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372 Final Project: Truss Design

Introduction

Truss designs are common because of their proven strength and lightweight characteristics. The advantage of lightweight trusses is that they are fast and cost-effective to install and do not require heavy expensive equipment or excessive preparation in order to be used effectively. Trusses are generally built in a factory and delivered as a complete set to a job site, where the structure is then built. High strength, lightweight structures are advantageous in countless scenarios; however, even though they are common, great care must be taken in designing the truss structure and the bracketing system anchoring the truss. There are many ways for the structure to fail, so the design approach must account for as many failure types as possible and be conservative. Truss members are loaded in either tension or compression. This scenario, a 20ft long truss structure with a 7ft by 7ft cross section must be designed with a bracket system on one end and will be pinned such that it connects in a cantilever fashion as shown in Figure 1.

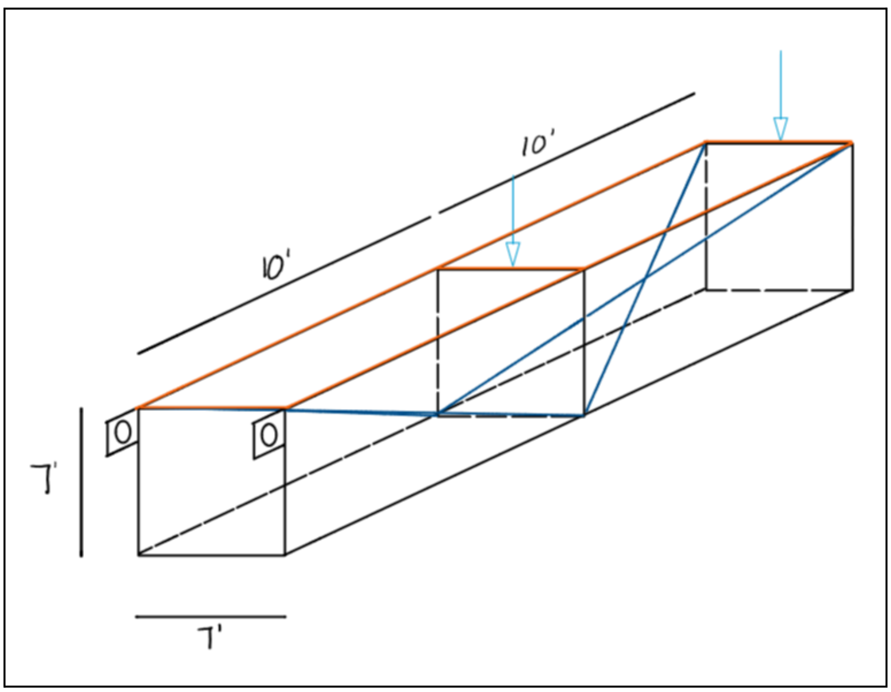

Figure 1. Schematic of the truss design and location of applied forces

The structure must not fail under two 500lb point loads (indicated by the light blue arrows in Fig. 1), and a distributed load that acts along the upper face of the top members of the structure (indicated by orange outline in Fig. 1). Both the truss and the brackets must be strong enough under these loads, as well as the gravitational force on the structure, to avoid failure. To be conservative, a safety factor of 2 will be included in the design allowing for a margin of safety between the operational load of the structure and the load that would cause failure. This will be done by doubling all the loads acting on the truss.

Methods

Truss Structure Optimization

In the development of a strategic approach for the design of the truss structure, it was convenient to consider standard sizing of square tubing. Based on these standard sizes, various beam profiles could be created and applied to the truss component in Ansys Workbench to test for failure. After some familiarization with standard sized beam profiles and their corresponding strengths and weights, it was determined that in order to arrive at the optimum beam profile (standard square tubing size), the largest thickness for each tube size would be tested. If the largest size thickness for a given tube size was strong enough, then smaller and smaller thickness of that same tube size would be tested until one didn't meet the criteria. For that size of tubing, the smallest thickness that didn't fail was considered the optimum candidate for that tube size because it would result in the lightest truss for that profile that didn't fail. This process would be used on a range of standard sizes, resulting in the most capable and lightest truss for the final selection. To determine failure for a cross section, the maximum combined stress was compared to the yield strength of the material, structural steel in this case. Because the safety factor was accounted for when the applied loads were doubled, if the ratio of the material yield strength to the maximum combined stress was greater than 1, that profile did not fail. The maximum combined stress in tension was used in each model for the comparison to the yield strength, since the tensile stress always exceeds the compressive stress for this design, and the material had the same magnitude of strength in tension as in compression.

To create an accurate model on which to test the plethora of beam profiles, a component based on the provided design (Fig. 1) was created on a 1:1 scale in Ansys Spaceclaim and opened in Ansys Mechanical. In Mechanical, this model was subjected to the two point loads, the line pressure corresponding to the distributed load. A gravitational force was originally considered, however for simplicity it was considered negligible because this is a lightweight structure. To account for the safety factor in this model, each of these applied loads were doubled. To model the bracketing connection, two simple supports were attached along with a displacement boundary condition all on one end to replicate the two pinned brackets and the compression joint. Both the specified loads and boundary conditions can be seen in Fig. 2.

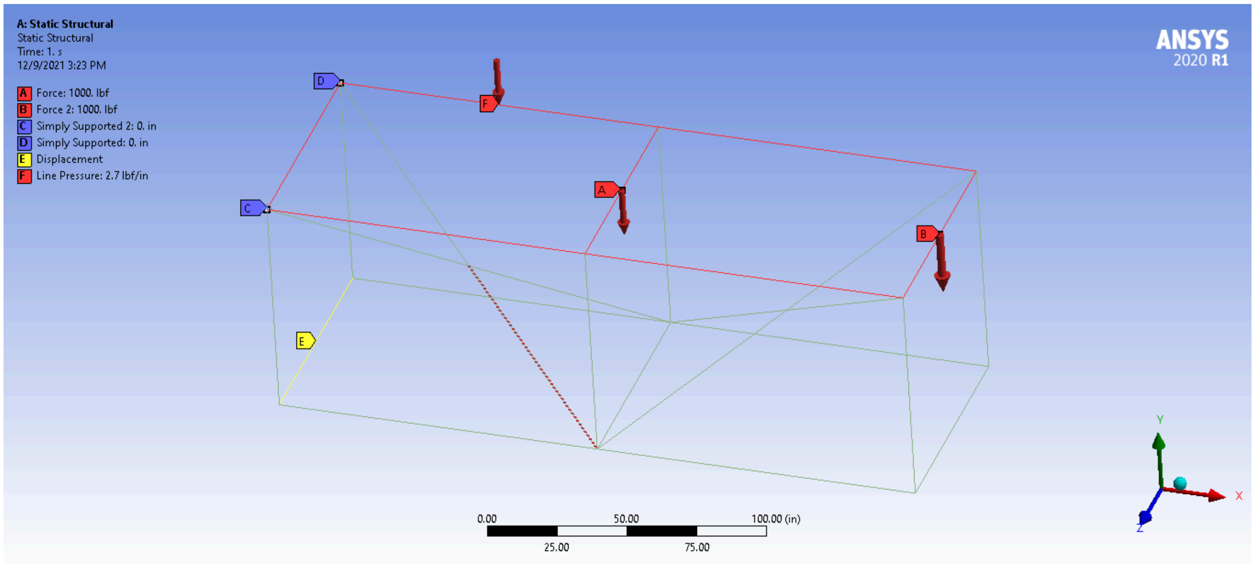

Figure 2. All applied loads and boundary conditions applied to the component

Hand Calculations

Using MATLAB, the load values were assigned to variables that allowed solving for reactionary forces along the brackets at the wall (see APPX. I). The equations used were (1) summing the forces in the vertical direction and (2) taking the moment about the brackets. (See the Appendix I for the code used and application of these equations.) Important parameters, such as the square cross sectional length and thickness, were found in ANSYS and then applied in the equations. The uniform load applied on the top of the truss was calculated as a resultant force acting on the centroid of the area applied. From there, reactionary forces were computed to use in analyzing the brackets' loads.

Additionally, the results of hand calculations were used to validate our analysis to the results in ANSYS for failure (see APPX. II). Failure from stress due to bending will be the most critical mode of failure with the given configuration of applied loads. Transverse shear stress is negligible because of the high width to length ratio of the truss. Torsion stress is also negligible because of the direction of loads and shape of truss.

Bracket Optimization

A 3.5in x 3.5in x .5in block of structural steel with a 1in diameter hole through the center was modeled as a base for the connection bracket between the truss and supports. Applied loads on each bracket were taken from the hand calculations. These loads were modeled as a bearing load with -x and +y components and the face in contact with the truss as fixed. If the results are less than the yield strength of structural steel, mass can be reduced and left in critical locations to minimize the weight while maintaining performance. The optimization objective was set to retain 65% of mass. The generated solid was used as a template to model in SpaceClaim to build a bracket for this design.

Results

ANSYS

Applying and analyzing the beam profiles on the truss component, as specified in the methods section, resulted in a final beam cross section of 2”x2” x 0.095”. Key results of the beam profiles tested are reported in Table 1. The important columns of this table are the “n” and the “Mass” columns. All the values highlighted in green in the “n” column are greater than one meaning that the structure didn’t fail in tension or compression with the safety factor of 2. Red highlighted values correspond to structures that didn’t meet the failure criteria. Of all the structures strong enough, the lightest was selected. The cross sections from Table 1 are also shown in Figure 2, which provides a plot weight versus the safety factor. This graphic is convenient because quick understanding of the selection criteria enables the cross section to be selected quickly. No cross sections to the left of 1 were considered, and low weight is desired, so the result is the 2”x2” x 0.095” in cross section. For verification, the maximum combined stress and total deformation plots are shown below in Figures 4 & 5 respectively.

Table 1. Results of Ansys Workbench truss model with various standard sizes of square tubing (in inches). The final selected cross section row is *italicized*. “n” was determined by comparing the max combined stress to the yield strength. 1 is considered the difference between succeeding and failing structures because the safety factor of 2 was applied earlier to the loads.

Cross Section	Max Combined Stress (kpsi)	n	Volume (in^3)	Mass (lbm)
1X1 - .12	137.55	0.264	1116.6	316.7
1.25X1.25 - .188	61.64	0.588	2111.1	598.7
1.5X1.5 - .188	39.63	0.915	2608.0	739.6
1.5X1.5 - .25	33.81	1.072	3304.0	937.0
1.75X1.75 - .12	38.22	0.949	2068.2	586.5
1.75X1.75 - .188	27.55	1.316	3105.0	880.6
2X2 - .083	39.04	0.929	1682.4	477.1
2X2 - .095	***34.74***	***1.044***	***1913.6***	***542.7***
2X2 - .313	14.72	2.464	5583.0	1583.0
2.25X2.25 - .065	37.90	0.957	1501.7	425.0
2.5X2.5 - .065	22.11	1.640	2702.0	766.5

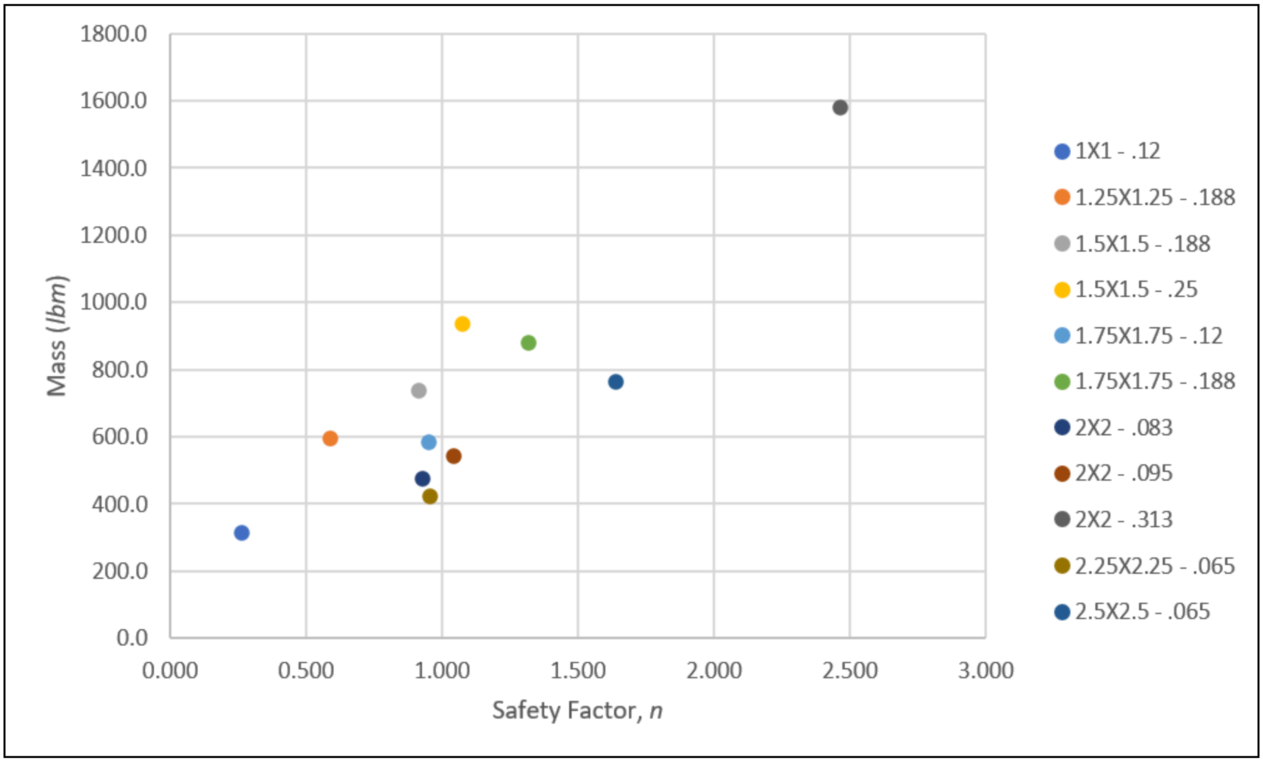

Figure 3. Weight versus Safety Factor for various standard sizes of square tubing. The ideal size is greater than 1 and with the lowest mass.

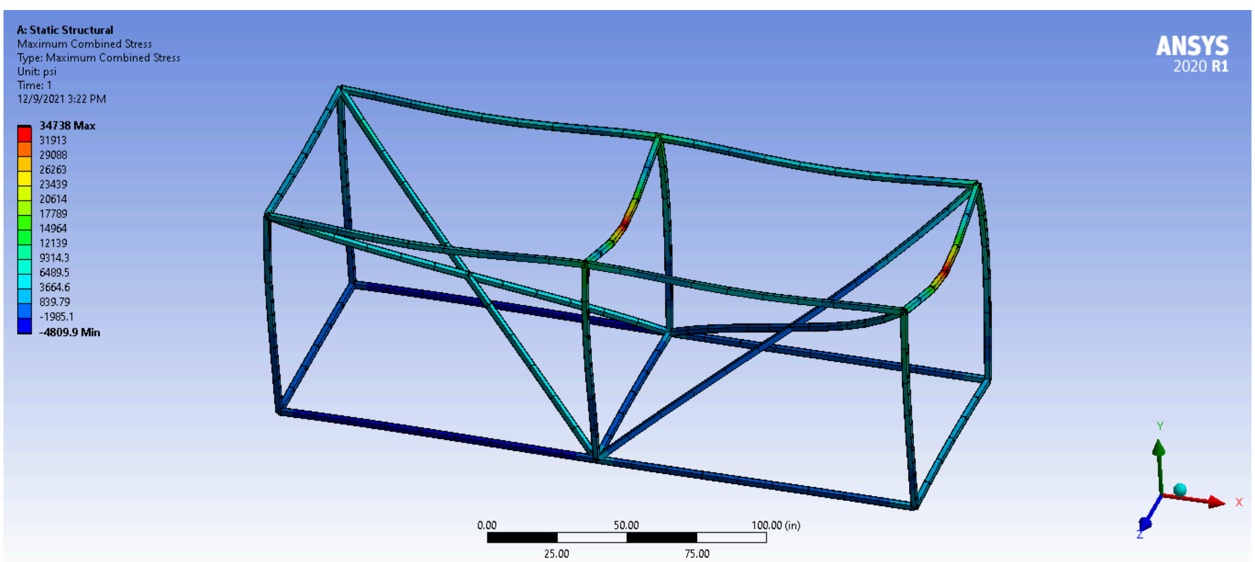

Figure 4. Maximum combined stress plot of the 2”x2” x 0.095” truss

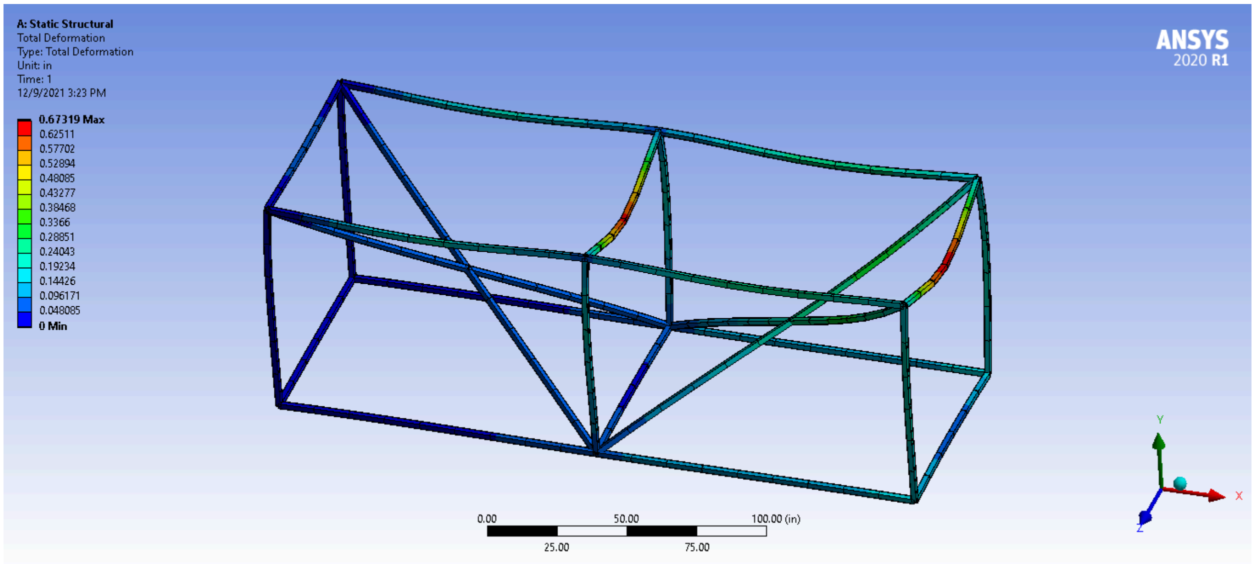

Figure 5. Total deformation of the 2”x2” x 0.095” truss

Hand Calculation

From the analysis and code in APPX. I it was determined that the reaction loads on the bracket are as follows:

In the -x-direction: 3594.3 lbf

In the +y-direction: 2016.3 lbf

From the analysis and code in APPX. II, it was determined that the maximum bending stress in the truss system, which occurs in one of the cross members with the 500lb point load applied, is 34,773 lbf/in^2.

Bracket

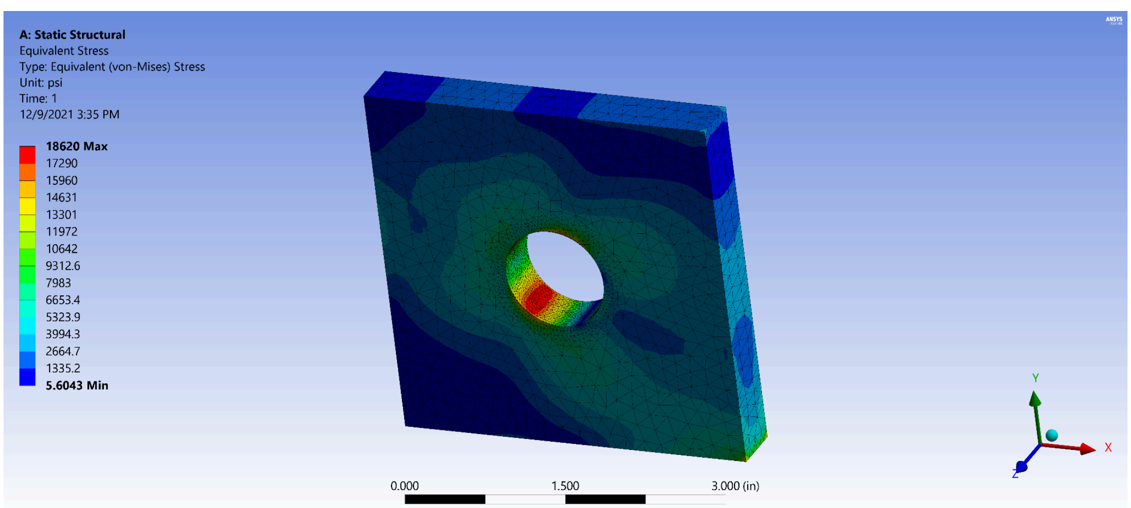

Figure 6. Bracket before topology optimization.

The initial load of the 3.5in x 3.5in x .5in experienced a maximum stress of 18,620 psi as shown in Figure 6. The ANSYS model with reduction to 60% mass had rough edges along the mesh and did not reduce any mass across the fixed face. The designed model smoothed the edges and shortened the face connected to the bracket. It experienced a maximum stress of 21,472 psi as shown in Figure 7.

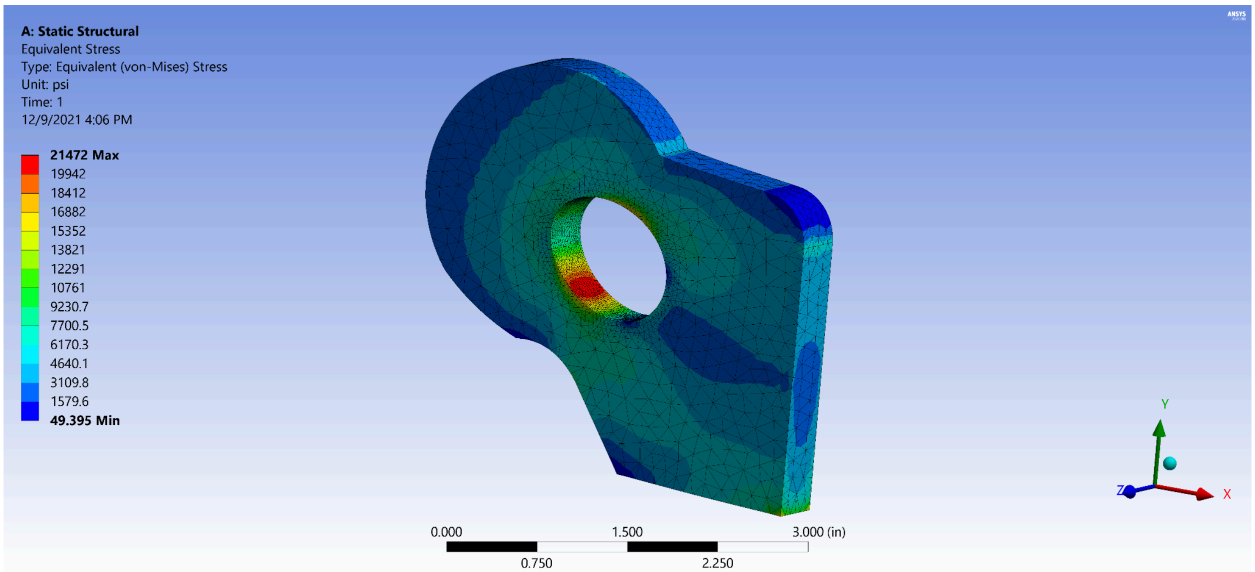

Figure 7. Bracket after topology optimization

Discussion

The Ansys truss solution shows that the 2" x 2" x 0.095" cross section will not fail under the applied loads and therefore is the recommended cross-section in the design to optimize desired parameters of strength and mass. This solution should be very accurate because the Ansys program uses bending stress, tensile stress, compressive stress, torsional stress, and shear stress as needed in its FEA solution. The largest error would come from an incorrect application of the forces. For the optimum beam profile, the hand calculations resulted in maximum stress of 34,773 psi. If the model developed by Ansys is correct, where the max combined stress is 34,738 psi, then the hand calculations are quite accurate as the percent error between these values is only 0.101%. This means that the bending stress evaluated in APPX. II was indeed the critical stress and the other forms of stress were not significant.

The reaction forces determined in APPX. I resulted in the reported bracket design. The bracket design stayed under the yield strength after the mass optimization design was completed, and material in the -x, +y side of the bracket proved critical to reduce shear tear-out and failure around the bearing. Further iterations of other bracket designs showed that a thickness of .25in for the bracket would surpass the yield strength. If material usage for the brackets were a greater concern, a thickness of 0.4in could be an alternative to the design.

APPENDIX I: Hand Calculation Matlab Code

```
% safety factor of 2
eta = 2;

%material properties
rho=.2836;%lbm/in^3
Sy=36259;%psi
Sut=66717;%psi

%environment propties
g=32.2*12;%in/s^2

%cross section parameters
t=.095;%in
l = 2; % Square bar width

%loads:
%500lbf 10 ft and 20 ft from the brackets
P = 500*eta;
%distributed load over whole platform
w = (7.14/144)*eta; %lbs/in^2
% Total load due to the distributed load
A = (10+10)*7*144;%in^2
W = A*w; %lbf
% Line pressure due to the distributed load on the platform
A_top = A - 2*((10*12-1.5*l)*(7*12-2*l));%in^2
Load = (W/A_top)*l %lb/in^2

% Determine the loads on the brackets
Across= l^2-(l-2*t)^2;%

%consoladate distributed loads
Fpress=Load*((20*12)*2+(7*12)*3); %force from the distributed load on the beams
L=20*4*12+7*12*12+((7^2+10^2+7^2)^(1/2))*4*12;%length of all beams combined
m=rho*Across*L;
v = Across*L; %volume of structure
Fg=m*g;

%Sum of the vertical forces
RBy=Fg+Fpress+2*P

%Moment about the top of one bracket (total moment divided by 2)
Rx=.5*((Fpress+P)*10*12+P*20*12)/(7*12)
Ry=.5*(Fpress+2*P)
```

APPENDIX II: Max stress hand calculations

```
eta = 2;
P = 500; %lbf
LP = 2.7; %lbf/in
L = 7*12; %in
D = LP*L; %lbf
S = 2; %outer side length (in)
t = .095; %thickness (in)
s = 2-(2*t); %inner square side length (in)

Ry = (P + D) * .5; %lbf% y reaction

M = -(L/2)*Ry;% moment

c = S/2; %in

% I = (1/12)*((S^4) - (s^4));
I = ((S^4)/12 - (s^4)/12);

sig = (M*c)/I;
```

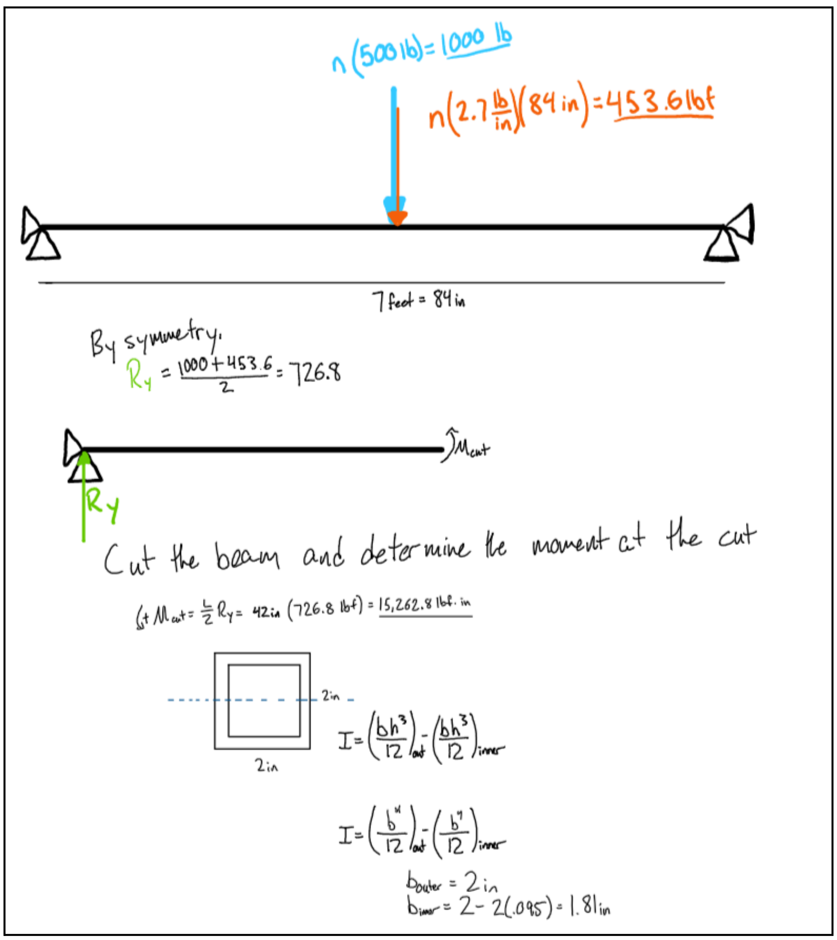

Figure 8. Summary of the hand calculations that compliment the code above to determine the max bending stress