors. In the final design of the truss, the horizontal members remained at 7.33 inches (Figure 11) but the angled members had to be shortened to account for the added width of the horizontal members, something in which MATLAB does not account for. They remain at the same angle as they did in the initial design steps but have been shortened to 6.28 inches (Figure 10) to leave room in the gusset plates on either end and keep the truss height at 7 inches. The height of the final design also changed. During calculations we used a height of 6.5 to leave room for real world situations, and this benefited us in the end as we would have had to shorten the angled members to a greater extent. The gusset plates cover 20% on either end of the members, for horizontal members 1.46 inches and for the angled 1.25 inches on either side. We had also designed our truss in matlab to be 22 inches which differs from our final length of 22.5 inches. Designing for 22 inches allowed us to leave space needed by the gusset plates.

*Figure 9 - CAD model of truss*

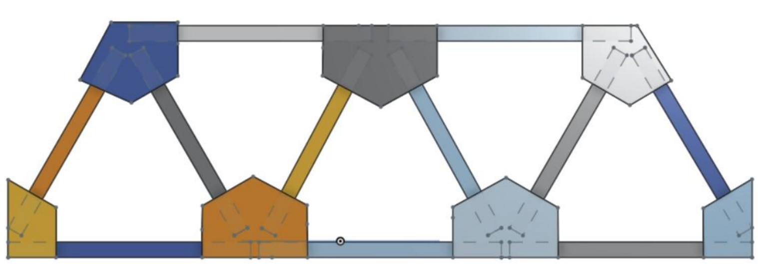
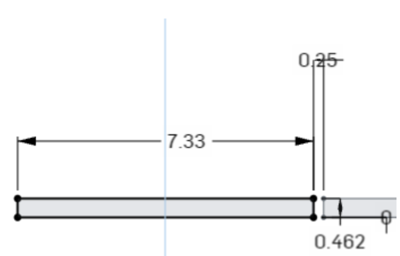


*Figure 10 - CAD of the length of horizontal beams*



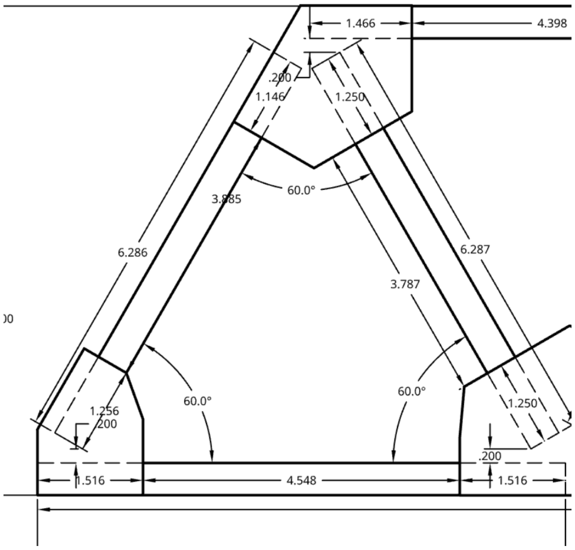



Figure 12 - Gusset plates and truss design

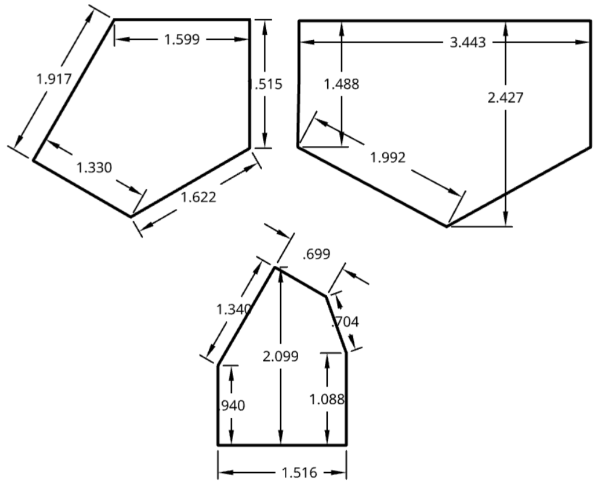



Figure 13 - Gusset plates

## Calculations Background

**Support Reactions:**
The truss will be tested by a downward force applied to the central joint. Two rollers will hold the truss at the bottom 22 inches apart (Figure 12). The truss is intended to support 1.2 kip so each roller will have an upward reaction of 6 kip (Table 4). The support reactions will be calculated by creating a free body diagram, then calculating the forces in each direction (Figure 12).

Table 4 - Support Reactions

| Support Reactions | |
|---|---|
| Ay | .6 kips |
| By | .6 kips |

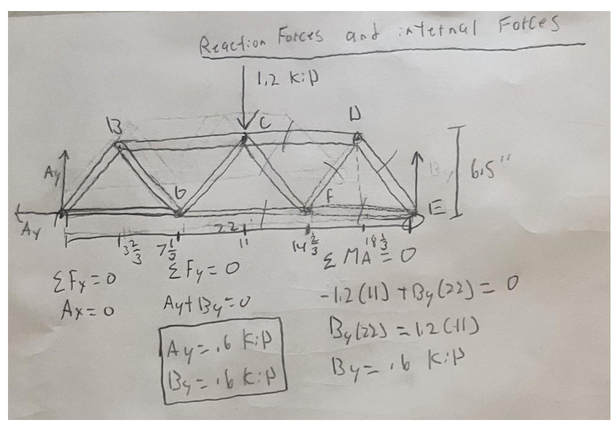



Figure 14 - Reaction forces

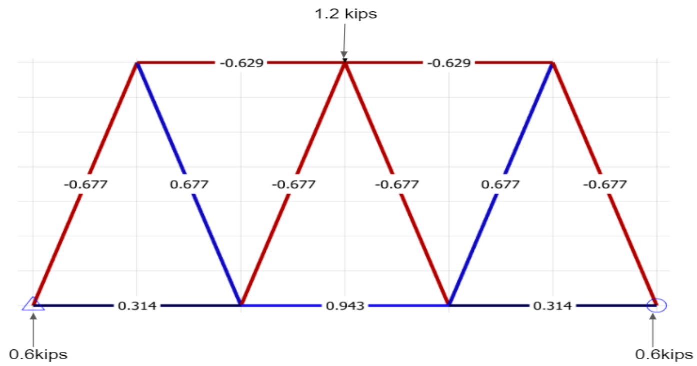



*Figure 15 - MATLAB drawing*

**Internal Forces, Normal, and Shear:**

Internal forces are the forces within the truss that are caused by surrounding members. The internal force for each member was calculated by hand (Table 5) using the minimum required load for the truss to withstand (1.2 kip) as the external downward force. The normal force and safety factor for each member was also determined (Table 5 and Figure 14) with member GF having the lowest safety factor. The safety factor was determined by using the calculated buckling ($P_{cr}$) and internal force (F) of each member.

$$Safety\ Factor = \frac{P_{cr}}{F}$$

| Member | Internal Forces (kip) | Normal Stress (ksi) | Shear Stress (ksi) | Safety Factor |
|---|---|---|---|---|
| DE | -.689 | -2.089 | -.321 | 4.57 |
| FE | .338 | 1.024 | .161 | 9.32 |
| DF | .689 | 2.087 | .321 | 4.57 |
| FC | -.689 | -2.087 | -.321 | 4.57 |
| GF | 1.002 | 3.091 | .483 | 3.09 |
| DC | -.677 | -2.051 | -.322 | 4.65 |
| CB | -.677 | -2.051 | -.322 | 4.65 |
| GC | -.689 | -2.087 | -.321 | 4.57 |
| GB | .689 | -2.087 | .321 | 4.57 |
| AG | .338 | 1.024 | .161 | 9.32 |

| | | | | |
|---|---|---|---|---|
| **AB** | -.689 | -2.087 | -.321 | 4.57 |

*Table 5 - Calculations table*

Shear stress is the force of a member and its gusset that move parallel to each other. Usually represented by τ (Tau), the shear stress was calculated using the following formula:

$$\tau = \frac{F}{A}$$

F is the force in each individual member, and the area is the amount of space covered by glue/gusset in each member (Figure 13).

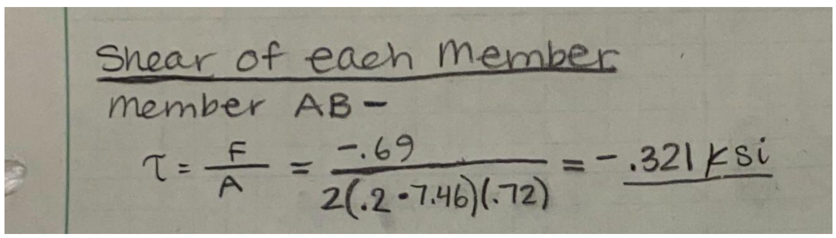



*Figure 13 - Calculations of Shear Stress in each member (only member AB is shown as a sample).*

**Buckling:**

Buckling of a beam is the opposite of bending. It is when a member has a force in the direction parallel to the long edge of a member. This only affects members in compression, so when the calculations were made, only the compression members were considered (Figure 12 and 14).The equation used was:

$$P_{cr} = \frac{\pi^2 EI}{L_u^2}$$

$P_{cr}$ is what we were solving for, which is the critical buckling load (Table 6). The variable E represents the modulus of the wood, and I is the moment of inertia of the two small cross sections of the beams. Lastly, L is the length of the beam between the two gusset plates.

*Table 6 - Buckling Calculations*

| Member | Critical Buckling Load [kips] | Safety Factor |
|---|---|---|
| **AB** | 4.67 | -6.77 |
| **AG** | 4.83 | 14.30 |
| **BG** | 4.67 | 6.77 |
| **BC** | 4.83 | -7.14 |

| | | |
|---|---|---|
| **GC** | 4.67 | -6.77 |
| **GF** | 4.83 | 4.74 |
| **CF** | 4.67 | -6.77 |
| **CD** | 4.83 | -7.14 |
| **DF** | 4.67 | 6.77 |
| **FE** | 4.83 | 14.30 |
| **DE** | 4.67 | -6.77 |

| **Design Parameters** | | | **Material Properties** | | | |
|---|---|---|---|---|---|---|
| Design Load: | 1.2 | kip | Wood Strength: | 9.54 | ksi | testing |
| Max Area: | 0.330792 | in^2 | Wood Modulus | 1,610 | ksi | Check this? Is this reasonable? |
| | | | Glue Shear Stength: | 1.0215 | ksi | |
| Truss Width | 0.72 | in | | | | |

| **Member Info** | | **Forces** | **Member Height Design** | | **Stress Check** | | **Buckling Check** | | **Shear Check** | | | **Min Saftey** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Member | Length [in] | F [kips] | h [in] (actual) | Area [in^2] | Stress [ksi] | Saftey Factor | Pcr [kips] | Saftey Factor | Overlap Allowed | Shear Stress [ksi] | Saftey Factor | |
| AB | 7.46 | **-0.69** | **0.46** | **0.33** | -2.08 | **-4.58** | 4.67 | -6.77 | **1 8/16** | -0.32 | -3.17 | **3.17** |
| AG | 7.33 | **0.34** | **0.46** | **0.33** | 1.02 | **9.34** | 4.83 | 14.30 | **1 7/16** | 0.16 | 6.34 | **6.34** |
| BG | 7.46 | **0.69** | **0.46** | **0.33** | 2.08 | **4.58** | 4.67 | 6.77 | **1 8/16** | 0.32 | 3.17 | **3.17** |
| BC | 7.33 | **-0.68** | **0.46** | **0.33** | -2.05 | **-4.66** | 4.83 | -7.14 | **1 7/16** | -0.32 | -3.17 | 3.17 |
| GC | 7.46 | **-0.69** | **0.46** | **0.33** | -2.08 | **-4.58** | 4.67 | -6.77 | **1 8/16** | -0.32 | -3.17 | 3.17 |
| GF | 7.33 | **1.02** | **0.46** | **0.33** | 3.08 | **3.09** | 4.83 | 4.74 | **1 7/16** | 0.49 | 2.10 | 2.10 |
| CF | 7.46 | **-0.69** | **0.46** | 0.33 | -2.08 | **-4.58** | 4.67 | -6.77 | **1 8/16** | -0.32 | -3.17 | 3.17 |
| CD | 7.33 | **-0.68** | **0.46** | 0.33 | -2.05 | **-4.66** | 4.83 | -7.14 | **1 7/16** | -0.32 | -3.17 | 3.17 |
| DF | 7.46 | 0.689 | **0.46** | 0.33 | 2.08 | **4.58** | 4.67 | 6.77 | **1 8/16** | 0.32 | 3.17 | 3.17 |
| FE | 7.33 | **0.34** | **0.46** | **0.33** | 1.02 | **9.31** | 4.83 | 14.30 | **1 7/16** | 0.16 | 6.34 | 6.34 |
| DE | 7.46 | **-0.69** | **0.46** | **0.33** | -2.08 | **-4.58** | 4.67 | -6.77 | **1 8/16** | -0.32 | -3.17 | 3.17 |
| | | | | | | | | | | | **Min Safety Factor Overall:** | **2.10** |

*Figure 16 - Picture of spreadsheet to check calculations*

**Maximum Load and Strength to Weight Ratio:**

The maximum load the truss can withstand was estimated (Figure 15) assuming the truss will break at the weakest point in member GF. The ratio of the strength to weight of the truss was determined by dividing the maximum load by the estimated weight of the truss.

$$Strength\ to\ Weight = \frac{Max\ Load}{Weight}$$

The density of the pine wood is estimated to be 37.5 lb per inch cubed and the density of balsa wood is .0063 lb which allowed us to estimate the total weight of the truss to be .599 lbs (Figure 16).

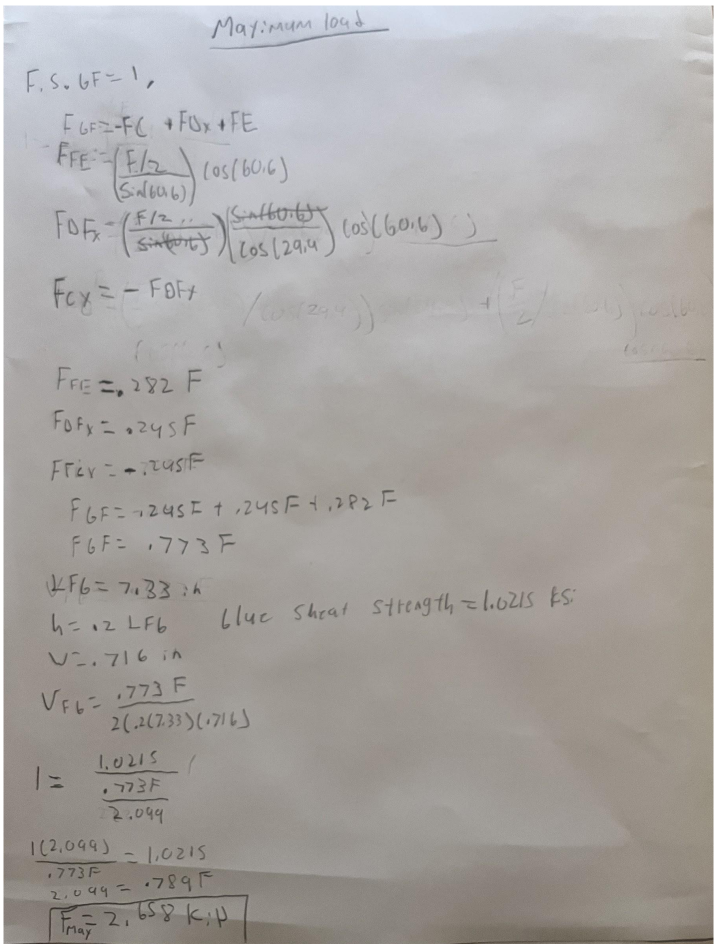



Figure 17 - Maximum load calculation

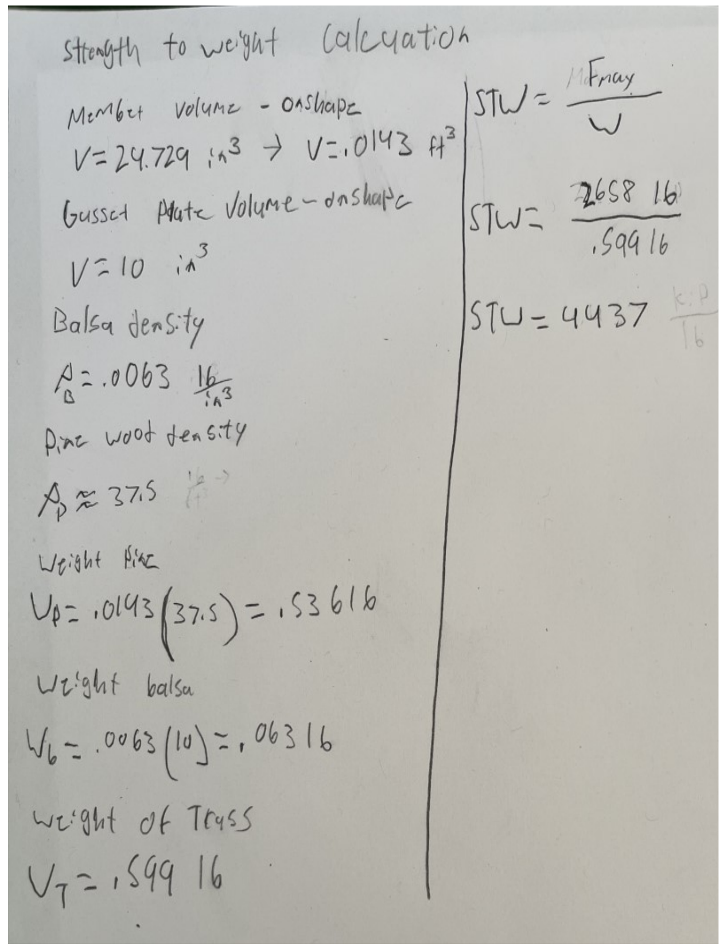



Figure 18 - Strength to weight calculation

## Type of Failure and Location of Failure

We believe that our truss will fail due to shear stress where member GF connects to the gusset plates at our predicted maximum load of 2.658 Kip. This is the result of the member GF being in tension in order to translate the applied point load in the direction of the supports. Member GF has to take the majority force of the applied load as a result of members FC and GC each taking the vertical force from the applied load and then connecting to member GF to disperse the load to other members.

## Fabrication

The first step in our fabrication process was to print out a to scale CAD drawing of the truss we designed. We printed it across 3 pieces of paper (Figure 17) and then measured important members with calipers to confirm our print out measurements were correct.

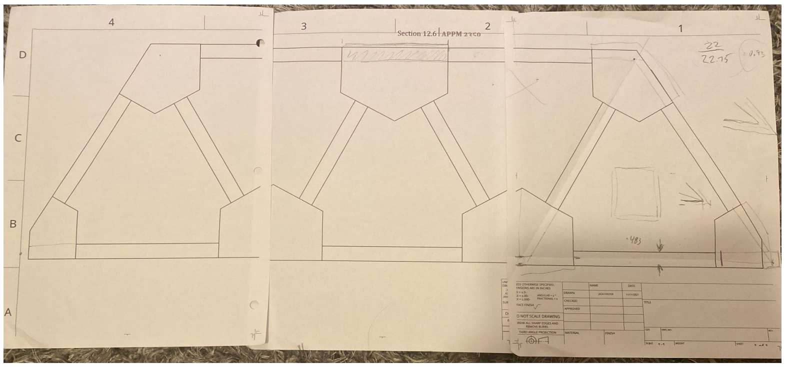


*Figure 19 - CAD printout*

For the next part of fabrication, we took the measurements from the drawing, marked our wood then cut and labeled each member. We then needed to cut out the gusset plates. To do this the CAD drawings of the gusset plates were imported to scale into coreldraw and sent to the laser cutter to be cut with the least amount of error.

After all of our components were cut, we taped down our drawing onto a wooden board then covered it with a thin layer of plastic. This step is necessary to ensure that our gusset plates and members get glued down in the correct spot. We started with gluing down the gusset plates onto the plastic sheet using a glue stick (Figure 18). This sets a good foundation for our members to get attached to. Then, one by one we placed each member in its corresponding position to be glued and clamped (Figure 19).

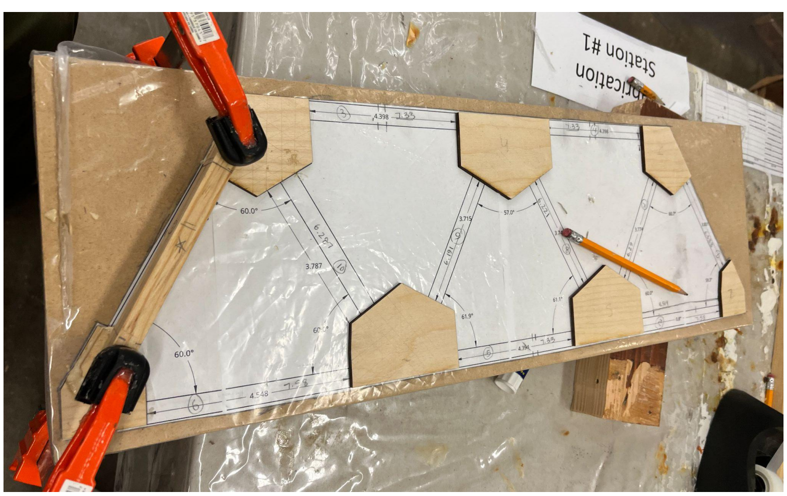


*Figure 20 - gluing gussets and placing members*

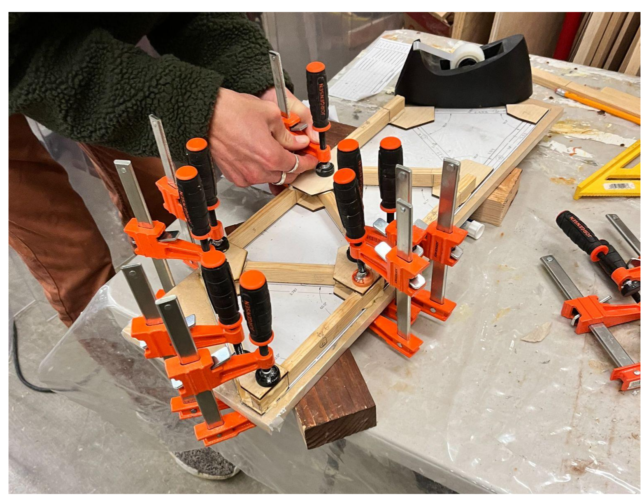


*Figure 21 - clamping members*

We let our truss dry for about two days and then came back to complete the final step. The last step to our fabrication was to create a place for the pin to sit once we began testing. If we left it how it was there would be a gap where the pin would push down during testing. The method we used was called sistering (Figure 20). This is where two more members are glued to the top/middle of our truss to take on the weight of testing. If we would not have added these pieces the pin would sit directly onto our gusset plate. Our test would have measured the strength of the gusset plate instead of testing our members and truss as a whole.

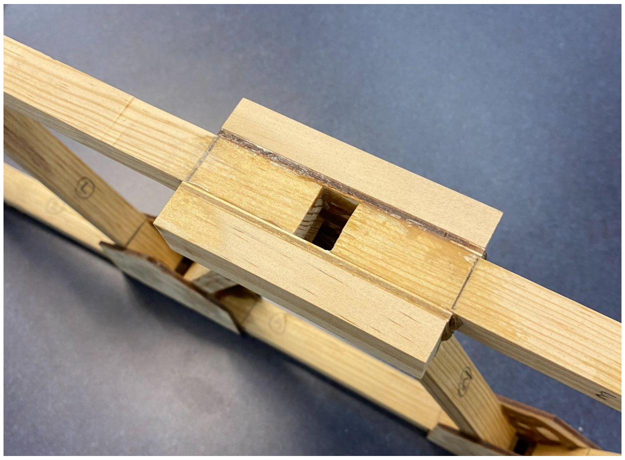


*Figure 22 - Sistering beam to support point load*

## Testing Results and Conclusion

Our truss was tested under a single point load with two rollers supporting the bottom 22.5 inches apart (Figure 22).

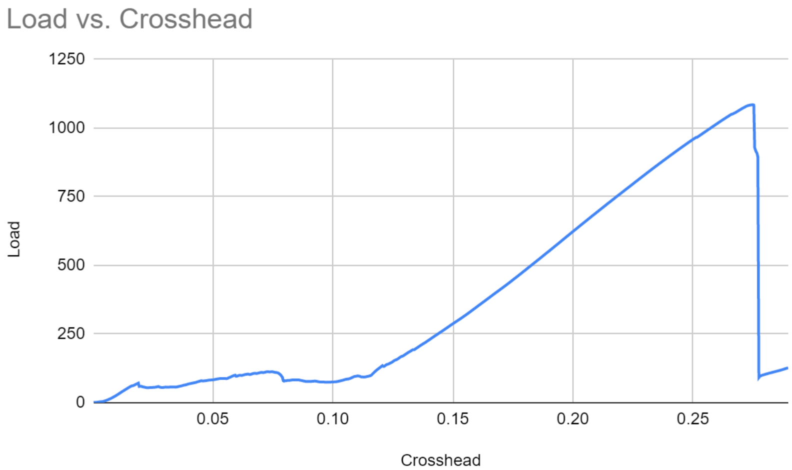



*Figure 23 - Lb/Inch Deflection Graph*

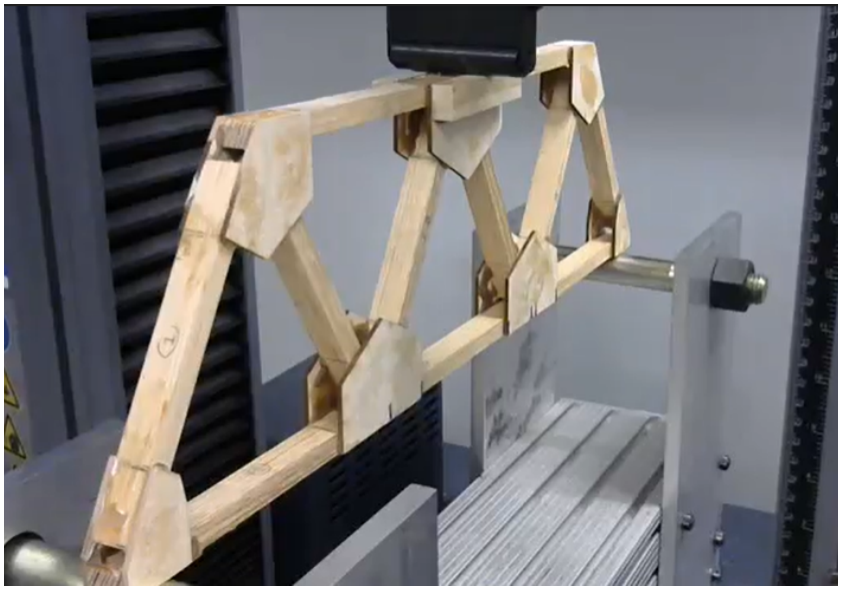


*Figure 24 - Completed truss in the testing machine.*

The load was applied to the truss until it reached failure at 1084.8 lb, where the truss broke on the far right bottom gusset plate (Figure 23). The load vs deflection increased in a mostly linear manner with some peaks in the beginning (Figure 21). These peaks were due to small adjustments with the beams settling into the glue and the truss settling onto the rollers as more force was applied. The truss failed due to shear stress on the gusset plate at E (Figure 23).

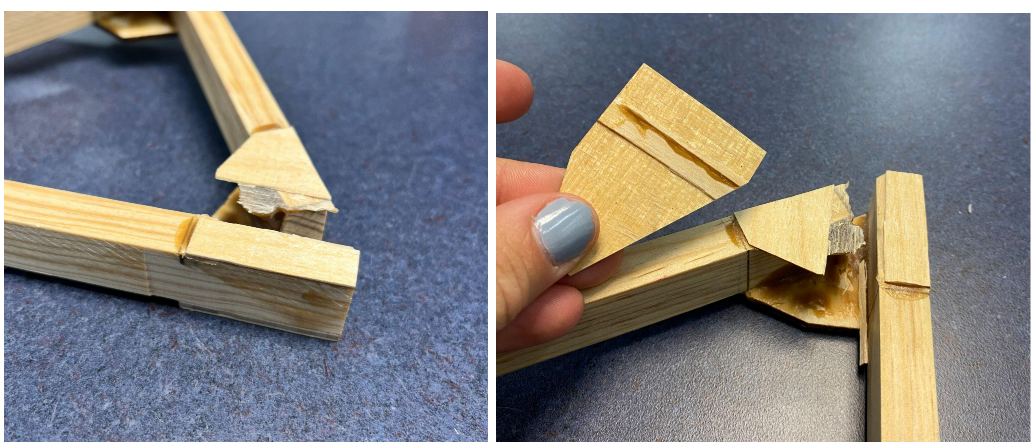


*Figure 25 - Broken gusset plate after testing*

Truss Testing Data:

| Weight (lb) | Projected Load (lb) | Projected Break Location | Truss Tested Load (lb) | Strength to weight ratio (lb/lb) | Actual place it broke |
|---|---|---|---|---|---|
| .83 | 2658 | Member GF | 1084 | 1391 | Gusset plate E |

*Table 7 - Testing data*

## Error and Improvements

The truss did not reach the estimated failure load of 2.658 kip and it did not break at the predicted locations due to possible errors in fabrication and estimated wood strength.

When we placed the truss on the rollers for testing it was not aligned correctly with the central loading point. This was a result of human error throughout the manufacturing process. In turn we had to decide if we wanted to align the center gusset with the loading point or align the end point gussets with the rollers. We chose to align the central gusset with the point load to try to maximize the force withheld. This unalignment of the end pieces went against the truss assumption that forces are applied at the pins.The roller at point E was not applied at the pin location causing it to fail first. In the future, we will check the exact measurements of the distance between rollers and the central point load on the testing equipment to ensure our truss would fit well before fabrication and testing. This would allow us time to make adjustments to the length of our truss before testing.

Another error with the truss during the manufacturing process was how the bottom beams were aligned when the gussets dried. The bottom and top pieces were not completely straight so when the truss was standing it had a slight U curved shape (concave up). This error possibly came from the glue drying and shrinking which led to the truss being under constant force leading to bending in the truss. The curved shape weakened the overall strength of the truss causing it to fail at a lighter load than predicted. In the future, to prevent this error we would use a straightedge to make sure all of the pieces were aligned correctly after clamping while the glue dried as well as possibly using less glue.