Design of an Intermediate Scale Fire Test Rig for Exterior Wall Assemblies

A Major Qualifying Project Report

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WORCESTER POLYTECHNIC INSTITUTE

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Project Number: NAD FN13

Abstract

Together with higher expectations for building performance such as energy efficiency, combustible materials are increasingly being added to exterior wall assemblies requiring them to pass the full scale fire test standard NFPA 285 (Multi-story building test). This testing procedure is expensive and time consuming to perform. The project aimed to design an intermediate scale fire testing rig for screening fire (and thermal) behavior of exterior facades. A light and easy to use intermediate scale rig would benefit many people in the construction industry. By reducing the size and cost of the assembly specimens in the screening test more effective and efficient assembly designs can be developed with confidence that these assemblies will pass the full scale NFPA 285 test.

Acknowledgements

We would like to express our sincere gratitude to the following individuals and organizations for their active support throughout the completion of this Major Qualifying Project:

- Kreysler & Associates, for providing us with the opportunity to design a new fire screening test and funding for the project.

- Professor Nicholas Dembsey and Professor Umberto Berardi, for providing us with guidance and knowledge throughout our project. Our accomplishments would not have been possible without their advice and input.

- Randall Harris, for assistance at the WPI Fire Science Laboratory and providing valuable input for the rig specifications.

Authorship

This report was written as a collaboration of all three group members: Christopher Ciampa, Ditton Kawalya, and Ethan Forbes. The research for this report was divided evenly among all group members. While each section was revised and edited by all group members to ensure the writing was clear, accurate, and represented the opinions of the project team. The list below displays the primary author for each section and task.

Christopher Ciampa:

Introduction, Characteristics of a Screening Test, Reference, APPENDIX

Other Tasks: Materials Catalog, SolidWorks Drawings, Analysis Calculations

Ditton Kawalya:

Analysis of the Rig, Thermal Analysis, Conclusion and Recommendations, APPENDIX

Other Tasks: Materials Catalog, SolidWorks Drawings, Analysis Calculations

Ethan Forbes:

Design of Intermediate Scale Testing Rig, Characteristics of a Screening Test, Thermal Analysis, Reference, APPENDIX

Other Tasks: Materials Catalog, SolidWorks Model, Analysis Calculations, Figure Drawings

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Introduction

In the effort to change the construction industry in developing a higher, more energy-efficient building envelope, focus has been put on the increase in performance, facility life, and occupant health and safety. The International Building Codes (IBC) [1], ASHRAE 90.1 [2] and International Energy Efficiency Codes (IECC) [2] define a baseline for what exterior walls should be and also set restrictions. The thickness and material of an assembly determine its safety. For this project, a full study of the IBC and IECC was done. From the understanding and guidance of the IBC, a Materials Catalog (found in appendix F) was created in order to compare different properties and U-values of common materials used on exterior wall assemblies.

Although combustible materials bring about a danger to exterior assemblies they are very attractive as components because they aid energy conservation and reduce construction cost. While the market demands for insulations, air gaps, and water barriers, combustible materials are at an all-time high. The National Fire Protection Association (NFPA) has created a specific test known as NFPA 285 [3], requiring all exterior walls to pass. This test enables designers to better understand how fire can spread along the exterior face of a building, as well as incorporating combustible materials into exterior wall assemblies.

NFPA 285 Test:

The NFPA 285 test is required by code for commercial buildings Type I, II, III and IV construction.

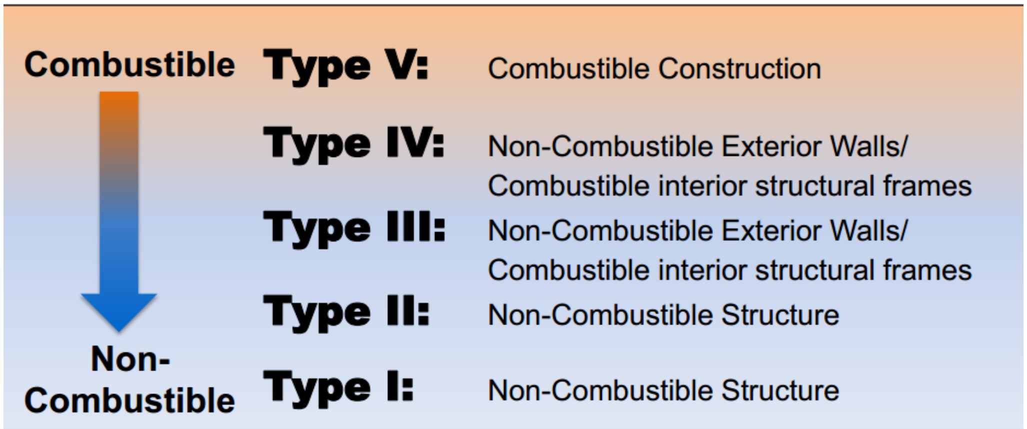


Figure 1: Combustible and Non-Combustible Materials [4]

 The 285 Test is the "standard fire test method for evaluation of fire propagation characteristics of exterior non-load-bearing wall assemblies containing combustible components" [5]. This means that a test must be run for any multistory building over 40ft that uses combustible materials in its wall assemblies. These assemblies include all products from interior finish to exterior cladding.

The current testing rig for 285 is composed of two concrete and masonry rooms stacked vertically in order to simulate a two-story building. The test wall is then built onto the concrete rooms and attached firmly to accurately simulate a real building.

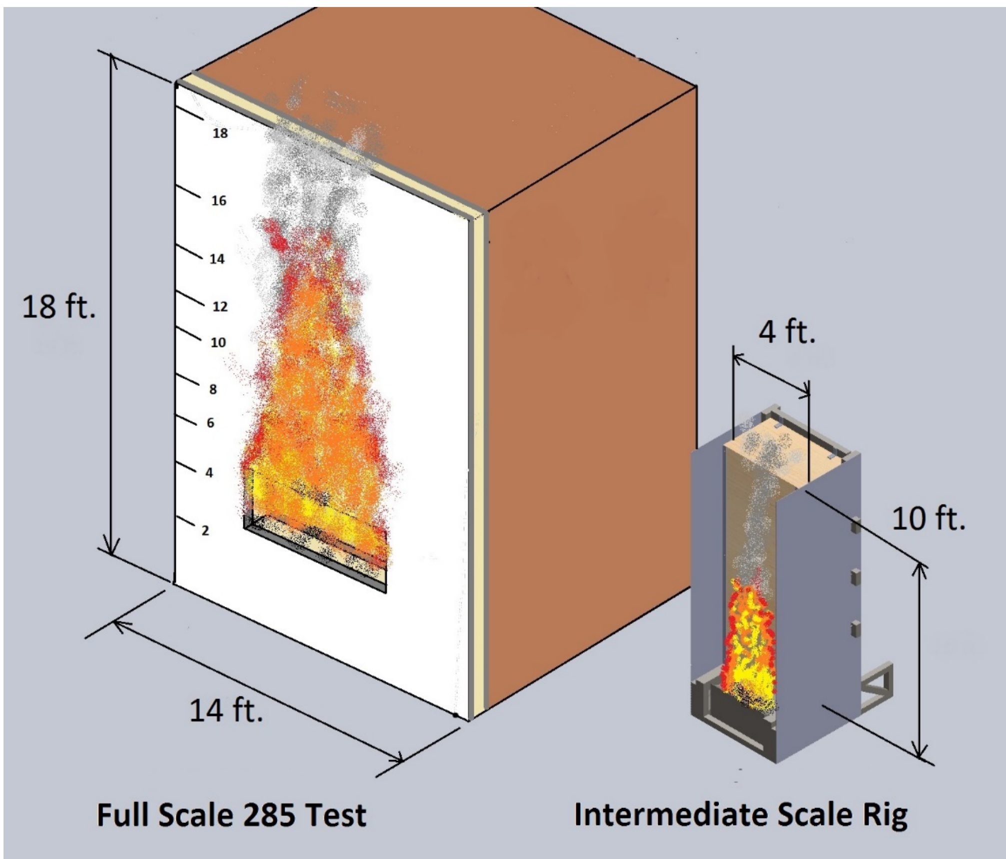


Figure 2: Full Scale Rig vs. Intermediate Scale Rig

The rig has two burners that simulate an interior fire that has broken out of a window. Real windows are not placed in the rig as it is assumed these would break after fire exposure. During the testing period, the flames on the wall cannot exceed 10 ft. above the window's top or 5 ft. laterally from the centerline of the window. The thermocouples present within the wall assembly cannot reach a temperature of more than 1000 ºF and there cannot be any fire present within the top room. The assembly is considered a fail if it breaks any of these rules. A more detailed list of specifications can be found in the official document at the NFPA [3] website.

Problems with Current Test

The current 285 test has a multitude of issues that make running a single test costly and time consuming. For many people, the current testing costs and limitations make it difficult for them to justify the investment when in the research stages of designing new building materials. The following list states the major problems with the current 285 Testing Rig:

- Price - current testing is very expensive with the price ranging from $15,000 to $50,000 per test and the costs must be paid even if the system fails
- Size- current test rig is 14’ by 18’. This can be too large for most laboratory environments.
- Portability- current rig utilizes concrete and brick walls, which cannot be moved. This means that the rig needs to occupy its own space, which happens to be a large area.
- Walls must be built on site- the exterior walls must be built onto the rig, which causes increases in testing time, manpower and costs.
- Test time- the test has a long turnaround time, which reduces the number of tests that can be performed.

If the problems from the current testing rig can be solved then a much more efficient setup can be designed. A more portable, affordable and faster testing rig would benefit many people in the industry. Reducing the size and cost of the test will allow researchers to pre-screen the performance of their materials before a full-scale test hence avoiding un-necessary money and time expenditure.

Characteristics of a Screening Test

The goal of a screening test is to simulate the full scale 285 test with a smaller testing rig. NFPA 285 requires a flame length of less than 10 ft. above the window’s top and a flame spread of less than 5 ft. laterally from the window’s centerline. In order to accommodate the appropriate index an intermediate scale rig will be the basis for the design. The Intermediate scale rig will be much smaller than the full-scale test, but will provide a large enough wall section to meet testing requirements. The burners used in the full-scale test must be scaled down in order to provide the proper thermal insult to the testing specimen.

Design of an Intermediate Scale Testing Rig

In order to create a rig that would meet the needs of the WPI Fire Laboratory and be able to be shipped back and forth between WPI and Kreysler & Associates in California, a set of design specifications were created.

Design Specifications

Table 1: Design Specifications

Intermediate Scale Rig Design Considerations		Corresponding Design Specifications
1.	NFPA 285 requires a flame length of less than 10 ft. above the window's top and a flame spread of less than 5 ft. laterally from the window's centerline, hence the intermediate scale must accommodate those index	• Specimen wall height should be 10 ft. • Specimen wall width should be 4 ft. • Wall should be raised off ground to allow burner to be placed underneath
2.	Intermediate scale rig that can appropriately simulate the NFPA 285 testing	• Rig needs to have side channels to help match the vertical flow produced by the 285 test's window opening • Burner must appropriately match the heat flux distribution of the 285 test
3.	Rig must be adjustable to different wall thicknesses between 6"-30" (based on max & min materials catalog walls)	• Adjustable to walls between 6"-30" thickness • A frame is necessary to distribute loads of 30" wall • Allow walls of smaller size to be hung from back frame for specimens that can't support their own weight

4.	Portability: Rig must be easily moved in the lab and be collapsible for long distance transportation	• Rig should be made of multiple pieces for decreasing profile for storage and transportation • Individual rig pieces should not exceed 75lbs • Be able to lay flat during transportation
5.	Ease of Assembly	• Rig should be able to be assembled without tools • Should be able to be assembled by 2 users
6.	Material used to build the rig must have suitable mechanical and thermal properties i.e. density (light), yield strength, tensile strength, fracture toughness, and corrosion resistance	• Needs to withstand heating and reheating from a burner • Needs to be able to support 1000 lb. wall sections
7.	Decrease time between tests	• Wall specimen should be modular allowing for easy wall specimen change
8.	Rig should be able to withstand heating to high temperatures	• Rig should be insulated from burner • Limit moving parts which can malfunction at high temperatures
9.	Durability: Rig must withstand abuse from transportation and accidental impacts	• Incorporate appropriate safety factor for repeated abuse

Final Rig Design & Functionality

The final rig design meets all design specifications. The user will need to provide the testers with a 10’ x 4’ wall specimen that does not exceed the 30” maximum thickness or 1000lb maximum weight capacity. A 36” width between the side rails means that up to a 3’ wide burner can be placed underneath the specimen. L-Brackets along the bottom frame connect to the specimen wall, and act as spacers to ensure that the burner has 12” of space in front of the face of the wall to allow for the correct plume and fire exposure. Flashing goes along the edge of the walls and insulation is inserted into the gaps between the wall specimen and fire channels.

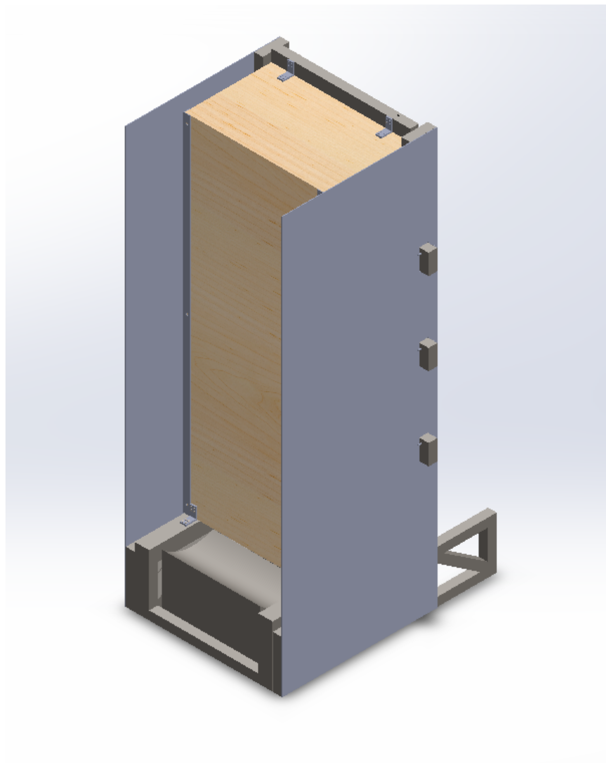


Figure 3: Fully Assembled Rig

The final rig consists of four main frames that lock together without the use of any tools, and can be disassembled to lay flat against a wall or floor. The rig will be able to be assembled with 2 individuals within a short 10 minute time period.

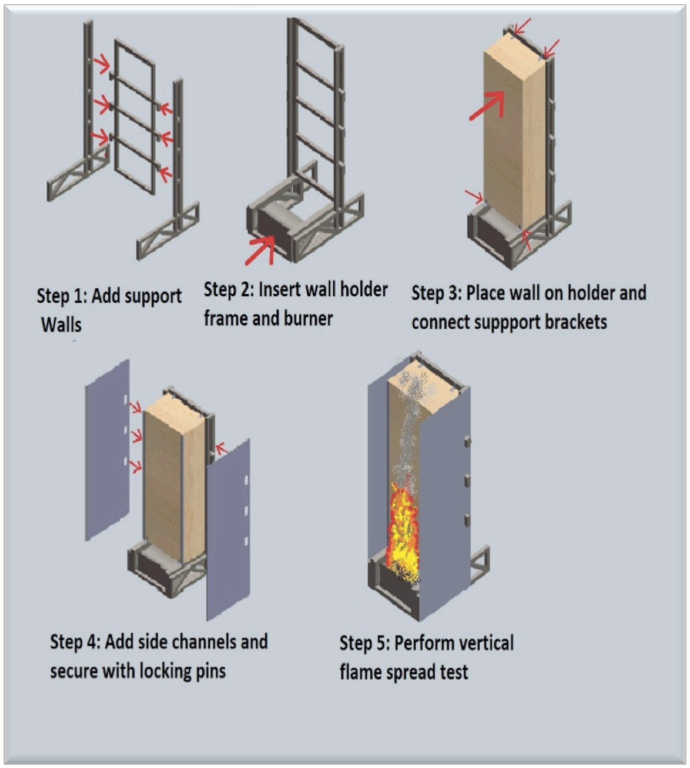


Figure 4: Instructions to Assemble the Rig

Locking pins are placed into holes on the backing wall to hold the fire channels to the side support walls. The wall holder frame can only be used for a specimen wall that can support its own weight without tipping over. For these cases, the specimen wall can be hung from the backing wall with brackets connected to the horizontal supports.

Note: Early Design iterations can be found in Appendix F.

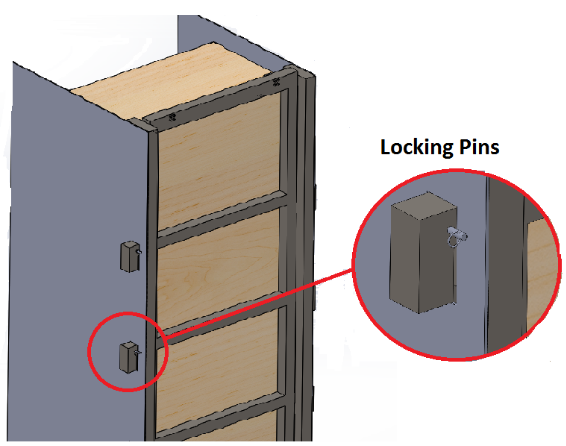


Figure 5: Locking Pins

Analysis of the rig

To ensure that the rig can handle the 1000lb wall and take repeated abuse, a stress analysis was performed on the wall holder frame and the side rails. In addition Impact and buckling analysis was performed on the holder and side rails respectively. This section will briefly explain the analysis process and present the final result obtained. The frame will be exposed to high temperatures during testing, a thermal analysis was performed to calculate the amount of heat that is transferred into structural members. To get accurate estimates of the temperatures within the beams, the burner heat release rate was calculated to match the wall heat flux distribution of the 285 test.

Holder Stress Analysis

The holder was simplified to a beam structure and the distributed wall load was simplified to a point load for the analysis as shown in appendix B. Passing the stress analysis with a simplified structure means that the holder is over designed but this is necessary due to the fact that the holder will be exposed to high temperatures. These temperatures will reduce the materials yield and tensile strength. Considering the maximum wall weight of 1000 lb. exerted on the holder, three major conditions were integrated to calculate the maximum moment and shear force that were used in the sizing of the holder design. Referring to Figure 6, the conditions were:

i. Point A and D have zero moments
ii. Both point A and D have moments
iii. Only point A has moment

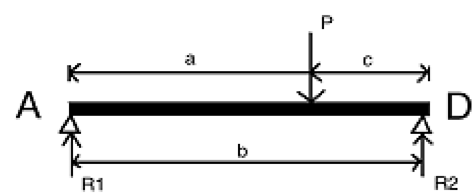


Figure 6: FBD for Analysis

The largest moment of $9.12*10^3$ lb.in was calculated from condition i. and a maximum shear force of 460.256 lbf from condition iii. This moment and shear force is used in the sizing of the holder.

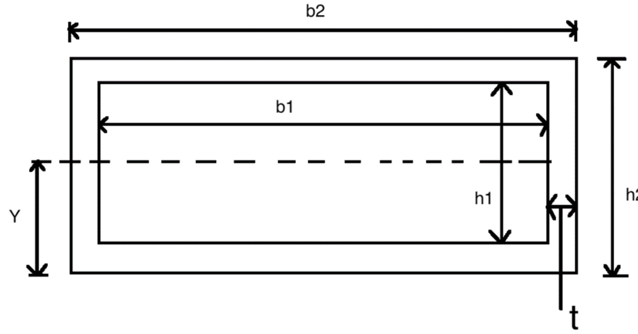
<u>Note</u>: For detailed calculation, refer to Appendix C

Holder Section Sizing

For sizing, hollow tubing was chosen to reduce weight and increase manufacturability over solid sections.

The properties of the material, A500 Steel, used for the analysis are:

- Yield strength of 50ksi
- Tensile strength of 62ksi
- Melting point of 2750 degrees F
- Density of 0.284 lb./in^3



Where:

b1 = inside width of the beam

b2 = outside width of the beam

h1 = inside height of the beam

h2 = outside height of the beam

t = material thickness

Y = ½ the outside height of the beam

Figure 7: Sizing the Cross Section

Analysis was done on the section cut shown in Figure 7 to calculate shear and bending stresses that would be applied on the holder. Basic shear and bending equations were used [6]. To optimize the results, eleven different trials were calculated. The difference in the trials was either thickness or section area. Approximate weight of the holder was calculated in every trial. Table 2 summarizes results of bending stress, shear stress, and the holder's weight for the eleven different trials. The results are arranged in ascending material thickness.

Table 2: Results of Analysis

in	lb/in^2	lb/in^2	lb		inches
thickness	bending stress	shear stress	weight of holder	Trials	size/ section
0.0156	41110	5436	22	10	4 x 3
0.0156	24260	4091	29	9	5 x 4
0.0625	6022	1033	118	8	5 x 4
0.0625	4545	839	132	5	5 x 5
0.085	3388	620	178	4	5 x 5
0.083	4500	782	160	7	5 x 4
0.125	3149	525	234	6	5 x 4
0.125	1888	425	260	3	5 x 5
0.25	1273	218	507	2	5 x 5
0.5	741	114	961	1	5 x 5

Below is a plot showing the effect on shear stress, bending stress, and weight due to change of wall section thickness. The plot shows the material's yield and tensile strength.

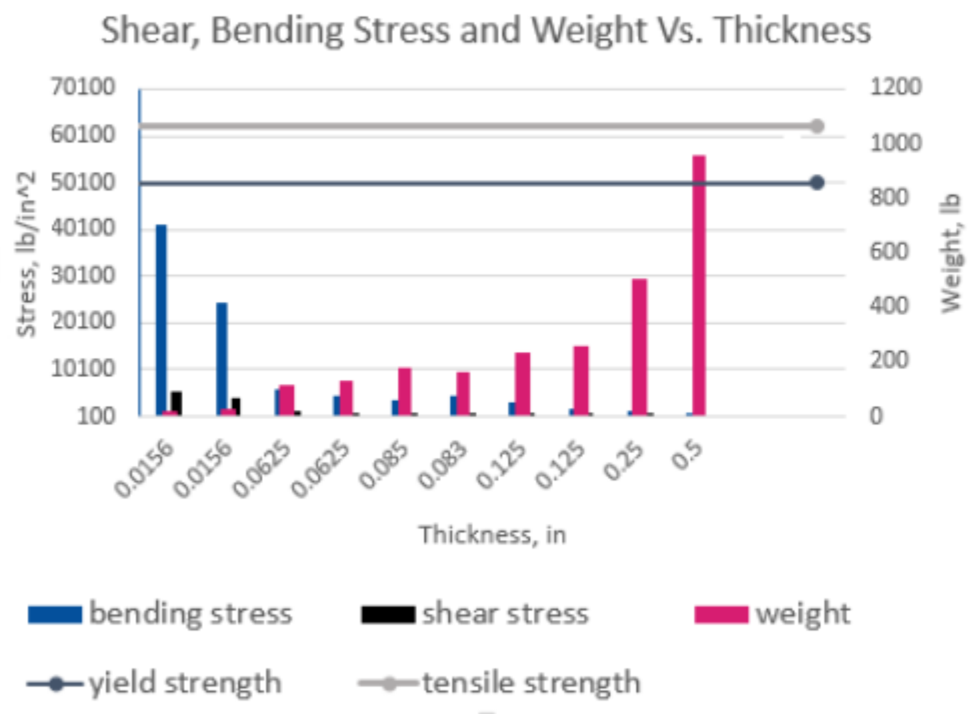


Figure 8: Shear, Bending Stress, and Weight of Holder vs. Thickness

From the above plot, it is clear that as thickness increases, both the shear and bending stress on holder due to the exerted load decreases but the weight increases. The results show that the holder will not fail in bending or shear in any of the 11 trials. Material thickness of 0.0625 inch was chosen since the holder will be reasonably light and this thickness can be manufactured with ease. The plot below shows the chosen material thickness of 0.0625 inch. Trials 8 & 5 have this thickness but different section dimensions.

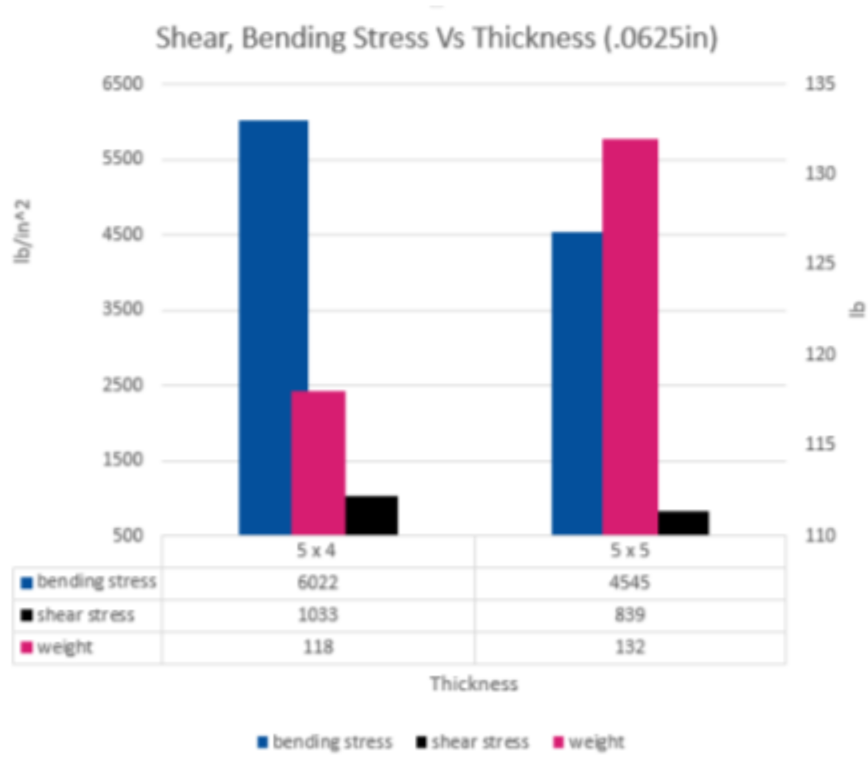


Figure 9: Shear, Bending Stress and Weight of Holder vs. Thickness

Both of the above sections are ideal for the holder design but since one of main design objectives is a light-weight frame, it is better to use the 5 x 4 section as it leads to a lighter total holder weight.

<u>Note</u>: Refer to appendix C for detailed calculation

Impact Analysis

Impact analysis was performed to ensure that the designed holder will not fail in bending or shear in the event of a wall being accidently dropped onto it from 2 feet. From the impact analysis, dropping a 1000lbf wall from 2 feet causes a 2005lbf impact force on the holder. Taking this impact force and re-calculating the bending and shear stresses for the chosen section size showed an increase in shear by a factor of 4 and bending stress by a factor of 2.

Table 3 shows comparison of shear and bending stress of normal and impacted load.

Table 3: Shear and Bending Stress of Normal and Impact Load

	Force on holder (lbf)	Shear Stress (lbf/in^2)	Bending Stress (lbf/in^2)
Normal Load	1000	1033	6022
Impact Load	2005	4136	12070
Increase Factor	2	4	2

The calculated stresses are not close to the material yield or tensile strength, therefore the designed holder will not fail if the wall is dropped on it from 2 feet. (It is highly advised not to drop the wall at all).

Note: Refer to appendix C for detailed calculations

Punching Analysis

Punching analysis was performed to ensure that when 1000lb is placed on the holder, the material thickness of 0.0625 in. will not be punctured by a foreign object. To evaluate this, a punching force necessary to punch through the material was calculated. Table 4 shows results considering an object with a circular surface of diameters 0.5 in and 0.125 in.

Table 4: Impact Force

Object diameter (inches)	Impact Force (lbf) to punch through
0.5	6087
0.125	1522

A500 Steel has a tensile strength of 62ksi and the max-applied load is 1000lbf, therefore it is safe to conclude that the designed holder is not at risk of getting punctured by a foreign object.

Note: Refer to appendix C detailed calculations

Side Rail stress Analysis

Stress analysis was performed on the side rails to determine whether a specimen weighing 500lb can be hung on the designed rig. The side rail was simplified to a simple cantilever structure for analysis as shown in appendix B. Compressional stress was calculated as well since it can be a possible failure factor. Estimated weight of one side rail was also calculated during this analysis.

Two different analyses were done, one for a side rail made out of a hollow structure and the other made out of a solid structure. Results showed that both cases are ideal for a side rail design of 0.0625 material thickness. Below are results for the solid structure case over 4 trials. Material used for the side is the same as holder, A500 Steel. Table 5 shows results of weight, bending and compressional stresses arranged by increasing thickness of the solid section.

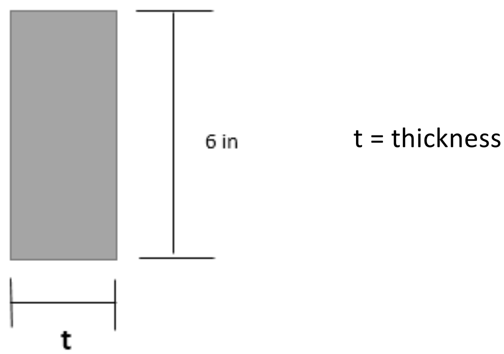


Figure 10: Solid Cross Section for the Side Rail

Table 5: Stresses and Weight of Side Rail for Specific Thickness

in	lb/in^2	lb/in^2	lb	
Thickness	Bending stress	Compressional stress	Weight of Side Rail	Trials
0.03125	8333	1333	7	3
0.0625	4167	667	13	4
0.667	390	63	142	2
1	260	42	213	1

Plot showing the effect on bending stress, compressional stress and weight due to change of thickness.

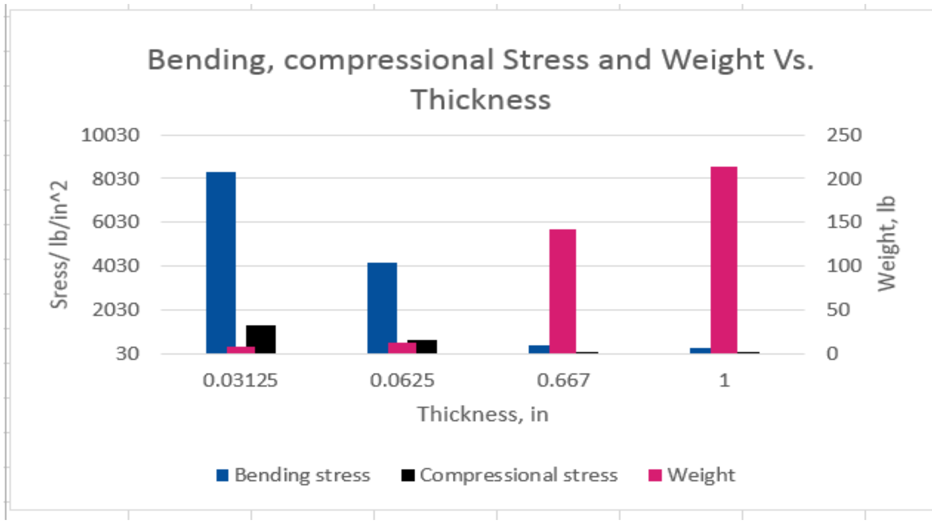


Figure 11: Bending Stress, Compression, and Weight of Side Rail vs. Thickness

Below are results for the hollow structure case over 5 trials.

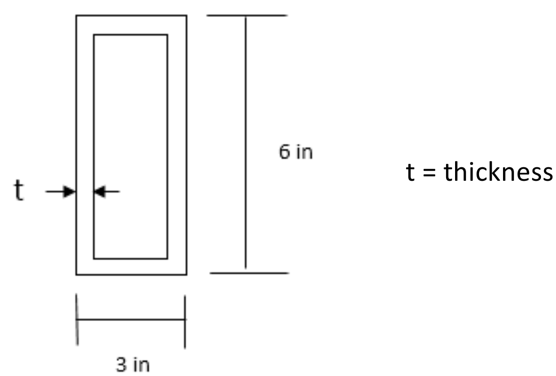


Figure 12: Sizing the Hollow Section for the Side Rail

Table 6 shows results of weight, bending and compressional stresses arranged by increasing thickness.

Table 6: Bending, Compression and Weight for Specific Thickness

in	lb/in^2	lb/in^2	Lb	
Thickness	Bending stress	Compressional stress	Weight of Side Rail	Trials
0.0156	3370	893	10	1
0.0313	1696	447	20	2
0.0417	1281	336	26	4
0.0625	865	225	39	3
0.5	141	31	284	0

Figure 13 shows the effect on bending stress, compressional stress and weight due to change in thickness.

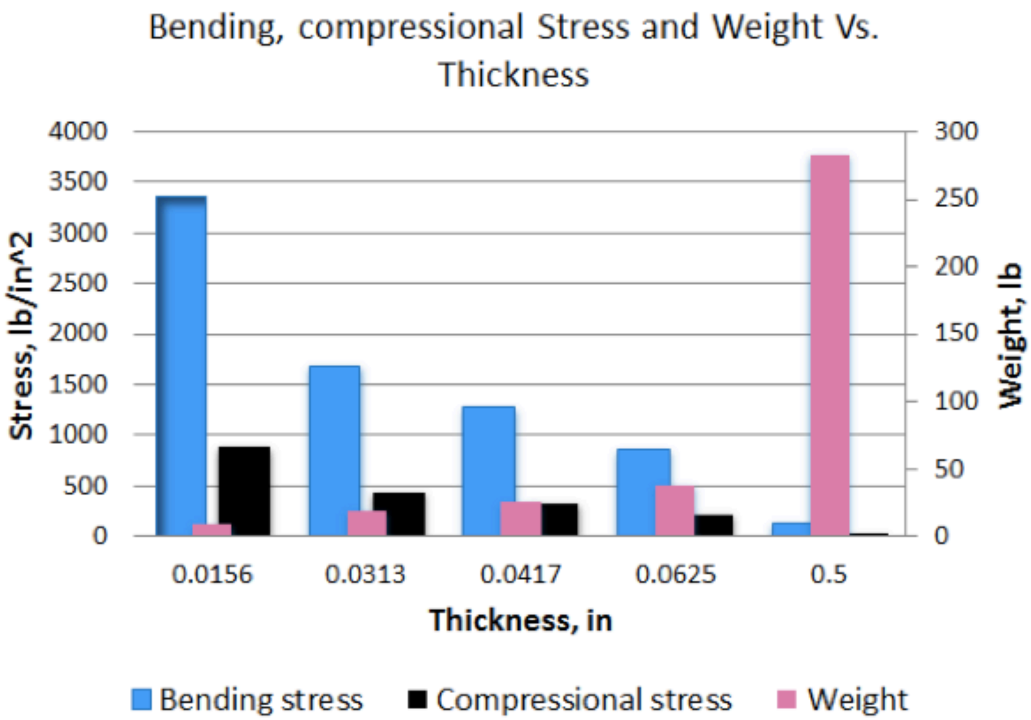


Figure 13: Bending Stress, Compression, and Weight vs. Thickness

According to the calculation and comparing material yield and tensile strength, a solid structure with a thickness of 0.0625". would support the assumed weight (500 lb.) if hung, but to securely hang a large heavy specimen, a larger surface area of more than 0.0625"x 6" is needed. This section would be prone to buckling therefore the side rail will be **designed as a hollow structure**, instead of a solid section.

Note: Refer to appendix D for detailed calculations

Buckling Analysis

Since the side rails are 10 feet long, buckling analysis was done to ensure that the designed side rail will not fail due to buckling. To achieve this, a critical bucking load was calculated using Euler's formula. Results showed that the side rail would only buckle if a 9923lb load is hung on the rig. Since the max-hanging wall is limited to 500lb, buckling will not be a problem for the designed rig.

Note: Refer to appendix D for detailed calculations

Thermal Analysis

To ensure that the intermediate scale rig would be able to withstand the heating caused by the burner during testing, a series of heat flux and heat transfer calculations were performed to:

1. Determine a burner heat release rate that simulates wall heat flux distribution of the 285 test.
2. Determine incident radiative heat flux on the exposed frame.
3. Determine surface temperature of frame and time to reach steady state conditions.
4. Determine heat fluxes due to conduction between burner and frame.
5. Determine necessary insulation thicknesses for frame.

Simulating 285 Test Conditions

When scaling down the dimensions of the 285 test, the burner size and heat release rate must also be scaled down to meet proper testing conditions. The full-scale test uses 2 pipe burners with heat release rates of 400 and 900 kW. The burners are calibrated to NFPA standards before every test by subjecting a test specimen to gas burners of gas flow rates found in Table 4.4.13 of NFPA 258 Document [3] or appendix F.

The test calibration wall is made of 5/8" TYPE X gypsum wall boards, conforming to ASTM C1396/C1396M [7], applied to both sides of nominal 18-gauge steel studs spaced 24" on center. Using a combination of heat flux gauges and Thermocouples, the burners' temperatures and heat fluxes are measured in intervals of 5 minutes for 30 minutes. The measurements gained from the test must be within 10% of the values presented in table 7.1.11 NFPA 258 Document [3] or appendix F.

The intermediate scale burner for the rig will need to match these calibration heat fluxes at similar z co-ordinates along the vertical wall face. In order to accurately compare heat flux distributions of different scale tests, the heat fluxes were graphed based on a ratio of distance (z) over flame height (L_f), used to normalize the height. This ratio $\frac{z}{L_f}$ is known as a normalized height above the burner. Figure 14 shows the graph of calibration heat fluxes against normalized flame height after the test has been running for 30 minutes.

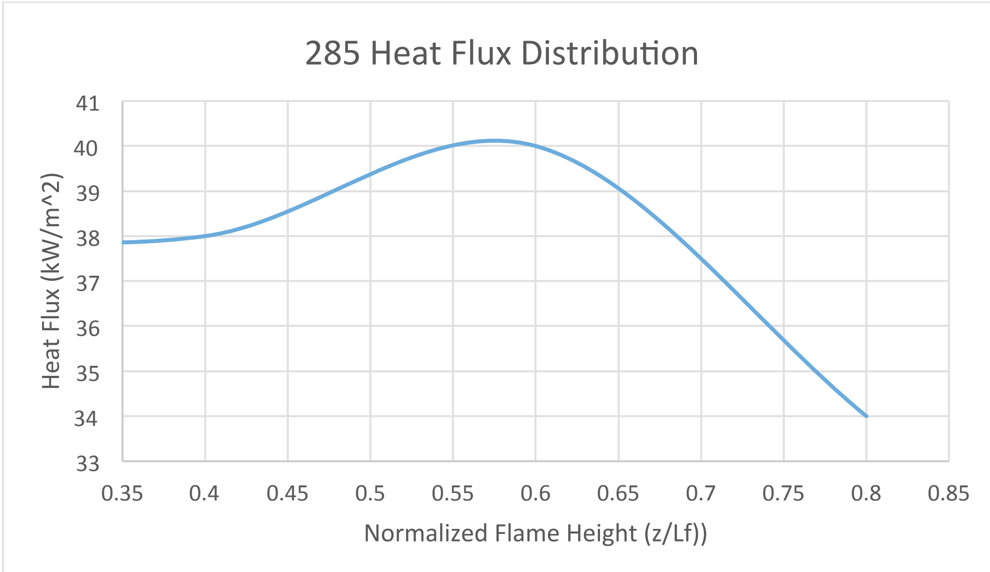


Figure 14: 285 Heat Flux Distribution

Calculations for the heat flux distributions of the intermediate scale burner were performed for various heat release rates. A study by Bryan Y. Lattimer from the SFPE Handbook of Fire Protection Engineering provided a model to calculate the heat flux distribution of fires adjacent to flat walls [8]. We used this model to calculate the flame heights and heat flux distributions for fires ranging from 50-100kW. The model uses the peak heat flux of the fire and determines the decrease in heat flux with increase in vertical distance (Z) from the base of the fire. The Hydraulic Diameter, $D_{H,}$ was calculated based on the intermediate square burner dimensions and used in calculating flame height.

Peak Heat Flux (based on gray-gas radiation theory)

$$q"_{peak} = 200[\,1 - \exp\,(-.09\; Q^{1\backslash 3})$$

Flame Heights from Heskestad [9]

$$L_f = 0.23Q^{2/5} - 1.02D_h$$

The method has 3 equations which model heat fluxes at 3 distinct zones above the fire.

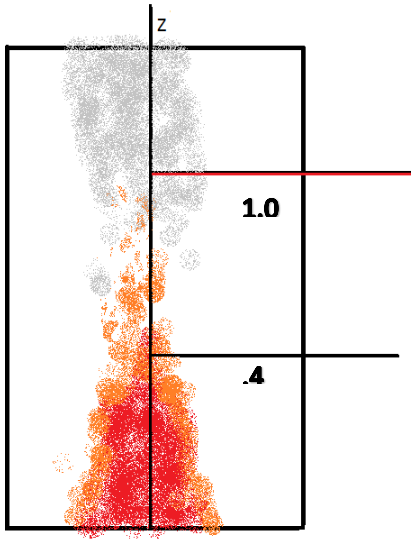


Figure 15: Flame Zones

Fire Plume Zone

$$\frac{Z}{L_f} < 1 \qquad q"_{cl} = 20\left({}^{Z}/_{L_f}\right)^{-5/3}$$

Intermittent Flame Zone

$$.4 < \frac{Z}{L_f} > 1 \qquad q"_{cl} = q"_{peak} - \frac{5}{3}\left(z/L_f - {}^{2}/_{5}\right)\left(q"_{peak} - 20\right)$$

Continuous Flame Zone

$$\frac{Z}{L_f} \geq .4 \qquad q"_{cl} = q"_{peak}$$

Plotting the results based on normalized flame heights provided flame distributions that could be compared to the 285 distribution.

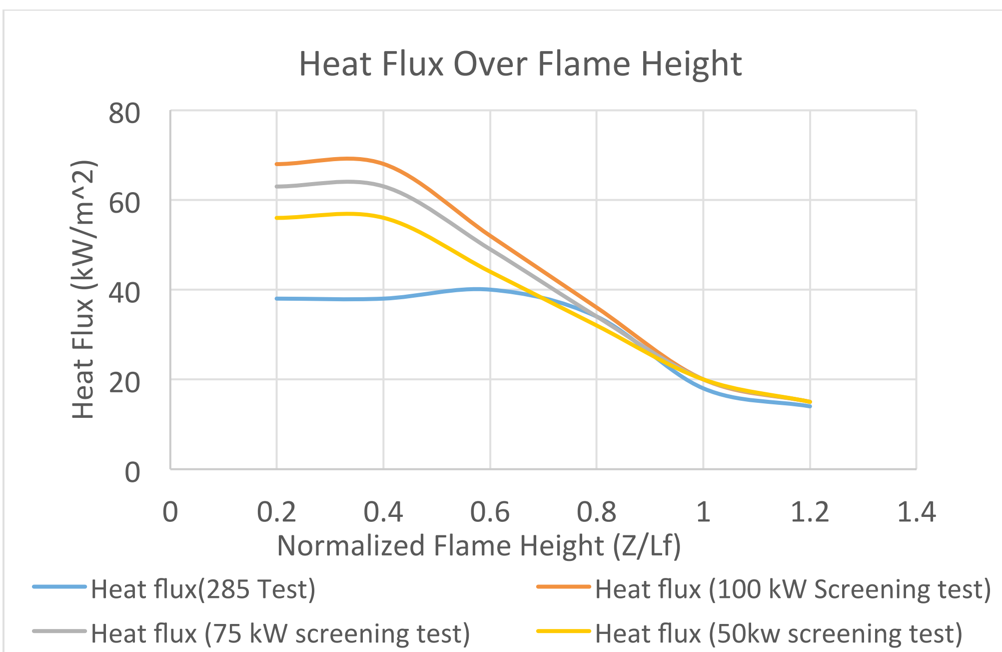


Figure 16: Heat Flux over Flame Height

Note: For Full Detailed Calculations Refer to Appendix D.

The results pictured in Figure 16 have a slightly larger peak heat flux value, but with such a low heat release rate turbulent flame dispersion can occur. At Heat releases of 75-100kW the flame creates a distinct vertical flame column necessary from vertical wall flame spread testing.

<u>Note</u>: Refer to appendix D for detailed calculations

Thermal Insult Due to Radiation

While the test is running, the fire will radiate heat downwards onto the support frame. Based on a 100kW fire, we calculated the incident radiative heat flux on the surface of the steel frame members. Using the hydraulic diameter we assumed the flame to be a large pool fire radiating to a distance. From Shokri and Beyler's Pool fire testing model [10] we can take the flame to be a point source and calculate the radiative heat flux to the target. Results from this analysis returned extremely low and inaccurate heat fluxes. Due to the short distance from the burner to the frame, a different approach was taken for close targets using a finite flame method. This method models the flame as a plane through the centerline of the burner. Using the view factor and radiative fraction, the amount of radiation absorbed from the fire plane to the surface of the frame was determined.

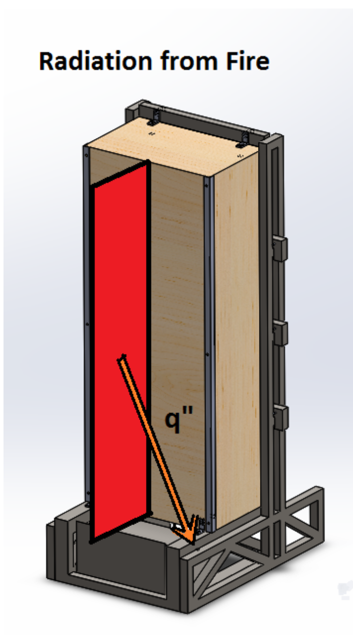


Figure 18: Radiation from Flame

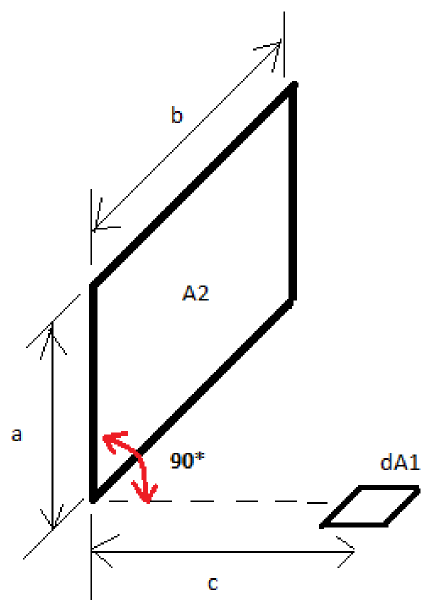


Figure 17: View Factor from Flame

Radiative Heat Flux Equation

$$q"_t = 2(F_{dl})\left(\frac{Q_r}{A_{fl}}\right) \qquad f_{dl} = View\ Factor \quad Q_r = Heat\ Release\ Rate \times Radiative\ fraction$$

$$A_{fl} = Area\ of\ Flame = hydraulic\ Diameter \times flame\ height\ (L_f)$$

The incident radiative heat flux was calculated to be 9 kW/m^2 for a 100 kW burner. This value was used to find temperatures at the steel's surface using a heat transfer equation incorporating radiative and convective cooling.

Heat Transfer Caused by Radiation

$$\varepsilon \cdot q_t = h_c \cdot (T - T_\alpha) + \varepsilon \cdot \sigma \cdot \left(T^4 - T_\alpha{}^4\right)$$

Solving this equation for T gives a temperature of 550K (277 deg C) at steady state conditions.

Solving a linear first order differential equation for the temperature over time and plotting the results shows that time to reach steady state conditions is 16 minutes.

Heat Transfer ODE

$$\rho \cdot c \cdot \Delta \cdot \frac{dT}{dt} = \varepsilon \cdot q_t - h_t(T - T\alpha)$$

ODE Solution for 1/6" steel tube

$$T(t) := C_1 e^{-(0.000084962t)} + 514.3$$

$$C_1 := -411.$$

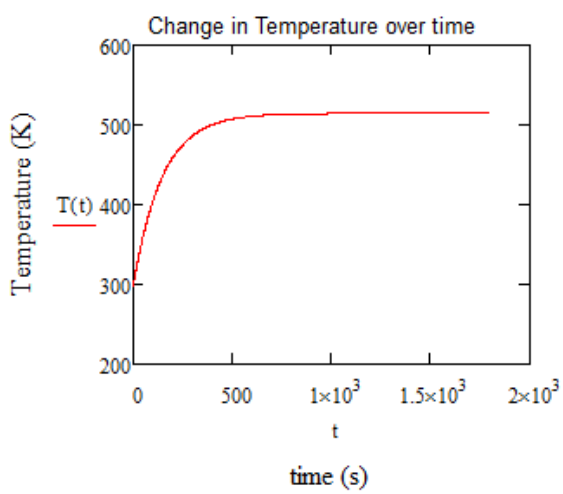


Figure 19: Change in Temperature over Time

Note: For Full Detailed Calculations Refer to Appendix D.

Conduction Analysis and Addition of insulation

Using a basic heat transfer equation for conduction [11], the net heat fluxes at the surface of the frame through the insulation were acquired for 1 and 2 inches of insulation. We assumed that the surface of the steel will be ambient (298K) and the fire would be at 1500K.

Net Heat Flux at surface of steel

$q_{net} = k \times \frac{\Delta T}{\Delta X}$ $\quad k = thermal\ conductivity\ of\ insulation$

$\Delta T = Change\ in\ Temperature \quad \Delta X = insulation\ thickness$

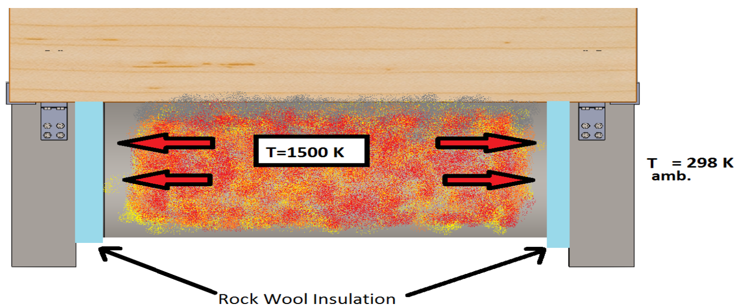


Figure 20: Conduction through Insulation

The above equation was used to calculate net heat fluxes of the radiation and conduction through the insulation. These calculated net fluxes were used to find the change in surface temperature over time. Lumped analysis was used to achieve results.

$$\rho \cdot c \cdot \Delta \cdot \frac{dT}{dt} = q_{net}$$

Table 7 shows net heat fluxes used to plot the change in temperature over the testing duration of 30 minutes.

Table 7: Heat Transfer through Insulation

	Radiation to Insulation on Top of Frame		**Conduction Through Insulation at Burner Edge**	
Insulation thickness (in.)	**Net Heat Fluxes From Radiation Through Insulation (kW/m^2)**	**Holder frame Temperatures after 30 minutes (K) Radiation**	**Net Heat Fluxes From Conduction Through Insulation (kW/m^2)**	**Holder frame Temperatures after 30 minutes (K) Conduction**
1	q_{net} = 0.5	T= 462 K	q_{net} = 2.7	T = 1168 K
2	q_{net} = 0.2	T=265 K	q_{net} = 1.35	T = 737 K

Using 2 inches of insulation will ensure that the yield strength of our material will only be reduced by 20% to 40 ksi after 30 minutes. The maximum load causes a bending stress of 6 ksi, hence our material selection and cross section sizing will provide adequate strength at high temperatures.

Note: Refer to appendix D for detailed calculations

Thermal Properties of Steel

The inability to find test data on temperature impacting yield strength of ASTM A500 steel [12], required the use of data for a steel of similar properties. The steel tested was Structural steel S460M. This is equivalent to the ASTM A572 steel [13], which is a high strength low alloy steel with a yield strength of 50,000 psi and a tensile strength of 65,000 psi. The maximum temperature that the frame will need to withstand is 737 K or 463 degrees Celsius. The following graph (Figure 17), taken from Outinen [14], shows the strength loss of the material when subjected to increasing temperature.

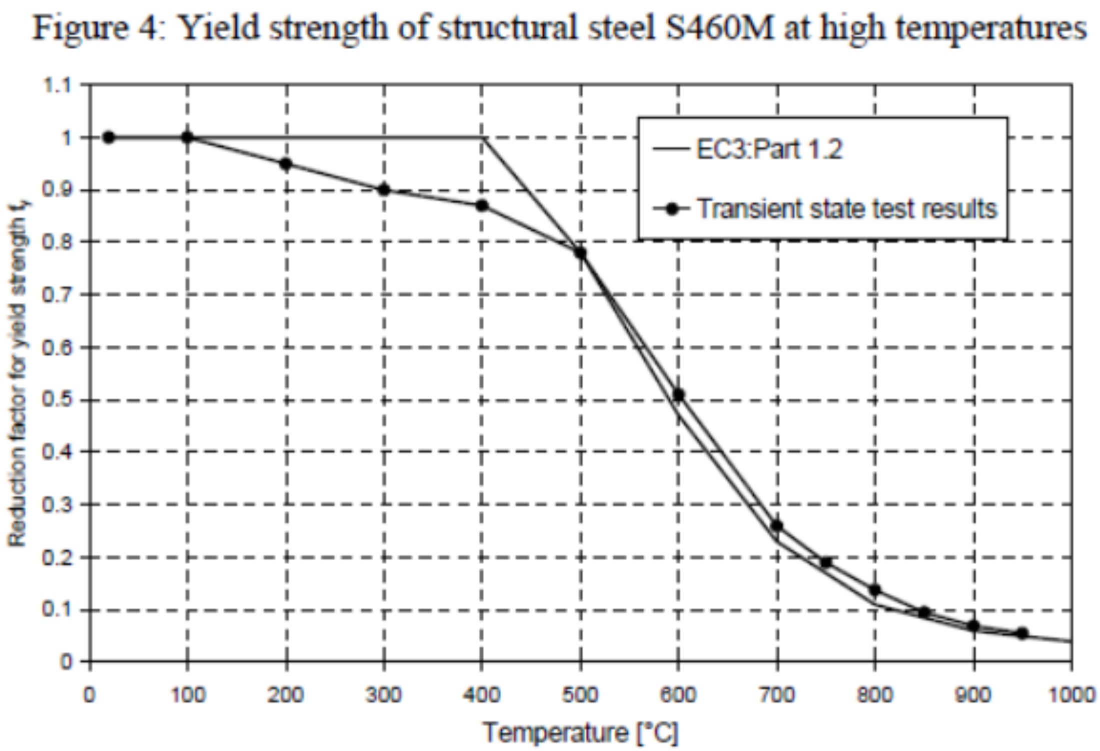


Figure 21: Reduction of Yield due to Temperature [14]

At 463 degrees Celsius, the yield strength of the material is reduced by 20%, providing a sufficient safety factor for the holder.

Conclusions & Recommendations

After a full stress and thermal analysis, the holder and side rails were designed with hollow rectangular tubing of 0.0625”thick A500 Steel. With the achieved results and consideration of the fact that the holder is over designed, the designed Intermediate Scale Fire Test Rig will not fail in bending, shear, or compressional stresses when loaded with the maximum wall assembly of 1000lb. The performed thermal analysis confirmed that radiation and conduction from the burner will not cause failure of the holder with 2” of fiber wool insulation. The designed intermediate scale rig weighs approximately 300 lb., meeting weight requirements by the WPI Fire Laboratory. The team strongly believes the rig accommodates all the requirements for a successful NFPA 285 Screening Test.

The team recommends that additional thermal analysis should be performed since the rig will be subjected to multiple heating and cooling reactions. It is necessary to know the effect of these reactions to the A500 Steel structure as this will provide an estimation on the life duration of the holder. Being able to predict warping behavior will allow for prevention of sudden failure after running several NFPA 285 tests on the rig.

Report Reference

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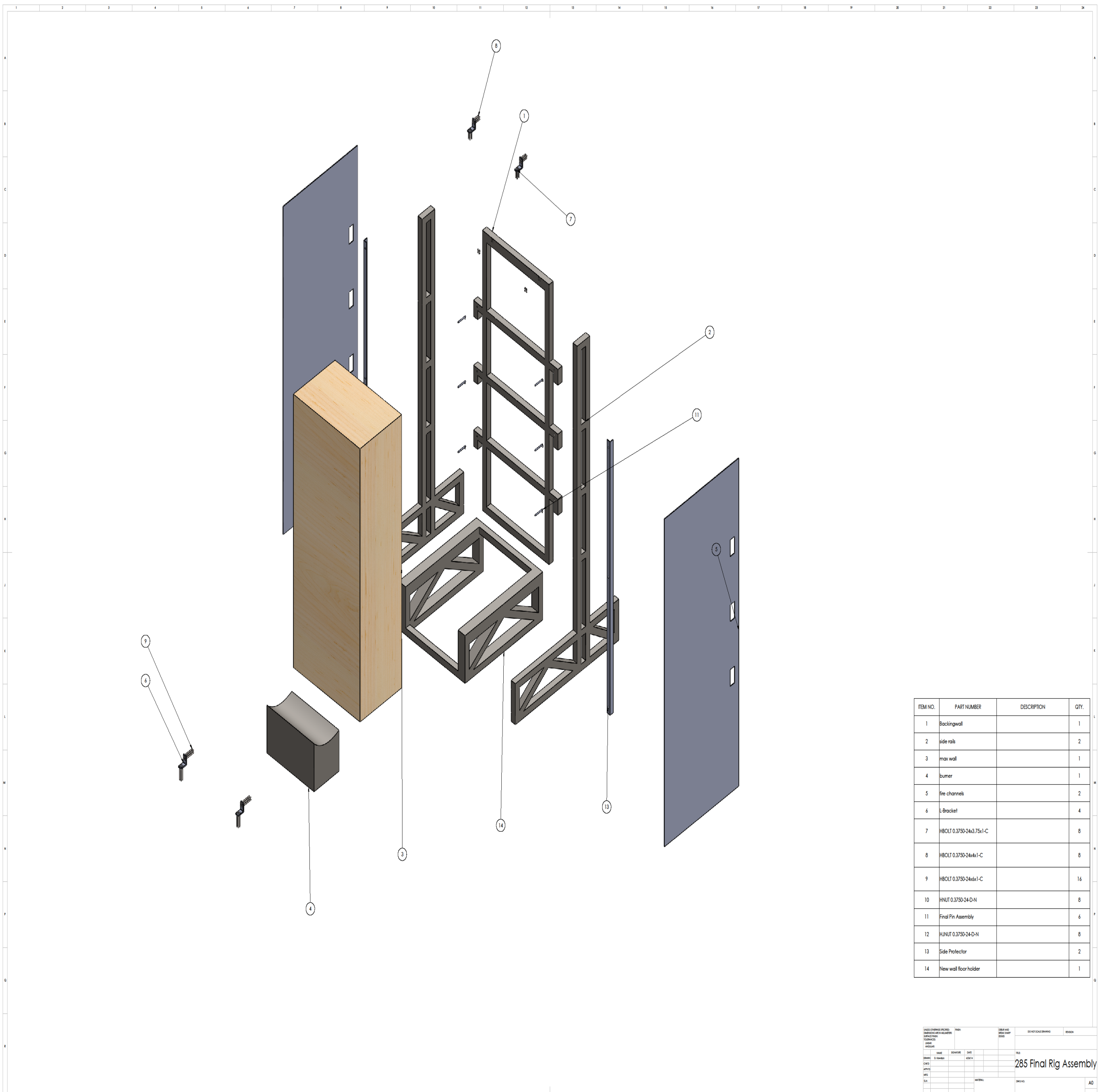
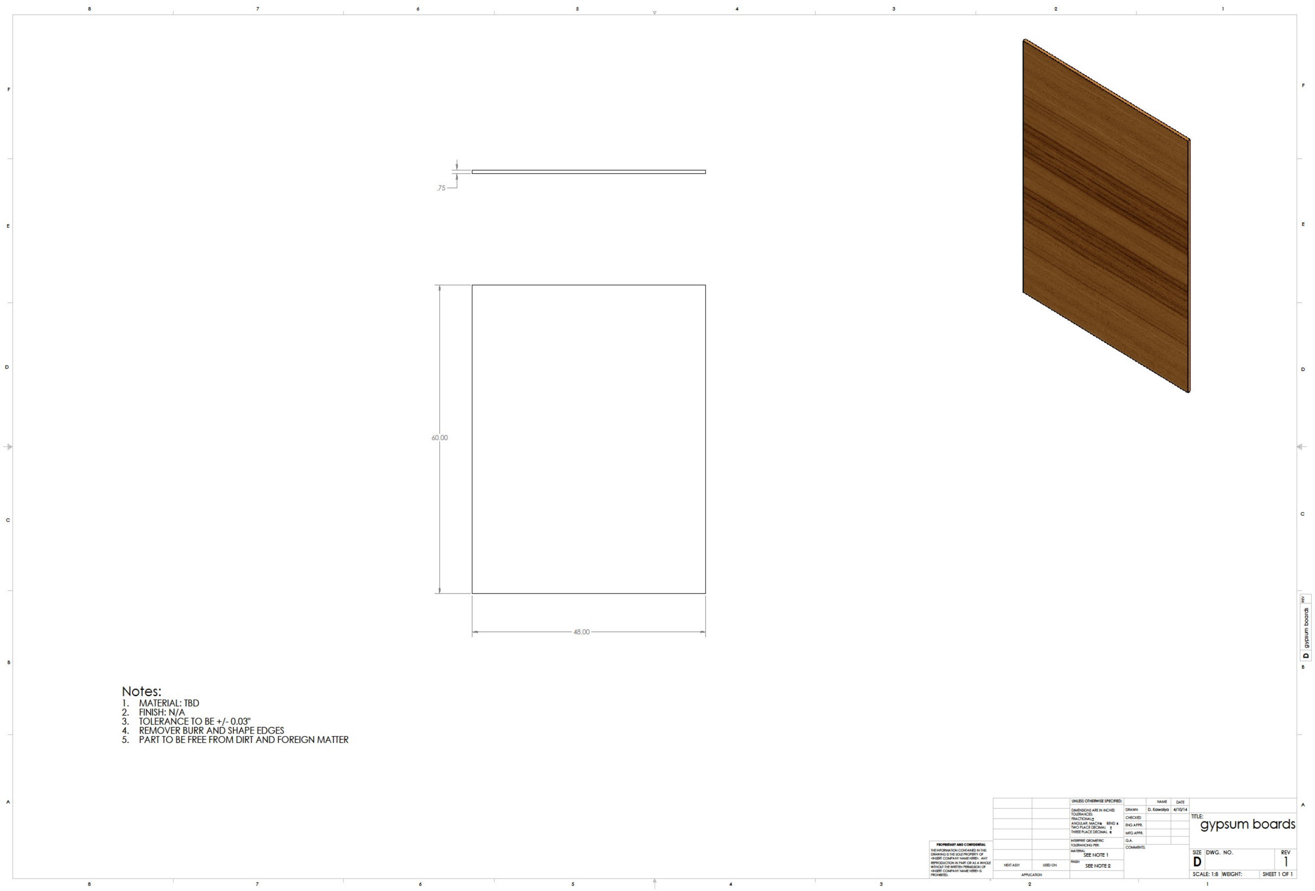
APPENDIX

APPENDIX A



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Backingwall		1
2	side rails		2
3	max wall		1
4	burner		1
5	fire channels		2
6	L-Bracket		4
7	HBOLT 0.3750-24x3.75x1-C		8
8	HBOLT 0.3750-24x4x1-C		8
9	HBOLT 0.3750-24x6x1-C		16
10	HNUT 0.3750-24-D-N		8
11	Final Pin Assembly		6
12	HJNUT 0.3750-24-D-N		8
13	Side Protector		2
14	New wall floor holder		1



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2. FINISH: N/A
3. TOLERANCE TO BE +/- 0.03"
4. REMOVER BURR AND SHAPE EDGES
5. PART TO BE FREE FROM DIRT AND FOREIGN MATTER
PROPRIETARY AND CONFIDENTIAL
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USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
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ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
SEE NOTE 1
FINISH
SEE NOTE 2
NAME
DATE
DRAWN
D. Kawalya
4/10/14
CHECKED
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MFG APPR.
Q.A.
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REV
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WEIGHT:
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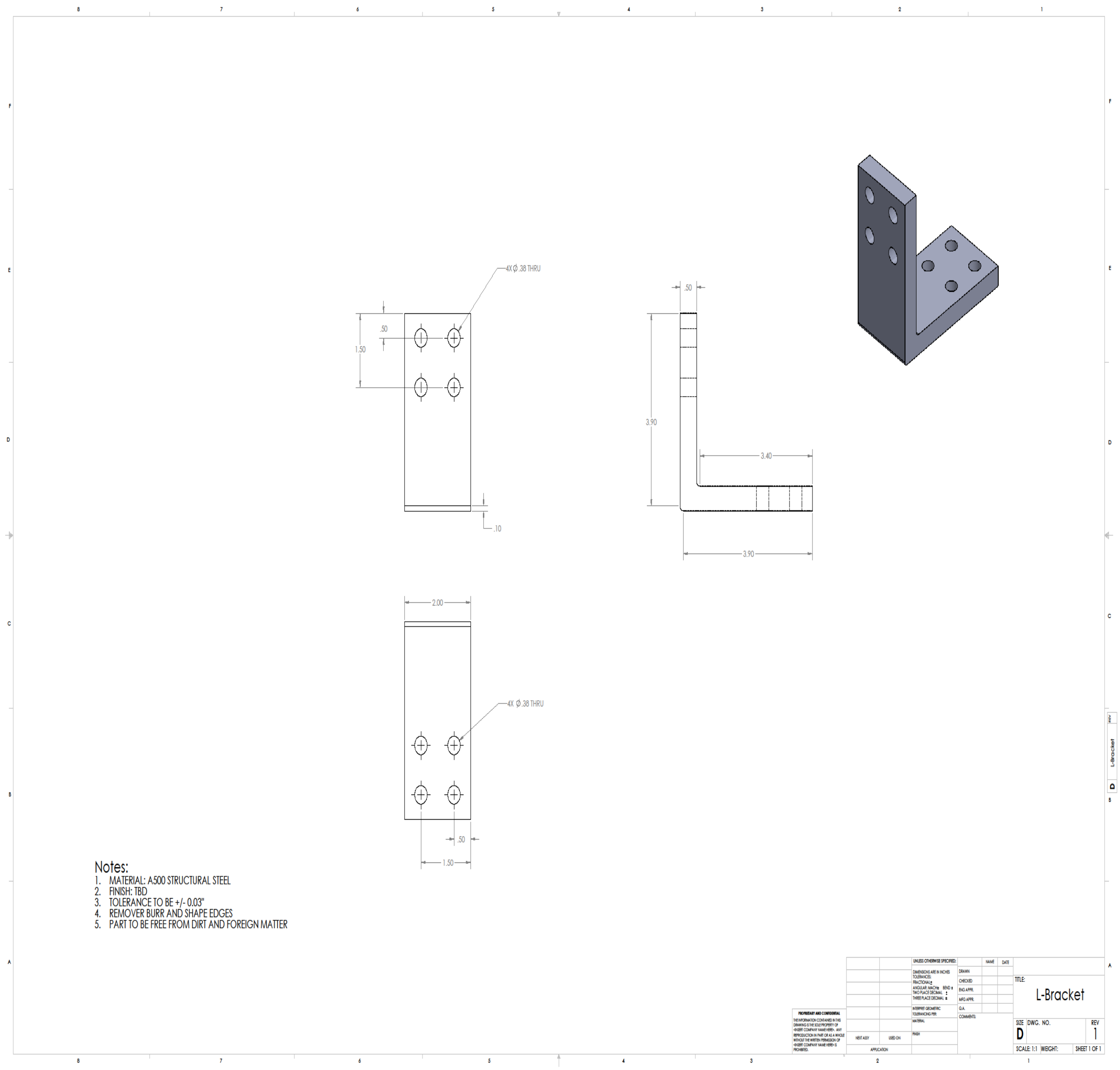
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3.90
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4X Ø .38 THRU
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1.50
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2. FINISH: TBD
3. TOLERANCE TO BE +/- 0.03"
4. REMOVER BURR AND SHAPE EDGES
5. PART TO BE FREE FROM DIRT AND FOREIGN MATTER
UNLESS OTHERWISE SPECIFIED:
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DATE
DIMENSIONS ARE IN INCHES
TOLERANCES:
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CHECKED
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MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC TOLERANCING PER:
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REV 1
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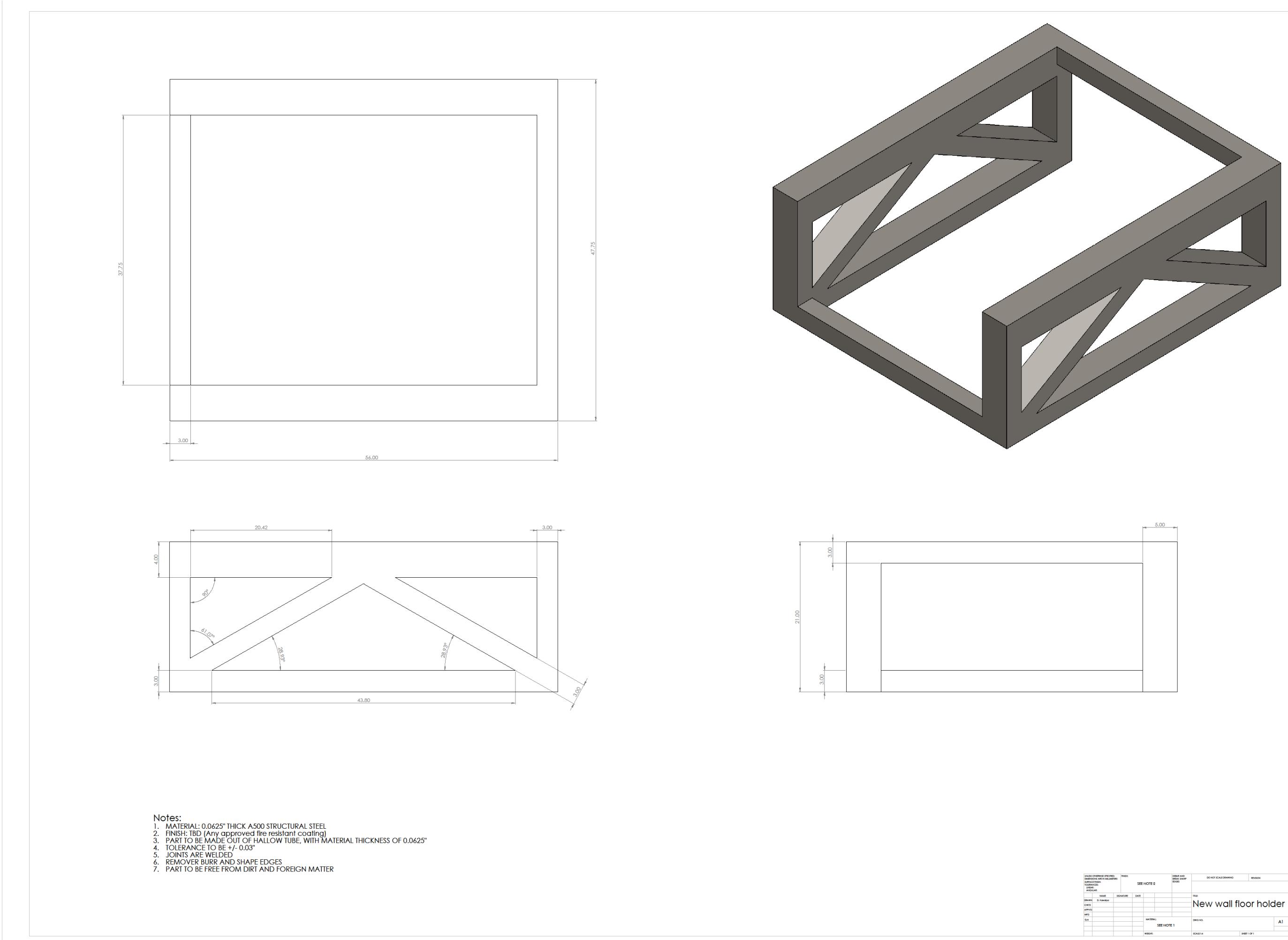
WEIGHT:
SHEET 1 OF 1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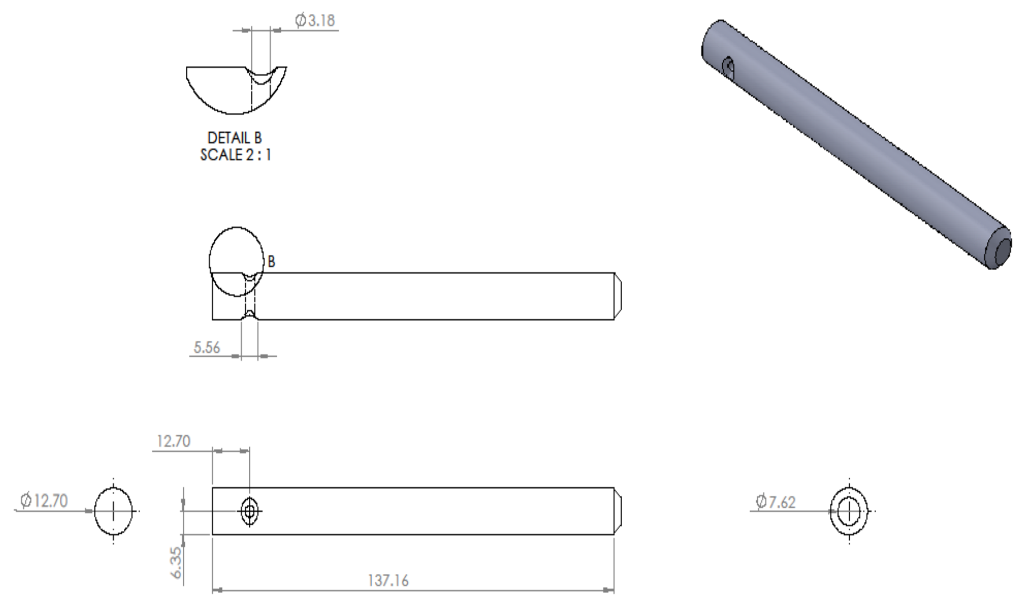
2. FINISH: TBD (Any approved fire resistant coating)
3. PART TO BE MADE OUT OF HALLOW TUBE, WITH MATERIAL THICKNESS OF 0.0625"
4. TOLERANCE TO BE +/- 0.03"
5. JOINTS ARE WELDED
6. REMOVER BURR AND SHAPE EDGES
7. PART TO BE FREE FROM DIRT AND FOREIGN MATTER
SEE NOTE 2
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
D. Kawalya
TITLE:
New wall floor holder
MATERIAL:
SEE NOTE 1
A1
SHEET 1 OF 1



Notes:

1. MATERIAL: A500 STRUCTURAL STEEL
2. FINISH: TBD
3. TOLERANCE TO BE +/- 0.03"
4. REMOVER BURR AND SHAPE EDGES
5. PART TO BE FREE FROM DIRT AND FOREIGN MATTER

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH: SEE NOTE 2

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 1

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DRAWN	D.Kawalya		
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: pin part 1

MATERIAL: SEE NOTE 1

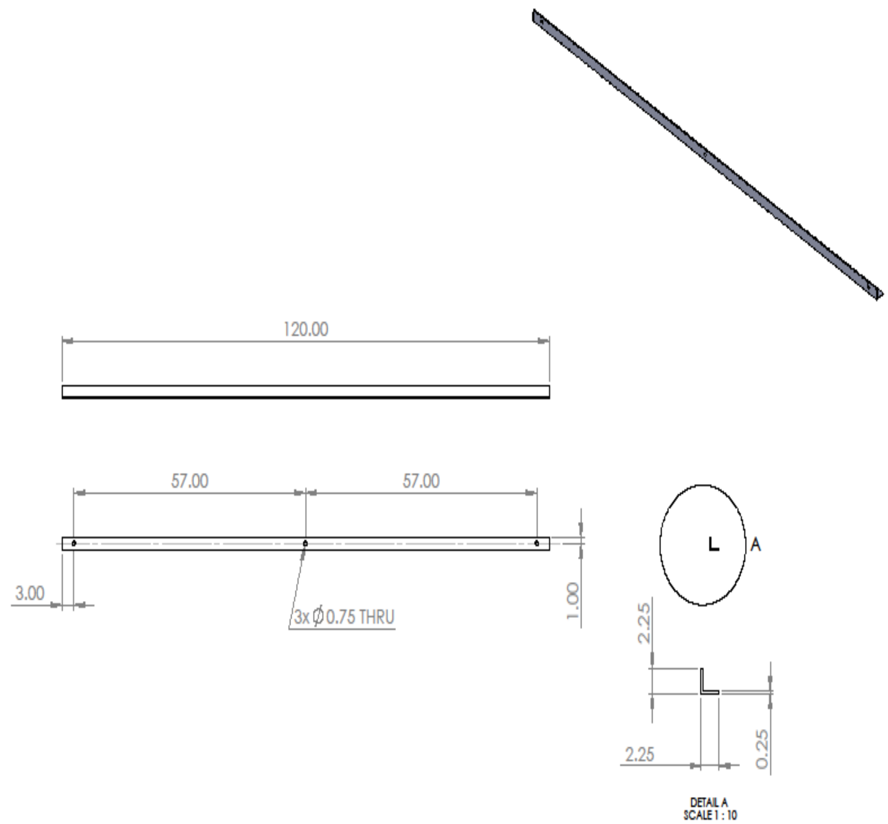
DWG NO.

A3

WEIGHT:

SCALE:1:1

SHEET 1 OF 1



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4. REMOVER BURR AND SHAPE EDGES
5. PART TO BE FREE FROM DIRT AND FOREIGN MATTER

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:
FINISH: SEE NOTE 2
DEBUR AND BREAK SHARP EDGES
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NAME SIGNATURE DATE
DRAWN D. Kawalya
CHK'D
APPV'D
MFG
Q.A
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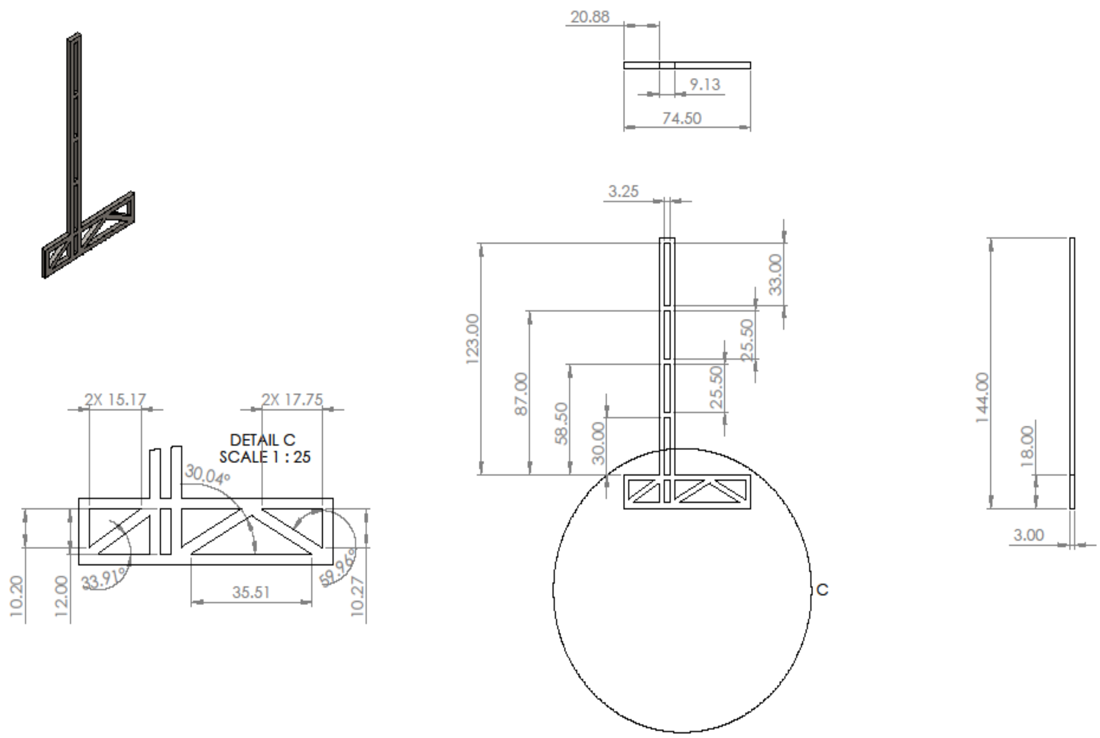

Notes:

1. MATERIAL: 0.0625" THICK A500 STRUCTURAL STEEL
2. FINISH: TBD (Any approved fire resistant coating)
3. PART TO BE MADE OUT OF HALLOW TUBE, WITH MATERIAL THICKNESS OF 0.0625"
4. TOLERANCE TO BE +/- 0.03"
5. JOINTS ARE WELDED
6. REMOVER BURR AND SHAPE EDGES
7. PART TO BE FREE FROM DIRT AND FOREIGN MATTER

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FINISH: SEE NOTE 2
DEBUR AND BREAK SHARP EDGES
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APPV'D
MFG
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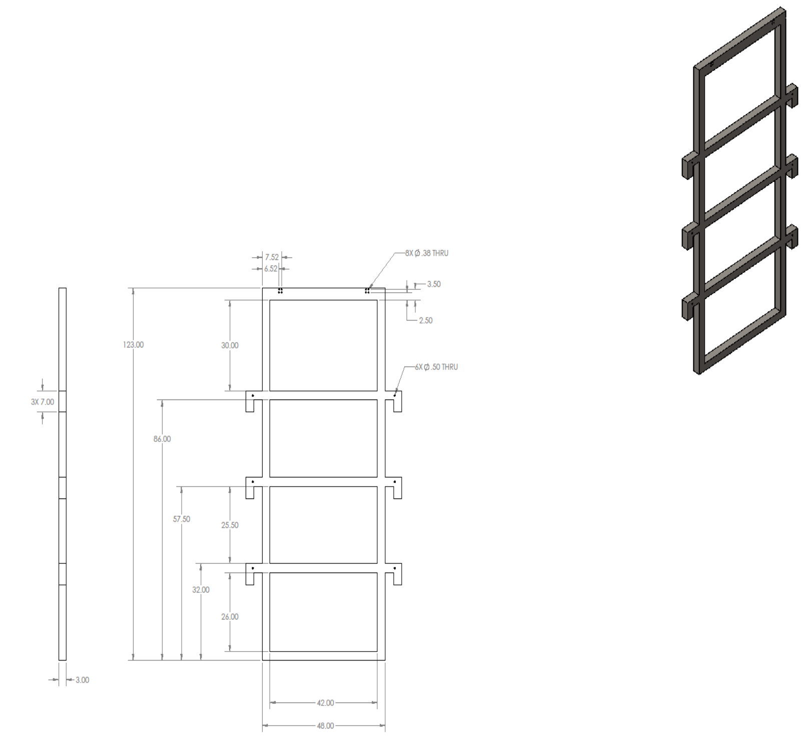

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5. JOINTS ARE WELDED
6. REMOVER BURR AND SHAPE EDGES
7. PART TO BE FREE FROM DIRT AND FOREIGN MATTER

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DIMENSIONS ARE IN INCHES
TOLERANCES:
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ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL: SEE NOTE 1
FINISH: SEE NOTE 2

	NAME	DATE
DRAWN	D. Kawalya	4/10/14
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MFG APPR.		
Q.A.		
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TITLE: Backingwall

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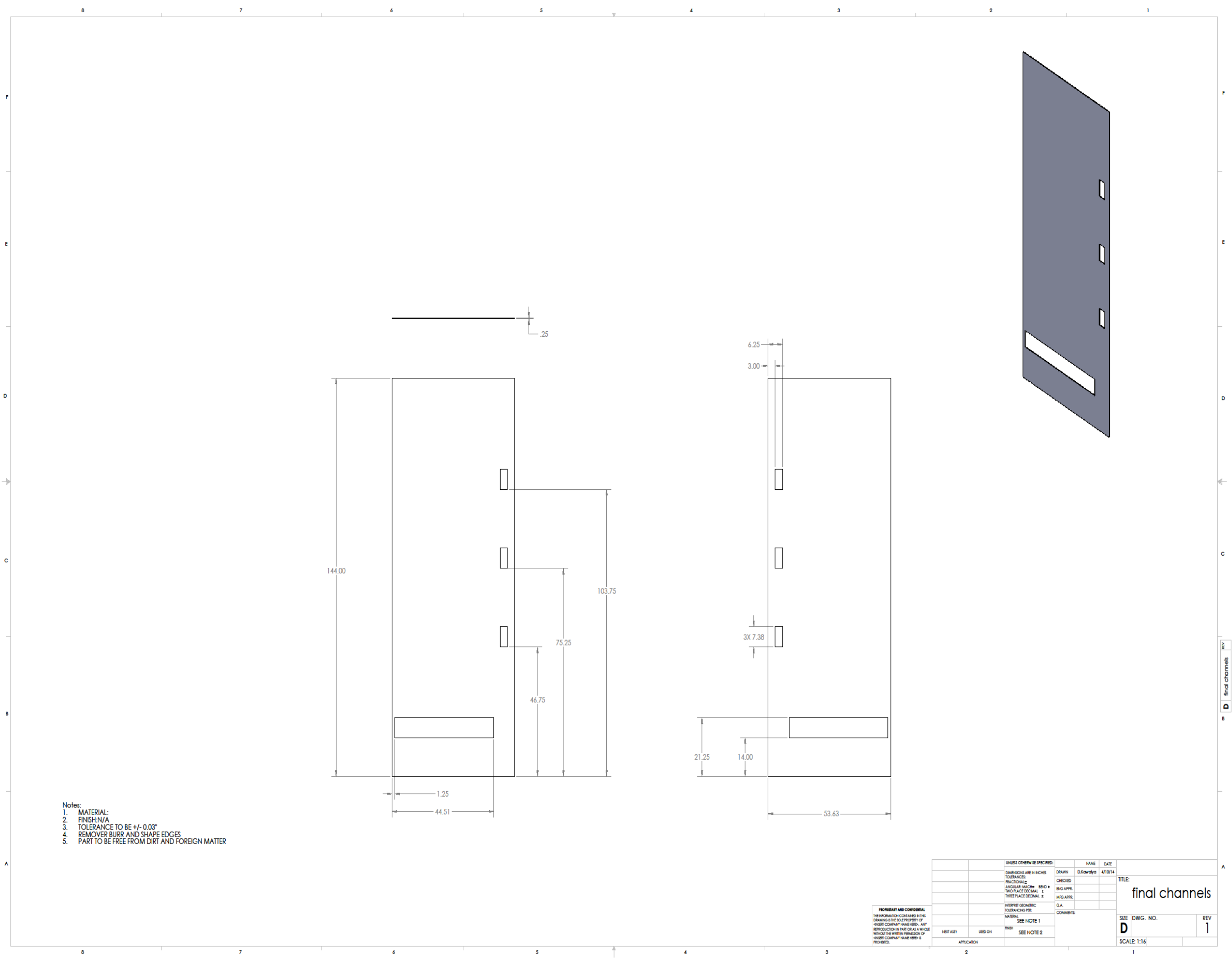

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4. REMOVER BURR AND SHAPE EDGES
5. PART TO BE FREE FROM DIRT AND FOREIGN MATTER
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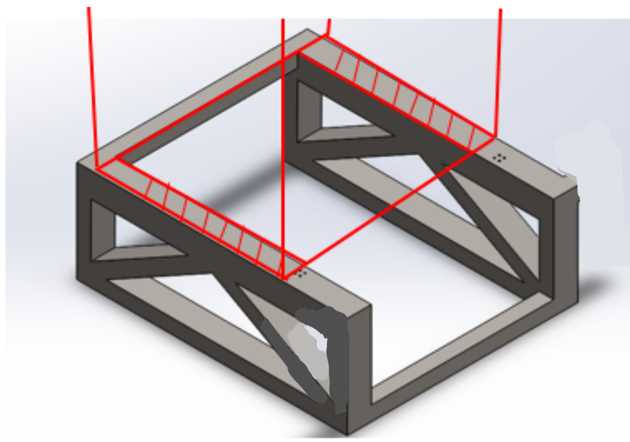
APPENDIX B

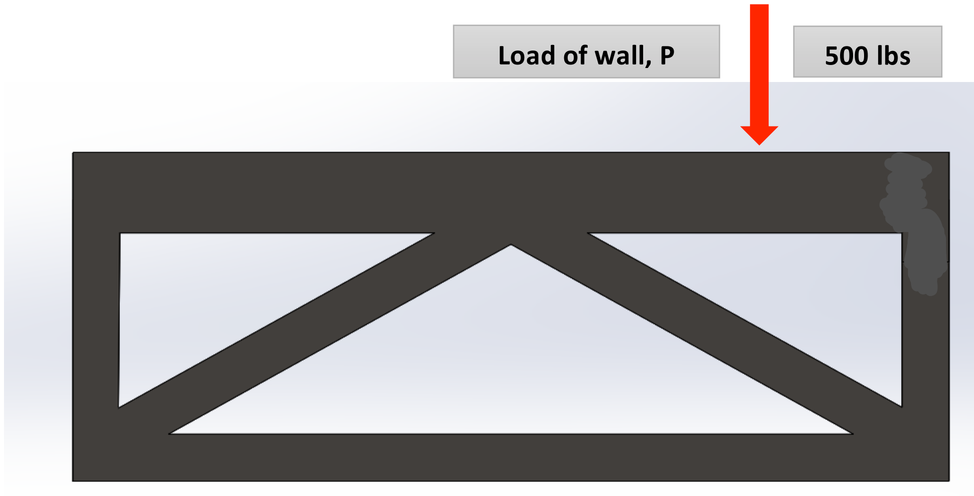
Assumptions to Simplify Stress Analysis on Frame

The Wall Floor holder will be used to support the full weight of a wall with the backing wall acting as a guide. The floor holder is required when a wall exceeds the maximum weight capacity for hanging off the backing wall. The holder will be required to hold a wall of 1000lbs ranging from a 3" min to 30" maximum width. We assume the wall can support its own weight and that the bottom of the wall will have negligible bending between each side of the holder. Under these assumptions we can take the wall to be an equally distributed load into both legs of the holder.



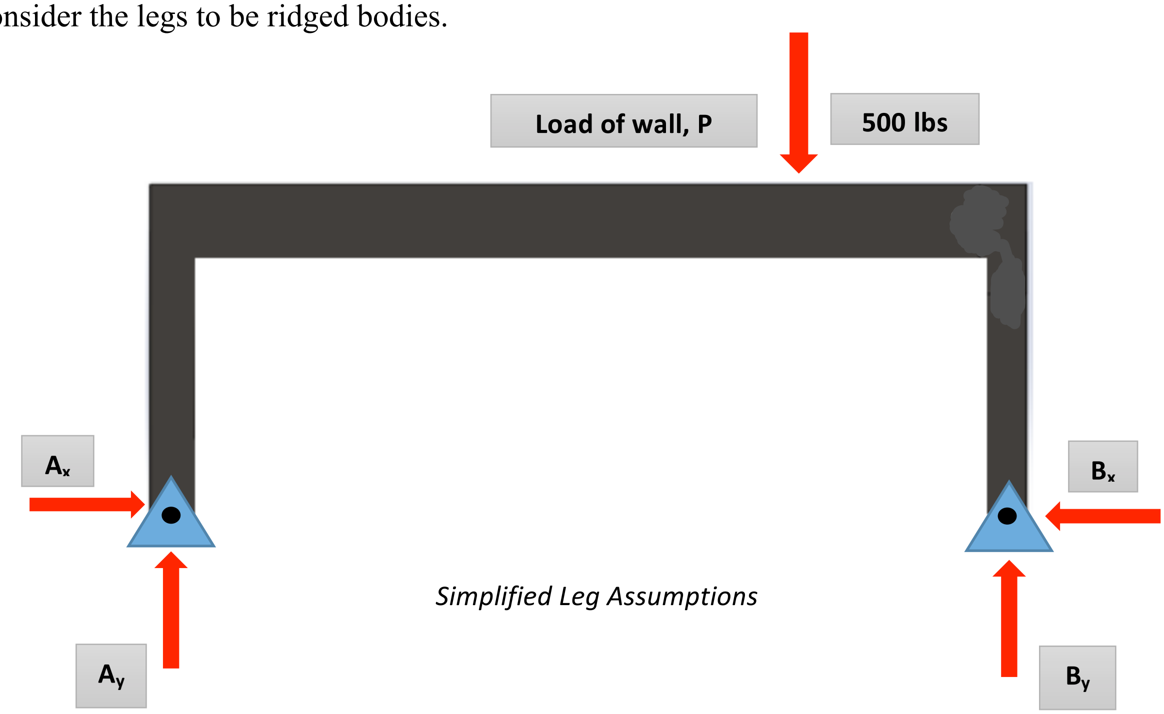
Area of Wall on Holder Assembly

We take the holder and split it into two, we split the 1000 lbs as well. We make the assumption that each side of the holder will support 500 lbs. The force is taken as a point load of 500 lbs. at the center of the distributed load. This is the worst-case scenario for failure. This will a good overestimate of the forces that would be applied since the load falls on a portion of the top beam that is not directly supported by the cross members.



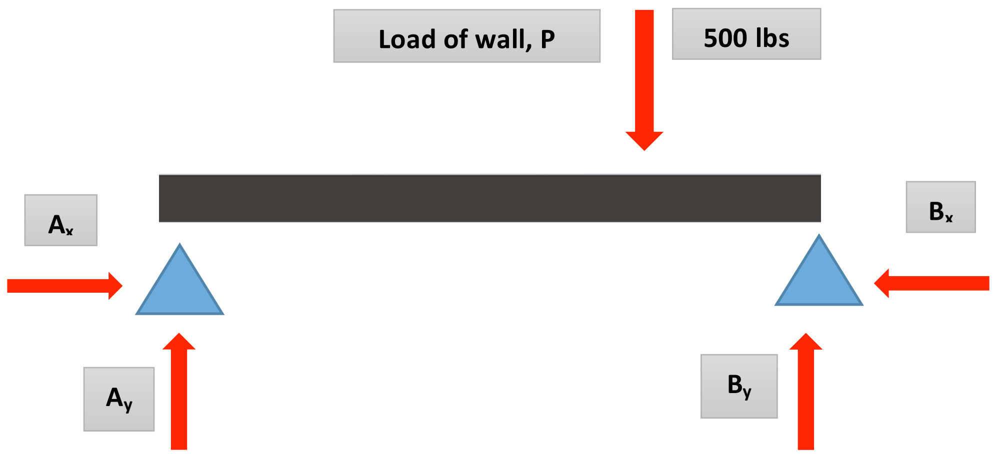
Single Holder Leg with Load of Wall

We get rid of the diagonal structure, staying with a box frame making the assumption that diagonal beams make our structure better in terms of strength and rigidness. If the analysis of the box frame can handle the 500 lb. load, then the original structure can withstand the 500 lb. without failure. Next we get rid of the bottom beam, making the assumption that the ground will act as this bottom beam. Finally we assume that there are pins at the bottom of each leg and consider the legs to be ridged bodies.

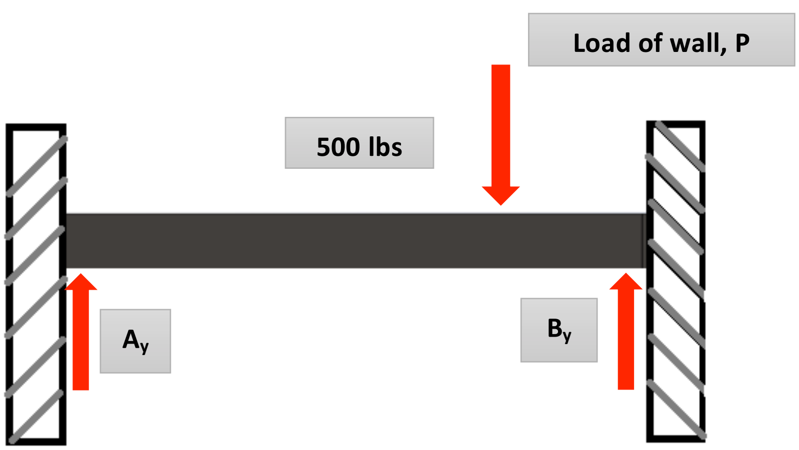


Simplified Leg Assumptions

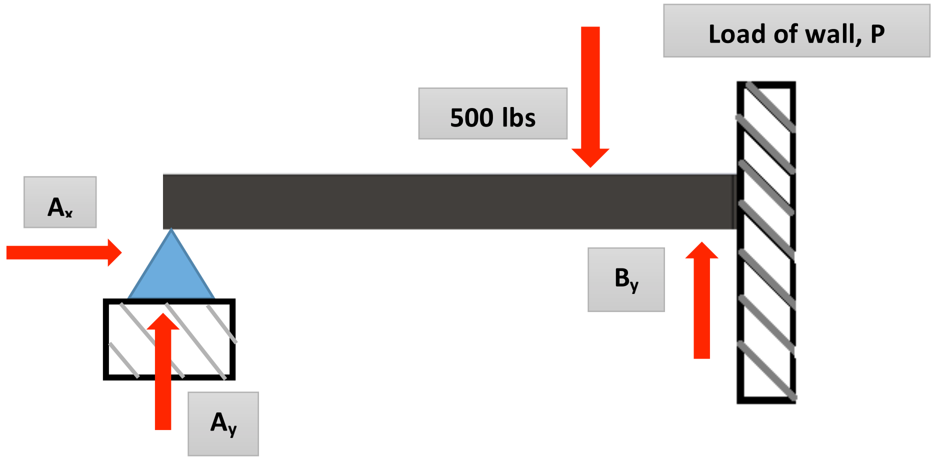
A simple static analysis showed that we could get rid of the legs and calculate the forces as if it were a single beam with a pin on both sides. Since the joints of the rig are rigid yet still flexible, we looked at three different joint scenarios to find the maximum shear and bending stresses that were most dangerous.



Beam Scenario 1: Two Pin Joints



Beam Scenario 2: Two Fixed Joints



Beam Scenario 3: One Fixed Joint, One Pin Joint

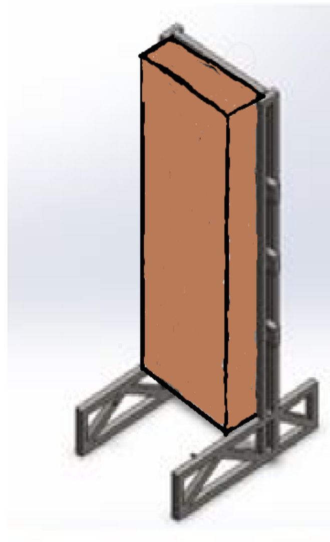
These three different analyses will allow us to size our beam cross section for the worst possible scenarios over all joint cases. The Beams will be taken as hollow square tubing sections to reduce weight

Assumptions to Simplify Stress Analysis on Side Rails and Backing Wall

Our rig is comprised of two side rail pieces and a backing wall. If a user wants to hang a specimen on the backing wall for a smaller wall, the sidewalls will need to resist rotation from the uneven loading caused by the walls thickness.

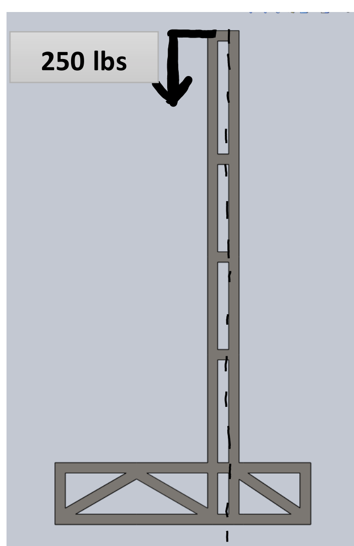
Side Legs and Backing Wall

We will assume a max wall size of 500lbs between 30" and 3" in length. This will be held by 8 brackets connected to the backing wall of the rig.



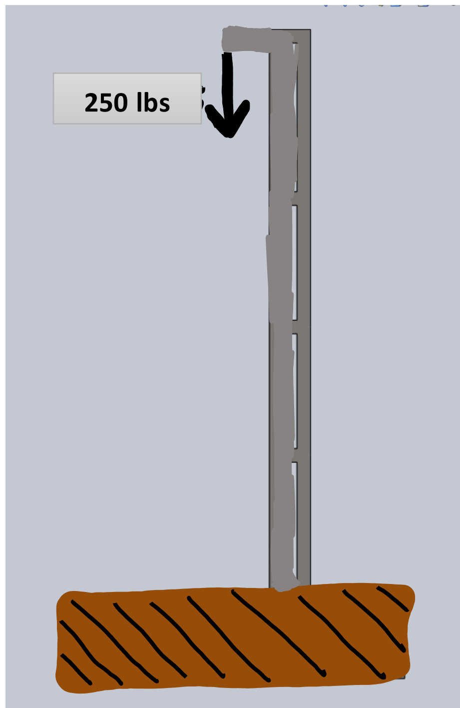
Rig with 3" Specimen

We will examine the loading in just a single sidewall piece, so the force will be split into 250lbs for each side. The force will be taken as a single point load offset from the top of the vertical beam by 6.25 inches from center; this distance is for a 3' wall section. An analysis will also be taken of the loading of a 30" wall section to provide a large moment over estimate.



Rig with Wall Loading

We will neglect the bottom support frame and take it as if it were the ground. The upright beam will be taken to have a hollow square tube cross-section for first estimation purposes. A static analysis will provide a bending moment at the critical point in the beam near the base.



Simplified Analysis

An analysis for the compression forces on the beam will also be conducted to ensure that the axial load will not be a limiting factor.

APPENDIX C

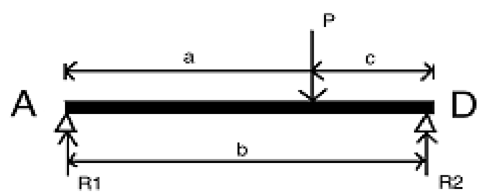
The following equations used were taken from APPENDIX References [1]-[3].

Note: See appendix A for detailed drawing and solidworks picture of holder and appendix B for structure break down to beam

Holder Stress Analysis

Considering Maximum Wall Assembly (30"X5"X120") 500lbs

1. Assuming point A and D have zero moment



$a := 38in$ $b := 50in$ $c := 12in$ $d := 3in$ $P := 500lb$

Using moment and reaction equations, calculating the reaction forces at A and D

Since moment at A and D is known to be zero.

$$M_A = P \cdot a - R_1 \cdot b = 0$$

$$M_D = -P \cdot c - R_1 \cdot a = 0$$

$$R_1 + R_2 = P$$

$$R_2 = P + R_1$$

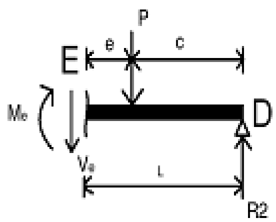
Therefore

$$38 \cdot L - 50P + 50 \cdot R_1 = 0$$

$$R_1 := \frac{c}{b} \cdot P = 120 \cdot lb$$

$$R_2 := P - R_1 = 380 \cdot lb$$

Cutting the beam in half at point E, we can calculate the moment and shear force at that point



$e := 13in$ $\qquad$ $l := 25in$

Calculating moment at point E

$$M_E := P \cdot e - R_2 \cdot l = -3 \times 10^3 \cdot lb \cdot in$$

$$\sum F_y = R_2 - P + V_E = 0$$

Known: summation of forces in the y-axis equals zero

We can then calculate the shear force at point E

$$V_E := -R_2 + P = 120 \cdot lb$$

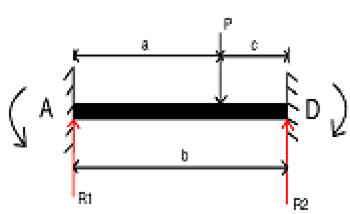
Calculating shear and moment at load point. In theory, this moment should be greater than the moment at point E and the shear force should be equal to the force applied by the load

$$M_P := R_1 \cdot a + R_2 \cdot c = 9.12 \times 10^3 \cdot lb \cdot in$$

Largest moment, used for sizing

$$V_P := 500 lb$$

2. Assuming the frame as a beam fixed at both ends



Shear (V1 and V2) at reaction points is equivalent to the reaction at that point respectively

(R1 and R2)

$$R_1 = V_1 = \frac{P \cdot c^2}{b^3} \cdot (3a + c) \qquad V_1 := \frac{P \cdot c^2}{b^3} \cdot (3a + c) = 72.576 lb$$

$$R_2 = V_2 = \frac{P \cdot a^2}{b^3} \cdot (a + 3 \cdot b) \qquad V_2 := \frac{P \cdot a^2}{b^3} \cdot (a + 3c) = 427.424 lb$$

Finding and comparing moments at point A, D, and at the load, P

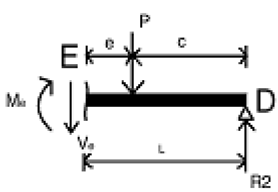
$$M_A := \frac{P \cdot a^2 c}{b^2} = 3.466 \times 10^3 \cdot lb \cdot in$$

$$M_D := \frac{P \cdot a \cdot c^2}{b^2} = 1.094 \times 10^3 \cdot lb \cdot in$$

$$M_P := \frac{2P \cdot a^2 \cdot c^2}{b^3} = 1.663 \times 10^3 \cdot lb \cdot in$$

Moment at point A is great than that at D and P. This is correct since the beam is fixed at both end and the distance between the load and point A is greater.

Cutting the beam in half at point E, we can calculate the moment and shear force at that point



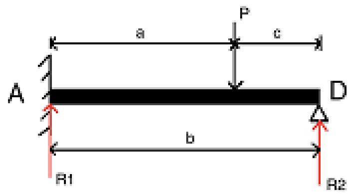
$e := 13 in \qquad l := 25 in$

$$M_E := P \cdot e - V_2 \cdot l = -4.186 \times 10^3 \cdot lb \cdot in$$

$$\sum F_y = V_2 - P + V_E = 0$$

$$V_E := -V_2 + P = 72.576 lb$$

3. Considering frame as beam fixed at one end



Shear (V1 and V2) at reaction points is equivalent to the reaction at that point respectively (R1 and R2)

$$R_1 = V_1 = \frac{P\cdot c^2}{b^3}\cdot(a + 3\cdot b) \qquad V_1 := \frac{P\cdot c^2}{2b^3}\cdot(a + 2\cdot b) = 39.744\,\mathrm{lt}$$

$$R_2 = V_2 = \frac{P\cdot a^2}{2\cdot b^3}\cdot\left(a^2 + 2\cdot b\right) \qquad V_2 := \frac{P\cdot a}{2\cdot b^3}\cdot\left(3b^2 - a^2\right) = 460.256\,\mathrm{lt}$$ Largest shear

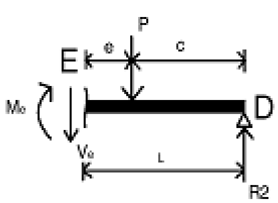
Finding moments at point A, D and at the load

$$M_A := V_1\cdot a = 1.51\times 10^3\cdot \mathrm{lb}\cdot\mathrm{ir}$$

$$M_D := 0\,\mathrm{lb}\cdot\mathrm{ir}$$

$$M_P := V_2\cdot c = 5.523\times 10^3\cdot \mathrm{lb}\cdot\mathrm{ir}$$

Cutting the beam in half at point E, we can calculate the moment and shear force at that point



$e := 13\,\mathrm{ir} \qquad l := 25\,\mathrm{ir}$

$$M_E := P\cdot e - V_2\cdot l = -5.006\times 10^3\cdot \mathrm{lb}\cdot\mathrm{ir}$$

$$\sum F_y = V_2 - L + V_E = ($$

$$V_E := -V_2 + P = 39.744lt$$

Material Sizing

For the sizing calculation (only considering moments at the point load), we will use the largest moment at of the three moments calculated in the above three conditions. The situation where we considered the frame as a beam with two pins has the largest moment. Also the largest shear force at of three conditions will be used. Using a moment and shear from different allows us to kind of integrate the three conditions in one. It also compensate a little for the over design.

Chosen moment, M and shear, V

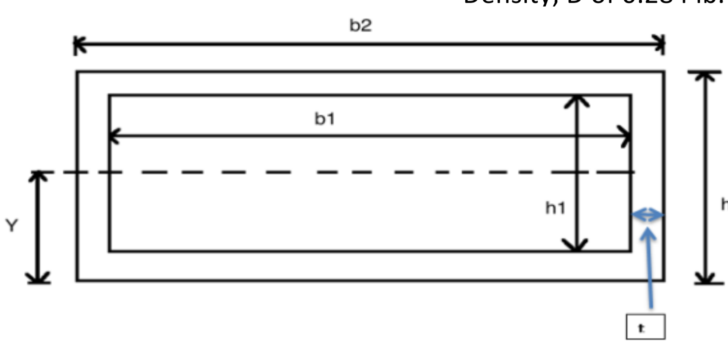
$M := 9.12 \times 10^3\ lb \cdot ir$ $\quad V := 460.256lt$ $\quad D := .284 \frac{lb}{in^3}$

Chosen ***Material:*** Material A500 Steel

Properties of Material A500 Steel:

- Yield strength of 50ksi
- Tensile strength of 62ksi
- Modulus, E of 2900ksi
- Melting point of 2750 deg. F
- Density, D of 0.284 lb. /in^3

Assume hollow tubing



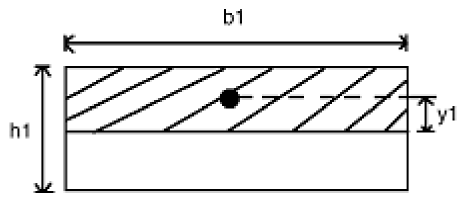
x – axis

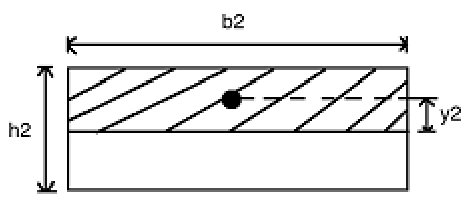
Where t is wall thickness

T1

$h_1 := 4in$ $h_2 := 5in$ $b_1 := 4in$ $b_2 := 5in$ $Y := 2.5in$ $t := 0.5in$

$$y_1 := \frac{h_1}{4} = 1 \cdot in \qquad y_2 := \frac{h_2}{4}$$





Calculating Area used when calculating the first moment of area Q

$$A_1 := \frac{h_1}{2} \cdot b_1 = 8 \cdot in^2 \qquad A_2 := \frac{h_2}{2} \cdot b_2 = 12.5 \cdot in^2$$

Calculate the area moment of inertia of a hollow rectangular tubing

$$I = I_{x1} - I_{x2}$$

$$I := \frac{b_2 \cdot h_2^3}{12} - \frac{b_1 \cdot h_1^3}{12} = 30.75 \, in^4$$

Beam shear/ shear stress

$$\tau = \frac{VQ}{I2t}$$

V = total shear force;

Q = statically/ first moment of area;

t = thickness in the material perpendicular to the shear;

I = Moment of Inertia of the entire cross sectional area.

Calculating Q for a hollow tubing

Fact: Q is maximum at Y

$$Q := y_2 \cdot (A_2) - y_1 \cdot (A_1) = 7.625 \cdot in^3$$

$$\tau := \frac{V \cdot Q}{I \cdot 2t} = 114.129 \frac{lb}{in^2}$$

Bending stress

$$\sigma_{bending} := \frac{M \cdot Y}{I} = 741.463 \frac{lb}{in^2}$$

$$weight := 436kg = 961.215lb$$

It's clear that having a 1in thick wall makes the structure way over designed as the calculated bending stress is no way close the chosen material yield or tensile strength. So several trials will be done to find a better thickness for the material. We need the material to be as thin as possible in order to accomplish the light weight goal.

T2

$h_1 := 4.5in$ $h_2 := 5in$ $b_1 := 4.5in$ $b_2 := 5in$ $Y := 2.5in$ $t := 0.25in$

$$y_1 := \frac{h_1}{4} = 1.125in \qquad y_2 := \frac{h_2}{4}$$

Calculating Area used when calculating the first moment if area Q

$$A_1 := \frac{h_1}{2} \cdot b_1 = 10.125in^2 \qquad A_2 := \frac{h_2}{2} \cdot b_2 = 12.5 \cdot in^2$$

Calculate the area moment of inertia of a hollow rectangular tubing

$$I = I_{x1} - I_{x2}$$

$$I := \frac{b_2 \cdot h_2^3}{12} - \frac{b_1 \cdot h_1^3}{12} = 17.911 \cdot in^4$$

Beam shear/ shear stress

$$\tau = \frac{VQ}{I2t}$$

V = total shear force;

Q = statically/ first moment of area;

t = thickness in the material perpendicular to the shear;

I = Moment of Inertia of the entire cross sectional area.

Calculating Q for a hollow tubing

Fact: Q is maximum at Y

$$Q := y_2 \cdot (A_2) - y_1 \cdot (A_1) = 4.234 \cdot in^3$$

$$\tau := \frac{V \cdot Q}{I \cdot 2t} = 217.614 \frac{lb}{in^2}$$

Bending stress

$$\sigma_{bending} := \frac{M \cdot Y}{I} = 1.273 \times 10^3 \cdot \frac{lb}{in^2}$$

Estimated Weight

$m_1 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot b \cdot D = 269.8 lb$ Long beam of holder

$H := 21 in$

$m_2 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot D \cdot H = 113.316 lb$ Side beam of holder

$s := 23 in$

$m_3 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot D \cdot s = 124.108 lb$

$weight := m_1 + m_2 + m_3 = 507.224 lb$ Approx. total weight of holder

T3

$h_1 := 4.75in$ $h_2 := 5in$ $b_1 := 4.75in$ $b_2 := 5in$ $Y := 2in$ $t := .125in$

$y_1 := \frac{h_1}{4} = 1.188 \cdot in$ $y_2 := \frac{h_2}{4}$

Calculating Area used when calculating the first moment if area, Q

$A_1 := \frac{h_1}{2} \cdot b_1 = 11.281 \cdot in^2$ $A_2 := \frac{h_2}{2} \cdot b_2 = 12.5 \cdot in^2$

Calculate the area moment of inertia of a hollow rectangular tubing

$I = I_{x1} - I_{x2}$

$I := \frac{b_2 \cdot h_2^3}{12} - \frac{b_1 \cdot h_1^3}{12} = 9.661 \cdot in^4$

Beam shear/ shear stress

$\tau = \frac{VQ}{I2t}$

V = total shear force;

Q = statically/ first moment of area;

t = thickness in the material perpendicular to the shear;

I = Moment of Inertia of the entire cross sectional area.

Calculating Q for a hollow tubing

Fact: Q is maximum at Y

$Q := y_2 \cdot (A_2) - y_1 \cdot (A_1) = 2.229 \cdot in^3$

$\tau := \frac{V \cdot Q}{I \cdot 2t} = 424.666 \frac{lb}{in^2}$

Bending stress

$$\sigma_{bending} := \frac{M \cdot Y}{I} = 1.888 \times 10^{3} \cdot \frac{lb}{in^{2}}$$

Estimated Weight

$m_1 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot b \cdot D = 138.451lb$ Long beam

$H := 21in$

$m_2 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot D \cdot H = 58.149lb$ Side beam

$s := 23in$

$m_3 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot D \cdot s = 63.687lb$

$weight := m_1 + m_2 + m_3 = 260.286lb$ Approx. total weight of holder

T4

$h_1 := 4.83in$ $h_2 := 5in$ $b_1 := 4.83in$ $b_2 := 5in$ $Y := 2.5in$ $t := 0.085in$

$y_1 := \frac{h_1}{4} = 1.208 in$ $y_2 := \frac{h_2}{4}$

Calculating Area used when calculating the first moment if area, Q

$A_1 := \frac{h_1}{2} \cdot b_1 = 11.664 in^{2}$ $A_2 := \frac{h_2}{2} \cdot b_2 = 12.5 \cdot in^{2}$

Calculate the area moment of inertia of a hollow rectangular tubing

$I = I_{x1} - I_{x2}$

$$I := \frac{b_2 \cdot h_2^{3}}{12} - \frac{b_1 \cdot h_1^{3}}{12} = 6.73 \cdot in^{4}$$

Beam shear/ shear stress

$$\tau = \frac{VQ}{I2t}$$

V = total shear force;

Q = statically/ first moment of area;

t = thickness in the material perpendicular to the shear;

I = Moment of Inertia of the entire cross sectional area.

Calculating Q for a hollow tubing

Fact: Q is maximum at Y

$$Q := y_2 \cdot (A_2) - y_1 \cdot (A_1) = 1.54 \cdot in^3$$

$$\tau := \frac{V \cdot Q}{I \cdot 2t} = 619.574 \frac{lb}{in^2}$$

Bending stress

$$\sigma_{bending} := \frac{M \cdot Y}{I} = 3.388 \times 10^3 \cdot \frac{lb}{in^2}$$

Estimated Weight

$$m_1 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot b \cdot D = 94.918 lb$$ Long beam

$$H := 21 in$$

$$m_2 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot D \cdot H = 39.866 lb$$ Side beam

$$s := 23 in$$

$$m_3 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot D \cdot s = 43.663 lb$$

$$weight := m_1 + m_2 + m_3 = 178.447 lb$$ Approx. total weight of holder

T5

$h_1 := 4.875 in$ $h_2 := 5 in$ $b_1 := 4.875 in$ $b_2 := 5 in$ $Y := 2.5 in$ $t := 0.0625 in$

$$y_1 := \frac{h_1}{4} = 1.219 in \qquad y_2 := \frac{h_2}{4}$$

Calculating Area used when calculating the first moment if area, Q

$A_1 := \frac{h_1}{2} \cdot b_1 = 11.883 in^2$ $A_2 := \frac{h_2}{2} \cdot b_2 = 12.5 \cdot in^2$

Calculate the area moment of inertia of a hollow rectangular tubing

$I = I_{x1} - I_{x2}$

$I := \frac{b_2 \cdot h_2^3}{12} - \frac{b_1 \cdot h_1^3}{12} = 5.016 in^4$

Beam shear/ shear stress

$\tau = \frac{VQ}{I2t}$

V = total shear force;

Q = statically/ first moment of area;

t = thickness in the material perpendicular to the shear;

I = Moment of Inertia of the entire cross sectional area.

Calculating Q for a hollow tubing

Fact: Q is maximum at Y

$Q := y_2 \cdot (A_2) - y_1 \cdot (A_1) = 1.143 \cdot in^3$

$\tau := \frac{V \cdot Q}{I \cdot 2t} = 838.858 \frac{lb}{in^2}$

Bending stress

$\sigma_{bending} := \frac{M \cdot Y}{I} = 4.545 \times 10^3 \cdot \frac{lb}{in^2}$

Estimated Weight

$m_1 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot b \cdot D = 70.113 lb$ Long beam

$H := 21 in$

$m_2 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot D \cdot H = 29.447 lb$ Side beam

$s := 23in$

$m_3 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot D \cdot s = 32.252lb$

$weight := m_1 + m_2 + m_3 = 131.812lb$ Approx. total weight of holder

T6

$h_1 := 3.75in$ $h_2 := 4in$ $b_1 := 4.75in$ $b_2 := 5in$ $Y := 2in$ $t := .125in$

$y_1 := \frac{h_1}{4} = 0.938in$ $y_2 := \frac{h_2}{4}$

Calculating Area used when calculating the first moment if area, Q

$A_1 := \frac{h_1}{2} \cdot b_1 = 8.906in^2$ $A_2 := \frac{h_2}{2} \cdot b_2 = 10in^2$

Calculate the area moment of inertia of a hollow rectangular tubing

$I = I_{x1} - I_{x2}$

$I := \frac{b_2 \cdot h_2^3}{12} - \frac{b_1 \cdot h_1^3}{12} = 5.793in^4$

Beam shear/ shear stress

$\tau = \frac{VQ}{I2t}$

V = total shear force;

Q = statically/ first moment of area;

t = thickness in the material perpendicular to the shear;

I = Moment of Inertia of the entire cross sectional area.

Calculating Q for a hollow tubing

Fact: Q is maximum at Y

$Q := y_2 \cdot (A_2) - y_1 \cdot (A_1) = 1.65 \cdot in^3$

$\tau := \frac{V \cdot Q}{I \cdot 2t} = 524.529 \frac{lb}{in^2}$

Bending stress

$\sigma_{bending} := \frac{M \cdot Y}{I} = 3.149 \times 10^3 \cdot \frac{lb}{in^2}$

Estimated Weight

$m_1 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot b \cdot D = 124.251lb$ Long beam

$H := 21in$

$m_2 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot D \cdot H = 52.185lb$ Side beam

$s := 23in$

$m_3 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot D \cdot s = 57.155lb$

$weight := m_1 + m_2 + m_3 = 233.591lb$ Approx. total weight of holder

T7

$h_1 := 3.83in$ $h_2 := 4in$ $b_1 := 4.83in$ $b_2 := 5in$ $Y := 2in$ $t := 0.083in$

$y_1 := \frac{h_1}{4} = 0.957in$ $y_2 := \frac{h_2}{4}$

Calculating Area used when calculating the first moment if area, Q

$A_1 := \frac{h_1}{2} \cdot b_1 = 9.249 in^2$ $A_2 := \frac{h_2}{2} \cdot b_2 = 10 in^2$

Calculate the area moment of inertia of a hollow rectangular tubing

$I = I_{x1} - I_{x2}$

$$I := \frac{b_2 \cdot h_2^3}{12} - \frac{b_1 \cdot h_1^3}{12} = 4.053 \cdot in^4$$

Beam shear/ shear stress

$$\tau = \frac{VQ}{I2t}$$

V = total shear force;

Q = statically/ first moment of area;

t = thickness in the material perpendicular to the shear;

I = Moment of Inertia of the entire cross sectional area.

Calculating Q for a hollow tubing

Fact: Q is maximum at Y

$$Q := y_2 \cdot (A_2) - y_1 \cdot (A_1) = 1.144 \cdot in^3$$

$$\tau := \frac{V \cdot Q}{I \cdot 2t} = 782.275 \frac{lb}{in^2}$$

Bending stress

$$\sigma_{bending} := \frac{M \cdot Y}{I} = 4.5 \times 10^3 \cdot \frac{lb}{in^2}$$

Estimated Weight

$$m_1 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot b \cdot D = 85.262 lb$$ Long beam

$$H := 21 in$$

$$m_2 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot D \cdot H = 35.81 \cdot lb$$ Side beam

$$s := 23 in$$

$$m_3 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot D \cdot s = 39.221 lb$$

$$weight := m_1 + m_2 + m_3 = 160.293 lb$$ Approx. total weight of holder

T8

$h_1 := 3.875in$ $h_2 := 4in$ $b_1 := 4.875in$ $b_2 := 5in$ $Y := 2in$ $t := 0.0625in$

$y_1 := \frac{h_1}{4} = 0.969\,in$ $y_2 := \frac{h_2}{4}$

Calculating Area used when calculating the first moment if area, Q

$A_1 := \frac{h_1}{2} \cdot b_1 = 9.445\,in^2$ $A_2 := \frac{h_2}{2} \cdot b_2 = 10\,in^2$

Calculate the area moment of inertia of a hollow rectangular tubing

$I = I_{x1} - I_{x2}$

$I := \frac{b_2 \cdot h_2^3}{12} - \frac{b_1 \cdot h_1^3}{12} = 3.029\,in^4$

Beam shear/ shear stress

$\tau = \frac{VQ}{I2t}$

V = total shear force;

Q = statically/ first moment of area;

t = thickness in the material perpendicular to the shear;

I = Moment of Inertia of the entire cross sectional area.

Calculating Q for a hollow tubing

Fact: Q is maximum at Y

$Q := y_2 \cdot (A_2) - y_1 \cdot (A_1) = 0.85\,in^3$

$\tau := \frac{V \cdot Q}{I \cdot 2t} = 1.033 \times 10^3 \cdot \frac{lb}{in^2}$

Bending stress

$\sigma_{bending} := \frac{M \cdot Y}{I} = 6.022 \times 10^3 \cdot \frac{lb}{in^2}$

Estimated Weight

$m_1 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot b \cdot D = 63.013 lb$ Long beam

$H := 21 in$

$m_2 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot D \cdot H = 26.465 lb$ Side beam

$s := 23 in$

$m_3 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot D \cdot s = 28.986 lb$

$weight := m_1 + m_2 + m_3 = 118.464 lb$ Approx. total weight of holder

T9

$h_1 := 3.97 in$ $h_2 := 4 in$ $b_1 := 4.97 in$ $b_2 := 5 in$ $Y := 2 in$ $t := 0.0156 in$

$y_1 := \frac{h_1}{4} = 0.993 in$ $y_2 := \frac{h_2}{4}$

Calculating Area used when calculating the first moment if area, Q

$A_1 := \frac{h_1}{2} \cdot b_1 = 9.865 in^2$ $A_2 := \frac{h_2}{2} \cdot b_2 = 10 in^2$

Calculate the area moment of inertia of a hollow rectangular tubing

$I = I_{x1} - I_{x2}$

$I := \frac{b_2 \cdot h_2^3}{12} - \frac{b_1 \cdot h_1^3}{12} = 0.752 in^4$

Beam shear/ shear stress

$\tau = \frac{VQ}{I2t}$

V = total shear force;

Q = statically/ first moment of area;

t = thickness in the material perpendicular to the shear;

I = Moment of Inertia of the entire cross sectional area.

Calculating Q for a hollow tubing

Fact: Q is maximum at Y

$$Q := y_2 \cdot (A_2) - y_1 \cdot (A_1) = 0.209 \cdot in^3$$

$$\tau := \frac{V \cdot Q}{I \cdot 2t} = 4.091 \times 10^3 \cdot \frac{lb}{in^2}$$

Bending stress

$$\sigma_{bending} := \frac{M \cdot Y}{I} = 2.426 \times 10^4 \cdot \frac{lb}{in^2}$$

Estimated Weight

$$m_1 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot b \cdot D = 15.285 lb$$ Long beam

$$H := 21 in$$

$$m_2 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot D \cdot H = 6.42 \cdot lb$$ Side beam

$$s := 23 in$$

$$m_3 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot D \cdot s = 7.031 \cdot lb$$

$$weight := m_1 + m_2 + m_3 = 28.736 lb$$ Approx. total weight of holder

T10

$h_1 := 2.97 in$ $h_2 := 3 in$ $b_1 := 3.97 in$ $b_2 := 4 in$ $Y := 1.5 in$ $t := 0.0156 in$

$$y_1 := \frac{h_1}{4} = 0.743 \cdot in \qquad y_2 := \frac{h_2}{4}$$

Calculating Area used when calculating the first moment if area, Q

$$A_1 := \frac{h_1}{2} \cdot b_1 = 5.895 in^2 \qquad A_2 := \frac{h_2}{2} \cdot b_2 = 6 \cdot in^2$$

Calculate the area moment of inertia of a hollow rectangular tubing

$I = I_{x1} - I_{x2}$

$$I := \frac{b_2 \cdot h_2^{\,3}}{12} - \frac{b_1 \cdot h_1^{\,3}}{12} = 0.333 \cdot in^4$$

Beam shear/ shear stress

$$\tau = \frac{VQ}{I2t}$$

V = total shear force;

Q = statically/ first moment of area;

t = thickness in the material perpendicular to the shear;

I = Moment of Inertia of the entire cross sectional area.

Calculating Q for a hollow tubing

Fact: Q is maximum at Y

$$Q := y_2 \cdot (A_2) - y_1 \cdot (A_1) = 0.123 \cdot in^3$$

$$\tau := \frac{V \cdot Q}{I \cdot 2t} = 5.436 \times 10^3 \cdot \frac{lb}{in^2}$$

Bending stress

$$\sigma_{bending} := \frac{M \cdot Y}{I} = 4.111 \times 10^4 \cdot \frac{lb}{in^2}$$

Estimated Weight

$m_1 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot b \cdot D = 11.877 lb$ Long beam

$H := 21 in$

$m_2 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot D \cdot H = 4.988 lb$ Side beam

$s := 23 in$

$m_3 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot D \cdot s = 5.463 lb$

$weight := m_1 + m_2 + m_3 = 22.329 lb$ Approx. total weight of holder

T11

$h_1 := 3.94in$ $h_2 := 4in$ $b_1 := 4.94in$ $b_2 := 5in$ $Y := 2in$ $t := 0.0313in$

$y_1 := \frac{h_1}{4} = 0.985\,in$ $y_2 := \frac{h_2}{4}$

Calculating Area used when calculating the first moment if area, Q

$A_1 := \frac{h_1}{2} \cdot b_1 = 9.732\,in^2$ $A_2 := \frac{h_2}{2} \cdot b_2 = 10\,in^2$

Calculate the area moment of inertia of a hollow rectangular tubing

$I = I_{x1} - I_{x2}$

$I := \frac{b_2 \cdot h_2^3}{12} - \frac{b_1 \cdot h_1^3}{12} = 1.488\,in^4$

Beam shear/ shear stress

$\tau = \frac{VQ}{I2t}$

V = total shear force;

Q = statically/ first moment of area;

t = thickness in the material perpendicular to the shear;

I = Moment of Inertia of the entire cross sectional area.

Calculating Q for a hollow tubing

Fact: Q is maximum at Y

$Q := y_2 \cdot (A_2) - y_1 \cdot (A_1) = 0.414\,in^3$

$\tau := \frac{V \cdot Q}{I \cdot 2t} = 2.047 \times 10^3 \cdot \frac{lb}{in^2}$

Bending stress

$\sigma_{bending} := \frac{M \cdot Y}{I} = 1.226 \times 10^4 \cdot \frac{lb}{in^2}$

Estimated Weight

$m_1 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot b \cdot D = 30.468\,lb$ Long beam

$H := 21\,in$

$m_2 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot D \cdot H = 12.796\,lb$ Side beam

$s := 23\,in$

$m_3 := 4(h_2 \cdot b_2 - h_1 \cdot b_1) \cdot D \cdot s = 14.015\,lb$

$weight := m_1 + m_2 + m_3 = 57.279\,lb$ Approx. total weight of holder

Table summarizing results of bending stress, shear stress, and weight calculated by changing

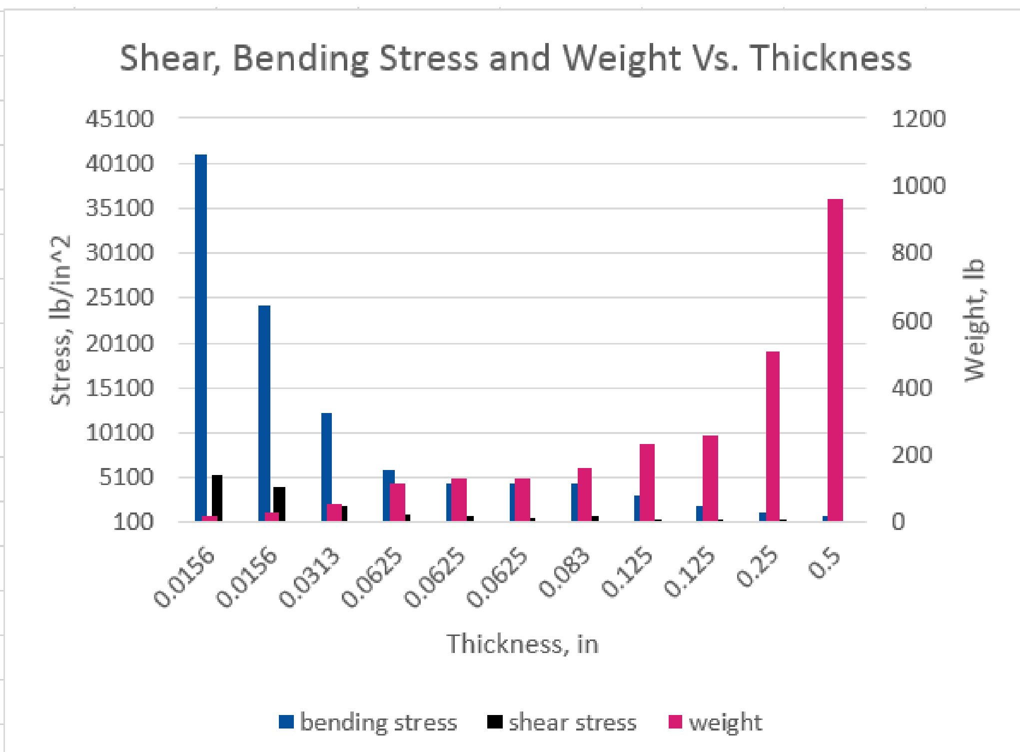
Thickness/ sizing the analyzed structure. Data is collect in 11 different trials

	in	lb/in^2	lb/in^2	lb
T	thickness	bending s	shear stre	weight
1	0.5	741	114	961
2	0.25	1273	218	507
3	0.125	1888	425	260
4	0.085	3388	620	178
5	0.0625	4545	839	132
6	0.125	3149	525	234
7	0.083	4500	782	160
8	0.0625	6022	1033	118
9	0.0156	24260	4091	29
10	0.0156	41110	5436	22
11	0.0313	12260	2047	57

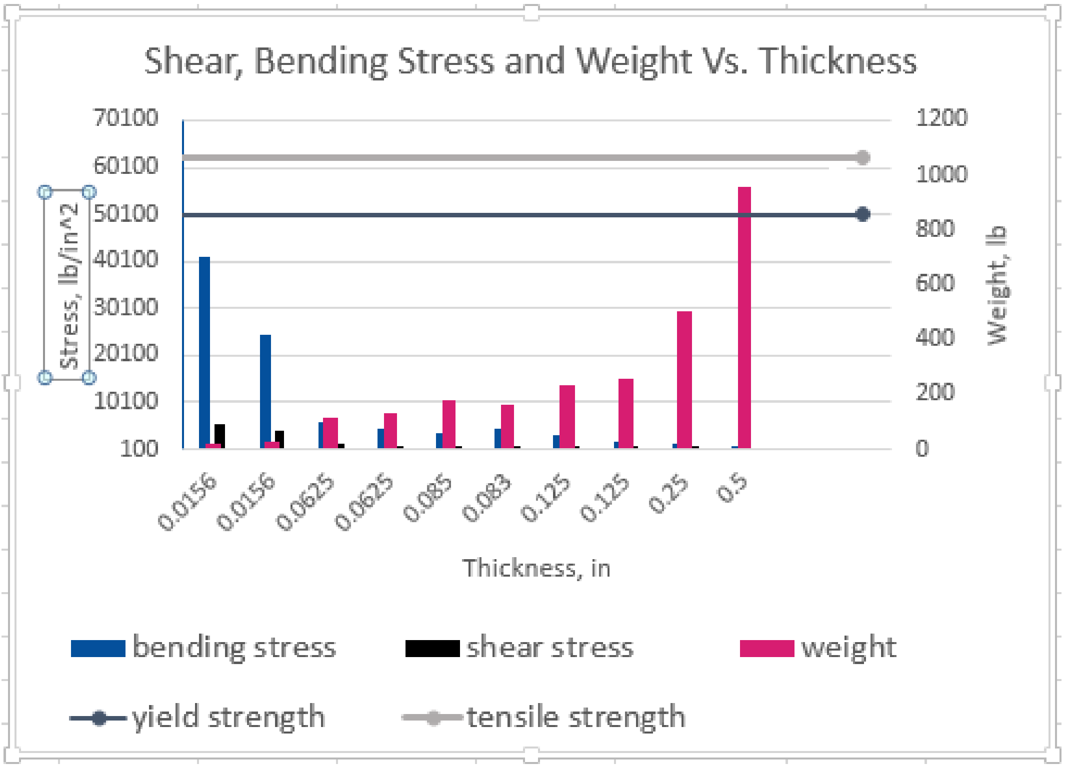
Table showing results rearranged by increasing thickness

in	lb/in^2	lb/in^2	lb		
thickness	bending s	shear stre	weight	T	size/ section
0.0156	41110	5436	22	10	4 x 3
0.0156	24260	4091	29	9	5 x 4
0.0625	6022	1033	118	8	5 x 4
0.0625	4545	839	132	5	5 x 5
0.085	3388	620	178	4	5 x 5
0.083	4500	782	160	7	5 x 4
0.125	3149	525	234	6	5 x 4
0.125	1888	425	260	3	5 x 5
0.25	1273	218	507	2	5 x 5
0.5	741	114	961	1	5 x 5

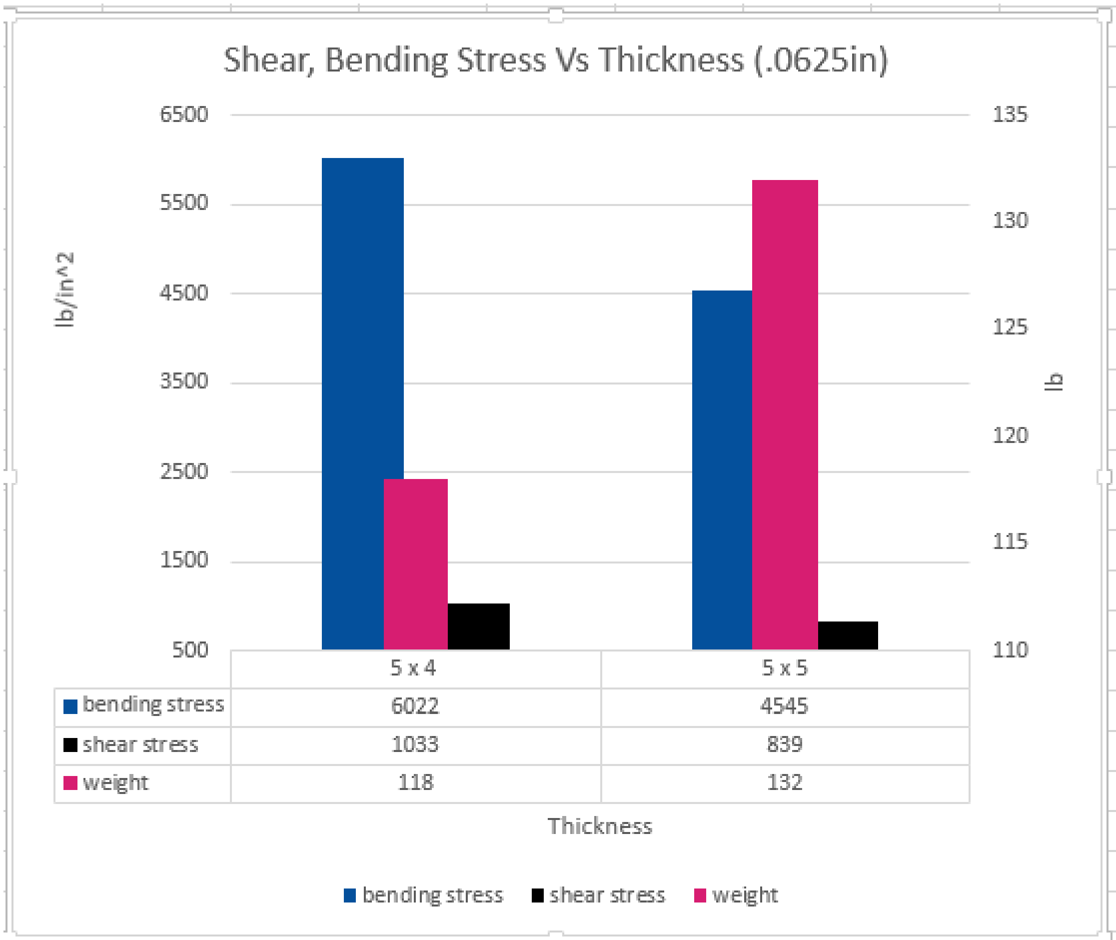
Graph showing the effect on shear stress, bending stress, and weight due to changing thickness.



Graph showing the effect on shear stress, bending stress, and weight due to changing thickness. Material's yield and tensile strength are included



The chosen material thickness is 0.0625 inches. Trials T8 and T5 have the same thickness BUT different section dimensions.



Both of the above sections are ideal for the holder design but since one of our main objectives is a light weight rig, it is better to use the 5*4 section as it leads to a lighter total holder weight

Impact Force on holder part if assembly is drop from 2 feet.

Now will do some impact analysis to make sure that the holder will not fail/ be damaged in case a wall is accidently dropped on it, say from 2 feet.

$m := 1000lb = 453.592kg$ Load $H := 2ft = 0.61m$ Distance dropped

$g := 9.81\frac{m}{s^2}$ Acceleration due to gravity

$F = ma$ $F = m\cdot\frac{dV}{dt}$

Calculating impact velocity

$V_P = \sqrt{2gH}$ $V_P := 3.46\frac{m}{s}$

Calculating time take for that assemble to drop from 2ft

$Time = \frac{Distance}{Velocity}$ $T = \frac{H}{V_P}$ $T := 0.176s$

Acceleration

$a = \frac{V_P}{T}$ $a := 20\frac{m}{s^2}$

Calculating impact force

$F_p = m\cdot a$ $F_P := 8917N$ or $F_P := 2005lbf$

To check the impact of this force to the holder. We will divide the force by 2 like how we divided the 1000lb to become 500lb during the stress analysis. Then use T8 and observe the change that happens to the shear and bending stress.

New impact force of: $P := 1002.5lbf$ Dropping the wall from 2 feet cause the force to double, from 500lbf to approx. 1000lbf

Dimension for the holder

$a := 38in$ $b := 50in$ $c := 12in$ $d := 3in$ $P := 1002.5lb$

$h_1 := 3.875in$ $h_2 := 4in$ $b_1 := 4.875in$ $b_2 := 5in$

$y_1 := \frac{h_1}{4} = 0.969in$ $y_2 := \frac{h_2}{4}$

Caculating Area used when calculating the first moment if area, Q

$A_1 := \frac{h_1}{2} \cdot b_1 = 9.445in^2$ $A_2 := \frac{h_2}{2} \cdot b_2 = 10 \cdot in^2$

Calculate the area moment of inertia of a hollow recutanglar tubing

$I = I_{x1} - I_{x2}$

$$I := \frac{b_2 \cdot h_2^3}{12} - \frac{b_1 \cdot h_1^3}{12} = 3.029in^4$$

Beam shear/ shear stress

$$\tau = \frac{VQ}{I2t}$$

$$Q := y_2 \cdot (A_2) - y_1 \cdot (A_1) = 0.85 \cdot in^3$$

Calculating shear force, V

$$V := \frac{P \cdot a}{2 \cdot b^3} \cdot \left(3b^2 - a^2\right) = 922.813lb$$

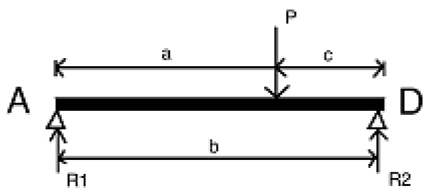
$$\tau := \frac{V \cdot Q}{I \cdot 2t} = 4.136 \times 10^3 \cdot \frac{lb}{in^2}$$

Shear stress increased by a factor of approximately 4

Bending stress

Since the load force change the moment will change as well. So we will calculate the new moment and use it to find the bending stress due to the impact force.

Using the assumption of zero moment at point A and D to find the moment at point Load.



$a := 38in$ $\quad b := 50in$ $\quad c := 12in$ $\quad d := 3in$ $\quad P := 1002.5lb$

$$R_1 := \frac{c}{b} \cdot P = 240.6lb$$

$$R_2 := P - R_1 = 761.9lb$$

$$M_P := R_1 \cdot a + R_2 \cdot c = 1.829 \times 10^4 \cdot lb \cdot in$$

$$\sigma_{bending} := \frac{M_P \cdot Y}{I} = 1.207 \times 10^4 \cdot \frac{lb}{in^2}$$

The bending stress increased by a factor of

Approximately 2

The holder structure won't fail if the wall assembly is accidentally dropped on it from 2 ft.

Since the chosen material had a yield strength 50ksi of and tensile strength of 62ksi

Punching force

Considering an object with a circular surface

Diameter

$D := .5in$

thickness

$t := 0.0625in$

Tensile strength

$\sigma := 62000\frac{lb}{in^2}$

$F_P := t\pi \cdot D \cdot \sigma = 6.087 \times 10^3 \cdot lbf$

Impact force

Considering an object with smaller diameter

Diameter

$D := \frac{1}{8}in$

thickness

$t := 0.0625in$

Tensile strength

$\sigma := 62000\frac{lb}{in^2}$

$F_P := t\pi \cdot D \cdot \sigma = 1.522 \times 10^3 \cdot lbf$

To punch a hole through the material with an object that has a diameter of 0.125in, a force of at least 1522lbf has to be generate. It is safe to conclude that the designed structure (holder) is not at risk of getting punched through.

APPENDIX D

The following equations used were taken from APPENDIX References [4]-[5].

Note: See appendix A for detailed drawing and solidworks picture of analyzed structure and appendix B for structural break down.

HANGING WALL

For this section of stress analysis, we will be analyzing side supporting structure to determine how much weight that can be hang on the rig.
We will consider hanging a 500 pounds 3 inches thick wall.
Force is hanging 6.25 inches since the structure length of 3.25 inches is considered as well.
Considering two hanging points, the weight will be split into two for the analysis.

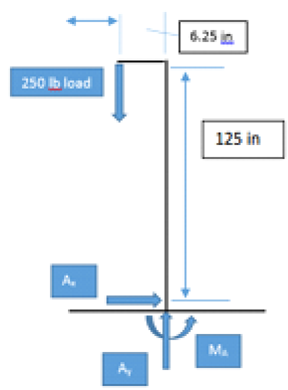


Figure 1: FBD for 3 inch Hanging Wall

Load	density	Total height	Young's modulus
$P := 250lb$	$D := 0.284\frac{lb}{in^3}$	$H := 125in$	$E := 2.9\cdot 10^6\frac{lb}{in^2}$

Chosen ***Material:*** Material A500 Steel

Properties of Material A500 Steel:

Yield strength of 50ksi
Tensile strength of 62ksi
Modulus, E of 2900ksi
Melting point of 2750 deg. F
Density, D of 0.284 lb. /in^3

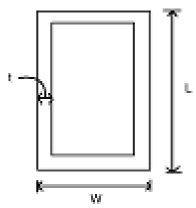
Calculating the moment caused by the force of the hanging wall at bottom of the rail

$$M_A = 0 = M + 250(6.25)$$

$$M := 1562.5lb\cdot in$$

L is the length of the side rail. L is also constant. w remains constant as well

$L := 6ir$ $\qquad$ $w := 3ir$



The critical section c_t at the base, the critical point is the point where failure/ bending is most likely to happen. We assume that failure won't happen at the connection joint, y=0 in since the joint is engineered not to fail. So the critical is assumed to be at half the length of the rail.

Moment of inertia

$$c_t := 0.5L = 3 \cdot ir$$

TC

Material thickness of $\quad t := 0.5ir$

Calculating the area moment of inertia, which will be used to calculated the bending stress. The bending stress will be used to that whether the thickness of the material used can support a hanging weight of 500lb

$$I := \frac{w \cdot L^3}{12} - \frac{(w - 2t) \cdot (L - 2t)^3}{12} = 33.167 in^4$$

Bending Stress

$$\sigma_{bend} := M \cdot \frac{c_t}{I}$$

$$\sigma_{bend} = 141.332 \cdot \frac{lb}{in^2}$$

Cross section area

$$A := L \cdot w - (L - 2t) \cdot (w - 2t) = 8 \cdot in^2$$

Compressional Stress

$$\sigma_{comp} := \frac{P}{A} = 31.25\,\frac{lb}{in^2}$$

Calculating estimated weight of one side

$$Weight := A \cdot H \cdot D = 284\,lb$$

Considering different thickness of the material, to check how small thickness should be before the material fails. The thinner the better as this makes the design lighter. Below are different trials with different thinnest

Trial 1

$$t := 0.0156\,in$$

$$I := \frac{w \cdot L^3}{12} - \frac{(w - 2t)\cdot(L - 2t)^3}{12} = 1.391\,in^4$$

Bending Stress

$$\sigma_{bend} := M \cdot \frac{c_t}{I}$$

$$\sigma_{bend} = 3.37 \times 10^3 \cdot \frac{lb}{in^2}$$

Cross section area

$$A := L \cdot w - (L - 2t)\cdot(w - 2t) = 0.28\,in^2$$

Compressional Stress

$$\sigma_{comp} := \frac{P}{A} = 893.411\,\frac{lb}{in^2}$$

Calculating estimated weight of one side

$$Weight := A \cdot H \cdot D = 9.934\,lb$$

Trial 2

$t := 0.0313\,in$ possible

$$I := \frac{w \cdot L^3}{12} - \frac{(w - 2t)\cdot(L - 2t)^3}{12} = 2.765\,in^4$$

Bending Stress

$$\sigma_{bend} := M \cdot \frac{c_t}{I}$$

$$\sigma_{bend} = 1.696\times 10^3 \cdot \frac{lb}{in^2}$$

Cross section area

$$A := L \cdot w - (L - 2t)\cdot(w - 2t) = 0.559\,in^2$$

Compressional Stress

$$\sigma_{comp} := \frac{P}{A} = 446.843\,\frac{lb}{in^2}$$

Calculating estimated weight of one side

$$Weight := A \cdot H \cdot D = 19.862\,lb$$

Trial 3

$t := 0.0625\,in$

$$I := \frac{w \cdot L^3}{12} - \frac{(w - 2t)\cdot(L - 2t)^3}{12} = 5.417\,in^4$$

Bending Stress

$$\sigma_{bend} := M \cdot \frac{c_t}{I}$$

$$\sigma_{bend} = 865.258 \frac{lb}{in^2}$$

Cross section area

$$A := L \cdot w - (L - 2t) \cdot (w - 2t) = 1.109\, in^2$$

Compressional Stress

$$\sigma_{comp} := \frac{P}{A} = 225.352 \frac{lb}{in^2}$$

Calculating estimated weight of one side

$$Weight := A \cdot H \cdot D = 39.383\, lb$$

Trial 4

$$t := 0.0417 in$$

$$I := \frac{w \cdot L^3}{12} - \frac{(w - 2t) \cdot (L - 2t)^3}{12} = 3.66\, in^4$$

Bending Stress

$$\sigma_{bend} := M \cdot \frac{c_t}{I}$$

$$\sigma_{bend} = 1.281 \times 10^3 \cdot \frac{lb}{in^2}$$

Cross section area

$$A := L \cdot w - (L - 2t) \cdot (w - 2t) = 0.744\, in^2$$

Compressional Stress

$$\sigma_{comp} := \frac{P}{A} = 336.182 \frac{lb}{in^2}$$

Calculating estimated weight of one side

$$Weight := A \cdot H \cdot D = 26.399 lb$$

We chose to use a wall thickness of 1/16 in as bending caused by the on this thickness won't cause failure to structure as the material picked has a much higher yield strength and bending stress. And also have a this thickness makes the structure lighter

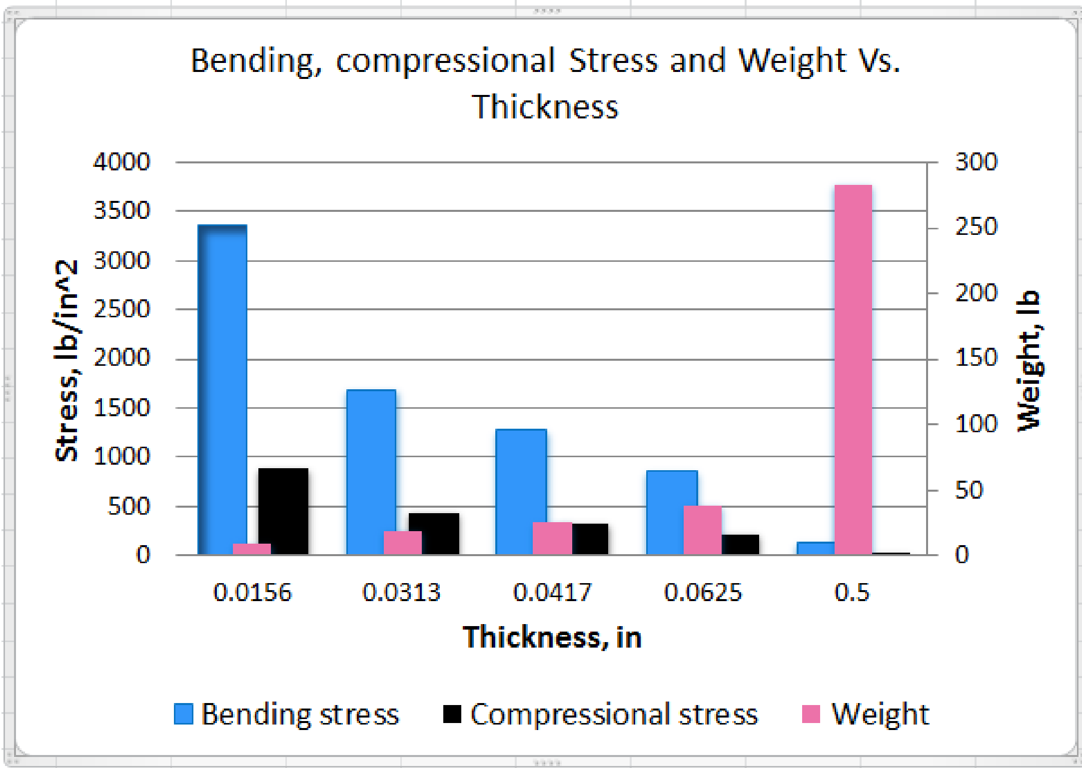
Table summarizing results of bending stress, compressional stress, and weight calculated by changing thickness/ sizing the analyzed structure. Data is collect in 5 different trials

	in	lb/in^2	lb/in^2	lb
T	Thickness	Bending s	Compress	Weight
0	0.5	141	31	284
1	0.0156	3370	893	10
2	0.0313	1696	447	20
3	0.0625	865	225	39
4	0.0417	1281	336	26

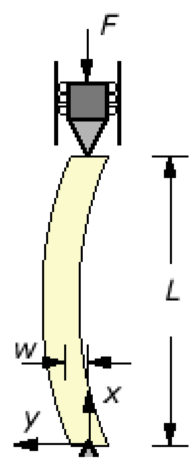
Table showing results rearranged by increasing thickness

in	lb/in^2	lb/in^2	lb	
Thickness	Bending s	Compress	Weight	T
0.0156	3370	893	10	1
0.0313	1696	447	20	2
0.0417	1281	336	26	4
0.0625	865	225	39	3
0.5	141	31	284	0

Graph showing the effect on bending stress, compressional stress and weight due to changing thickness.



Calculating the Critical Buckling Load, using Euler's Formula



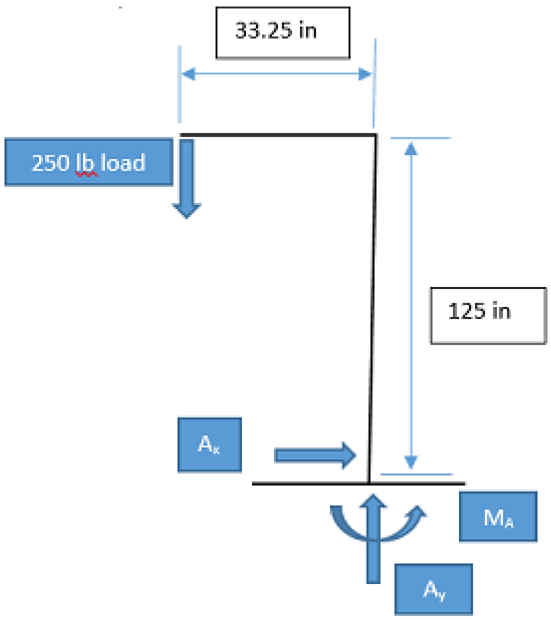
$L := 125in$

$I := 5.417\,in^4$

$$F := \frac{E \cdot I \cdot \pi^2}{L^2} = 9.923 \times 10^3 \cdot lb$$

The critical buckling load is 9923 lb., we will only be hanging 500 lb. on the Rig. Therefore buckling will not be a problem for the designed rig.

Hanging a 30in wall. Hanging a thicker wall will cause large moment at the bottom of the rail. (Adding 3.35 inches of structure length



$$M_A = 0 = M + 250(33.25)$$

$$M := 8312.5\,lb\cdot in$$

$$t := \frac{1}{16}\,in$$

$$I := \frac{w\cdot L^3}{12} - \frac{(w-2t)\cdot(L-2t)^3}{12} = 2.175\times 10^4\cdot in^4$$

Bending Stress

$$\sigma_{bend} := M\cdot\frac{c_t}{I}$$

$$\sigma_{bend} = 1.147\,\frac{lb}{in^2}$$

Cross section area

$$A := L \cdot w - (L - 2t) \cdot (w - 2t) = 15.984\, in^2$$

Compressional Stress

$$\sigma_{comp} := \frac{P}{A} = 15.64 \frac{lb}{in^2}$$

Calculating estimated weight of one side

$$Weight := A \cdot H \cdot D = 567.445\, lb$$

Considering a different structure for the stress analysis. Solid rectangular structure. In this section we will repeat the above stress calculation

Considering a 3 in wall

Total of 500 pounds to hang

Total height — Young's modulus

$P := 250\, lb$ $\quad H := 125\, in$ $\quad E := 2.9 \cdot 10^6 \frac{lb}{in^2}$

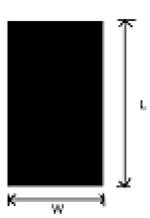
Moment caused by the force of the hanging wall

$$M_A = 0 = M + 250(6.25)$$

$$M := 1562.5\, lb \cdot in$$

L is the length of the side rail. L is also constant

$$L := 6\, in$$



$w = t$

The critical section at the base, the critical point is the point where failure/ bending is most likely to happen. We assume that failure won't happen at the connection joint, y=0 in since the joint is engineered not to fail. So the critical is assumed to be at half the length of the rail.

$$c_t := 0.5L = 3 \cdot in$$

Wall thickness of $t := 1 in$

Moment of inertia $I := \frac{t \cdot L^3}{12} = 18 \cdot in^4$

Bending Stress

$$\sigma_{bend} := M \cdot \frac{c_t}{I}$$

$$\sigma_{bend} = 260.417 \frac{lb}{in^2}$$

Cross section area

$$A := L \cdot t = 6 \cdot in^2$$

Compressional Stress

$$\sigma_{comp} := \frac{P}{A} = 41.667 \frac{lb}{in^2}$$

Calculating estimated weight of one side

$$Weight := A \cdot H \cdot D = 213 \cdot lb$$

Trial 2

Wall thickness of $t := \frac{2}{3} in$

$$I := \frac{t \cdot L^3}{12} = 12 \cdot in^4$$

Bending Stress

$$\sigma_{bend} := M \cdot \frac{c_t}{I}$$

$$\sigma_{bend} = 390.625 \frac{lb}{in^2}$$

Cross section area

$$A := L \cdot t = 4 \cdot in^2$$

Compressional Stress

$$\sigma_{comp} := \frac{P}{A} = 62.5 \cdot \frac{lb}{in^2}$$

Calculating estimated weight of one side

$$Weight := A \cdot H \cdot D = 142 \cdot lb$$

Trail 3

$$t := \frac{1}{32} in$$

$$I := \frac{t \cdot L^3}{12} = 0.562 \cdot in^4$$

Bending Stress

$$\sigma_{bend} := M \cdot \frac{c_t}{I}$$

$$\sigma_{bend} = 8.333 \times 10^3 \cdot \frac{lb}{in^2}$$

Cross section area

$$A := L \cdot t = 0.187 \cdot in^2$$

Compressional Stress

$$\sigma_{comp} := \frac{P}{A} = 1.333 \times 10^3 \cdot \frac{lb}{in^2}$$

Calculating estimated weight of one side

$$Weight := A \cdot H \cdot D = 6.656 lb$$

Trial 4

$$t := \frac{1}{16} in$$

$$I := \frac{t \cdot L^3}{12} = 1.125 in^4$$

Bending Stress

$$\sigma_{bend} := M \cdot \frac{c_t}{I}$$

$$\sigma_{bend} = 4.167 \times 10^3 \cdot \frac{lb}{in^2}$$

Cross section area

$$A := L \cdot t = 0.375 in^2$$

Compressional Stress

$$\sigma_{comp} := \frac{P}{A} = 666.667 \frac{lb}{in^2}$$

Calculating estimated weight of one side

$$Weight := A \cdot H \cdot D = 13.312 lb$$

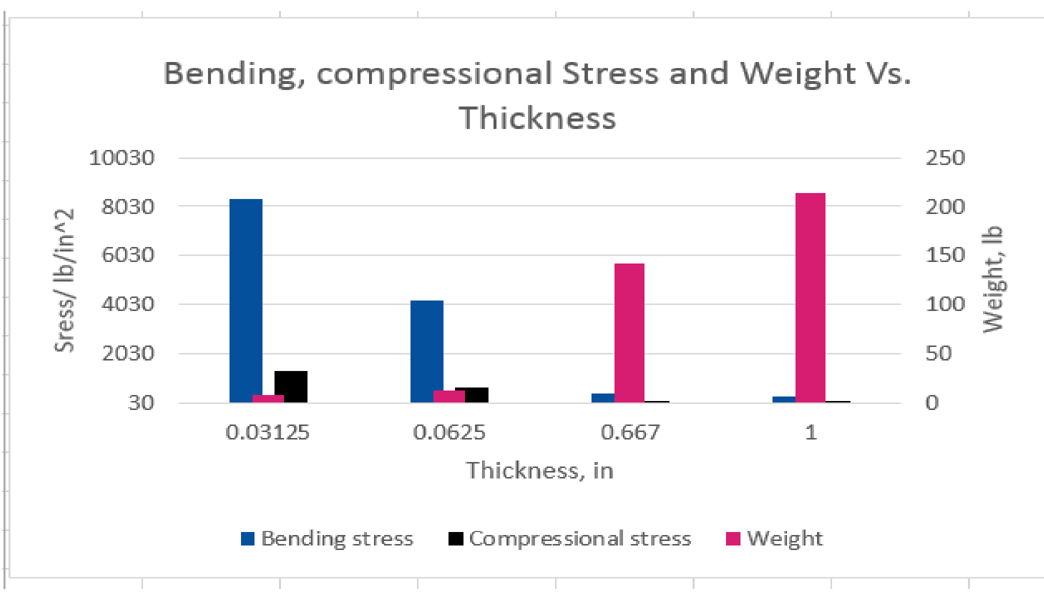
Table summarizing results of bending stress, compressional stress, and weight calculated by changing thickness/ sizing the analyzed structure. Data is collect in 4 different trials

	in	lb/in^2	lb/in^2	lb
T	Thickness	Bending s	Compress	Weight
1	1	260	42	213
2	0.667	390	63	142
3	0.03125	8333	1333	7
4	0.0625	4167	667	13

Table showing results rearranged by increasing thickness

in	lb/in^2	lb/in^2	lb	
Thickness	Bending s	Compress	Weight	T
0.03125	8333	1333	7	3
0.0625	4167	667	13	4
0.667	390	63	142	2
1	260	42	213	1

Graph showing the effect on bending stress, compressional stress and weight due to changing thickness.



According to the calculation, a solid structure with a thickness of 0.0625 in would support
The assumed weight (500 lb.) if hanged, but to securely hang a large heavy specimen, a larger surface area of more than 0.0625 in * 6 inches is needed. Therefore we will use the hollow structure, instead of the solid one.

APPENDIX E

The following equations used were taken from APPENDIX References [6]-[8].

Thermal Analysis on Holder

$Q := 15($	kW	Heat Release Rate
$A := 0.8636 0.4572 = 0.395$	m^2	Area of Burner
$P := 2.641($	m	Perimeter of Burner
$D_h := 4\frac{A}{P} = 0.598$	m	Hydraulic Diameter

$$f_0 = \frac{z}{L_f} \qquad f_1 = \frac{z}{L_f} \qquad f_2 = \frac{z}{L_f}$$

$$q_{peak} := 200\left[1 - e^{-.09\cdot(Q)^{\frac{1}{3}}}\right] = 76.02 \quad \frac{kW}{m^2} \quad \text{Peak Heat Flux}$$

$$L_f := 0.23\cdot Q^{\frac{2}{5}} - 1.02\cdot D_h = 1.097 \quad m \quad \text{Flame Length}$$

Calculation for Heat Fluxes in Continuous Flame zone

$f_0 := 0, .1 .. .4$

$q_0(f) := q_{peak}$

$q_0(f_0) =$

76.02	$\frac{kW}{m^2}$
76.02	
76.02	
76.02	
76.02	

Calculation for Heat Fluxes in Intermittent Flame zone

$f_1 := .4, .5 .. 1$

$q_1(f) := q_{peak} - \frac{5}{3}\left(f - \frac{2}{5}\right)\left(q_{peak} - 20\right)$

$q_1(f_1) =$

76.02
66.683
57.347
48.01
38.673
29.337
20

$\frac{kW}{m^2}$

Calculation for Heat Fluxes in Plume zone

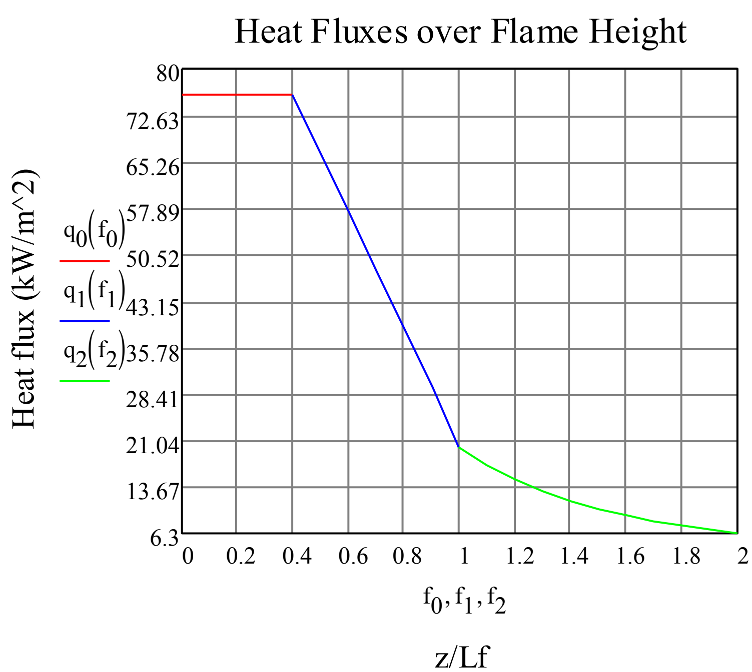
$f_2 := 1, 1.1 .. 2$

$q_2(f) := 20(f)^{\left(\frac{-5}{3}\right)}$

$q_2(f_2) =$

20
17.062
14.759
12.916
11.415
10.175
9.138
8.259
7.509
6.862
6.3

$\frac{kW}{m^2}$



$Q := 10($ kW — Heat Release Rate

$A := 0.8636 \cdot 0.4572 = 0.395$ m^2 — Area of Burner

$P := 2.641($ m — Perimeter of Burner

$D_h := 4\frac{A}{P} = 0.598$ m — Hydraulic Diameter

$f_0 = \frac{z}{L_f}$ $f_1 = \frac{z}{L_f}$ $f_2 = \frac{z}{L_f}$

$q_{peak} := 200\left[1 - e^{-.09\cdot(Q)^{\frac{1}{3}}}\right] = 68.294$ $\frac{kW}{m^2}$ — Peak Heat Flux

$L_f := 0.23\cdot Q^{\frac{2}{5}} - 1.02\cdot D_h = 0.841$ m — Flame Length

Calculation for Heat Fluxes in Continuous Flame zone

$f_0 := 0, .1 .. .4$

$q_0(f) := q_{peak}$

$q_0(f_0) =$

68.294
68.294
68.294
68.294
68.294

$\frac{kW}{m^2}$

Calculation for Heat Fluxes in Intermittent Flame zone

$f_1 := .4, .5 .. 1$

$q_1(f) := q_{peak} - \frac{5}{3}\left(f - \frac{2}{5}\right)\left(q_{peak} - 20\right)$

$q_1(f_1) =$

68.294
60.245
52.196
44.147
36.098
28.049
20

$\frac{kW}{m^2}$

Calculation for Heat Fluxes in Plume zone

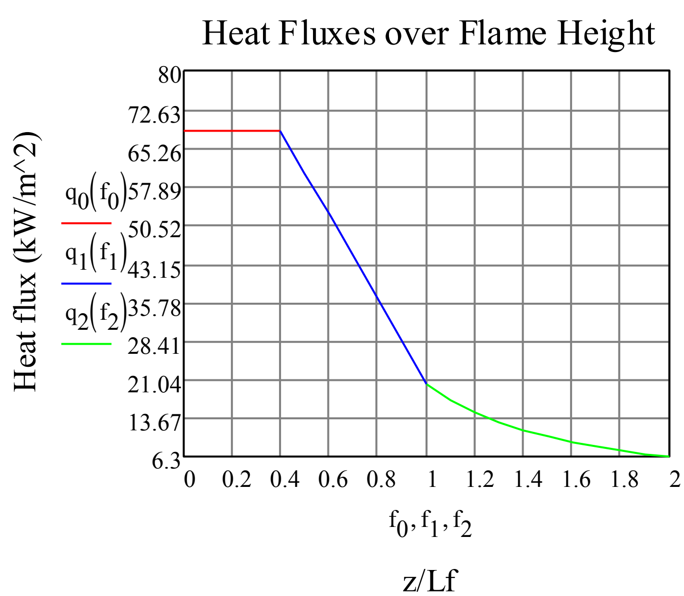
$f_2 := 1, 1.1 .. 2$

$q_2(f) := 20(f)^{\left(\frac{-5}{3}\right)}$

$q_2(f_2) =$

20
17.062
14.759
12.916
11.415
10.175
9.138
8.259
7.509
6.862
6.3

$\frac{kW}{m^2}$



Incident Radiative Heat Flux for 100 kW Fire

$X_r := .3$ m — Radiative Fraction

$Q_r := X_r \cdot Q = 30$ $\frac{kW}{m}$ — Total radiative energy output of fire

$c := \frac{D_h}{2} = 0.299$ m

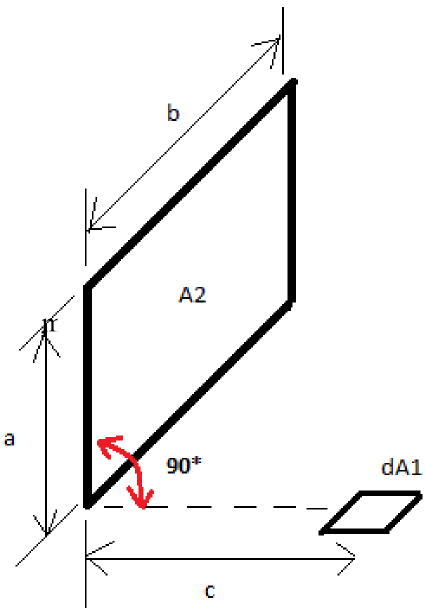
$a := \frac{L_f}{2} = 0.421$ m

$b := \frac{D_h}{2} = 0.299$ m

$X := \frac{a}{b} = 1.407$

$Y := \frac{c}{b} = 1$

$A_{f1} := D_h \cdot L_f = 0.503$ m^2



$$F_{d1\_2} := \frac{1}{2\pi}\left(\operatorname{atan}\left(\frac{1}{Y}\right) - \frac{Y}{\sqrt{X^2 + Y^2}} \cdot \operatorname{atan}\left(\frac{1}{\sqrt{X^2 + Y^2}}\right)\right) = 0.077$$ Radians

$$q_t := 2\left(F_{d1\_2}\right) \cdot \frac{Q_r}{A_{f1}} = 9.136 \quad \frac{kW}{m^2}$$ Incident Radiative Heat flux

Calculating surface temperature of holder due to radiation

$h_c := 0.01$ $\frac{kW}{m^2 \cdot K}$

$T_\alpha := 298$ K

$$\varepsilon \cdot q_t = h_c \cdot (T - T_\alpha) + \varepsilon \cdot \sigma \cdot (T^4 - T_\alpha{}^4)$$

$$\varepsilon \cdot q_t + h_c \cdot T_\alpha + \varepsilon \cdot \sigma \cdot T_\alpha{}^4 = h_c \cdot T + \varepsilon \cdot \sigma \cdot T^4 = T(h_c + \varepsilon \cdot \sigma \cdot T^3)$$

$\varepsilon := 0.9$

$\sigma := 5.67 \cdot 10^{-11} \quad \frac{kW}{m^2 \cdot K^4}$

$\varepsilon \cdot q_t + h_c \cdot T_\alpha + \varepsilon \cdot \sigma \cdot T_\alpha{}^4 = 13.095$

$T := 551 \quad K$ 277 deg. C

At 277 deg C our steel will have its yield strength reduced by 10%. This shows that Radiation is not the primary concern and an analysis of conduction needs to be completed. Radiation is still a safety hazard and should be covered with insulation.

Time to reach steady state for radiation of 9 kW/m^2 for 5 inch section

$$\varepsilon \cdot q_t = h_t \cdot (T - T_\alpha)$$

$$(0.9) \cdot (9) = h_t \cdot (551 - 298)$$

$h_t := 0.038 \quad \frac{kW}{m^2 \cdot K}$ Total Heat Transfer Coefficient

$\rho := 786 \quad \frac{kg}{m^3}$ Density of A500 Steel

$c := .448 \quad \frac{kJ}{kg \cdot C}$ Specific Heat Capacity of A500 Steel

$\Delta := 0.127 \quad m$ Thickness of beam

$$\rho \cdot c \cdot \Delta \cdot \frac{dT}{dt} = \varepsilon \cdot q_t - h_t(T - T\alpha)$$

$\rho \cdot c \cdot \Delta = 447.259$

$\varepsilon \cdot q_t = 8.223$ $\quad C_1 := -411.$

$T := 298$

$$T(t) := C_1 e^{-(0.00084962t)} + 514.3$$

$t := 0, 1 .. 10000$ — Time step of 1 second

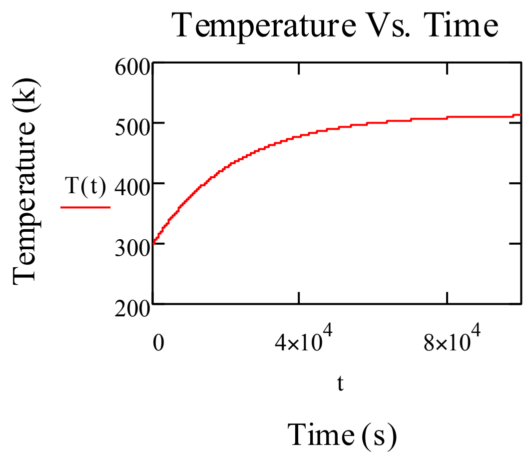
$T(t) := -216e^{-(0.0000447168t)} + 514.39$

$T(t) =$

298.39
298.4
298.409
298.419
298.429
298.438
298.448
298.458
298.467
298.477
298.487
298.496
298.506
298.516
298.525
...

K

Change in Temperature over time



It takes 13 hours to reach steady state for 5 inches of steel

This is not exactly our scenario so we chose a 1/16 inch steel below

Time to reach steady state for radiation of 9 kW/m^2 for 1/16 inch section

$\varepsilon \cdot q_t = h_t \cdot (T - T_\alpha)$

$(0.9) \cdot (9) = h_t \cdot (551 - 298)$

$h_t := 0.038 \frac{kW}{m^2 \cdot K}$ — Total Heat Transfer Coefficient

$\rho := 7861 \frac{kg}{m^3}$ — Density of A500 Steel

$c := .448 \frac{kJ}{kg \cdot C}$ — Specific Heat Capacity of A500 Steel

$\Delta := 0.0015 \ m$ — Thickness of beam

$$\rho \cdot c \cdot \Delta \cdot \frac{dT}{dt} = \varepsilon \cdot q_t - h_t(T - T\alpha)$$

$\rho \cdot c \cdot \Delta = 5.564$

$\varepsilon \cdot q_t = 8.223$

$C_1 := -21($

$T := 29($

$T(t) := C_1 e^{-(0.00682962t)} + 514.39:$

Time step of 1 second

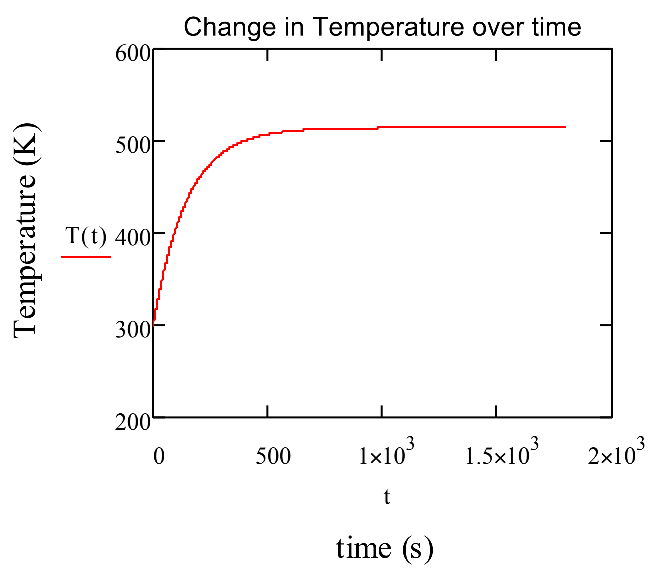
$t := 0, 1 .. 180($

$T(t) := -216e^{-(0.00682962t)} + 514.39:$

$T(t) =$

298.395
299.865
301.325
302.776
304.216
305.646
307.067
308.478
309.88
311.272
312.655
314.028
315.391
316.746
318.091
...

K



Time to steady state is 16 minutes for a 1/16 inch piece of steel

Conduction from radiation on top beam through 1 inch insulation

Assume

$k := 0.04$ Rock wool insulation $T_1 := 55$ K At burner edge

$\Delta T := 25$ K $T_2 := 30$ K Surface of steel

$\Delta X := 0.0$ m

$$q := k \cdot \frac{\Delta T}{\Delta X} = 564.75 \quad \frac{W}{m^2}$$

$$q_{net} := 0. \quad \frac{kW}{m^2}$$

Conduction from radiation on top beam through 2 inch insulation

Assume

$k := 0.04$ Rock wool insulation $T_1 := 55$ K At burner edge

$\Delta T := 25$ K $T_2 := 30$ K Surface of steel

$\Delta X := 0.0$ m

$$q := k \cdot \frac{\Delta T}{\Delta X} = 282.375 \quad \frac{W}{m^2}$$

$$q_{net} := 0. \quad \frac{kW}{m^2}$$

Conduction from flame attached to burner edge 1 inch of insulation

Assume

$k := 0.04$ Rock wool insulation $T_1 := 150$ K At burner edge

$\Delta T := 120$ K $T_2 := 30$ K Surface of steel

$\Delta X := 0.0$ m

$$q := k \cdot \frac{\Delta T}{\Delta X} = 2.7 \times 10^3 \quad \frac{W}{m^2}$$

$$q_{net} := 2. \quad \frac{kW}{m^2}$$

Time to reach steady state for of 2.7 kW/m^2 for 1/16

$\varepsilon \cdot q_{net} = h_t \cdot (T - T_\alpha)$

$(0.9) \cdot (2.7) = h_t \cdot (1500 - 300)$

$h_t := 2.025 \times 10^{-3}$ $\frac{kW}{m^2 \cdot K}$ Total Heat Transfer Coefficient

$\rho := 786$ $\frac{kg}{m^3}$ Density of A500 Steel

$c := .448$ $\frac{kJ}{kg \cdot C}$ Specific Heat Capacity of A500 Steel

$\Delta := 0.0015$ m Thickness of beam

$\rho \cdot c \cdot \Delta \cdot \frac{dT}{dt} = \varepsilon \cdot q_{net} - h_t (T - T\alpha)$

$\rho \cdot c \cdot \Delta = 5.564$

$\varepsilon \cdot q_{net} = 2.43$

$C_1 := -1200$

$T := 298$

$T(t) := C_1 e^{-(0.000363947t)} + 1500$

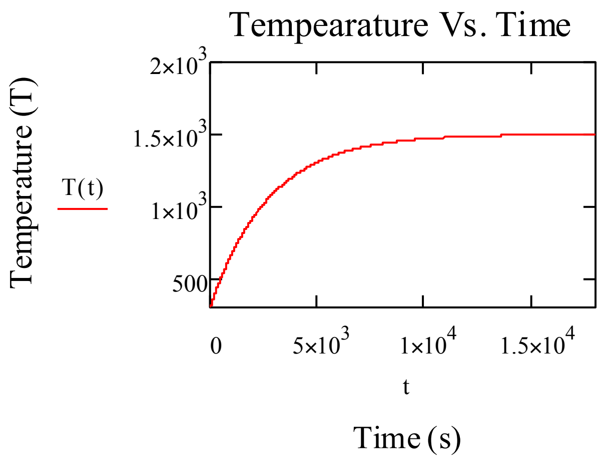
$t := 0, 1 .. 18000$ Time step of 1 second

$T(t) := -1200e^{-(0.000363947t)} + 1500$

$T(t) =$

300
300.437
300.873
301.309
301.746
302.182
302.618
303.053
303.489
303.924
304.359
304.794
305.229
305.664
306.099
...

K



With 1" of insulation, the metal underneath will be subject to a 2.7kW/m^2 heat flux and will reach steady state conditions after 4 hours

After 30 minutes, the surface of the frame will be heated 876 K

Conduction from flame attached to burner edge 2 inch of insulation

Assume

$k := 0.04$ Rock wool insulation

$T_1 := 150$ K At burner edge

$\Delta T := 120$ K

$T_2 := 30$ K At surface of steel

$\Delta X := 0.0$ m

$$q := k \cdot \frac{\Delta T}{\Delta X} = 1.35 \times 10^3 \quad \frac{W}{m^2}$$

$$q_{net} := 1.3 \quad \frac{kW}{m^2}$$

Time to reach steady state for of 1.35 kW/m^2 for 1/16

$\varepsilon \cdot q_{net} = h_t \cdot (T - T_\alpha)$

$(0.9) \cdot (1.35) = h_t \cdot (1500 - 300)$

$h_t := 1.013 \times 10^{-3} \quad \frac{kW}{m^2 \cdot K}$ Total Heat Transfer Coefficient

$\rho := 786 \quad \frac{kg}{m^3}$ Density of A500 Steel

$c := .448 \quad \frac{kJ}{kg \cdot C}$ Specific Heat Capacity of A500 Steel

$\Delta := 0.0015 \quad m$ Thickness of beam

$\rho \cdot c \cdot \Delta \cdot \frac{dT}{dt} = \varepsilon \cdot q_{net} - h_t(T - T\alpha)$

$\rho \cdot c \cdot \Delta = 5.564$

$\varepsilon \cdot q_{net} = 1.215$ $C_1 := -119$

$T := 30$

$T(t) := C_1 e^{-(0.000182063t)} + 1499.4$

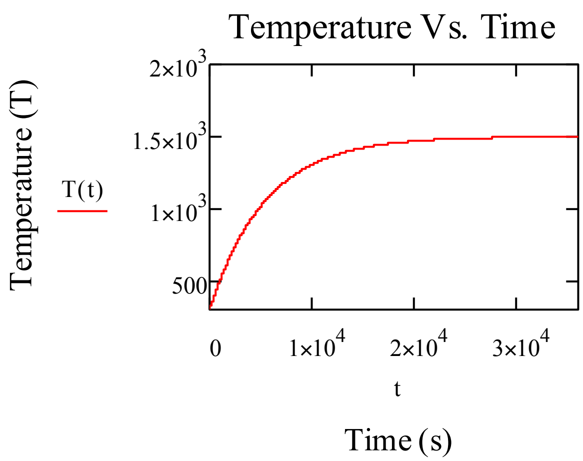
$t := 0, 1 .. 3600$ Time step of 1 second

$T(t) := -1199 e^{-(0.000182063t)} + 1499.4$

$T(t) =$

300.41
300.628
300.847
301.065
301.283
301.501
301.719
301.937
302.155
302.373
302.591
302.809
303.027
303.244
303.462
...

K



With 2" of insulation, the metal underneath will be subject to a 1.35kW/m^2 heat flux and will reach steady state conditions after 7 hours

After 30 minutes, the surface of the frame will be heated 635 K or 362 C, The yield strength is reduced by 13% considering 1500 K fire at surface of insulation

Net heat flux through isolation

$$\rho \cdot c \cdot \Delta \cdot \frac{dT}{dt} = q_{net}$$ $\rho \cdot c \cdot \Delta = 5.564$ Lumped analysis

Radiation to insulation on top of frame

Net flux of: $q_{1in} := 0.5$ $\frac{kW}{m^2}$ 1in insulation $T_0 = 300K$

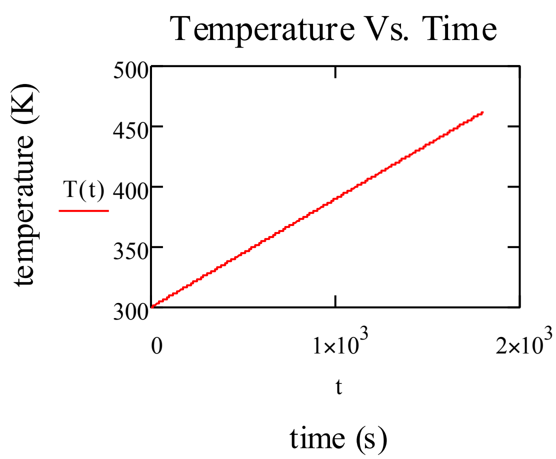
$t := 0, 1.. 1800$ $C_1 := 300$ K

$T(t) := C_1 + 0.0898634$

$T(t) =$

460.406
460.496
460.586
460.676
460.766
...

K



After 30 minutes the temperature at surface is 462 K or 189 deg C

Net flux of: $q_{1in} := 0.2$ $\frac{kW}{m^2}$ 2in insulation $T_0 = 300K$

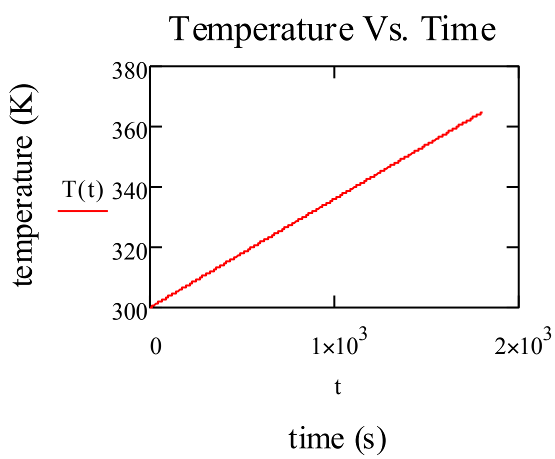
$t := 0, 1 .. 180($ $C_1 := 30($ K

$T(t) := C_1 + 0.0359454$

$T(t) =$

364.522
364.558
364.594
364.63
364.666
...

K



After 30 minutes the temperature at surface is 365 K or 92 deg C

Flame attached to burner

Net flux of: $q_{1in} := 2.7$ $\frac{kW}{m^2}$ 1in insulation $T_0 = 300K$

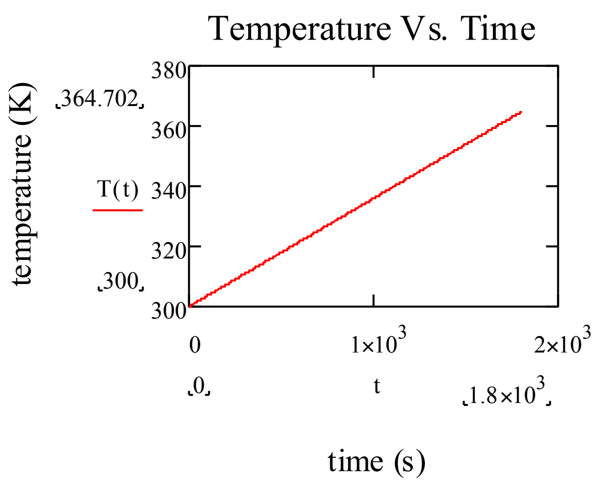
$t := 0, 1 .. 1800$ $C_1 := 300$ K

$T(t) := C_1 + 0.485262$

$T(t) =$

$1.164 \cdot 10^3$
$1.164 \cdot 10^3$
$1.165 \cdot 10^3$
$1.165 \cdot 10^3$
$1.166 \cdot 10^3$
$1.166 \cdot 10^3$
$1.167 \cdot 10^3$
$1.167 \cdot 10^3$
...

K



After 30 minutes the temperature at surface is 1168 K or 895 deg C

Net flux of: $q_{1in} := 1.35$ $\frac{kW}{m^2}$ 2in insulation $T_0 = 300K$

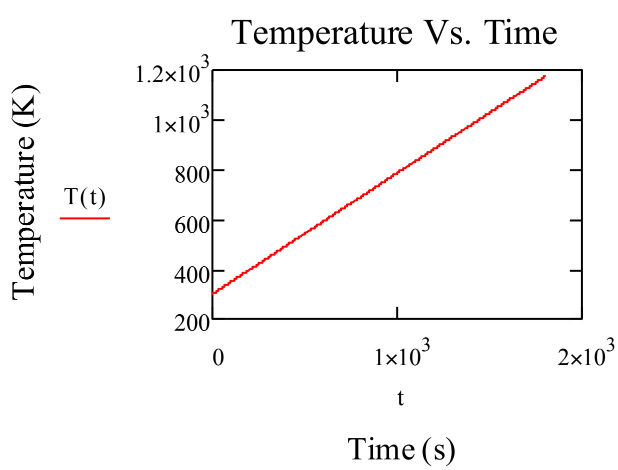
$t := 0, 1 .. 1800$ $C_1 := 300$ K

$T(t) := C_1 + 0.242631$

$T(t) =$

735.28
735.523
735.765
736.008
736.251
736.493
...

K



After 30 minutes the temperature at surface is 737 K or 464 deg C

Considering 75kW

$Q := 75$ kW Heat Release Rate

$A := 0.8636 \cdot 0.4572 = 0.395$ m^2 Area of Burner

$P := 2.6416$ m Perimeter of Burner

$D_h := 4\frac{A}{P} = 0.598$ m Hydraulic Diameter

$f_0 = \frac{z}{L_f}$ $f_1 = \frac{z}{L_f}$ $f_2 = \frac{z}{L_f}$

$q_{peak} := 200\left[1 - e^{-.09\cdot(Q)^{\frac{1}{3}}}\right] = 63.165$ $\frac{kW}{m^2}$ Peak Heat Flux

$L_f := 0.23\cdot Q^{\frac{2}{5}} - 1.02\cdot D_h = 0.684$ m Flame Length

Calculation for Heat Fluxes in Continuous Flame zone

$f_0 := 0, .1 .. .4$

$q_0(f) := q_{peak}$

$q_0(f_0) =$

63.165
63.165
63.165
63.165
63.165

$\frac{kW}{m^2}$

Calculation for Heat Fluxes in Intermittent Flame zone

$f_1 := .4, .5 .. 1$

$q_1(f) := q_{peak} - \frac{5}{3}\left(f - \frac{2}{5}\right)\left(q_{peak} - 20\right)$

$q_1(f_1) =$

63.165
55.971
48.777
41.583
34.388
27.194
20

$\frac{kW}{m^2}$

Calculation for Heat Fluxes in Plume zone

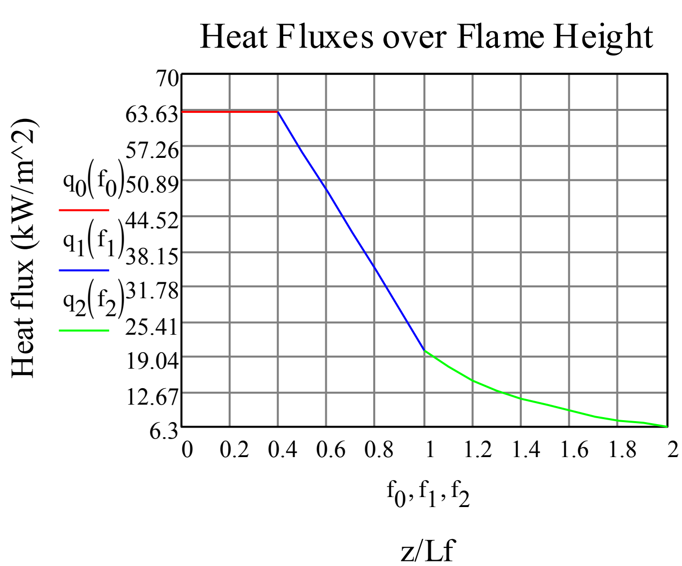
$f_2 := 1, 1.1 .. 2$

$q_2(f) := 20(f)^{\left(\frac{-5}{3}\right)}$

$q_2(f_2) =$

20
17.062
14.759
12.916
11.415
10.175
9.138
8.259
...

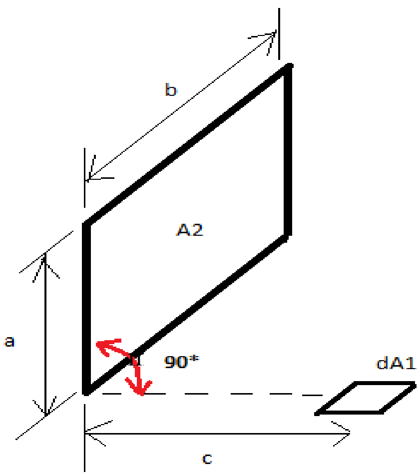
$\frac{kW}{m^2}$



Incident Radiative Heat Flux for 75 kW Fire

$X_r = 0.3$ m — Radiative Fraction

$Q_r := X_r \cdot Q = 22.5 \ \frac{kW}{m}$ — Total radiative energy output of fire



$c := \frac{D_h}{2} = 0.299$

$a := \frac{L_f}{2} = 0.342$ m

$b := \frac{D_h}{2} = 0.299$ m

$X := \frac{a}{b} = 1.143$

$Y := \frac{c}{b} = 1$

$A_{f1} := D_h \cdot L_f = 0.409 \ m^2$

$$F_{d1\_2} := \frac{1}{2\pi}\left(\operatorname{atan}\left(\frac{1}{Y}\right) - \frac{Y}{\sqrt{X^2 + Y^2}} \cdot \operatorname{atan}\left(\frac{1}{\sqrt{X^2 + Y^2}}\right)\right) = 0.064 \quad \text{Radians}$$

$$q_t := 2\left(F_{d1\_2}\right) \cdot \frac{Q_r}{A_{f1}} = 7.046 \ \frac{kW}{m^2}$$ Incident Radiative Heat flux

Considering 50kW

$Q := 5($	kW	Heat Release Rate
$A := 0.8636 0.4572 = 0.395$	m^2	Area of Burner
$P := 2.641($	m	Perimeter of Burner
$D_h := 4\frac{A}{P} = 0.598$	m	Hydraulic Diameter

$$f_0 = \frac{z}{L_f} \qquad f_1 = \frac{z}{L_f} \qquad f_2 = \frac{z}{L_f}$$

$$q_{peak} := 200\left[1 - e^{-.09\cdot(Q)^{\frac{1}{3}}}\right] = 56.44 \quad \frac{kW}{m^2}$$ Peak Heat Flux

$$L_f := 0.23\cdot Q^{\frac{2}{5}} - 1.02\cdot D_h = 0.49 \quad m$$ Flame Length

Calculation for Heat Fluxes in Continuous Flame zone

$f_0 := 0, .1 .. .4$

$q_0(f) := q_{peak}$

$q_0(f_0) =$

56.44
56.44
56.44
56.44
56.44

$\frac{kW}{m^2}$

Calculation for Heat Fluxes in Intermittent Flame zone

$f_1 := .4, .5 .. 1$

$q_1(f) := q_{peak} - \frac{5}{3}\left(f - \frac{2}{5}\right)\left(q_{peak} - 20\right)$

$q_1(f_1) =$

56.44
50.366
44.293
38.22
32.147
26.073
20

$\frac{kW}{m^2}$

Calculation for Heat Fluxes in Plume zone

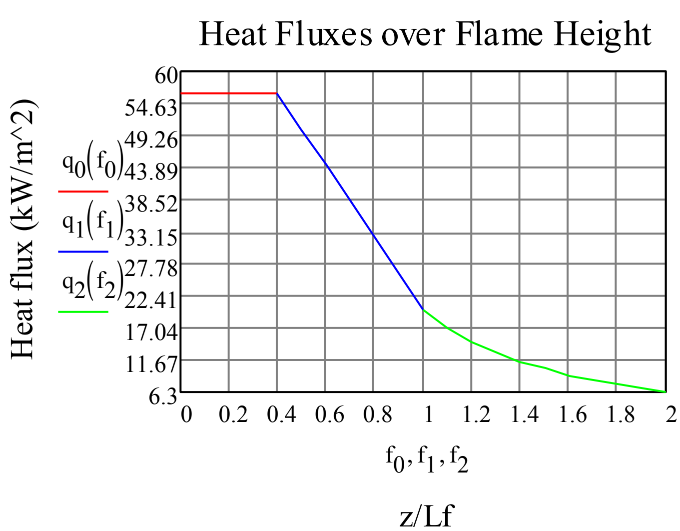
$f_2 := 1, 1.1 .. 2$

$q_2(f) := 20(f)^{\left(\frac{-5}{3}\right)}$

$q_2(f_2) =$

20
17.062
14.759
12.916
11.415
10.175
9.138
...

$\frac{kW}{m^2}$

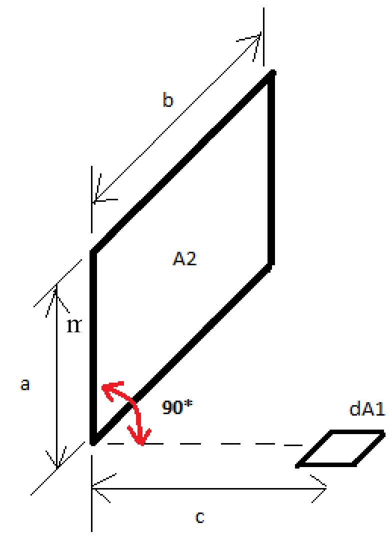


Incident Radiative Heat Flux for 50 kW Fire

$X_r := .3$ m — Radiative Fraction

$Q_r := X_r \cdot Q = 15 \quad \frac{kW}{m}$ — Total radiative energy output of fire

$c := \frac{D_h}{2} = 0.299$



$a := \frac{L_f}{2} = 0.245$ m

$b := \frac{D_h}{2} = 0.299$ m

$X := \frac{a}{b} = 0.82$

$Y := \frac{c}{b} = 1$

$A_{f1} := D_h \cdot L_f = 0.293$ m^2

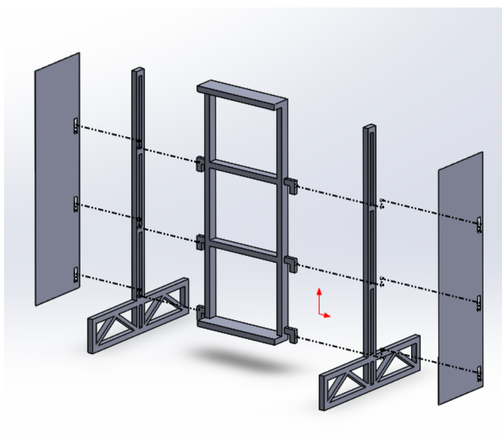
$$F_{d1\_2} := \frac{1}{2\pi}\left(\operatorname{atan}\left(\frac{1}{Y}\right) - \frac{Y}{\sqrt{X^2+Y^2}} \cdot \operatorname{atan}\left(\frac{1}{\sqrt{X^2+Y^2}}\right)\right) = 0.044$$ Radians

$$q_t := 2\left(F_{d1\_2}\right) \cdot \frac{Q_r}{A_{f1}} = 4.502 \quad \frac{kW}{m^2}$$ Incident Radiative Heat flux

APPENDIX F

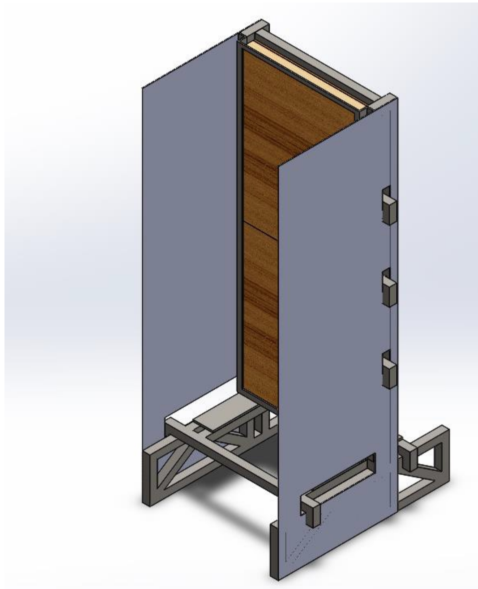
Early Design Iterations

Based on our design specifications, each team member created preliminary designs of how we thought the rig should be constructed. After comparing designs and discussing them with Professor Dembsey and Professor Umberto our group decided that our original designs were too complicated in the adjustment mechanism. Using various components of the three designs, a new design was created.



Design #1

This first Design iteration would become the fundamental design of which all other designs would be formulated. Design one was simple, but lacked a way to support the full weight and width of a 30 inch specimen wall. The addition of a longer fire channel, as well as a support base, would lead to a more stable and efficient rig. Design 2 was more refined and gave the burner a way to appropriately attack the base of the assembly as if it were the top of the window frame in the full scale rig. The bottom plate which is able to slide along the side rails to accommodate different wall thickness, supports the entire weight of the wall. Our team felt that support legs needed to be added to the bottom support plate to safely handle the stress of a maximum thickness wall.



Design #2

The picture frame style mechanism used to attach the backing wall also had a limited range of adjustability for walls larger than 1' thickness. The L shaped protrusion on the floor holder and corresponding slot in the fire channel needed to be removed to allow the wall holder to be easily slid under the backing wall and to prevent fire leakage. Design changes to fix these problems would lead to the final rig design iteration.

Exterior Wall Materials Catalog

APPENDIX References [9]-[21] were used to create the following Catalog of Materials.

In order to better understand the exterior wall assemblies, which the intermediate scale NFPA-285 test rig will need to accommodate, it is important to first understand the types of wall assemblies possible. The information Outlined in the Materials catalog will provide approximate thickness values for many different exterior wall materials. By examining the corresponding International Building Codes (IBC) and ASHRAE International Energy Efficiency Codes (IECC), a baseline for exterior wall thickness can be determined. The exterior wall thickness is dependent on achieving a passing u-value as well as complying with the IBC. Many energy modeling programs and code calculations require U-values of assemblies. The U-value is simply the reciprocal of the total R-value of the assembly.

$$U = \frac{1}{R_1 + R_2 + R_3 \text{ etc}}$$

The following table provided by the IECC provides information on the r and u value requirements for each climate zone:

TABLE C402.2
OPAQUE THERMAL ENVELOPE REQUIREMENTS[a]

CLIMATE ZONE	1		2		3		4 EXCEPT MARINE		5 AND MARINE 4		6		7		8	
	All Other	Group R	All Other	Group R	All Other	Group R	All Other	Group R	All Other	Group R	All Other	Group R	All Other	Group R	All Other	Group R
Roofs																
Insulation entirely above deck	R-20ci	R-20ci	R-20ci	R-20ci	R-20ci	R-20ci	R-25ci	R-25ci	R-25ci	R-25ci	R-30ci	R-30ci	R-35ci	R-35ci	R-35ci	R-35ci
Metal buildings (with R-5 thermal blocks)[a,b]	R-19 + R-11 LS	R-19 + R-11 LS	R-19 + R11 LS	R-19 + R-11 LS	R-19 + R-11 LS	R-19 + R-11 LS	R-19 + R-11 LS	R-19 + R-11 LS	R-19 + R-11 LS	R-19 + R-11 LS	R-25 + R-11 LS	R-25 + R-11 LS	R-30 + R-11 LS	R-30 + R-11 LS	R-30 + R-11 LS	R-30 + R-11 LS
Attic and other	R-38	R-38	R-38	R-38	R-38	R-38	R-38	R-38	R-38	R-49	R-49	R-49	R-49	R-49	R-49	R-49
Walls, Above Grade																
Mass	R-5.7ci	R-5.7ci	R-5.7ci	R-7.6ci	R-7.6ci	R-9.5ci	R-9.5ci	R-11.4ci	R-11.4ci	R-13.3ci	R-13.3ci	R-15.2ci	R-15.2ci	R-15.2ci	R-25ci	R-25ci
Metal building	R-13+ R-6.5ci	R-13 + R-6.5ci	R13 + R-6.5ci	R-13 + R-13ci	R-13 + R-6.5ci	R-13 + R-13ci	R-13 + R-13ci	R-13 + R-13ci	R-13 + R-13ci	R-13 + R-13ci	R-13 + R-13ci	R-13 + R-13ci	R-13 + R-13ci	R-13+ R-19.5ci	R-13 + R-13ci	R-13+ R-19.5ci
Metal framed	R-13 + R-5ci	R-13 + R-5ci	R-13 + R-5ci	R-13 + R-7.5ci	R-13 + R-7.5ci	R-13 + R-7.5ci	R-13 + R-7.5ci	R-13 + R-7.5ci	R-13 + R-7.5ci	R-13 + R-7.5ci	R-13 + R-7.5ci	R-13 + R-7.5ci	R-13 + R-7.5ci	R-13 + R-15.6ci	R-13 + R-7.5ci	R-13+ R17.5ci
Wood framed and other	R-13 + R-3.8ci or R-20	R-13 + R-3.8ci or R-20	R-13 + R-3.8ci or R-20	R-13 + R-3.8ci or R-20	R-13 + R-3.8ci or R-20	R-13 + R-3.8ci or R-20	R-13 + R-3.8ci or R-20	R-13 + R-3.8ci or R-20	R-13 + R-3.8ci or R-20	R-13 + R-7.5ci or R-20 + R-3.8ci	R-13 + R-7.5ci or R-20 + R-3.8ci	R-13 + R-7.5ci or R-20 + R-3.8ci	R-13 + R-7.5ci or R-20 + R-3.8ci	R-13 + R-7.5ci or R-20 + R-3.8ci	R-13 + R-15.6ci or R-20 + R-10ci	R-13 + R-15.6ci or R-20 + R-10ci
Walls, Below Grade																
Below-grade wall[d]	NR	NR	NR	NR	NR	NR	R-7.5ci	R-7.5ci	R-7.5ci	R-7.5ci	R-7.5ci	R-7.5ci	R-10ci	R-10ci	R-10ci	R-12.5ci
Floors																
Mass	NR	NR	R-6.3ci	R-8.3ci	R-10ci	R-10ci	R-10ci	R-10.4ci	R-10ci	R-12.5ci	R-12.5ci	R-12.5ci	R-15ci	R-16.7ci	R-15ci	R-16.7ci
Joist/framing	NR	NR	R-30	R-30	R-30	R-30	R-30	R-30	R-30	R-30	R-30	R-30[e]	R-30[e]	R-30[e]	R-30[e]	R-30[e]
Slab-on-Grade Floors																
Unheated slabs	NR	NR	NR	NR	NR	NR	R-10 for 24" below	R-10 for 24" below	R-10 for 24" below	R-10 for 24" below	R-10 for 24" below	R-15 for 24" below	R-15 for 24" below	R-15 for 24" below	R-15 for 24" below	R-20 for 24" below
Heated slabs[d]	R-7.5 for 12" below	R-7.5 for 12" below	R-7.5 for 12" below	R-7.5 for 12" below	R-10 for 24" below	R-10 for 24" below	R-15 for 24" below	R-15 for 24" below	R-15 for 36" below	R-15 for 36" below	R-15 for 36" below	R-20 for 48" below	R-20 for 24" below	R-20 for 48" below	R-20 for 48" below	R-20 for 48" below
Opaque Doors																
Swinging	U-0.61	U-0.61	U-0.61	U-0.61	U-0.61	U-0.61	U-0.61	U-0.61	U-0.37	U-0.37	U-0.37	U-0.37	U-0.37	U-0.37	U-0.37	U-0.37
Roll-up or sliding	R-4.75	R-4.75	R-4.75	R-4.75	R-4.75	R-4.75	R-4.75	R-4.75	R-4.75	R-4.75	R-4.75	R-4.75	R-4.75	R-4.75	R-4.75	R-4.75

For SI: 1 inch = 25.4 mm. ci = Continuous insulation. NR = No requirement.

LS = Liner System—A continuous membrane installed below the purlins and uninterrupted by framing members. Uncompressed, unfaced insulation rests on top of the membrane between the purlins.

a. Assembly descriptions can be found in ANSI/ASHRAE/IESNA Appendix A.

b. Where using *R*-value compliance method, a thermal spacer block shall be provided, otherwise use the *U*-factor compliance method in Table C402.1.2.

c. R-5.7ci is allowed to be substituted with concrete block walls complying with ASTM C 90, ungrouted or partially grouted at 32 inches or less on center vertically and 48 inches or less on center horizontally, with ungrouted cores filled with materials having a maximum thermal conductivity of 0.44 Btu-in/h-ft² °F.

d. Where heated slabs are below grade, below-grade walls shall comply with the exterior insulation requirements for heated slabs.

e. Steel floor joist systems shall be insulated to R-38.

For the state of Massachusetts, most buildings need a total wall R value of R-13+ regardless of metal or wooden framing.

Cladding Materials

Types of cladding	General Information and Fire Properties	Insulation properties	Average Thickness	Corresponding International Building Codes	Corresponding Green Building Codes
Vinyl Siding	-Vinyl siding is the most common exterior finish used on buildings in North America. -Made from rows of polyvinyl chloride (PVC) resin panels. -Waterproof - 391 deg. C ignition temperature with flame AND 454 deg. C ignition temperature without flame	Vinyl R-value is 1.8 (0.5" insulated) & 0.61 (not insulated)	-Thickness 0.035" to 0.052"	-Section 26.05 -Fire Endurance Rate- vinyl siding does not reduce the rating of combustible wall structures (ASTM E119 test)	As green building interests increase, much attention is focused on the off-gassing effects of PVC siding. It releases toxic fumes as it interacts with the air. These are potentially harmful to humans, and may irritate respiratory illnesses like asthma
Types of cladding	General Information and Fire Properties	Insulation properties	Average Thickness	Corresponding International Building Codes	Corresponding Green Building Codes
masonry veneers	- Masonry veneer may consist of various types of brick, stone, or clay. - It is installed with an empty air space between the building and the back of the stone. Weep holes placed at the bottom of this opening allow for excellent drainage - The cavity provides plenty of space to install building insulation, particularly rigid foam boards - Non combustible	Common brick have a R-value of 0.8	Typically 1" thick for stone veneer -Brick/ clay veneer has a maximum thickness of 1-3/4"	-Chapter 21 - Glass unit masonry- must have a minimum avg. glass face thickness of 4.8mm	-Environmentally friendly -Better thermal mass

Types of cladding	General Information and Fire Properties	Insulation properties	Average Thickness	Corresponding International Building Codes	Corresponding Green Building Codes
Metal Siding	-Metal siding comes in **Corrugated steel** (storage building) that is extremely strong and durable. **-Aluminum siding** is a popular cladding for homes in coastal areas. The aluminum will not rust or corrode when exposed to moisture or saltwater, and can withstand storms and harsh conditions better than many other cladding products -Non combustible	Al R-value is 1.8 (0.5" insulated) & 0.61 (not insulated)	thickness range: 0.0172" to 0.0187"	-Chapter 22 for steel -Chapter 20 for Al	-Environmentally friendly
Types of cladding	General Information and Fire Properties	Insulation properties	Average Thickness	Corresponding International Building Codes	Corresponding Green Building Codes
Wood siding	-Wood siding is a common type of cladding used mainly in North America. Combustible -Weather resistant	-Thermally insulating R-value of .34	.5 "	-Chapter 23	-Environmentally friendly
Types of cladding	General Information and Fire Properties	Insulation properties	Average Thickness	Corresponding International Building Codes	Corresponding Green Building Codes
Fiber Reinforced Polymers	FRP composites are manufactured using processes such as pultrusion, resin transfer molding, and filament winding. Because of their strength, FRP composites used in the construction and maintenance of bridges. FRP composites consist of fiber reinforcements, resin, fillers, and additives. Therefore FRP mechanical properties will depend on fiber types, orientation or structure. Fibers include: glass, aramid and carbon. Resin systems include: unsaturated polyesters, epoxies, vinyl esters, polyurethanes, phenolics.		-CFRP have thickness up to 1.5mm	-Section 14.04 -Section 26.12	-Environmentally friendly

Weather Resistive Barriers

Types of WRB's	General Information and Fire Properties	Insulation properties	Average Thickness	Corresponding International Building Codes	Corresponding Green Building Codes
Weather Resistive Barriers	WRB'S provide an added layer of protection against air and moisture. They come in many forms of thin plastic sheeting and spray on applications.	negligible	negligible	-section 14.4	

Air Gaps/ Vapor Gaps

Type	General Information and Fire Properties	Insulation properties	Average Thickness	Corresponding International Building Codes	Corresponding Green Building Codes
Wall Air Gap	Air gaps exist in many building elements from the way we build and may provide a small improvement in a building's thermal performance. Air gaps have a thermal resistance to heat flow that is represented by an R-Value with the optimum or best R-Value achieved for a gap of 30mm (about 1.1 inches). Wider air gaps do not achieve higher R-Values. To achieve higher Total R-Values, multiple air gaps must be incorporated into the building. For an air gap to improve the thermal performance of a building element, it requires the addition of a low emittance surface (shiny aluminium foil) to one or both sides of the air gap. Without the addition of the foil surfaces, the R-Value of the non-reflective air gap is small (R0.16).	The R-Value achieved by an air gap is dependent on the emittance of the surfaces on either side of the gap. A sample value of an air gap with a low emmitance surface on both sides is about R-.5 to.7	.5 inches to 1.1 inches		

Sheathing Materials					
Material	General Information				
Sheathing Materials	Exterior wall sheathings serve to enclose wood or metal-framed buildings and provide a surface for application of exterior claddings and finish materials. Gypsum-based sheathings are widely used in non-combustible construction. Excellent fire resistance and other performance attributes. Surface-reinforced with paper or a glass-fiber.				
Types of Gypsum-Based Sheathing	General Information and Fire Properties	Insulation properties	Average Thickness	Corresponding International Building Codes	Corresponding Green Building Codes
Paper-faced	-Fire resistant -Weather resistant -Adds to structural strength -When exposed to moisture for prolonged periods of time, the paper surface plies can separate or the paper can delaminate from the gypsum core. -If water is trapped in the core, it can soften or dissolve it.	R-value of 0.043	½" to 5/8" thick	Chapter 14.04	
Types of Gypsum-Based Sheathing	General Information and Fire Properties	Insulation properties	Average Thickness	Corresponding International Building Codes	Corresponding Green Building Codes
Glass-mat-faced gypsum sheathings	-Popular choice for non-combustible construction -Light weight -Provides increased mold resistance -Will with stand up to 12 months of exposure to typical weather conditions -Rely on the face layer for water resistance and strength. -Under prolonged exposure to moisture, the core can soften and degrade Susceptible to pull-off by lateral wind loads	R-value of 0.45	½" to 5/8" thick	Chapter 25.06	

Types of Gypsum-Based Sheathing	General Information and Fire Properties	Insulation properties	Average Thickness	Corresponding International Building Codes	Corresponding Green Building Codes
Gypsum/cellulose core-reinforced sheathing	-Does not rely on a surface layer for strength, fastener holding power or moisture resistance. -Stiffer than other gypsum-based sheathings, providing a flatter, smoother surface, even under high wind load conditions. -Can offer significant installed cost savings	R-value of 0.45	½" to 5/8" thick	Chapter 25.06	
Types of cement-Based Sheathing	General Information and Fire Properties	Insulation properties	Average Thickness	Corresponding International Building Codes	Corresponding Green Building Codes
Cement board panels	-Top choice moisture resistance -They will not rot or delaminate, bend or warp. -Panels are water-durable -Offer excellent racking and shear strength -Inelastic, making it sensitive to building movement from seismic and other sources.	R-Value of 0.043	½" to 5/8" thick	Chapter 19.11	

Types of cement-Based Sheathing	General Information and Fire Properties	Insulation properties	Average Thickness	Corresponding International Building Codes	Corresponding Green Building Codes
Fiber cement	-Excellent water durability -Typically more dense than cement board panels -Their greater mass makes them inelastic and brittle, and therefore more installation sensitive -Do not provide the level of fire resistance that cement panels offer.	R-value of 1.32	½" to 5/8" thick	Chapter 14.04	-Environmentally friendly
Types of wood-Based Sheathing	General Information and Fire Properties	Insulation properties	Average Thickness	Corresponding International Building Codes	Corresponding Green Building Codes
Wood sheathing	-Plywood or OSB (oriented strand board) -Offer excellent racking and shear strength -Wood-based sheathings work with the framing to resist wind -May swell, warp or rot when exposed to damp environments. -Provide little or no fire resistance	R-value of 1.25	½" to 5/8" thick	Section 14.04	-Environmentally friendly

Insulation Materials

Material	General Information				
Loose-Fill Insulation	Loose-fill insulation includes loose fibers or fiber pellets that are blown into building cavities or attics using special equipment. It generally costs more than batt insulation. However, it usually fills nooks and crannies easier, reduces air leakage better, and provides better sound insulation than batt-type insulation.				
Types of Loose Fill insulation	General Information and Fire Properties	Insulation properties	Average Thickness	Corresponding International Building Codes	Corresponding Green Building Codes
Cellulose fiber	Made from recycled newspapers, is chemically treated for fire and moisture resistance. It can be installed in walls, floors or attics using a dry-pack process or a moist-spray technique.	Cellulose fiber has approximately 30% more insulating value than loose-fill rock wool for the same number of inches installed.	Not applicable		
Fiberglass and rock wool	Provides full coverage with a "Blow-in Blanket" System (BIBS) that involves blowing insulation into open stud cavities behind a net.	Insulation value of R-3 to R-4 per inch	Not applicable		
Material	General Information and Fire Properties	Insulation Properties	Average Thickness	Corresponding International Building Codes	Corresponding Green Building Codes
Spray Foam	Spray foam insulation is a two-part liquid containing a polymer (such as polyurethane or modified urethane) and a foaming agent. The liquid is sprayed through a nozzle into wall, ceiling, and floor cavities. As it is applied it expands into a solid cellular plastic with millions of tiny air-filled cells that fill every nook and cranny. It is good for irregularly shaped areas and around obstructions.	Open-cell SPF has an R-value around 3.5 per inch and typically uses water as the blowing agent. Closed-cell SPF has an R-value of around 6.0 per inch (aged R-value) and uses high R-value blowing agents.	Not applicable	Chapter 26	

Material	General Properties					
Batt and Blanket insulation	Batt and blanket insulation is made of mineral fiber either processed fiberglass or rock wool and is used to insulate below floors, above ceilings, and within walls. Generally, batt insulation is the least expensive wall insulation material but requires careful installation for effective performance. This type of insulation is best suited to a standard joist, rafter, or stud spacing of 16 or 24 inches. Batts and blankets come in widths to fit securely between the wood-framing members. Some come with a radiant barrier backing. Batts generally come in lengths of 4 or 8 feet. Blankets come in long rolls that are cut to the desired length for installation. Both batts and blankets					
Types of Batt and Blanket insulation	General Information and Fire Properties	Insulation Properties		Average Thickness	Corresponding International Building Codes	Corresponding Green Building Codes
Fiberglass	Fiberglass is the most widely used batt insulation material. Made from molten glass, usually with 20% to 30% recycled industrial waste and post-consumer content. Nonflammable, except for the facing (if present). Sometimes, the manufacturer modifies the facing so that it is fire-resistant. Some fiberglass is unfaced, some is paper-faced with a thin layer of asphalt, and some is foil-faced.	R Value	Costs (cents/sq. ft)	Thickness (in)	-Section 14.04 -Section 26.12	-Environmentally friendly
		11	12-16	3 1/2		
		13	15-20	3 5/8		
		15	34-40	3 1/2 (high density)		
		19	27-34	6 to 6 1/4		
		21	33-39	5 1/4 (high density)		
		25	37-45	8 to 8 1/2		
		30 +	45-60	8+		
Rock wool	Usually made from rock (basalt, diabase) or iron ore blast furnace slag. Some rock wool contains recycled glass. Nonflammable.	3.125		1		
		11		3.5		
		19		6		
		34		11		

Material	General Information
Rigid Board Insulation	Rigid board insulation is commonly made from fiberglass, polystyrene, or polyurethane and comes in a variety of thicknesses with a high insulating value (approximately R-4 to R-8 per inch). This type of insulation is used for reproofing work on flat roofs, on basement walls and as perimeter insulation at concrete slab edges, and in cathedral ceilings.

Types of Rigid Board Insulation	General Information and Fire Properties	Insulation Properties	Average Thickness	Corresponding International Building Codes	Corresponding Green Building Codes
Fiberglass Boards	These are mainly used for acoustic applications, but can be found in certain forms that apply well to building applications.	R values	Thickness(in.)	Section 26.03 All Rigid board insulation must follow specific building codes. For interior applications it must be covered with 1/2-inch gypsum board or other building-code approved material for fire safety. For exterior applications it must be covered with weather-proof facing -	Environmentally friendly
		4	1		
		11	3		
		19	4		
		34	8.5		
Polystyrene boards	These boards can vary greatly in their makeup, but all have fairly high insulative properties. This includes EPS, MEPS, XPS, bead board, blue board, and Styrofoam.	3.6	1		
		11	3		
		19	5.5		
		34	9.5		
Polyurethane Boards	Produced through mixing of isocyanate and polyether in presence of catalyst and blowing agent. Contains many tiny, closed cells. Relatively waterproof, and low water absorption, but must protect from prolonged exposure to water. Can use underground if conditions are relatively dry.	6	1		
		11	2		
		19	3.1		
		34	5.6		

Polyisocyanate Boards (polyiso)	More stable at high temperatures and less flammable than polyurethane. Higher R-value vs. polystyrene and polyurethane due to its gas-filled closed-cell foam structure. Denser and more rigid than polystyrene panels, but more expensive. Must protect from prolonged exposure to water. It usually contains some recycled plastic, such as from PET beverage containers.	7	1		
		11	1.5		
		19	3		
		34	5		

Material	General Information and Fire Properties	Insulation Properties	Average Thickness	Corresponding International Building Codes	Corresponding Green Building Codes
Insulated concrete Forms (ICF)	Insulating concrete forms (ICFs) are forms for poured concrete walls, which remain as part of the wall assembly. This system creates walls with a high thermal resistance. Even though ICF homes are constructed using concrete, they look like traditional stick-built homes. ICF systems consist of interconnected foam boards or interlocking, hollow-core foam insulation blocks. Foam boards are fastened together using plastic ties. Along with the foam boards, steel rods (rebar) can be added for reinforcement before the concrete is poured.	Depending on variations in manufacturing and brand ICF's have a range of r values. The average value is typically about R-20.	Most ICF's incorporate 2" of foam insulation on both sides of the concrete wall. Average wall thicknesses range from as small as 8" to as big as 20"	-Section 26.03.5	Environmentally friendly

In order to gauge the range of wall thicknesses that will need to be accommodated in the 285 test rig, we complied a few wall assemblies and estimated their total thickness.

<u>Assembly Using Thickest materials from Catalog:</u>

*Assembly does not include non-combustible frame components

Assembly Component	Material	R-Value	Thickness
Cladding	Brick Masony Veneer	0.8	1.75”
Weather Resistive Barriers	Thickest WRB		0.433”
Air Gaps	Low Emittance Foil	0.6	1.1”
Sheathing	Fiber Cement	1.32	.5”
Insulation	Polystyrene Foam Board	18	5”
	Total	20.72	8.783”

Table 4.4.13 Calibration Gas Flow Rates (Based on Natural Gas)

	Room Burner				Window Burner			
Time Interval	SCFM	m^3/min	kW	Btu/min	SCFM	m^3/min	kW	Btu/min
0:00–5:00	38.0	1.08	687	39,064	0.0	0.00	0	0
5:00–10:00	38.0	1.08	687	39,064	9.0	0.25	163	9,252
10:00–15:00	43.0	1.22	777	44,204	12.0	0.34	217	12,336
15:00–20:00	46.0	1.30	831	47,288	16.0	0.45	289	16,448
20:00–25:00	46.0	1.30	831	47,288	19.0	0.54	343	19,532
25:00–30:00	50.0	1.42	904	51,400	22.0	0.62	398	22,616

Calibration Gas Flow Rate [3]

Table 7.1.11 Calibration Average Values for Time Periods Indicated

	Temperature											
Thermocouple Location and Numbers	0–5 min		5–10 min		10–15 min		15–20 min		20–25 min		25–30 min	
	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C
Test room ceiling: Nos. 18–22	1151	622	1346	730	1482	806	1600	871	1597	869	1648	898
Interior wall surface of test room: Nos. 15–17	1065	574	1298	703	1433	778	1578	859	1576	858	1655	902
1 ft (305 mm) above top of window opening: No. 2	602	317	870	466	952	511	992	533	1046	563	1078	581
2 ft (610 mm) above top of window opening: No. 3	679	359	1015	546	1121	605	1183	639	1245	674	1296	702
3 ft (914 mm) above top of window opening: No. 4	646	341	971	521	1096	591	1174	634	1245	674	1314	712
4 ft (1219 mm) above top of window opening: No. 5	577	302	858	459	982	528	1063	573	1135	613	1224	662
5 ft (1524 mm) above top of window opening: No. 6	521	272	765	407	875	469	949	509	1007	542	1106	597
6 ft (1829 mm) above top of window opening: No. 7	472	244	690	366	787	419	856	458	913	489	1010	543

Calorimeter Locations and Numbers	Heat Flux (W/cm^2) 0–5 min	5–10 min	10–15 min	15–20 min	20–25 min	25–30 min
2 ft (610 mm) above top of window opening: No. C–2ft	0.9 ± 0.2	1.9 ± 0.4	2.5 ± 0.5	2.9 ± 0.6	3.4 ± 0.7	3.8 ± 0.8
3 ft (914 mm) above top of window opening: No. C–3ft	1.0 ± 0.2	2.0 ± 0.4	2.6 ± 0.5	3.2 ± 0.6	3.7 ± 0.7	4.0 ± 0.8
4 ft (1219 mm) above top of window opening: No. C–4ft	0.8 ± 0.2	1.5 ± 0.3	2.0 ± 0.4	2.5 ± 0.5	3.0 ± 0.6	3.4 ± 0.7

Average Values for Time Periods of 285 Test [3]

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