Redesign of a Greenhouse to Withstand Snow Load in Paxton, Massachusetts

A Major Qualifying Project Submitted to the Faculty of
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Abstract

The goal of this project is to design a greenhouse that can support the snow load of Paxton, Massachusetts and be used for educational purposes at Turn Back Time Farm. This was accomplished by conducting simulations of the distributed snow load on the greenhouse frame. The computer program ANSYS was used to simulate stresses and deformation of the calculated load to determine if the greenhouse would be able to withstand the snow load. Additionally, a scaled-down model of the greenhouse was built in order to physically test the predicted snow load. In all testing and simulations, the greenhouse and the materials used were able to support the load resulting in a structurally stable design for the farm to utilize.

Chapter 1: Introduction

1.1 Turn Back Time Farm

Turn Back Time Farm is a non-profit nature based educational center located in Paxton, Massachusetts. The farm was born in 2010 from the minds of Lisa Burris and her husband Jim. Through her children, Lisa was able to recognize the effects of nature as a tool for growth and learning in kids. Turn Back Time's mission is to "help people recognize nature's ability to teach and heal with a commitment to offering programs to underserved populations."[1] They do this through the use of structured educational programs and unstructured exploration of the outside world. Turn Back Time offers programs for all ages, allowing parents to enroll their kids in drop-off preschool, homeschool, afterschool enrichment, or summer camp programming, or even signing up themselves to workshops or wellness gatherings. Most of the programs provided by the farm, since they are outdoor, are geared toward spring and summer whether. Once the cold winter weather enters New England there are limited options for programming on the farm. The greenhouse will serve as a way for children to learn about nature and the process of plant growth, regardless of weather (Turn Back Time Farm).

1.2 Problem Definition

Turn Back Time Farm wants a greenhouse for the purpose of educating children about nature during the winter so they are inside but still interacting with nature. The last one was designed and built in 2019 by another WPI team however, it succumbed to structural failure due to excessive snow load during the winter. The farm desires a new greenhouse that will be able to withstand the snow load, is smaller and does not require staff to manually clear snow off of it.

1.3 Project Goals

Our goal is to redesign and rebuild a greenhouse with the structural stability to withstand year-round weather conditions including heavy snow and wind. The greenhouse on Turn Back Time Farm is designed to educate children on the growing process and increase interaction with nature while they cannot be in a garden outside.

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[1] Turn Back Time Farm. (n.d.)

Chapter 2: Background Research

2.1 Greenhouse Redesign for Elementary Education Needs (G.R.E.E.N)

Previously, a group of six students at WPI designed a greenhouse for the same farm in order to provide an education space for youth programs during the winter. This project was called *Greenhouse Redesign for Elementary Education Needs (G.R.E.E.N.)* and was built in the school year 2018-2019. The trouble this team ran into with the greenhouse, however, is that the hoop house design that they implemented, was not the best design for handling the snow load of Massachusetts. During a heavy snow storm, snow piled up on the roof of the greenhouse, causing the greenhouse to collapse (Figure 1). This could be due to many factors of the way the greenhouse was designed or built.

Figure 1: Previous Greenhouse Collapse

The main reason the greenhouse failed to support the snow is because of the hoop house design the previous team implemented. The hoop design of the greenhouse is known to collapse under a heavy snow load because it easily collects on the top of the roof.[2] The snow will fall off the steep sides of the greenhouse but will accumulate on top, causing the covering to sag. Once it starts to sag, more snow can build up and collect in that area. Because of the excessive buildup of

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[2] Grubinger, V. (2014, December). Prevent Greenhouse Collapse.

snow on the roof, the structure of the greenhouse can no longer support the added weight and collapses (Figure 2). One way to ensure it does not collapse with this design is to manually clear the snow from the roof after every snowfall. This method is not feasible for the farm since it snows a great deal in New England and would be too much work for a small farm.

Figure 2: Snow Accumulation and Collapse

Other factors that could have played a part in the collapse of the greenhouse was the glazing material the previous team chose, and the snow load calculations they performed. Due to budget constraints, the material used was a single layer of polyethylene film. Unfortunately, it ended up sagging when the snow accumulated in certain locations on the roof. If the material was sturdier it may not have sagged, preventing the greenhouse from collapsing. Additionally, the team's snow load calculations did not account for the accumulation of snow on the roof due to the sagging of the material. This underestimation of the potential force applied to the greenhouse structure opened it up to failure and ultimately collapse.

Any one of these three reasons could be why the greenhouse failed, or it could be a combination of the three. The important part is that we learn from it and make the necessary corrections. This can be done by choosing a design that allows the snow to fall off on its own, choosing a sturdier covering material, or even adjusting the calculations to account for buildup of snow in sagging areas. In our project, we take all three of these into account to maximize the stability and success of the greenhouse.

2.2 Greenhouse Standards

The legal definition of a greenhouse is "a Group U occupancy structure with a glass or plastic roof and frequently glass or plastic walls. The structural frame is made of aluminum, galvanized steel, or redwood. It is used for the production of fruits, vegetables, flowers, and any other plants requiring special temperature conditions."[3]

Under Massachusetts state building codes, allowable dimensions for Group U buildings are given in Table 1 below. The first row of the table indicates the type of construction based on building materials. A construction with noncombustible building elements is classified as Type I and II. Type III buildings have noncombustible exterior walls and any allowed material for interior walls. Type IV buildings also have noncombustible exterior walls, but the interior walls are either solid or laminated wood without concealed spaces. Finally, Type V buildings have exterior and interior walls of any allowed material. The second row of Table 1 further specifies the type of construction. Type A is the most fire resistant, and Type B is less so. There is no additional fire rating in Type A, but some non-combustibles are used in the construction of Type B.

Table 1: Allowable Dimensions for Group U Buildings[4]

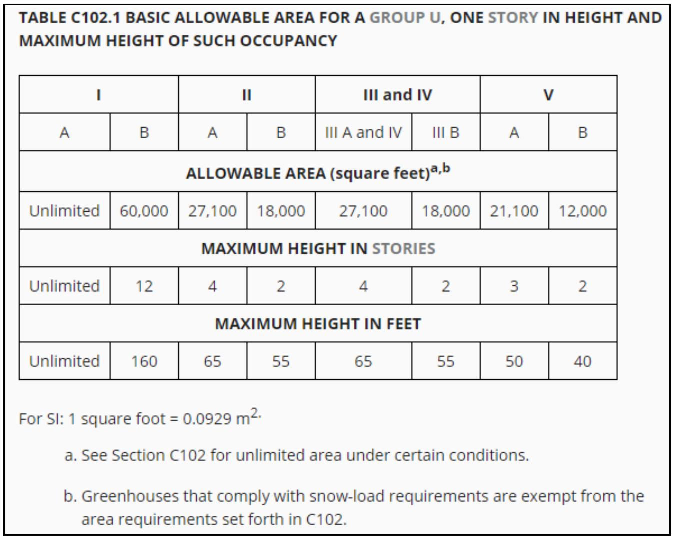

TABLE C102.1 BASIC ALLOWABLE AREA FOR A GROUP U, ONE STORY IN HEIGHT AND MAXIMUM HEIGHT OF SUCH OCCUPANCY

I		II		III and IV		V	
A	B	A	B	III A and IV	III B	A	B
ALLOWABLE AREA (square feet)^{a,b}							
Unlimited	60,000	27,100	18,000	27,100	18,000	21,100	12,000
MAXIMUM HEIGHT IN STORIES							
Unlimited	12	4	2	4	2	3	2
MAXIMUM HEIGHT IN FEET							
Unlimited	160	65	55	65	55	50	40

For SI: 1 square foot = 0.0929 m^2.

a. See Section C102 for unlimited area under certain conditions.

b. Greenhouses that comply with snow-load requirements are exempt from the area requirements set forth in C102.

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[3] Department of public works. Building code manual: Greenhouse not for public use.

[4] Department of public works. Building code manual: Greenhouse not for public use.

For our project, we will be using Type IB for the building group of our greenhouse. This is because the elements we will be building with are made from aluminum or steel, which is non combustible. Additionally, the material covering the greenhouse is polyethylene, which is a highly combustible material unless it is treated with a fire retardant chemical. This would make the entire structure less flame resistant even though the frame of the greenhouse is noncombustible. Resulting in our greenhouse being classified as IB with an allowable area of 60,000 ft^2, 12 stories maximum, and maximum height of 160 ft.

2.3 Greenhouses on Local Farms

In order to get a better understanding of functional and successful greenhouses in the greater Worcester area, we asked local farms about theirs. Specifically, we wanted to know the style and design of the greenhouse, the materials chosen, and how the farm dealt with snow on the greenhouse. Two farms we were able to get into contact with were Cotyledon Farm and Brookfield Farm.

2.3.1 Cotyledon Farm

Cotyledon Farm is located in Leicester, Massachusetts and has two different greenhouses with two different designs. Their greenhouses are utilized in the winter for extending the growing season of multiple plants. One of the greenhouses is a high tunnel from Nolt's Greenhouse Supplies in Pennsylvania, which is of the gothic style (Figure 3). This greenhouse requires snow removal with a broom when the snow is particularly heavy or sticks to the greenhouse. When the sun is strong, the snow will usually melt and slide right off.

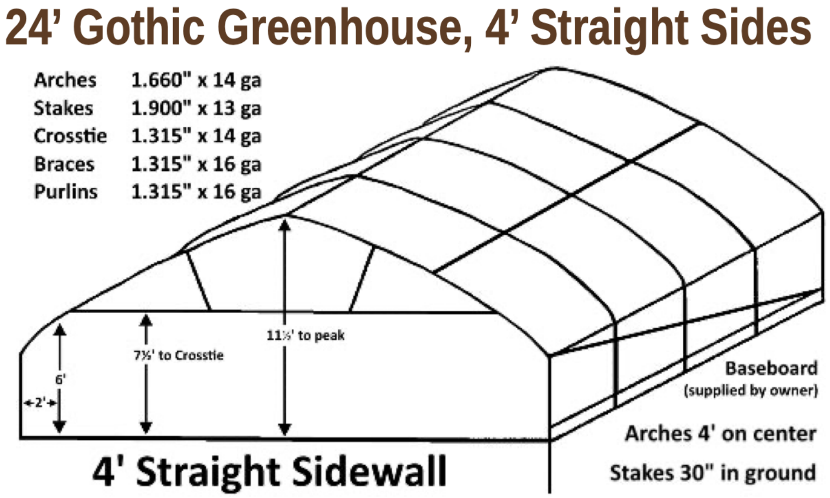

Figure 3: Gothic Greenhouse Designed by Nolt's Greenhouse Supplies[5]

The second is a heated greenhouse that is a half round caterpillar greenhouse (Figure 4) and requires support on the ridge line for the snow load in the winter. This style was not their ideal choice because of the additional support required but was used on the farm because the frame was donated to them. Polycarbonate is used on the end walls of each of the greenhouses due to its sturdiness and ability to let light pass through. The covering is an inflated double layer of plastic because it is significantly cheaper than polycarbonate and easier to install due to its flexibility. This is especially beneficial since both greenhouses have a design with a curve to it that the plastic sheets can easily form to.

Figure 4: Half Round Caterpillar Type [6]

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[5] Nolt's Greenhouse Supplies. (n.d.).
[6] Caterpillar Tunnel. (n.d.). Retrieved October 07, 2020

2.3.2 Brookfield Farm

Brookfield Farm is located in Amherst, Massachusetts and has several different greenhouses that are used for various purposes (Figure 5). These include storage of different machines and tools, growing of plants in the ground, and one specially used to nurture seedlings in their specific environment. The majority of the greenhouses on this farm are of the gothic style with a peaked roof. The peak in the greenhouse roof helps with the snow load, since most of the snow will fall off the slope of the greenhouse. Typically, the farm does not need to clear any of the snow off the top of the greenhouses; however, when the snow is either super heavy or there are multiple snowstorms in a week, manual removal of the snow is needed. One of the greenhouses on the farm is heated during the winter, which helps melt the snow off the roof and aids with the snow loads. The covering of these greenhouses are all the same standard greenhouse film from Nolts Farm in Pennsylvania. The average size of their greenhouses is 30 ft wide by 96 ft long, which is larger than our target dimensions. Finally, the greenhouses are all grounded through stakes in the ground. These stakes are about 3 ft into the ground and 2 ft above the ground with ribs in it so the metal poles of the greenhouses can be attached to the stakes. This is all very insightful information from the farm for reference when we build our own greenhouse.

Figure 5: Greenhouses at Brookfield Farm[7]

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[7] Brookfield Farm. (n.d.). Retrieved October 13, 2020,

Chapter 3: Design

3.1 Functional Requirements

The following functional requirements were taken into consideration when designing the greenhouse for Turn Back Time Farm. These were made and agreed upon both by the team and by Lisa Burris for Turn Back Time Farm.

- Functional during all seasons
- Able to withstand any and all weather conditions, particularly snow and wind
- Resistant to rot/deterioration
- Able to absorb sunlight (direction of greenhouse and material)
- Large enough to be a learning environment with kids and teachers inside
- Follow all standards set for greenhouses

3.2 Greenhouse Design Options

Our team proposed two design options to Turn Back Time and chose which one was most beneficial to build. The two options we were between were a post and-rafter design and a gothic arch design.

3.2.1 Post and Rafter Design

Post and rafter is one of the most common greenhouse structures due to its simple design. It is also one of the strongest, with the rafter providing additional support and reinforcing the strength of the roof. This is beneficial to our project since we are focused on making sure the greenhouse is able to support the snow load in Massachusetts. The slanted roof will also help the snow slide off the structure instead of building up to create more pressure on the structure. Additionally, it has the potential for maximized space and air circulation. The downside is that it requires more materials than other designs due to the need for a footed frame, granting it a higher material cost.[8] Our preliminary model is shown in Figure 6 below and consists of a triangular roof on top of a rectangular base, a very simple design.

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[8] Understanding Greenhouse Structures - Gothic Arch Greenhouses - Blog. (2016, August 07).

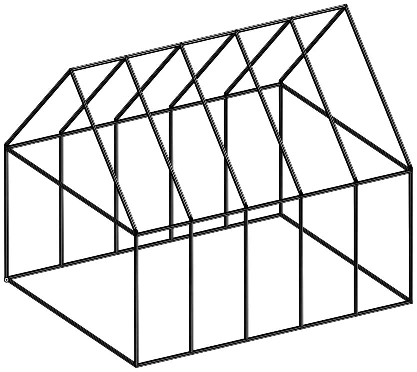

Figure 6: Preliminary Design of the Post and Rafter Greenhouse

3.2.2 Gothic Greenhouse Design

The gothic arch design is renowned for a variety of reasons, primarily its structural integrity even in conditions of strong wind or heavy snowfall. The roof's half-teardrop shape allows for easy water and snow runoff, preventing damage from excessive build-up of precipitation. This technique also removes the need for structural trusses, lowering the material cost of the structure as well as construction time. The design also benefits from its adequate heat conservation and more overhead space along the middle of the greenhouse. The tradeoff is that the curve of the arch results in lower heights at the sidewall, which could affect headroom and available space along the sides.[9] Figure 7 depicts our preliminary model of the gothic design.

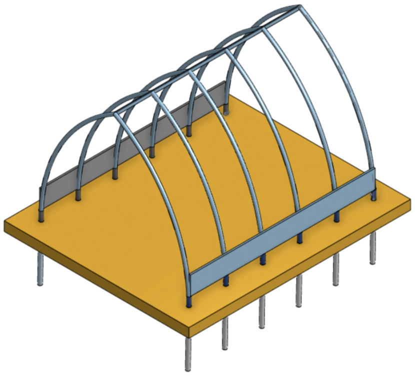

Figure 7: Preliminary Design of the Gothic Greenhouse Design

3.2.3 Comparison of Designs

The two designs have both their advantages and disadvantages which are outlined in Table 2 below. Both options have a good number of advantages and both are considered better

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[9] 5 Benefits of a Gothic Arch-Style Greenhouse - Gothic Arch Greenhouses - Blog. (2017, October 05)

than the hoop house at supporting snow load. The biggest advantage to the post and rafter design is the simplicity of the design and how it can be built easily without having to bend poles. A post and rafter greenhouse could also be assembled with cylindrical aluminum poles, but we opted to use square extrusions instead. The square extrusions have t-slot channels where connectors can be screwed in to connect two extrusions together. This allows the greenhouse to be assembled and disassembled very easily in case adjusting is needed. The main disadvantage of the gothic arch design is that it would require us to bend the poles at specific angles, and each pole would have to be identically bent so that it was structurally stable. Additionally, at the top of the structure, connectors would be needed to connect the top ridge pole to the outer ones. The connectors shown in Figure 8 below are what would need to be used. However, because of the bent poles, these connectors would need to be custom-made to fit the angles the poles produced, which would be difficult and expensive to find or make ourselves. Because of the complexity of building the gothic greenhouse, our team chose to pursue the post and rafter design instead of the gothic arch.

Table 2 : Comparison of the Post and Rafter to the Gothic Arch Design

Post and Rafter		Gothic Arch	
Advantage	Disadvantage	Advantage	Disadvantage
Simple design means it is easy to build	Need to buy all new materials	Easy water and snow runoff	Arches must have identical bends
Can be disassembled and reassembled	Need to cut the extrusions to the correct length	Can use parts (long poles) donated to the farm	Will need to buy a pipe bender to bend pipes ourselves
Easy water and snow runoff	Lots of parts needed for joining	Conserves heat	Difficult to build
No custom built parts needed will make it less expensive			Lower height at sidewall (from arch) affects headroom
Maximizes space and air circulation			Custom parts needed to join make it more expensive

Figure 8: Connectors for Top of Gothic Arch Greenhouse

3.3 Post and Rafter Design Elements

3.3.1 Materials Used

For the frame, we chose to use metal extrusions instead of wood because Turn Back Time Farm was worried about the moisture and humidity rotting and deteriorating the wooden framework of the structure. Aluminum 6105-T5 was selected as the material of these metal extrusions because it is inexpensive and commonly used in greenhouse frames. The aluminum t-slot extrusions (Figure 9) selected for this build include a channel for easy connection between two of the extrusions. There are two options for width of the square extrusions, 30mm x 30mm and 20mm x 20mm. Turn Back Time Farm preferred to use the 30mm x 30mm extrusion because it is stronger and can hold the weight of snow or wind load better.

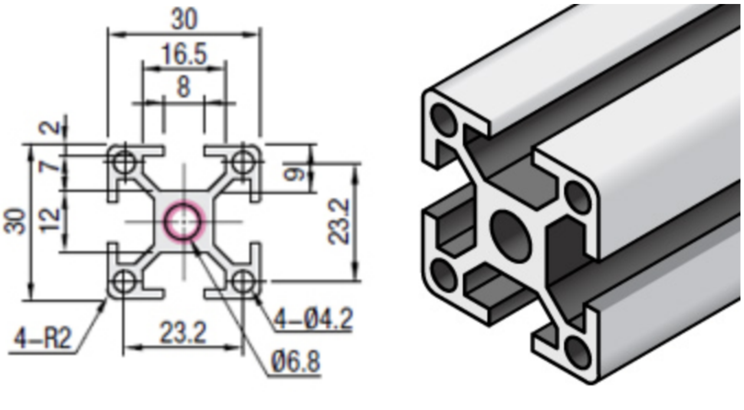

Figure 9: Aluminum T-slot Extrusion[10]

These extrusions are connected by brackets that go through the channels of the frame and screw into the inside of the extrusion. There are multiple connectors for the frame depending on

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[10] 30x30 Aluminum Extrusion - 6 Series, Base 30 (MISUMI). (n.d.).

what angle they should be connecting. The most simple is the inner L bracket (Figure 10), which is used when the frame is connected at a 90° angle. Another connector is used on the top rail of aluminum that connects the angled roof together. This end corner bracket (Figure 11) can connect three of the extrusions, and two of these are needed, with one at either end of the top rail. The final connector our team is using is the pivot joint (Figure 12), which is for connecting the angled roof extrusions to the top rail on the sides of the frame. This joint can be positioned at any angle and can be connected to the ends of the extrusion or even the middle of it. All these joints are included in the bill of materials (Table 3).

Figure 10: Inner L Bracket[11]

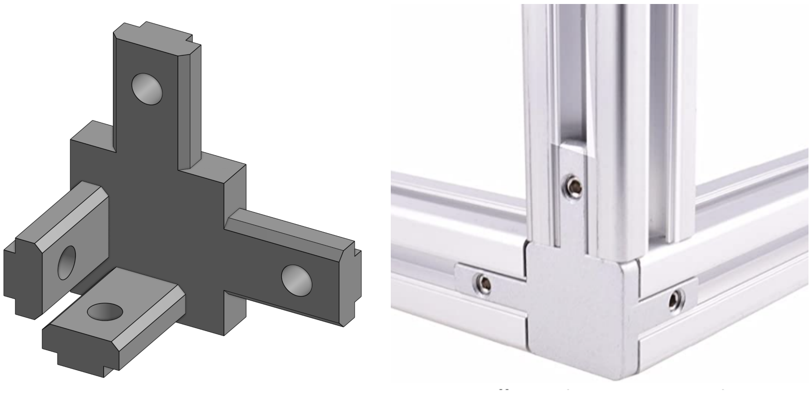

Figure 11: End Corner Bracket[12]

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[11] Boeray Inner L Bracket for European Standard 3030 Series Aluminum Extrusion Profile Slot 8mm- Interior Joint.

[12] PZRT 4-Pack 3030 Series 3-Way End Corner Bracket Connector, with Screws for Standard 8mm T Slot Aluminum Extrusion Profile.

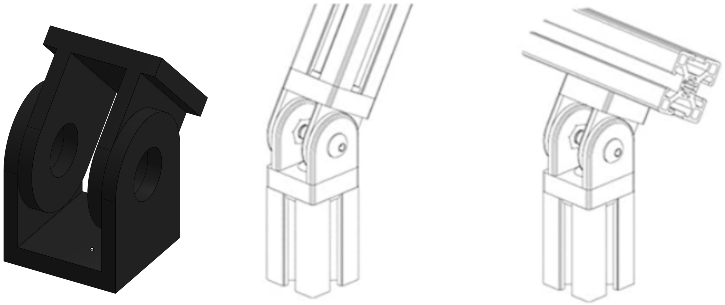

Figure 12: Angle Connectors[13]

For the covering of the greenhouse, our team chose to use polyethylene film. We chose this covering because of the relative inexpensiveness but effectiveness of the material. When comparing polyethylene and polycarbonate options on Amazon.com, polyethylene was 16 times cheaper.[14] [15] Polyethylene is translucent, allowing sunlight transmission while providing adequate heat retention for productive plant growth. The plastic film can be attached in a single or double layer along the frame. By installing a double layer of the film, it creates a higher ability to resist heat transfer and cuts down on heating costs. The other options for greenhouse coverings are polycarbonate panels and glass which are more effective at preventing heat transfer but more expensive.[16] In order to attach the film to the greenhouse, a wiggle wire is used inside of a polylock channel (Figure 13). The channel is attached to the frame by self-tapping screws along the extrusion. The parts of the frame that will have the polylock channel attached to it are highlighted in orange in Figure 14.

Figure 13: Wiggle Wire and Rail[17]

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[13] Amazon 2020. Boeray 2pcs Die-Cast Zinc Alloy Pivot Joint for Aluminum Extrusion Profile 3030 Series, Flexible Pivot Joint for 3030 Aluminum Profile.

[14] Amazon 2020. Macrolux Polycarbonate Greenhouse Cover 4mm - Clear.

[15] Amazon 2020. A&A Green Store Greenhouse Plastic 4 Year 6 mil Film Clear Polyethylene Cover UV Resistant.

[16] Grubinger, V. (2014, December). Prevent Greenhouse Collapse.

[17] Poly Lock Channel and Spring Wire Greenhouse Film Fastening System - 6 ft.

Figure 14: Area of the Frame that Needs Channel and Wiggle Wire

The final cost of all the materials is presented in Table 3 below. The total cost is around $1,500 which is a very reasonable price for a greenhouse, as it typically costs about $25 per square foot for a mid-sized commercial greenhouse,[18] meaning a greenhouse of this size would cost around $3,125. Our minimalistic approach of using only the essentials produced a very cost-effective solution.

Table 3: Post and Rafter Greenhouse Bill of Materials

10ft x 12.5ft Post and Rafter (3030)				
Part	Quantity	Unit Cost	Cost	Notes
Aluminum frame	100m	$44 for 4m	$1,100	Aluminum T-slot extrusion for the frame
Inner L bracket	112	$17 for 16	$119	Connector for extrusions at 90 degree angles
End corner bracket	2	$17 for 4	$17	Connection for the top and angled extrusions
Pivot joint	16	$18 for 2	$144	Connector for extrusions not 90 degrees
Polyethylene	400 ft²	$66 for 16ft x 25ft	$66	Covering of the greenhouse
Wiggle wire & rail	150ft	$6.20 for 6ft	$155	To attach the polyethylene to the frame
3/4" self tapping screw	200	$9.56 for 100	$19.12	To screw the wiggle wires into the frame
Butt hinge & screws	2	$15 for 2	$15	Connector for door onto frame
Door handle & screws	2	$11 for 2	$11	Door handle
Total:			$1,646	

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[18] Allied Buildings. How Much Does It Cost to Build A Commercial Greenhouse?

3.3.2 Ventilation

During the summer, heat from the sun will be trapped inside the greenhouse making it uncomfortable for anyone inside and the plants optimal growing temperature. In order to decrease the temperature inside the greenhouse, proper ventilation is required. The most efficient way is to have vents both along the bottom for cooler air to enter and small ones at the top through which the hot air can leave from. The surface area of ventilation inside the greenhouse should cover ⅕ to ⅙ of the floor area. Since our team's greenhouse floor area is 125ft² this would mean that 21-25ft² should be the area of ventilation. Our greenhouse is designed to include the option of having half the back wall be able to roll up and the front door open so that air can circulate. This would total to about 20ft² from the back wall and 18ft² from the door if it is open which is more than adequate for ventilation of the green house. Additionally, a fan can be installed in the front wall to manually move the air through the greenhouse and out the back end.[19]

3.3.3 Heating

The greenhouse needs heating in the winter for it to be operational during all seasons to grow plants and be a learning space for kids. Optimal growing temperatures range from 35℉ to 85℉, and for people the most comfortable temperature would be around 68℉ to 70℉. There are many options for heating the structure including, natural gas, LP gas, fuel oil, wood, and electricity.[20] Heating will most likely be done with propane gas heaters, as that is the method the farm currently uses for their other facilities and agreed to have on the last greenhouse.

The covering our team chose, polyethylene, has a relatively low resistance to heat flow (R value) at 0.8 $K*m^2/W$. Because of the low R value, the greenhouse will have high heat flow into and out of the structure. One way to increase the R value, and therefore, decrease the heat flow is to use a double layering of polyethylene which will make the heating more efficient and less money will be lost on it.[21]

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[19] Center for Sustainable Building Research, University of Minnesota. Cold-climate-greenhouse-resource.pdf. (n.d.)

[20] CSBR, University of Minnesota. Cold-climate-greenhouse-resource.pdf. (n.d.)

[21] Chappell, M., Worley, J., & Thomas, P. (2010, June 01). Georgia Green*A*Syst: Environmental Checklist for Nurseries, Greenhouses and Turfgrass Producers

3.4 Calculations

The two weather conditions that would have the greatest impact on the greenhouse are snow and wind. We came to this conclusion as they are included in the Massachusetts building codes. Therefore, calculations and simulations were conducted to ensure the design was structurally sound.

3.4.1 Snow Load

To determine the snow load on a roof, the flat roof snow load must be found first. This is done using the equation $p_f = 0.7C_eC_tI_sp_g$, where C_e is the exposure factor, C_t is the thermal factor, I_s is the importance factor, and p_g is the ground snow load.[22] In our case, since the greenhouse is in a wooded area with numerous closely spaced obstructions, it falls under Terrain B sheltered, which has an exposure factor of 1.2 (Table 4). Since we plan on the greenhouse being continuously heated, the thermal factor for it will be 0.85 (Table 5). Importance factor is 1.0 because that is the most common case. According to Chapter 16 of Massachusetts' structural design building code, Paxton, MA averages a ground snow load of 50 lb/ft^2.[23] The calculations of the flat roof snow load are shown below and results in a 35.7 lb/ft^2 load.

$$p_f = 0.7C_eC_tI_sp_g$$

$$p_f = (0.7) \times (1.2) \times (0.85) \times (1.0) \times (50\frac{lb}{ft^2})$$

$$p_f = 35.7\frac{lb}{ft^2}$$

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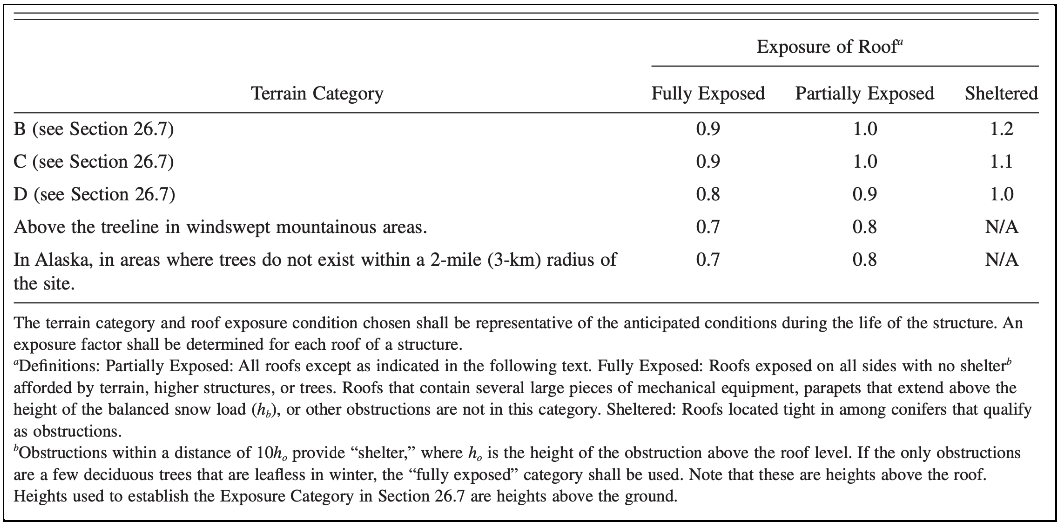
[22] Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-10). (2013)

[23] State Board of Building Regulations and Standards (MA). (2017, October 20)

Table 4: Exposure Factor, C_e[24]



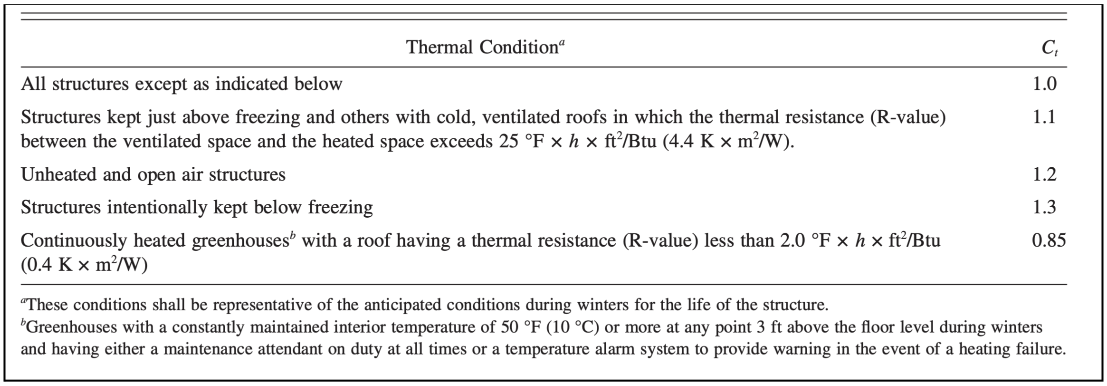
	Exposure of Roof[a]		
Terrain Category	Fully Exposed	Partially Exposed	Sheltered
B (see Section 26.7)	0.9	1.0	1.2
C (see Section 26.7)	0.9	1.0	1.1
D (see Section 26.7)	0.8	0.9	1.0
Above the treeline in windswept mountainous areas.	0.7	0.8	N/A
In Alaska, in areas where trees do not exist within a 2-mile (3-km) radius of the site.	0.7	0.8	N/A

The terrain category and roof exposure condition chosen shall be representative of the anticipated conditions during the life of the structure. An exposure factor shall be determined for each roof of a structure.

[a] Definitions: Partially Exposed: All roofs except as indicated in the following text. Fully Exposed: Roofs exposed on all sides with no shelter[b] afforded by terrain, higher structures, or trees. Roofs that contain several large pieces of mechanical equipment, parapets that extend above the height of the balanced snow load (h_b), or other obstructions are not in this category. Sheltered: Roofs located tight in among conifers that qualify as obstructions.

[b] Obstructions within a distance of $10h_o$ provide "shelter," where h_o is the height of the obstruction above the roof level. If the only obstructions are a few deciduous trees that are leafless in winter, the "fully exposed" category shall be used. Note that these are heights above the roof. Heights used to establish the Exposure Category in Section 26.7 are heights above the ground.

Table 5: Thermal Factor, C_t[25]



Thermal Condition[a]	C_t
All structures except as indicated below	1.0
Structures kept just above freezing and others with cold, ventilated roofs in which the thermal resistance (R-value) between the ventilated space and the heated space exceeds 25 °F × h × ft²/Btu (4.4 K × m²/W).	1.1
Unheated and open air structures	1.2
Structures intentionally kept below freezing	1.3
Continuously heated greenhouses[b] with a roof having a thermal resistance (R-value) less than 2.0 °F × h × ft²/Btu (0.4 K × m²/W)	0.85

[a] These conditions shall be representative of the anticipated conditions during winters for the life of the structure.

[b] Greenhouses with a constantly maintained interior temperature of 50 °F (10 °C) or more at any point 3 ft above the floor level during winters and having either a maintenance attendant on duty at all times or a temperature alarm system to provide warning in the event of a heating failure.

The next step is to substitute the flat roof snow load value into the sloped roof snow load equation. This equation is $p_s = C_s * p_f$, where C_s is the roof slope factor and p_f is the flat roof snow load from the above calculations. The roof slope factor can be determined using the graph below (Figure 15). As can be seen by this graph, portions of curved roofs with a slope exceeding 70° have a C_s of zero, and if the slope is 5° or below, it is considered a flat roof and assigned a C_s of 1. The slope of the greenhouse our team is building is 45° which is in between the 30° and 70° roof slope on the graph. In order to find the correct roof slope factor for the greenhouse, the team

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[24] Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-10). (2013)

[25] Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-10). (2013)

interpolated between the two points where we knew both the angle and the factor (30°,1) and (70°,0) shown on the graph in Figure 15.

$$\frac{C_s - 1}{45-30} = \frac{0-1}{70-30}$$

$$C_s = 0.625$$

$$p_s = C_s p_f$$

$$p_s = 0.625 \times 35.7 \frac{lb}{ft^2}$$

$$p_s = 22.3125 \frac{lb}{ft^2}$$

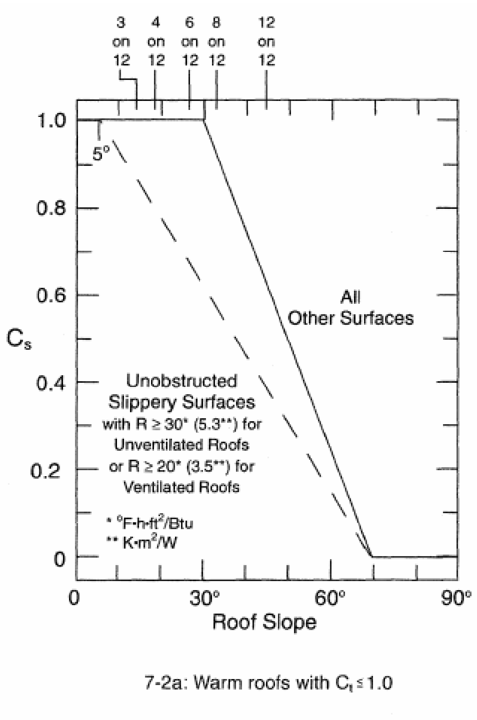

Figure 15: Roof Slope Factor Graph

This force p_s is applied as a distributed load on the structure to analyze if the material can withstand the snow load. It is first converted into a distributed load by multiplying the force by the roof's surface area, in square feet. The force is then structurally analyzed on the beams to find the moment about the grounded point on the left hand side of the structure (Figure 16). The moment is then used to find the stress applied from the load which is compared to the maximum stress the frame material can handle. The stress the load caused is around 21.6 kPa which is well under the maximum allowable stress of 181 MPa.

$$\text{Distributed Load: } 22.3125\frac{lb}{ft^2} * 12.5\,ft = 278.875\frac{lb}{ft}$$

$$\text{Point Force: } P = 278.875\frac{lb}{ft} * 14.2ft = 3960.025lb$$

$$\Sigma F_y = 2F - 3960.025lb = 0$$

$$F_y = 1980.0125lb$$

$$\Sigma M_A =- 976.06(2.5) - 976.06(5) - 976.06(7.5) - 488.03(10) + 1980.0125(10) + M_A = 0$$

$$M_A = 17533.575lb * ft$$

$$\sigma = \frac{M*y}{I} = \frac{19521.2*0.04921}{2.1282} = 451.39\frac{lb}{ft^2} = 21.61265kPa$$

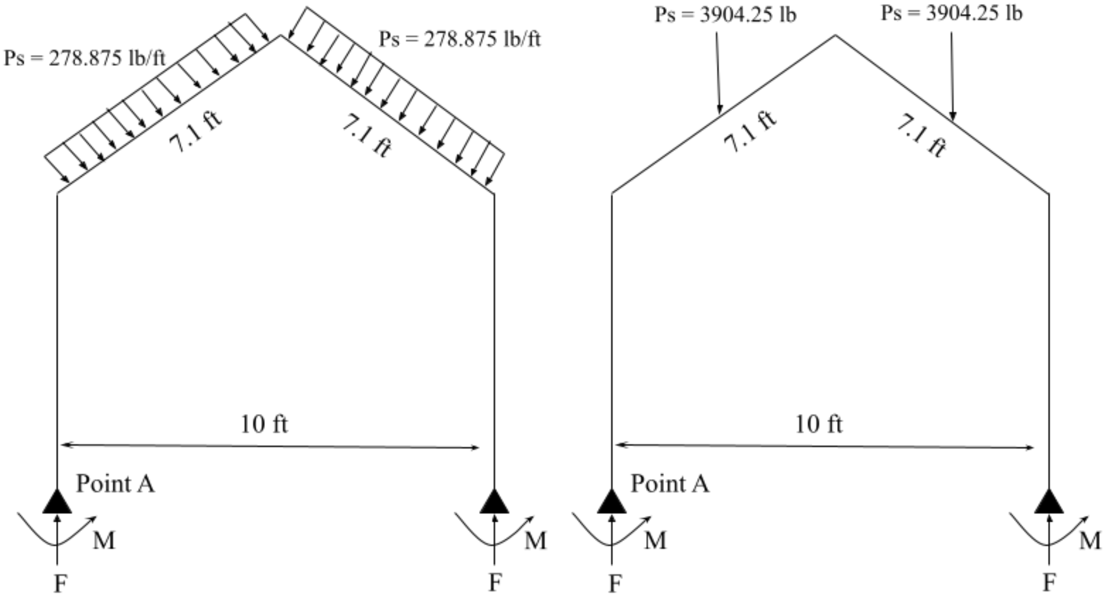

Figure 16: Schematic of Structurally Analyzed Greenhouse

Below are a series of ANSYS simulations displaying the three most important effects of snow load on the post and rafter frame: total deformation (Figure 17), elastic strain (Figure 18), and equivalent stress (Figure 19). The distributed load of 22.3125 lb/ft^2 was applied to the frame across the area of the greenhouse roof pointing in the negative z-direction, and the underside of the greenhouse base was set as fixed.

$$Young's\ Modulus = E = \frac{stress}{strain} = \frac{\sigma}{\varepsilon}$$

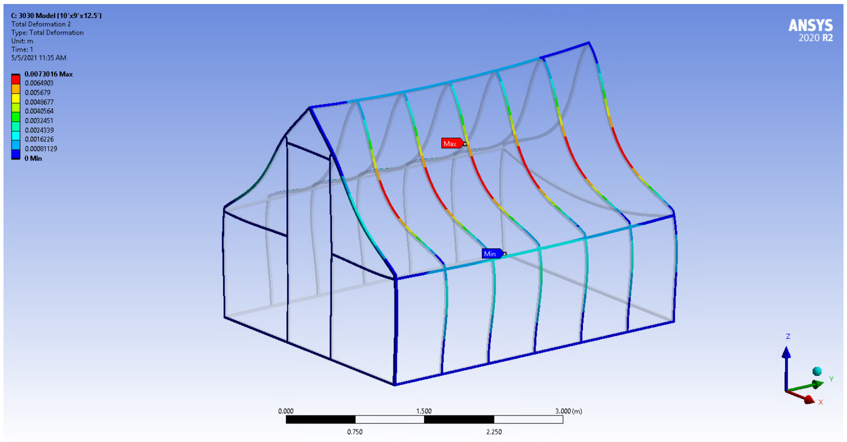

Figure 17: Total Deformation due to Snow Load

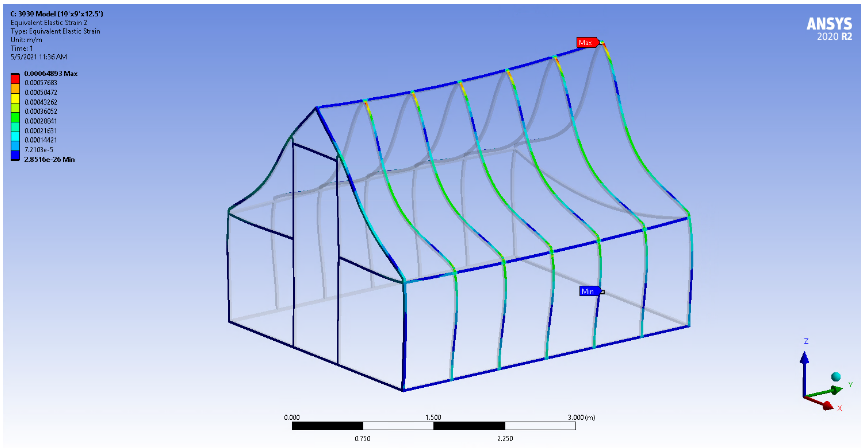

Figure 18: Elastic Strain due to Snow Load

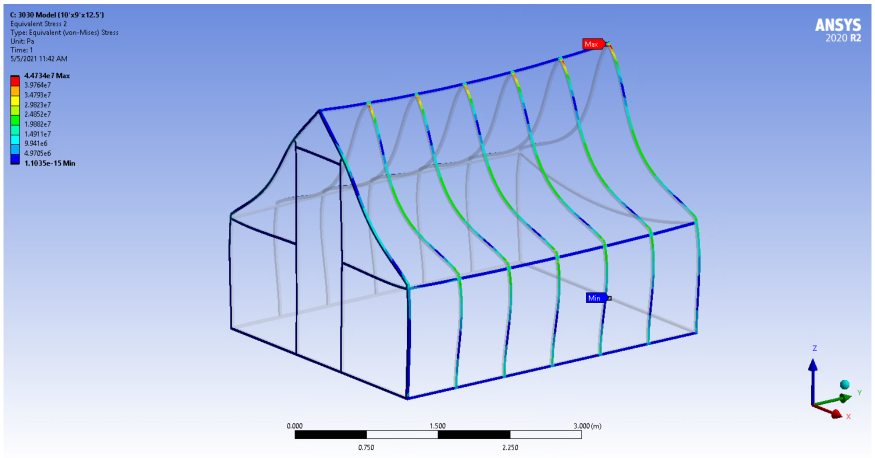

Figure 19: Equivalent Stress due to Snow Load

The largest deformation occurred at the midpoints of the diagonal roof beams. This deformation is exaggerated in the above figures to better visualize where the deformation is occurring. From the simulations, the deformation was found to be only about 0.2cm, and the equivalent stress at these points, about 34.7MPa, was well below the point of plastic deformation of 181.91MPa. The greatest points of stress occurred just below the peak of the roof, but this value of 69.5MPa was also well within parameters. The static stress-strain curve of the material used in this simulation can be seen in Figure 20. The parameters are termed "engineering" as the curve is based on a constant original cross-section and gauge length. The elastic strain was miniscule as well, having a maximum of only 0.001.

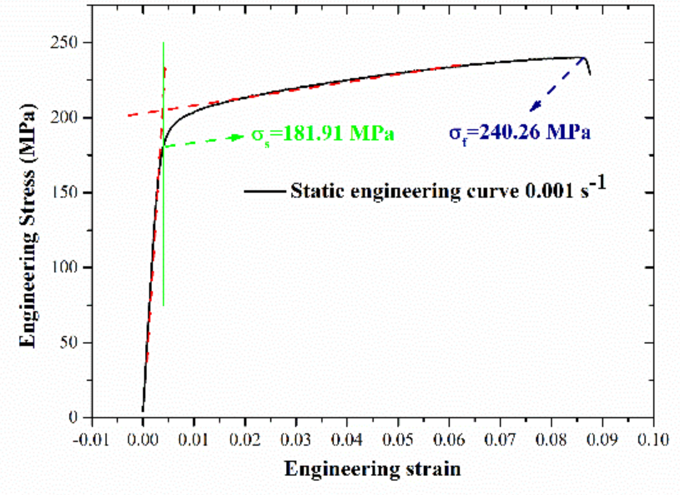

Figure 20: Theoretical Stress-Strain Curve of A6N01S-T5 Aluminum Alloy[26]

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[26] Dynamic experimental studies of A6N01S-T5 aluminum alloy material and structure for high-speed trains.

A nodal analysis was also performed on the structure to determine if the bolts in the joints were able to withstand loads from snow or wind. The part of the structure that was analyzed was the view from the front of the greenhouse and these nodes were analyzed using the software ANSYS. The structure was modeled with the 3D beam element type and the same real constants the aluminum extrusion would also have. These include the cross-sectional area of 900 mm^2, an elastic modulus of 68.9 GPa, a poisson's ratio of 0.33, and a moment of inertia of 0.01837 m^2 which was found on the website providing the aluminum extrusion. Once the frame was modeled in the software, boundary conditions were added to the bottom two nodes of the frame. This can be seen in Figure 21 where the blue triangles are attached to the part of the greenhouse that would be placed in the ground. The distributed load was applied to one of the beam structures out of the seven that are included in the frame (Figure 21). This load was a structural pressure on the slanted beams of the greenhouse modeled as the roof. The value of the pressure load applied to the frame was the snow load our team calculated from the ground snow load in Paxton, multiplied by the ratio of the total surface area multiplied by the aluminum extrusion surface area.

$$\text{Pressure Load: } 22.3125\frac{lb}{ft^2} * \frac{100}{6.82} = 327\frac{lb}{ft^2} = 15,600\frac{N}{m^2}$$

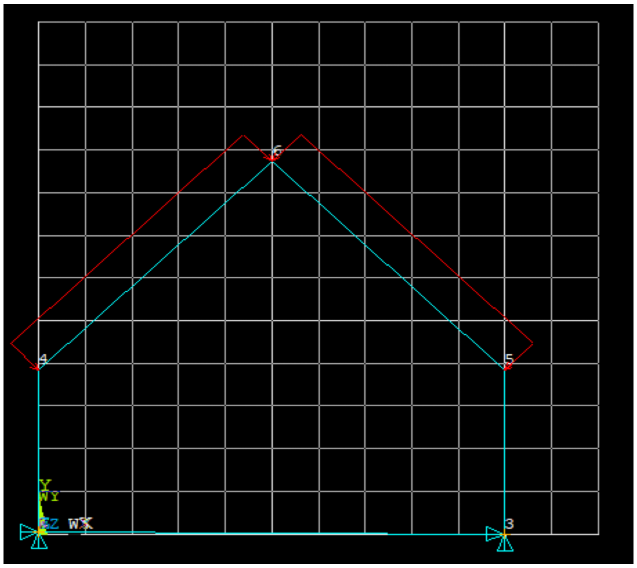


Figure 21: Loads on Greenhouse Frame

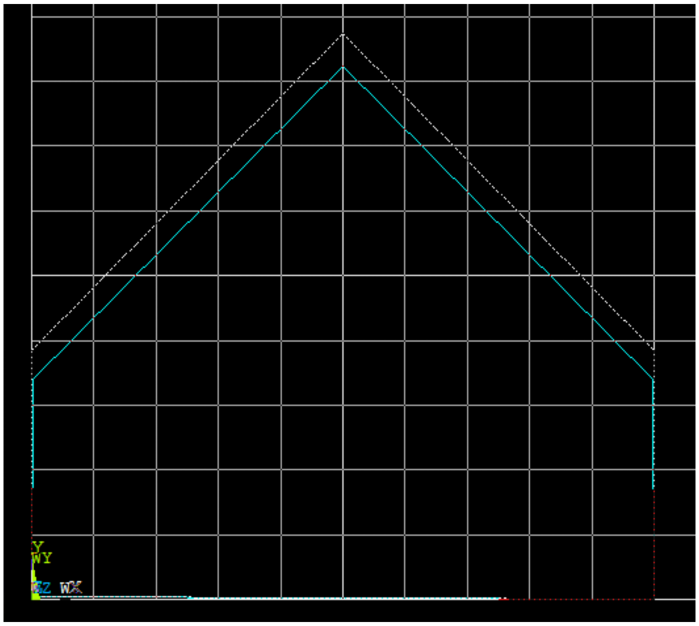
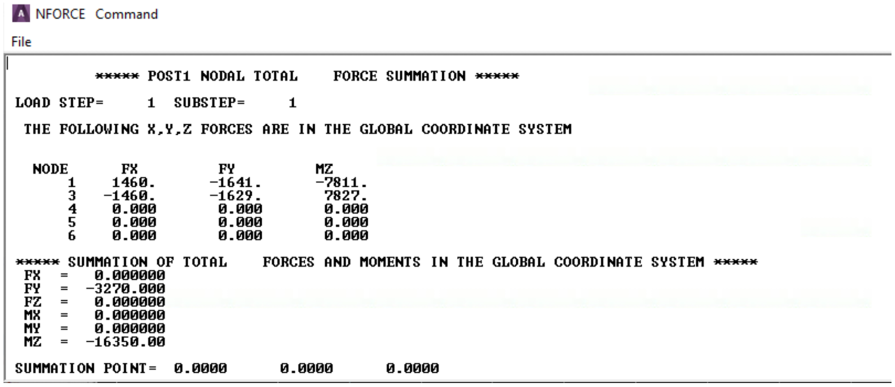


Figure 22: Deformed Shape After Snow Load

The deformed shape in Figure 22 shows the result of applying the pressure load on the structure. Then the structure was analyzed at the nodes to determine the sum of forces applied at each node (Figure 23). These values were then compared to the maximum allowable stress of the connectors at the nodes of the greenhouse. The material of the both the pivot joint and the L-bracket was die cast zinc alloy whose yield strength is 40*10^3 psi or 276 MPa.[27] The measured forces at every node were well below both yield strengths with the highest force being 7827psi or 53.97 MPa. These simulations using ANSYS determined that the material at the joints will not fail due to the snow load because the force is under its yield strength.



```
         ***** POST1 NODAL TOTAL    FORCE SUMMATION *****

LOAD STEP=     1  SUBSTEP=     1

 THE FOLLOWING X,Y,Z FORCES ARE IN THE GLOBAL COORDINATE SYSTEM


  NODE       FX          FY          MZ
     1     1460.       -1641.      -7811.
     3    -1460.       -1629.       7827.
     4     0.000        0.000       0.000
     5     0.000        0.000       0.000
     6     0.000        0.000       0.000

***** SUMMATION OF TOTAL    FORCES AND MOMENTS IN THE GLOBAL COORDINATE SYSTEM *****
 FX  =   0.000000
 FY  =  -3270.000
 FZ  =   0.000000
 MX  =   0.000000
 MY  =   0.000000
 MZ  =  -16350.00

SUMMATION POINT=  0.0000      0.0000      0.0000
```

Figure 23: Nodal Reaction Forces after Load

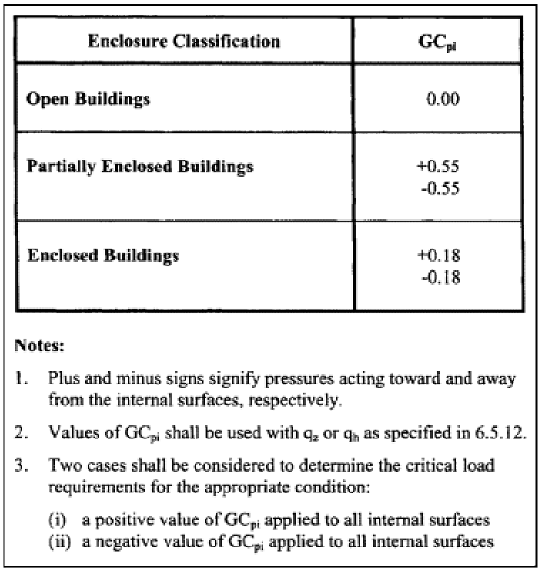
---

[27] *Zinc Diecasting Alloys Mechanical Properties*. Zinc Die Casting. (2016, December 13).

3.4.2 Wind Load

According to the Massachusetts structural design building code mentioned previously, in Paxton, a wind speed of 112 mph is considered risk category one, 122 mph is risk category two, and 133 is risk category three or four.[28] There are many factors to consider when calculating wind load, consequently, the method for finding it is not a simple one and many equations are used to find the wind load. The final equation is $p = q_h \times [GC_{pf} - (\pm\ GC_{pi})]$. Where p, which is what is being calculated, is the wind pressure and q_h is wind velocity pressure which is found through a different equation described below. GC_{pf} is the product of the gust effect factor and equivalent external pressure coefficient which produces a different value for each face of the building. Finally, GC_{pi} (found in Table 6) is the product of the gust effect factor and internal pressure coefficient.

Table 6: GC_{pi} Values[29]



Enclosure Classification	GC_{pi}
Open Buildings	0.00
Partially Enclosed Buildings	+0.55 -0.55
Enclosed Buildings	+0.18 -0.18

Notes:

1. Plus and minus signs signify pressures acting toward and away from the internal surfaces, respectively.
2. Values of GC_{pi} shall be used with q_z or q_h as specified in 6.5.12.
3. Two cases shall be considered to determine the critical load requirements for the appropriate condition:
   (i) a positive value of GC_{pi} applied to all internal surfaces
   (ii) a negative value of GC_{pi} applied to all internal surfaces

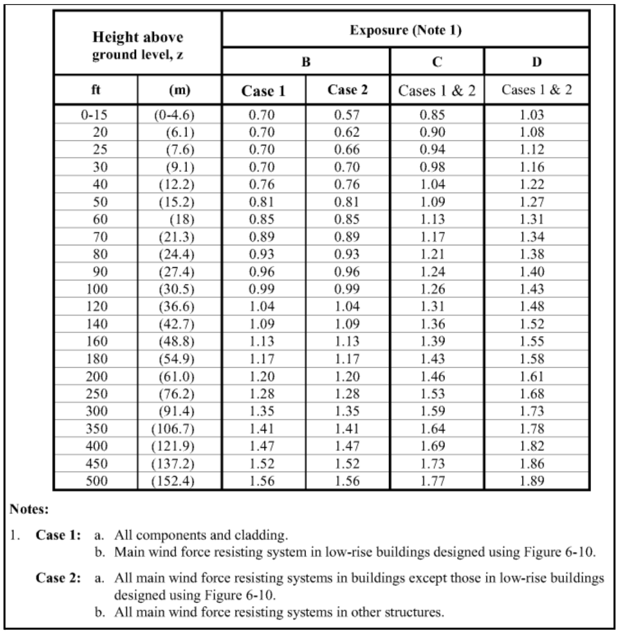
To find the velocity pressure the equation $q_h = 0.00256 K_h K_{zt} K_d V^2 I$ is used, where K_h (from Table 7) is the velocity pressure exposure coefficient evaluated at height h, K_{zt} is the topographic factor (see appendix A), K_d (from Table 8) is the wind directionality factor, V is the wind speed, and I is the importance factor (from Table 9).

---

[28] State Board of Building Regulations and Standards (MA). (2017, October 20)

[29] ASCE Standards 7-05, Figure 6-5.

Table 7: Velocity Pressure Exposure Coefficient (K_h) Values[30]



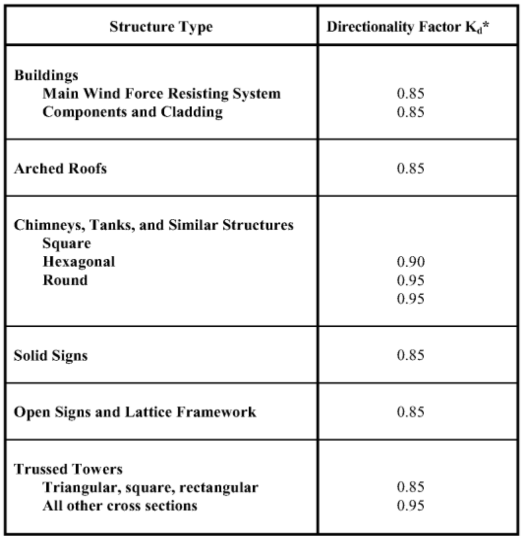
Height above ground level, z		Exposure (Note 1)			
		B		C	D
ft	(m)	Case 1	Case 2	Cases 1 & 2	Cases 1 & 2
0-15	(0-4.6)	0.70	0.57	0.85	1.03
20	(6.1)	0.70	0.62	0.90	1.08
25	(7.6)	0.70	0.66	0.94	1.12
30	(9.1)	0.70	0.70	0.98	1.16
40	(12.2)	0.76	0.76	1.04	1.22
50	(15.2)	0.81	0.81	1.09	1.27
60	(18)	0.85	0.85	1.13	1.31
70	(21.3)	0.89	0.89	1.17	1.34
80	(24.4)	0.93	0.93	1.21	1.38
90	(27.4)	0.96	0.96	1.24	1.40
100	(30.5)	0.99	0.99	1.26	1.43
120	(36.6)	1.04	1.04	1.31	1.48
140	(42.7)	1.09	1.09	1.36	1.52
160	(48.8)	1.13	1.13	1.39	1.55
180	(54.9)	1.17	1.17	1.43	1.58
200	(61.0)	1.20	1.20	1.46	1.61
250	(76.2)	1.28	1.28	1.53	1.68
300	(91.4)	1.35	1.35	1.59	1.73
350	(106.7)	1.41	1.41	1.64	1.78
400	(121.9)	1.47	1.47	1.69	1.82
450	(137.2)	1.52	1.52	1.73	1.86
500	(152.4)	1.56	1.56	1.77	1.89

Notes:

1. **Case 1:** a. All components and cladding.
   b. Main wind force resisting system in low-rise buildings designed using Figure 6-10.

   Case 2: a. All main wind force resisting systems in buildings except those in low-rise buildings designed using Figure 6-10.
   b. All main wind force resisting systems in other structures.

Table 8: Wind Directionality Factor (K_d) Values[31]



Structure Type	**Directionality Factor K_d***
Buildings	
Main Wind Force Resisting System	0.85
Components and Cladding	0.85
Arched Roofs	0.85
Chimneys, Tanks, and Similar Structures	
Square	0.90
Hexagonal	0.95
Round	0.95
Solid Signs	0.85
Open Signs and Lattice Framework	0.85
Trussed Towers	
Triangular, square, rectangular	0.85
All other cross sections	0.95

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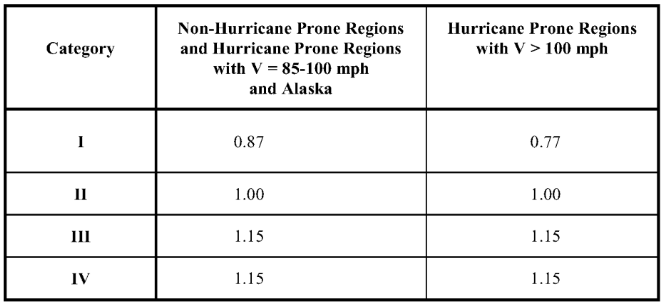
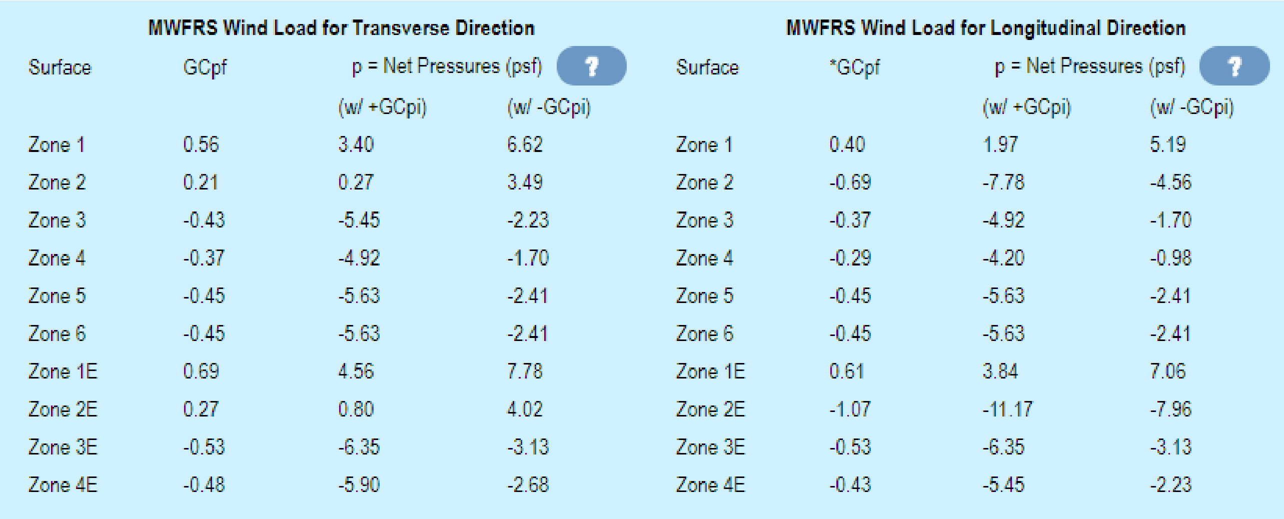
[30] ASCE Standards 7-05, Table 6-3.
[31] ASCE Standards 7-05, Table 6-4.

Table 9: Importance Factor (I) Values[32]



Category	Non-Hurricane Prone Regions and Hurricane Prone Regions with V = 85-100 mph and Alaska	Hurricane Prone Regions with V > 100 mph
I	0.87	0.77
II	1.00	1.00
III	1.15	1.15
IV	1.15	1.15

By both referencing the ASCE Standards 7-05 and substituting all the known values into an online calculator [33], a set of results was able to be found for the wind load on each face of the greenhouse. For the detailed values placed in the online calculator, see Appendix B. The results produced from the calculator are shown in Figure 24 and are all below the wind load limit of 10 psf for winds in both the transverse and longitudinal directions. Also because of the firm foundation of the greenhouse into the ground, the structure should be able to withstand winds of the speed without being blown over.



MWFRS Wind Load for Transverse Direction

Surface	GCpf	p = Net Pressures (psf) (w/ +GCpi)	p = Net Pressures (psf) (w/ -GCpi)
Zone 1	0.56	3.40	6.62
Zone 2	0.21	0.27	3.49
Zone 3	-0.43	-5.45	-2.23
Zone 4	-0.37	-4.92	-1.70
Zone 5	-0.45	-5.63	-2.41
Zone 6	-0.45	-5.63	-2.41
Zone 1E	0.69	4.56	7.78
Zone 2E	0.27	0.80	4.02
Zone 3E	-0.53	-6.35	-3.13
Zone 4E	-0.48	-5.90	-2.68

MWFRS Wind Load for Longitudinal Direction

Surface	*GCpf	p = Net Pressures (psf) (w/ +GCpi)	p = Net Pressures (psf) (w/ -GCpi)
Zone 1	0.40	1.97	5.19
Zone 2	-0.69	-7.78	-4.56
Zone 3	-0.37	-4.92	-1.70
Zone 4	-0.29	-4.20	-0.98
Zone 5	-0.45	-5.63	-2.41
Zone 6	-0.45	-5.63	-2.41
Zone 1E	0.61	3.84	7.06
Zone 2E	-1.07	-11.17	-7.96
Zone 3E	-0.53	-6.35	-3.13
Zone 4E	-0.43	-5.45	-2.23

Figure 24: Wind Load Calculation Inputs and Results[34]

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[32] ASCE Standards 7-05, Table 6-1.

[33] Wind load calculator, https://www.buildingsguide.com/calculators/structural/ASCE705W/.

[34] Wind load calculator.

3.5 Final Design

Originally the farm wanted a greenhouse that fit 15 children, which the 2019 team estimated would require an area of at least 525 ft^2. The farm realized after it was built that a greenhouse of that size was unnecessary and hard to maintain. As a result, the size of this greenhouse was scaled back considerably compared to the 2019 team's, going from a 24'x24'x12' design to a 10'x12.5'x9' design. This creates an area of 125ft^2 on the base of the greenhouse which is enough room for about 4 children. Additionally, this will grant room for 2-ft benches on either side of a 4-ft wide aisle, which allows enough space for it to be used for educational purposes.

This new greenhouse design also shifted away from the hoop house structure. Instead, the post and rafter style was examined after taking into consideration the impact heavy snow loads had on the previous design. This structure shape allows snow to slide off the surface more readily due to the peaked roof, preventing the accumulation of snow on the roof.

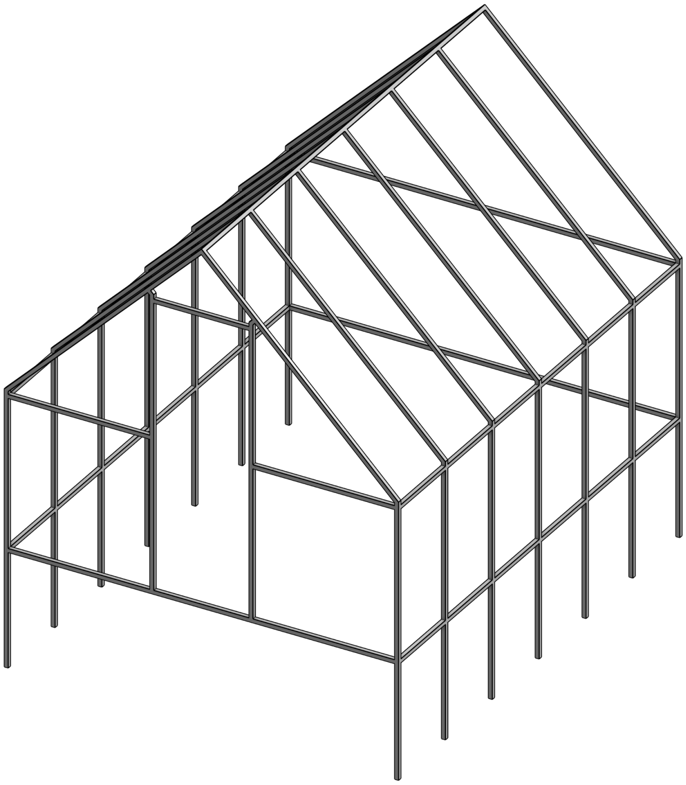

Figure 25: Final Post and Rafter Design Model

Chapter 4: Verification of Design

4.1 Scaled-Down Model

Before building the full-size greenhouse at the farm, we decided it would be best to build a smaller model at WPI and perform tests on it to verify the structural integrity of the design. Then an instruction manual would be prepared so that the farm could build the structure on its own or a new MQP team could build it for them, this manual can be found in Appendix C. This will give added reassurance that the greenhouse will be able to withstand any loads that it would experience at the farm, particularly snow load. The model (Figure 26) is one third the size of the model created for the farm and measures 3.4'x 4.1'x 2.8'.

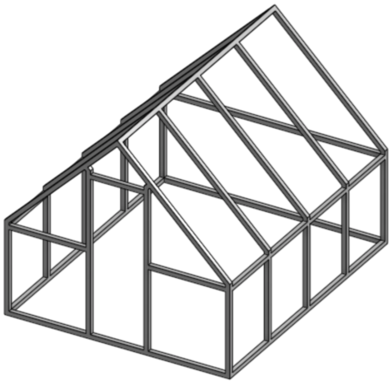

Figure 26: Scaled Down Greenhouse Model

If wind load were to be tested, the scaled down greenhouse would be grounded via aluminum extrusions buried approximately one foot into the ground, compared to the three feet we were planning on inserting the extrusions into the ground. The area which makes up the ground for this simulation would be made up of a raised garden bed filled with dirt and concrete. Planter wall blocks would make up the corners and wood would make up the walls of the bed (Figure 27).

Figure 27: Raised Garden Bed with Planter Wall Blocks

4.2 Snow Load Simulation

To test the strength and durability of the aluminum extrusions which make up the greenhouse frame during Massachusetts winter conditions, thin-film strain gauges (Figure 28) will be attached to the points of the structure that are expected to be under the most strain when supporting snow. According to the ANSYS snow load simulation, those points would be located just below the peak of the roof.

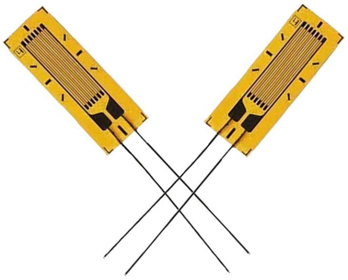

Figure 28: Thin-film Strain Gauge[35]

Testing will involve depositing snow or some similar substance in controlled amounts on top of the roof of the scaled down version of the original greenhouse model. This will continue until the snow load reaches the previously calculated value of 22.3125 lb/ft^2, which is the maximum value this greenhouse is expected to support. The deformation of the greenhouse will then be observed to make sure it will not collapse and can still function as a proper greenhouse.

4.3 Wind Load Simulation

If the wind load on the greenhouse were to be tested, extreme wind conditions of 112 mph or more would be applied. In order for this to be accurate, a wind tunnel which could blow three times that speed would have to be used on the one-third scale model. Each side of the greenhouse would be tested, with the response of the greenhouse to the high wind speeds being observed and recorded. Because winds in Massachusetts come predominantly from the west, the results of this experiment will determine the best orientation for the greenhouse. Additionally, this test would make sure the greenhouse is firmly grounded and will not blow over if the wind speeds were to reach hurricane level. Our team, however, did not have the resources or budget to perform this test so we relied on the computer software simulation results of the wind load.

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[35] Culler Strain Gauge Used in Mechanics Experiment for Material, Industry or Science

Chapter 5: Assembly

The building of the greenhouse was accomplished over the course of roughly five weeks. There were some difficulties the team had to overcome in order to successfully complete the frame. We built it in a different way that we would recommend. The most efficient way to build it is found in the instructions in Appendix C and is what we sent to Turn Back Time Farm in case they want to build the greenhouse on their own. The inefficiencies in our building process were identified and taken into account when writing up the final building instructions.

Our first step was preparation where we cut the aluminum extrusions from their bulk order of 4m into the smaller lengths that were needed for the greenhouse model. We had 7 extrusions total and we cut them to get the most use out of the extrusions. The lengths of each extrusion we cut are depicted in the bar graphs below in Figure 29. We had about 3m of extrusion left over in case we cut some wrong or more was needed for another use.

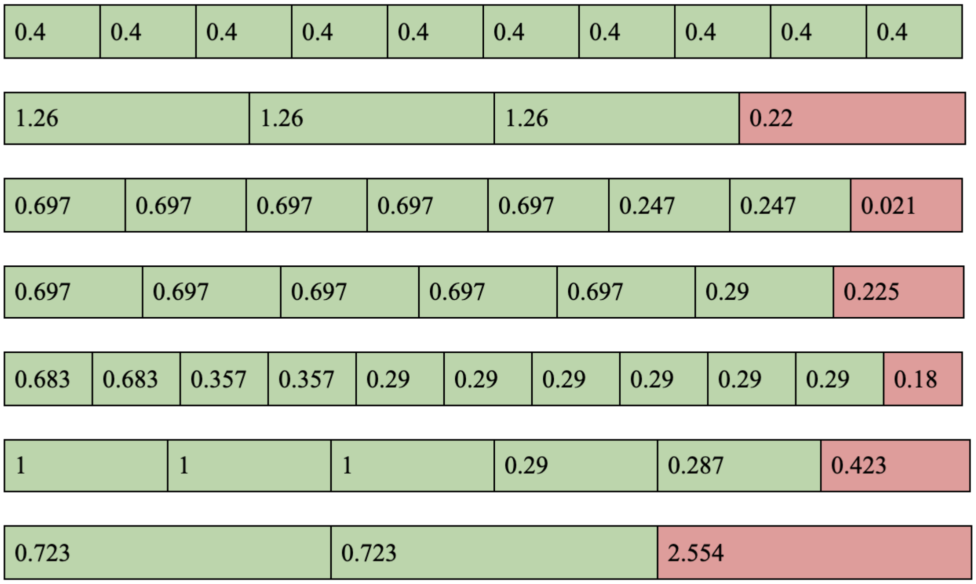


Figure 29: Lengths of Cut in Each Aluminum Extrusions

On the first day of building we successfully installed the base, sides, and door frame of the greenhouse. This was done through laying out the configuration and inserting L-brackets between the extrusions. We quickly realized it was important which side of the bracket was being inserted into the extrusions and made sure to note which side was in the extrusion. After the brackets were inserted, they were tightened with an allen wrench. Care had to be taken when tightening the screws as overtightening would strip the inside of the screws and the Allen wrench would not be able to remove it anymore. Once the sides were done, the top was added by sliding eight brackets into the bottom of each bar and positioning them over the vertical side extrusions. The back and the front were connected to the ends of the side extrusions to create a corner, and then the door frame was connected to the base extrusion. Here, we learned to put the brackets inside the base before connecting it to the sides or else the door would have nothing to connect to. After the first day, the frame had four sides and the frame for a door.

Figure 30: Greenhouse Frame after Day One of Building

On the second day, we tried to connect the angle brackets on top of the side of the frame and realized that they were not exactly the perfect solution for our need of a connection for non 90 degree angles between extrusions. On one base of the connector, there are four small metal bits meant to fit on to the end of an extrusion, which was fine for our design. However, on the other end there were only two (which is what we needed), but they were in the wrong direction with the pivot motion being parallel to the side of the greenhouse instead of perpendicular. To solve this first problem, we used a file to shave off the two nubs to create a flat base and then drilled a screw into the side extrusion to secure half the connector to the frame. To do this we had to take off the entire top side extrusion so that we could secure it then drill holes and screws to fasten the connector in the extrusion. Once we did this, our second problem was that the screw extended into the slot on the opposite side of the extrusion, blocking the path for sliding the L-brackets in the slow. For this we used another thinner file and used it to grind down the tip of the screw so that it was not sticking out anymore and the bracket could slide through. Once that was completed, the sides were again attached to the vertical bars of the frame in the same process as above, so the greenhouse looked like Figure 31.

Figure 31: Greenhouse Frame after Day Two of Building

The next thing that we had to assemble for the greenhouse was the roof. We took the roof peak extrusion and inserted eight inner L brackets into two adjacent sides of it. The brackets were facing alternating ways for three pairs and an additional one was inserted facing the inside on each end. We slid all ten extrusions into the brackets in the one long roof peak beam and tightened them loosely so we could move them around, since they would not be perfectly where they were supposed to. Then we placed the top of the greenhouse onto the base, however it was not secured instead it rested on the angle connector which was precarious. At this point we decided we needed a more secure connection between the two pieces and we brainstormed different ways to do so. We decided that we would order smaller and longer screws to drill into the end of the extrusion to secure the connector and extrusion together.

Figure 32: Greenhouse Roof after Day Three of Building

On the fourth day, we removed the ten slanted roof extrusions from the greenhouse, and disconnected half of each angle connector from its counterpart. By disconnecting the beam we could clamp it down in a vice so it would not turn while drilling. We then drilled a hole into the small hole at the end of the extrusion's profile using a 6/32" drill bit and then drilling a self tapping screw into the new hole. This was done because the screw was unable to fit into the original extrusion hole when drilled by itself. Care had to be taken to ensure the drill did not go too far, as to leave a smaller diameter for the screw to hook into (no more than ¾ the length of the screw). However, at the same time, ensure to not drill the hole too short or else the screw would be unable to work its way far enough into the hole to be flush with the angle connector later. Once the angle connectors were attached to the profile of the extrusion by screw, we took the ten roof pieces and attached them back to the roof peak extrusion and reconnected the angle connectors with their counterparts located on the top of the side walls. We then built the door by attaching the four pieces for the door in a rectangle and put it aside. Finally, we filed off two metal bits of the last two angle connectors that would sit on top of the door and hold the roof frame up.

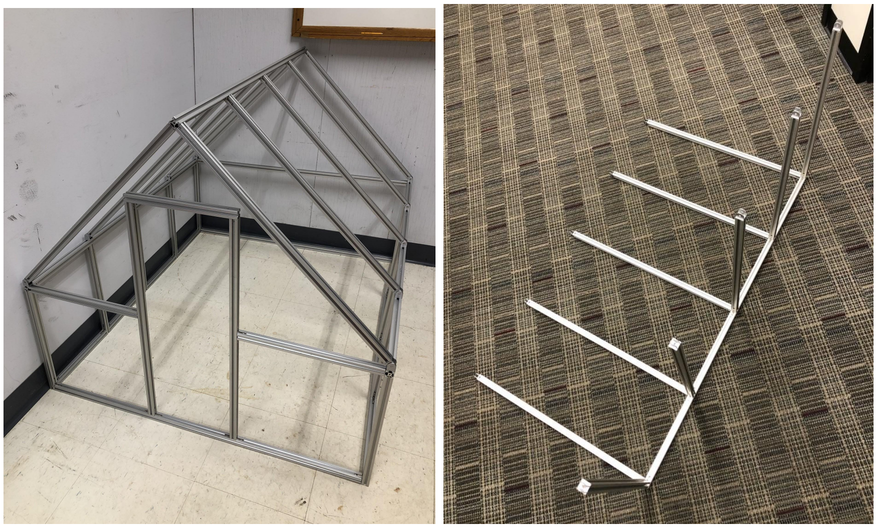


Figure 33: Greenhouse Frame after Day Four of Building

The next day, we added supports on top of the door frame and also attached the door and handle to the frame with butt hinges. First, to drill the angle connectors into the top of the outer door frame we had to take the top door frame extrusion off so we could secure it while drilling. The angle connector part with the wider base opening was then drilled into the opposite ends of the extrusion, as the connector's counterpart can hold the roof in place without needing a screw.

The angle connector was put in place and the hole location was marked in pencil. A small pilot hole was drilled all the way through the extrusion at the marking and a self tapping screw was inserted through the angle connector base hole and drilled into the pilot hole. We then filed down the screw that was sticking through the other end so that the L-Bracket could slide through the slot still. The beam, now with two angle connectors on top, was then attached back to the outer door frame. Next, we assembled the door with L-Brackets and four extrusions in a rectangle and attached the door to the frame with butt hinges. We did not account for tolerances of the door on the frame when deciding the extrusion length and the door ended up not being able to close properly. We recommended a 3mm change in the door length to the farm if they decide to build it on their own so the door can properly close. We placed drop-in T-nuts into the slot of the door and door frame extrusion, put screws into the butt hinge, and screwed them tightly into the T-nuts. We then put a handle on the outside of the door using the same method with the drop-in T-nuts as before. It might be easier to assemble the door frame separately before it is connected to the entire frame and then attach the door and handle to the frame so that it does not have to be assembled while it is standing up like how we did it.

Figure 34: Greenhouse Frame after Day Five of Building

Finally, since some corners did not allow for inner L brackets, we attached some outer corner brackets instead. We placed two drop-in T-nuts into the slot, put the corner bracket into position, screwed in two hex screw bolts with an Allen wrench until tight, and repeated for each of the ten corners. The bottom four corners on the ground were doable leaving the greenhouse as is, but we had to lift the frame and place the back face of the greenhouse on the floor to do the two roof peak corners and four corners just below pivot joints.

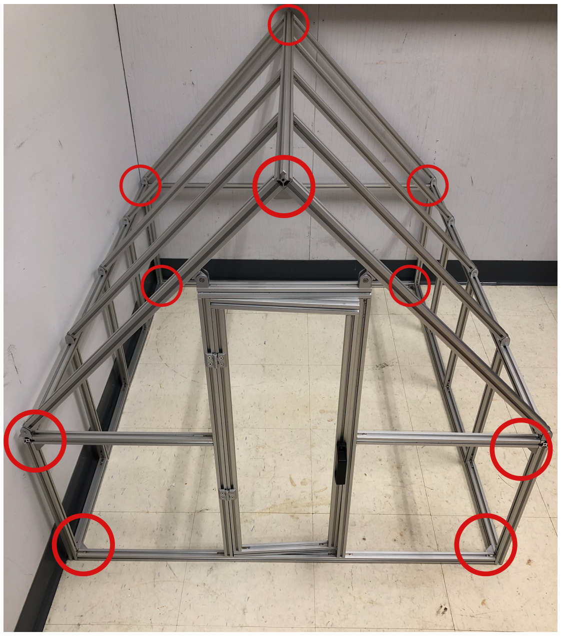
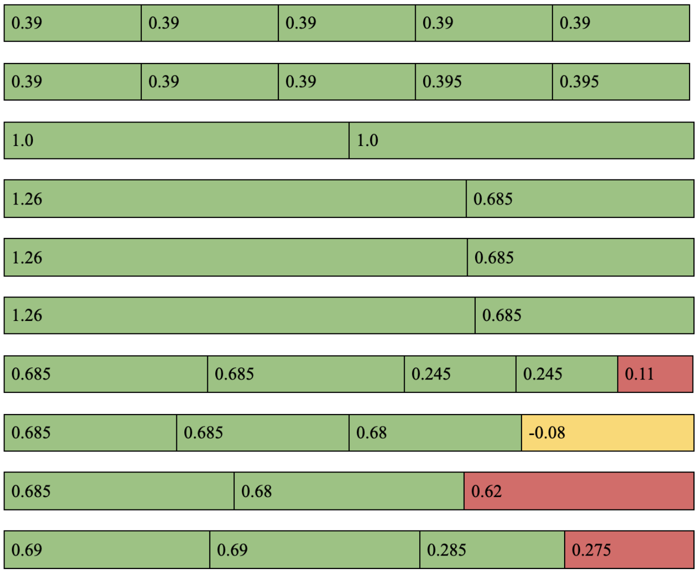


Figure 35: Greenhouse Frame after Day Six of Building

We also were able to add the polyethylene to around the greenhouse so that it is a mockup of the greenhouse that would have been built at the farm. First, the rail and the wiggle wire were cut using a hacksaw to the desired lengths. The lengths of each portion of the rail and wire are shown below in Figure 36.



0.39	0.39	0.39	0.39	0.39
0.39	0.39	0.39	0.395	0.395
1.0	1.0			
1.26	0.685			
1.26	0.685			
1.26	0.685			
0.685	0.685	0.245	0.245	0.11
0.685	0.685	0.68	-0.08	
0.685	0.68	0.62		
0.69	0.69	0.285	0.275	

Figure 36: Lengths of Each Wiggle Wire and Rail Cut

After the correct lengths of wiggle wire were produced, we were able to use a drill and secure the pieces with wiggle wire. The rail was attached all around the base, on the roof and on the sides of the frame. A hole in the door was cut out so we could add another sheet of polyethylene to the door if needed (Figure 37).

Figure 37: Finished Greenhouse with Polyethylene

Chapter 6: Testing & Results

To best simulate the effects of snow accumulating across the entire roof of the greenhouse, weight was equally distributed along the peak of the roof. Since the roof would need to support 22.3125 lb/ft^2 and the roof had an area of 19.95 ft^2, 445 lb of distributed weight would be needed to adequately test the integrity of the structure.

For the first part of the testing procedure, large buckets were hung from the aluminum extrusion running horizontally at the roof peak. The buckets were then filled with water eight quarts at a time, with the water being distributed equally among them (Figure 38). As the water was not enough to reach the 445 lb threshold of the snow load we needed to simulate, large bags of sand were placed evenly along the peak of the roof. Each bag weighed 50 lb. This experiment was done to observe the structure's response to increasing distributed loads, which the snow load would be in the case of snow gathering on a roof. Applying the force along the peak bar would have the greatest effect on the stress/strain. Once the weight was removed, any bending that had occurred was no longer visible.

Figure 38: Distributed Load Test on Frame

The testing equipment consisted of an Arduino Uno, a Wheatstone bridge, 14 wires, an analog to digital converter (ADC), and a strain gauge (Figure 39).

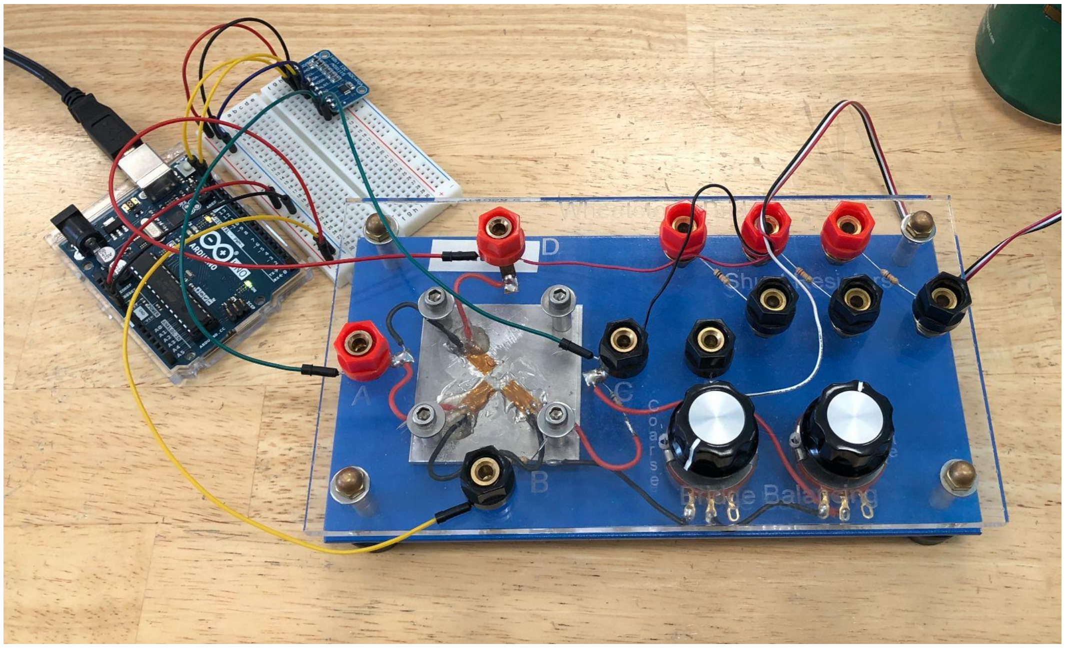


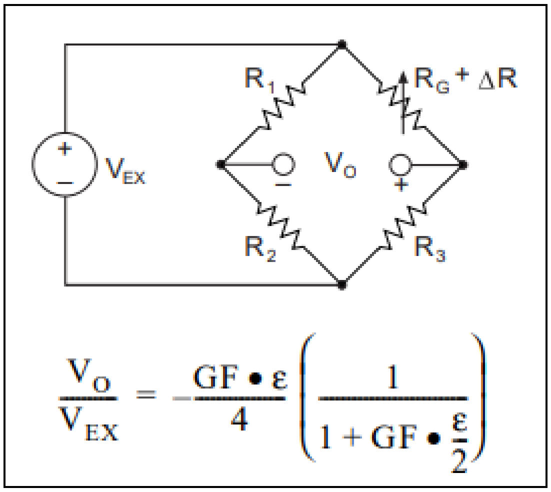
Figure 39: Strain Measurement Circuit Configuration

Figure 40 shows the code used to record the change in output voltage as weight was added to the greenhouse frame. The voltage differential between two inputs (2 & 3) on the analog-to-digital converter were read and then multiplied by a 16x gain in order to better the signal resolution and obtain more detailed readings from the strain gauge by being able to measure very small changes in voltage.

```
#include <Wire.h>
#include <Adafruit_ADS1015.h>

Adafruit_ADS1115 ads;

void setup(void)
{
  Serial.begin(9600);

  //                                                                ADS1015  ADS1115
  //                                                                -------  -------
  // ads.setGain(GAIN_TWOTHIRDS);  // 2/3x gain +/- 6.144V  1 bit = 3mV      0.1875mV (default)
  // ads.setGain(GAIN_ONE);        // 1x gain   +/- 4.096V  1 bit = 2mV      0.125mV
  // ads.setGain(GAIN_TWO);        // 2x gain   +/- 2.048V  1 bit = 1mV      0.0625mV
  // ads.setGain(GAIN_FOUR);       // 4x gain   +/- 1.024V  1 bit = 0.5mV    0.03125mV
  // ads.setGain(GAIN_EIGHT);      // 8x gain   +/- 0.512V  1 bit = 0.25mV   0.015625mV
     ads.setGain(GAIN_SIXTEEN);    // 16x gain  +/- 0.256V  1 bit = 0.125mV  0.0078125mV

  ads.begin();
}

void loop(void)
{
  int16_t results;

  /* Be sure to update this value based on the IC and the gain settings! */
  //float   multiplier = 3.0F;    /* ADS1015 @ +/- 6.144V gain (12-bit results) */
  float multiplier = 0.0078125F; /* ADS1115  @ +/- 6.144V gain (16-bit results) */

  results = ads.readADC_Differential_2_3();

  Serial.print("Differential: ");
  Serial.print(results);
  Serial.print("(");
  Serial.print(results * multiplier);
  Serial.println("mV)");

  delay(1000);
}
```

Figure 40: Code for Recording Output Voltage Change

In order to convert the recorded output voltage measurements into usable data (strain measurements), the equation seen in Figure 41 below was used. Our Wheatstone bridge was classified as a quarter bridge circuit because only one strain gauge was inserted into the circuit. The strain gauge data can be referenced in Appendix D.



$$\frac{V_O}{V_{EX}} = -\frac{GF \bullet \varepsilon}{4}\left(\frac{1}{1 + GF \bullet \frac{\varepsilon}{2}}\right)$$

Figure 41: Quarter-Bridge Circuit

Figure 42 below displays the resulting strain as the total distributed load across the peak of the roof increased from 0 lb to 445 lb, which reaches a maximum strain of about 0.000672. This strain is greater than the 0.000106 value that was found in the ANSYS simulation of the small-scale greenhouse because all of the weight was placed on the peak, which has a greater effect on the structure than if the weight was placed further down the roof. Despite this, further calculations of the stress-strain curve indicated that the experimental strain was still safe. The full list of strain values and the ANSYS simulations can be found in Appendix D.

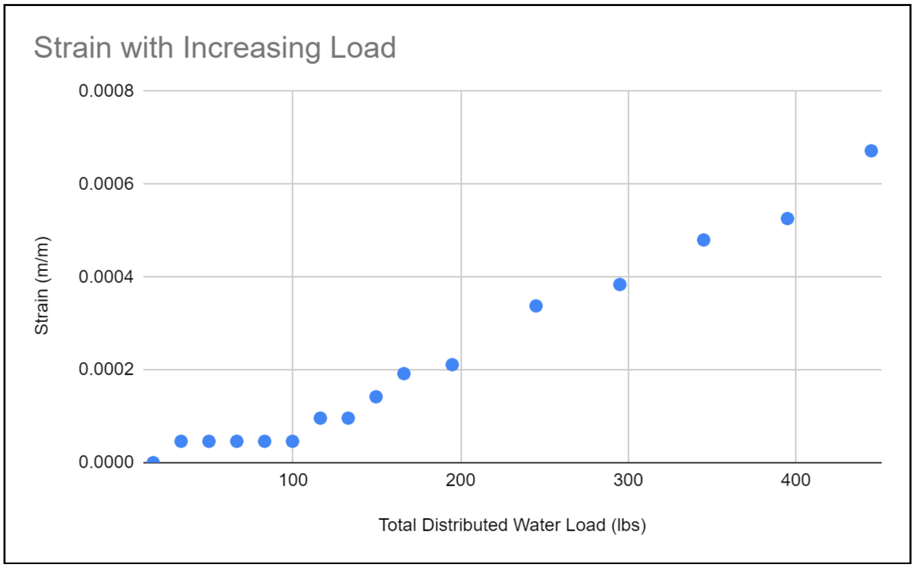


Figure 42: Observed Strain Graph

The aluminum alloy that was used for the frame has a Young's Modulus of Elasticity of 69.972 GPa. This value was used in the equation $E = \sigma/\varepsilon$ to calculate the resulting tensile stress in the material at the point where the strain gauge was fixed, where E is Young's Modulus, σ is stress, and ε is strain. Figure 43 below shows the experimental stress-strain values in blue. The red dot marks the location at which plastic deformation would begin (181.91 MPa). The graph reveals that the frame's stress-strain ratio (47.02 MPa) will not come close to this point even under the maximum expected snow load. Full list of values can be found in Appendix D.

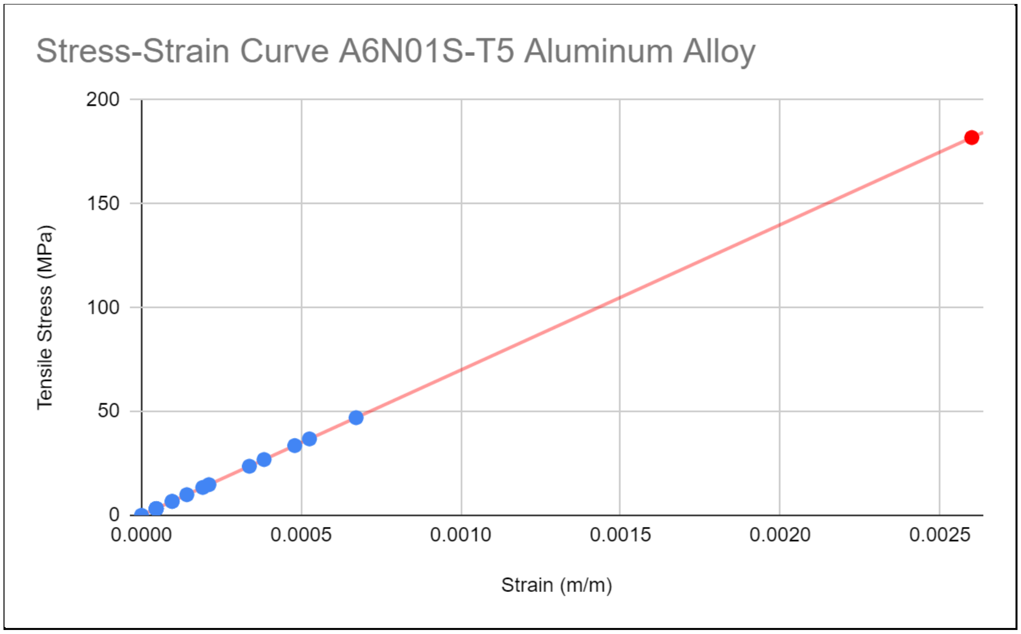


Figure 43: Experimental Stress-Strain Curve of A6N01S-T5 Aluminum Alloy

Chapter 7: Broader Impacts

The group employed the principles of engineering ethics throughout the entire project to ensure proper impacts on the environment and society while following all codes and standards. The two main fundamental canons of the code of ethics for mechanical engineers that we focused on were “Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties” and “Engineers shall consider environmental impact and sustainable development in the performance of their professional duties.” All the other ethic standards were followed, however these two were focused as they were the most important and relevant to our project. We designed the greenhouse so that it was safe for all people to go inside of it without it collapsing or injuring anyone. Additionally, we made sure the design was secure enough to withstand snow load so that it would not collapse, which would be a safety issue for anyone inside or around the structure. We also prioritized environmental impact and sustainable development by ensuring both what we built the greenhouse out of and how or where we built the greenhouse would not affect the environment around it

There are many positive societal impacts that stem from this greenhouse project. The farm aims to use the greenhouse as a learning space mainly for children, so they can continue running their programs throughout the winter months. This will benefit the society directly involved with Turn Back Time Farm, especially the younger generation who the farm targets their programs towards. This greenhouse will be a space for them to learn about nature and appreciate all it does for everyone in the world. This will have a lasting impact on the students involved in this program and create a space of learning for them.

In addition to societal impacts, our greenhouse will also have environmental impacts from both its creation and use as a learning center. Greenhouses are meant to grow plants or crops in the cold months so they can stay at the correct temperature. The farm would be growing extra plants in the winter months which is beneficial to the environment to stay green and growing. Additionally, with the learning space created inside the greenhouse, children and youth will learn about the environment, nature, and how to respect it. This is an unintended consequence of our project, but teaching people to respect nature and our environment at a young age will carry into their adult life and have a positive influence on the environment as they are more environmentally aware, depending on what they learn at the farm.

Chapter 8: Conclusion

The main goal of this project was to design and build a greenhouse that is usable as a learning environment for Turn Back Time Farm, follows all safety and standard regulations and can withstand the weather conditions of Paxton, MA without the need for maintenance, such as snow removal. The team faced many challenges during this project and obstacles that prohibited the actual construction of the greenhouse on Turn Back Time Farm. Instead, we have provided all the necessary tools and instructions for the farm to be able to build their own greenhouse if they decide to do so. The greenhouse was designed with snow load in mind the entire process. All the calculations and simulations were to make sure the greenhouse would support the load and ensure the safety of people inside that it would not collapse on them. Furthermore, since the team was not able to build the greenhouse at the farm, a scaled down model was built on our WPI campus and additional testing was completed for more verification that the greenhouse would not collapse. In all the tests completed it was determined that the design and material used would be able to withstand the 22.3125lb/ft^2 snow load of Paxton, MA.

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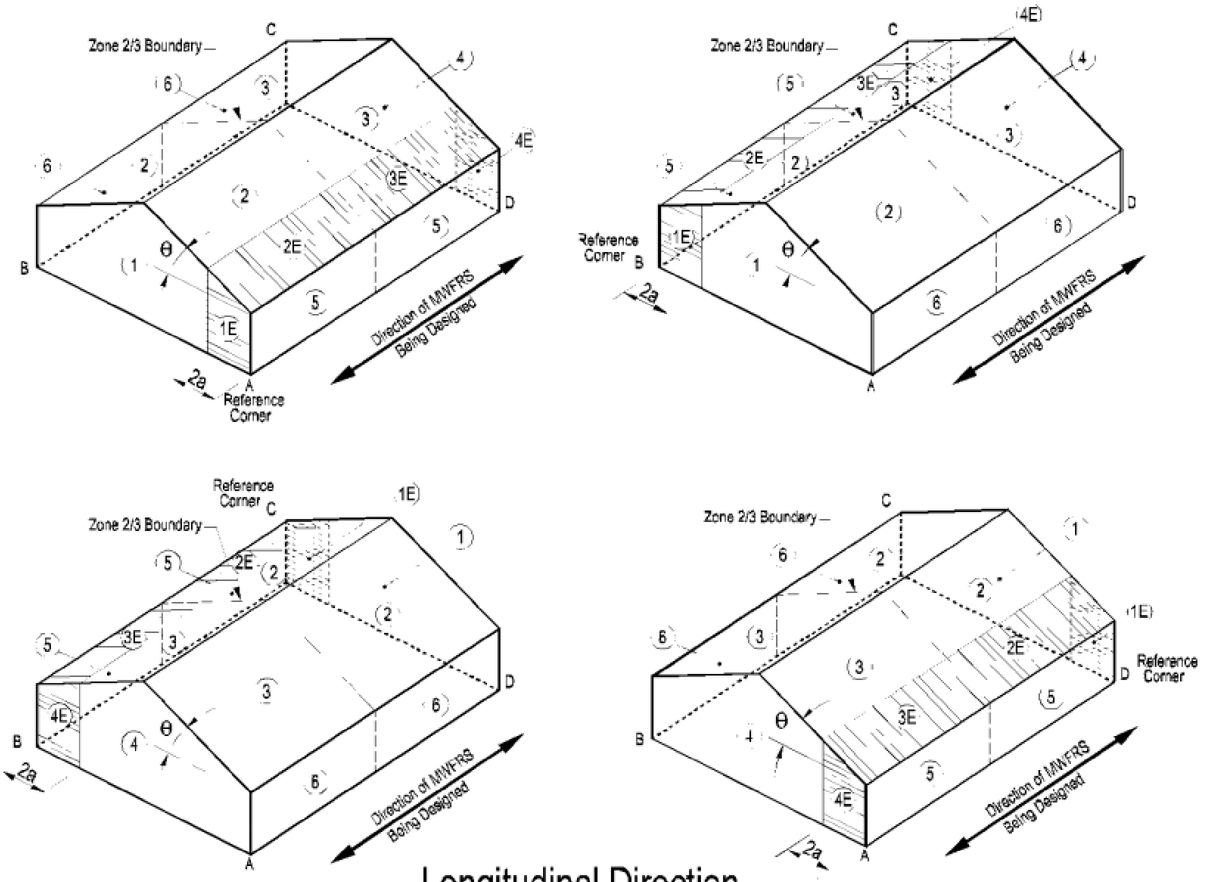
Appendix A - Wind Load Values



Longitudinal Direction

Basic Load Cases

Nature of Occupancy	Occupancy Category
Buildings and other structures that represent a low hazard to human life in the event of failure, including, but not limited to: • Agricultural facilities • Certain temporary facilities • Minor storage facilities	I

6.5.10 Velocity Pressure. Velocity pressure, q_z, evaluated at height z shall be calculated by the following equation:

$$q_z = 0.00256 K_z K_{zt} K_d V^2 I \text{ (lb/ft}^2\text{)} \qquad (6\text{-}15)$$

[In SI: $q_z = 0.613 K_z K_{zt} K_d V^2 I$ (N/m^2); V in m/s]

where K_d is the wind directionality factor defined in Section 6.5.4.4, K_z is the velocity pressure exposure coefficient defined in Section 6.5.6.6, K_{zt} is the topographic factor defined in Section 6.5.7.2, and q_h is the velocity pressure calculated using Eq. 6-15 at mean roof height h.

6.5.6.2 Surface Roughness Categories. A ground surface roughness within each 45° sector shall be determined for a distance upwind of the site as defined in Section 6.5.6.3 from the categories defined in the following text, for the purpose of assigning an exposure category as defined in Section 6.5.6.3.

Surface Roughness B: Urban and suburban areas, wooded areas, or other terrain with numerous closely spaced obstructions having the size of single-family dwellings or larger.

6.5.6.3 Exposure Categories

Exposure B: Exposure B shall apply where the ground surface roughness condition, as defined by Surface Roughness B, prevails in the upwind direction for a distance of at least 2,600 ft (792 m) or 20 times the height of the building, whichever is greater.

6.5.7.1 Wind Speed-Up over Hills, Ridges, and Escarpments. Wind speed-up effects at isolated hills, ridges, and escarpments constituting abrupt changes in the general topography, located in any exposure category, shall be included in the design when buildings and other site conditions and locations of structures meet all of the following conditions:

1. The hill, ridge, or escarpment is isolated and unobstructed upwind by other similar topographic features of comparable height for 100 times the height of the topographic feature ($100H$) or 2 mi (3.22 km), whichever is less. This distance shall be measured horizontally from the point at which the height H of the hill, ridge, or escarpment is determined.
2. The hill, ridge, or escarpment protrudes above the height of upwind terrain features within a 2-mi (3.22 km) radius in any quadrant by a factor of two or more.
3. The structure is located as shown in Fig. 6-4 in the upper one-half of a hill or ridge or near the crest of an escarpment.
4. $H/L_h \geq 0.2$.
5. H is greater than or equal to 15 ft (4.5 m) for Exposures C and D and 60 ft (18 m) for Exposure B.

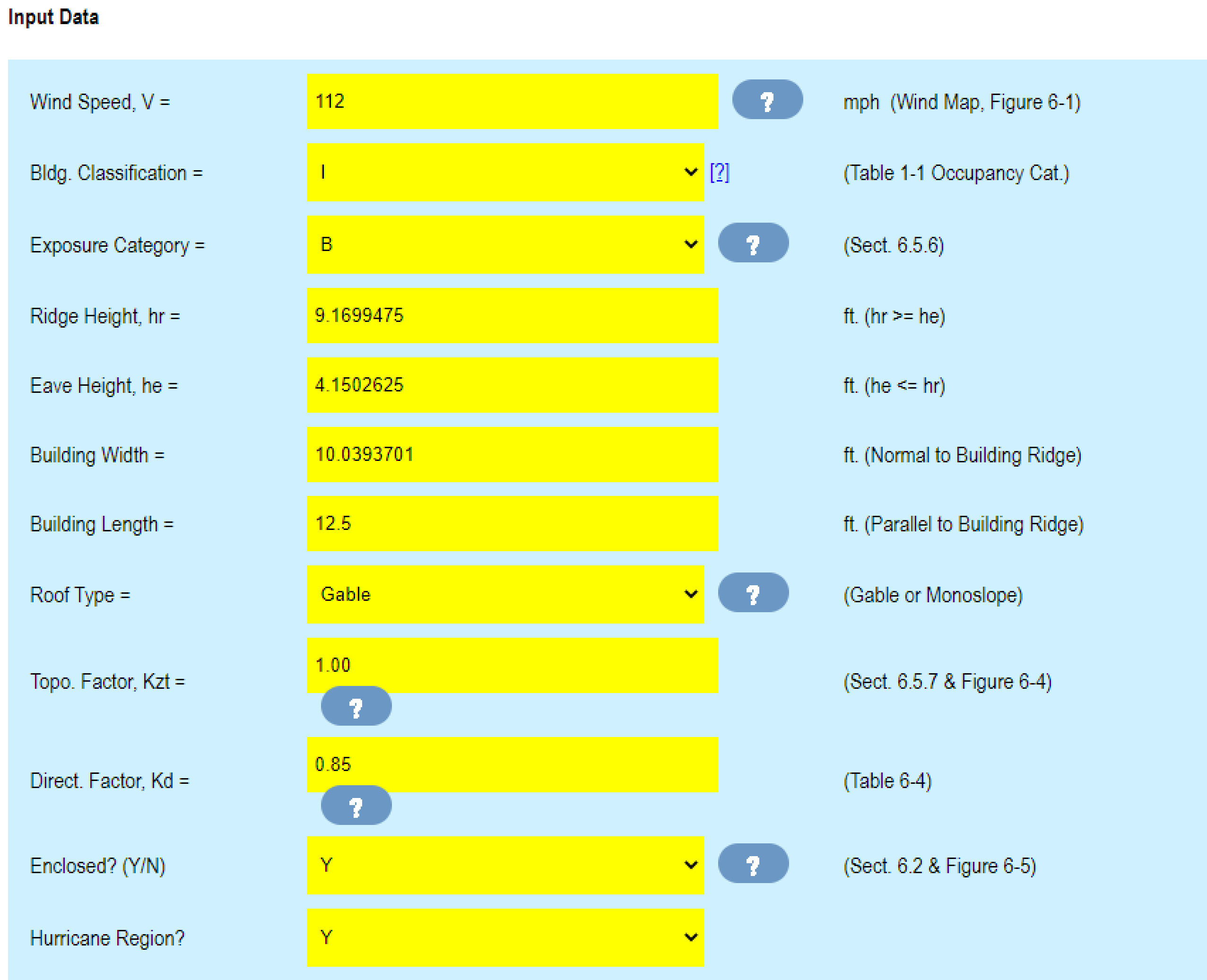
6.5.7.2 Topographic Factor. The wind speed-up effect shall be included in the calculation of design wind loads by using the factor K_{zt}:

$$K_{zt} = (1 + K_1K_2K_3)^2 \qquad (6\text{-}3)$$

where K_1, K_2, and K_3 are given in Fig. 6-4.

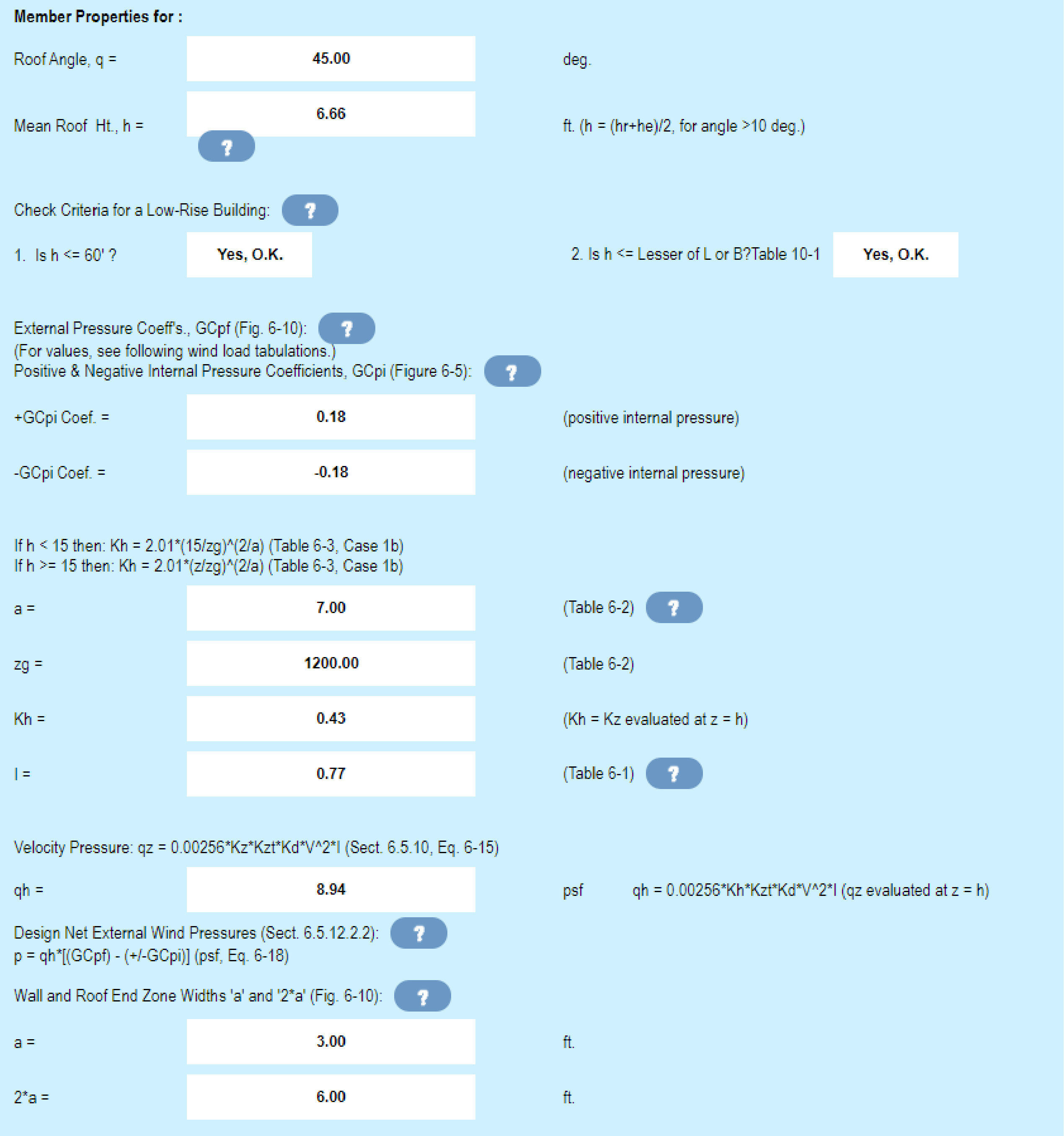
If site conditions and locations of structures do not meet all the conditions specified in Section 6.5.7.1 then $K_{zt} = 1.0$.

Appendix B - Wind Load Calculator Results



Input Data

Wind Speed, V =	112	mph (Wind Map, Figure 6-1)
Bldg. Classification =	I	(Table 1-1 Occupancy Cat.)
Exposure Category =	B	(Sect. 6.5.6)
Ridge Height, hr =	9.1699475	ft. (hr >= he)
Eave Height, he =	4.1502625	ft. (he <= hr)
Building Width =	10.0393701	ft. (Normal to Building Ridge)
Building Length =	12.5	ft. (Parallel to Building Ridge)
Roof Type =	Gable	(Gable or Monoslope)
Topo. Factor, Kzt =	1.00	(Sect. 6.5.7 & Figure 6-4)
Direct. Factor, Kd =	0.85	(Table 6-4)
Enclosed? (Y/N)	Y	(Sect. 6.2 & Figure 6-5)
Hurricane Region?	Y	



Member Properties for :

Roof Angle, q = **45.00** deg.

Mean Roof Ht., h = **6.66** ft. (h = (hr+he)/2, for angle >10 deg.)

Check Criteria for a Low-Rise Building:

1. Is h <= 60' ? **Yes, O.K.**

2. Is h <= Lesser of L or B?Table 10-1 **Yes, O.K.**

External Pressure Coeff's., GCpf (Fig. 6-10):
(For values, see following wind load tabulations.)
Positive & Negative Internal Pressure Coefficients, GCpi (Figure 6-5):

+GCpi Coef. = **0.18** (positive internal pressure)

-GCpi Coef. = **-0.18** (negative internal pressure)

If h < 15 then: Kh = 2.01*(15/zg)^(2/a) (Table 6-3, Case 1b)
If h >= 15 then: Kh = 2.01*(z/zg)^(2/a) (Table 6-3, Case 1b)

a = **7.00** (Table 6-2)

zg = **1200.00** (Table 6-2)

Kh = **0.43** (Kh = Kz evaluated at z = h)

I = **0.77** (Table 6-1)

Velocity Pressure: qz = 0.00256*Kz*Kzt*Kd*V^2*I (Sect. 6.5.10, Eq. 6-15)

qh = **8.94** psf qh = 0.00256*Kh*Kzt*Kd*V^2*I (qz evaluated at z = h)

Design Net External Wind Pressures (Sect. 6.5.12.2.2):
p = qh*[(GCpf) - (+/-GCpi)] (psf, Eq. 6-18)

Wall and Roof End Zone Widths 'a' and '2*a' (Fig. 6-10):

a = **3.00** ft.

2*a = **6.00** ft.

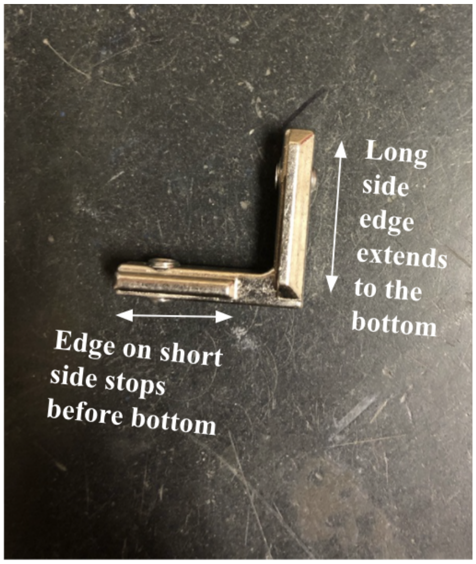
Appendix C - Greenhouse Build Instructions

Materials Needed (also included in bill of materials):

- Aluminum Extrusions:
    - **Fourteen 2.1m length** for the sides of the frame
    - **Fourteen 2.1m length** for the roof extrusions
    - **Three 3.81m length** for the top where the roof meets and the top of the two sides of the frame
    - **Three 3m length** for the bottom and top of back side and one for the bottom of the front side
    - **Two 2.24m length** for the sides of the door frame
    - **One 0.8m length** for the top of the door frame
    - **Two 1.1m length** for the pieces extending horizontally from the sides of the door frame and connecting to the frame sides
    - **Twelve 0.6m length** along the sides for in between the extrusions on the sides
    - **Two 0.735m length** for the top and bottom of the door
    - **Two 2.17m length** for the sides of the door
- **112 Inner L Bracket** to connect most of the extrusions
- **16 Pivot Joints** for the roof connection to the side of the frame
- **10 Corner Brackets** for reinforcing the corners without inner L brackets
- **20 Drop-In T-Nuts & Hex Screw Bolts** for attaching the corner brackets
- **36.75m^2 Polyethylene Film** to cover the entire greenhouse
- **150 ft of Wiggle Wire** to attach the polyethylene to the frame
- **1” Self Tapping Screws** for both attaching the pivot joints and the wiggle wire directly to the frame
- **Two Butt Hinge and Screws** to connect the door to the frame
- **Two Door Handles and Screws** for each side of the door
- **Drill with Multiple Bit Attachments** to be able to screw in easily

Notes:

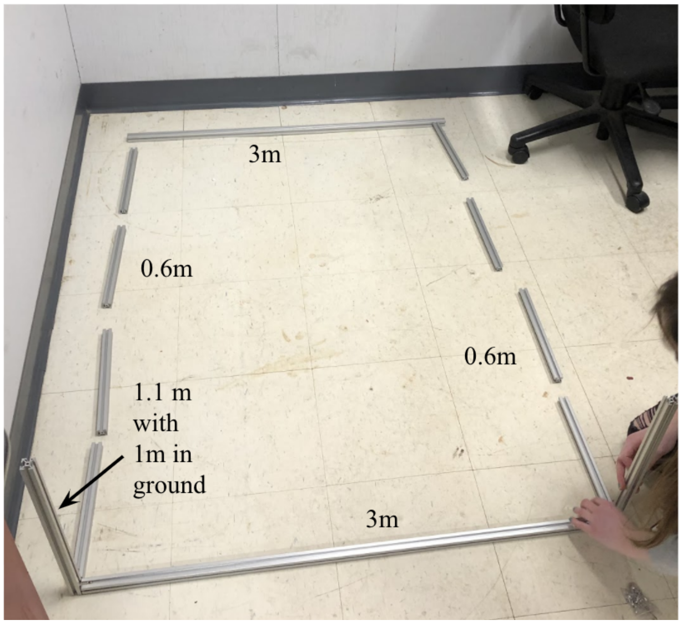
- In the instructions the “long side” and “short side” are referred to when talking about the inner L bracket used to connect most of the aluminum extrusions along the base. The picture below depicts which side is being referred to when saying long or short. The long side has the edge of the bracket extending all the way to the end, whereas the short side has the edge that stops before the end.



- Any other notes?

Steps:

1. Ground the sides of the greenhouse by digging a hole into the ground and placing the **2.1m** extrusions each **1 meter (3 feet)** deep into the ground.
    a. We suggest measuring the extrusion beforehand and marking the line which the soil should be at so that all the extrusions are even.
    b. It is pretty important to make sure the extrusions are level and even with each other so the greenhouse is not lopsided or crooked.
2. Lay out the base of the greenhouse structure.
    a. First lay out the two **3m** long extrusions for the front and back of the greenhouse which should fit between the two opposite side extrusions at the front and back of the greenhouse.
    b. Then, lay down the twelve **0.6m** extrusions for the sections between the **2.1m** pieces that have already been grounded. There should be one between each of the side extrusions in the ground.
    c. The schematic shows where the extrusions should be placed when we made the smaller version, so yours will look a little different with more of the smaller pieces and the sides already grounded instead of standing straight up like in the picture.



3. Before connecting any of the extrusions, slide four L-brackets into the front **3m** long extrusion to use later for the door. The direction these brackets face should be alternating so that there are two sets of two brackets facing away from each other. Additionally, the long side of the brackets should be slid into the extrusion on the ground so the short side points upward.
    a. The L's should look like this: _| |_ _| |_

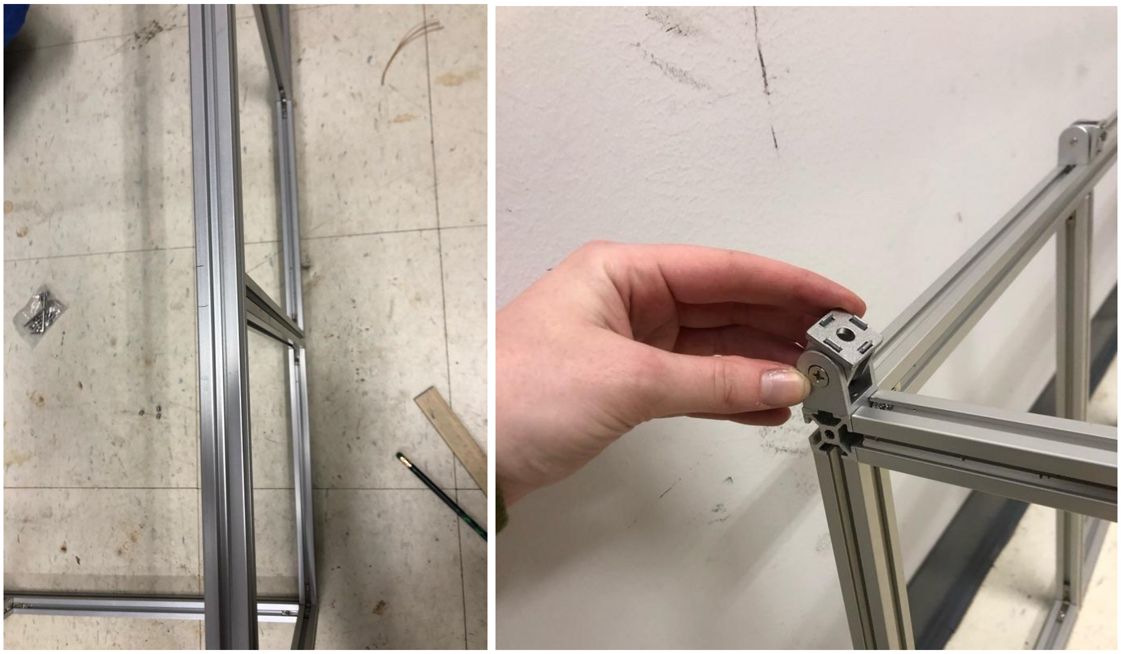
4. Now connect the two ends of the front **3m** extrusion to the side extrusions already secured in the ground. Do this on both sides of the front piece laying on the ground.
    a. Add the long side of a L-bracket to the top of the side extrusion straight up in the ground so that it falls and can connect the **2.1m** side to the **3m** front piece laying on the ground. The short side of the bracket will connect to the piece on the ground.

   b. Use the hex key/Allen wrench that comes with the bracket and screws to tighten the bracket on both extrusions.
   c. Be gentle when tightening these screws, as the threads of these screws can easily be stripped.
   d. Double check they are secure and not moving apart from each other.

5. Connect the **2.1m** vertical extrusion to the horizontal **0.6m** side extrusion to make a corner of the greenhouse between the front and the side.
   a. Place the long end of the L-bracket into the top of the side **2.1m** extrusions, like you did for the connection to the front, and the short side into the top of the **0.6m** extrusion that is laying on the ground
   b. Make sure they are flat against the ground before screwing them in
   c. Tighten the brackets with the screws and make sure there is no movement between the connections

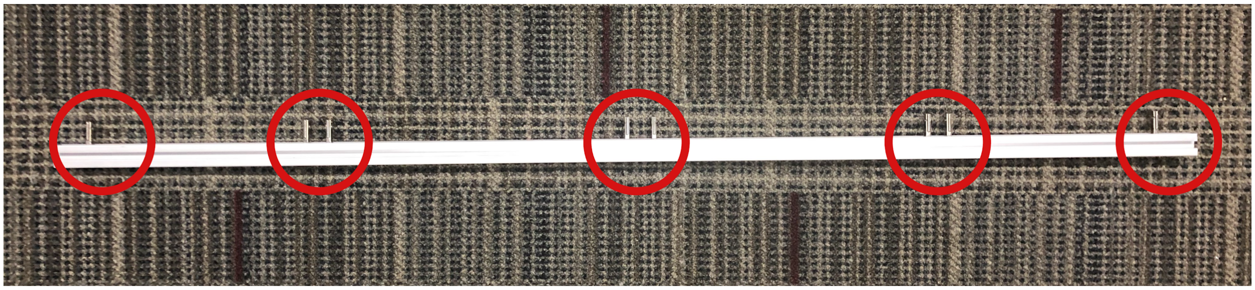
6. Repeat this process six times down the entire length of the greenhouse on both sides of the frame until you get to the base extrusion at the back where another corner will be created.
    a. Use the same steps as above where the longer side of the inner L-bracket is inserted into the top of the **2.1m** side extrusions and the shorter side is placed into the pieces that are flat on the ground.
    b. It might be easier to insert the brackets on either side of the **0.6m** extrusions at the same time since they might be hard to fit into when the **2.1m** extrusions are already secured into the ground.

7. Adjustable pivot joints need to be attached to the top of two of the **3.81m** extrusions so that the roof can connect to the sides. There will be 7 joints on each extrusion for a total of 14 pivot joints. This will set up the connection between the rectangular frame and the roof.
   a. Disconnect the two parts of the pivot joint from each other (the second part will be used in step 11).
   b. Put the pivot joint at the desired location on top of the frame and mark the location of the hole of the pivot joint in pencil.
      i. The desired location can be found by measuring the distance in between each joint or by temporarily placing the extrusion on top of the **2.1m** extrusions in the ground and marking with a pencil above where the pivot joint would be exactly above the vertical side extrusions.
   c. Take the pivot joint off and drill a pilot hole smaller than the 1” diameter of the screw into the extrusion at the pencil mark just created.
   d. Put the pivot joint back into position with the 1” self-tapping screw passing through the pivot joint hole and resting on the pilot hole in the extrusion. Make sure the pivot joint is facing the correct way, with the opening forward and the sides with the screws facing each other.
   e. Use a drill to screw it in until tight.
   f. Repeat until all 14 pivot joints are attached to the frame.
   g. Once they are attached to the frame, the screws will be extending into the slot on the opposite side of the extrusion. Since this will not allow for the L-brackets to slide into the slot, the screw tips need to be filed or grinded down a little bit to slide the L-brackets in and make sure they are placed in the optimal position.



(Image on right shows the correct orientation of the pivot joint on top of the frame)

8. Next is placing the top of the frame sides on top of all the vertical extrusions that are secured into the ground.
    a. Start by adding all the L-Brackets to the top **3.81m** extrusion; there should be 12 added by the long side with five pairs facing alternating directions and two on the end with the L pointing inwards. They should look like this on the extrusion:
    |_   _| |_   _| |_   _| |_   _| |_   _| |_   _|
    b. The picture only shows three pairs on the inside, however there should be five.



    c. These **3.81m** extrusions should have the pivot joints already attached on the opposite side of where the brackets are being placed.
    d. Place the other end of these brackets into the tops of the vertical **2.1m** extrusions that are secured into the ground.
    e. After the extrusion is in place, screw the L-brackets in with the Allen wrench tight enough to be secure without the wrench stripping the inside of the screw.
    f. Do this on both sides of the frame so that it looks similar to a crib.

9. Door frame instructions:
    a. Take two **1.1m** length extrusions and use an inner L bracket to join each to the top extrusions of the outer frame.

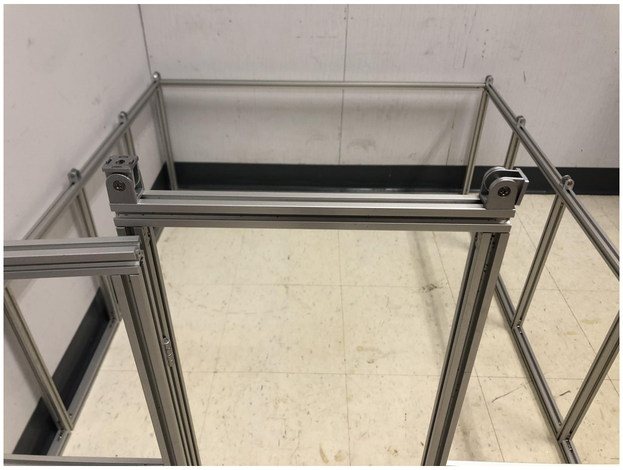
    b. Then place the two **2.24m** length extrusions (for the sides of the door frame) standing up on the inner L brackets that were put in place (in the **3m** length extrusion on the ground) in step 3.
    c. Slide a pair of inner L brackets down the outer side of both the **2.24m** extrusions so that the long side is in the slot of this extrusion and the short side will be

perpendicular to this extrusion. They should look like this but flipped vertically: _| |_

d. Line up the two inner L brackets on the door frame in step b with the **1.1m** extrusion perpendicular to it, slide them into the slot and screw tight so there is no movement.

e. Make sure the **1.1m** extrusions are level before continuing.

10. The top of the door frame needs two pivot joints to be secured by a screw on the extrusion, just like on the sides of the frame.
    a. Take the **0.8m** length extrusion for the top of the door frame and position two pivot joints on the top all the way to the left and right hand side.
        i. The pivot joints must keep the two metal bits in line with the extrusion gap for positional guidance on the top and bottom faces of the pivot joint.
        ii. On the extrusion they should be facing the same way as they are on the frame sides.
        iii. The piece of the pivot joint that has a wider base should be attached to the door frame and the narrower piece should be along the roof beam.



b. Mark the location of the pivot joint holes in pencil and remove the pivot joints.
c. Drill a pilot hole smaller than the 1” diameter of the screw into the extrusion at the pencil marks just created.
d. Slide the long side of two inner L brackets into the bottom of the extrusion so that they look like this: |_   _|

e. Put the pivot joints back into position with the 1” self-tapping screw passing through the pivot joint hole and resting on the pilot hole in the extrusion.
f. Use a drill to screw them both in until tight.
g. Secure the **0.8m** extrusion to the tops of the **2.24m** side extrusions by sliding the short side of the inner L brackets into the inside faces of the side door frame extrusions and gently screwing the nuts until tight.
h. The picture below does not include the addition of the pivot joints but at this stage they should be on them like shown above.

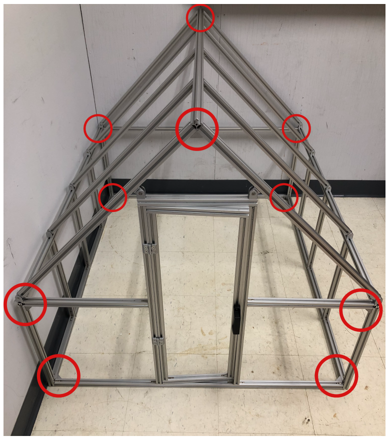
11. The roof assembly also required a bit of drilling to connect the other half of the pivot joint to the sides of the roof.
    a. To drill the screw into the end of the roof extrusions use these steps:
        i. Firmly secure a **2.1m** length roof extrusion so that it cannot twist.
        ii. Take the other half of the pivot joint that was set aside before (in step 7) along with another 1” self tapping screw.
        iii. Drill a pilot hole into the hole on the end of the extrusion far enough for the screw to be flush with the pivot joint but not so far that the screw cannot catch on the extrusion at the base of the hole.
        iv. Place the pivot joint on the 30mm x 30mm face of the 2.1m extrusion with the 1” self tapping screw passing through the pivot joint hole and resting on the 6.8mm center hole.
        v. Screw until tight.
        vi. Repeat for all fourteen **2.1m** length roof extrusions.
    b. Attach all fourteen pivot joint halves back together so that the roof beams are attached to the base of the greenhouse and can pivot back and forth.
    c. Take the **3.81m** length extrusion (peak of roof) and insert the long side of 12 inner L brackets into one side of the extrusion so that there are five pairs facing each other and one on each end both facing inward. They should look like this:

       |_   _| |_   _| |_   _| |_   _| |_   _| |_   _|

        i. Screw the brackets in loosely so that they can be loosened and adjusted later if the position is off, right now, we just want them in the general area.

   ii. Insert another 12 inner L brackets into an adjacent face of the **3.81m** extrusion using the same methodology and configuration as the other groove of the extrusion, described above.
   iii. Attach the **3.81m** length extrusion to the fourteen **2.1m** length pivoting roof extrusions, readjusting the inner L brackets when necessary and screwing them in tight. It might be easier to do all of one side of the roof before doing the other.

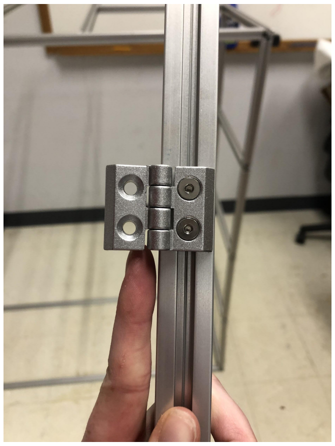
12. There are 10 corners on the greenhouse frame that lack inner L brackets. These are spaces that the inner L brackets do not work with due to the three extrusions meeting in one spot, there is no space on the inside of the extrusion. To reinforce these locations and prevent slipping, corner brackets will be installed there on the outside.
    a. The first 4 locations can be found on the base of the frame that is flat on the ground.
    b. The next 4 locations are in the top four corners of the rectangular frame, directly above the four on the base.
    c. The last 2 locations are at the front and back faces of the roof's peak.
    d. Place two drop-in T-nuts into the empty slots and put the corner bracket into position. Use a large hex key/Allen wrench to screw in 2 hex screw bolts until tight. Repeat this for all 10 location where the corner brackets are needed



13. Making and attaching the door
    a. Take two **0.735m** length extrusions for the top and bottom of the door and two **2.17m** length extrusions for the sides of the door.
    b. Slide two inner L brackets long side first into both of the **0.735m** extrusions. The configuration of the inner L bracket should have one facing up and another pointing down and look like: |_   _|

    c. Join the door extrusions together so that the longer **2.17m** extrusions are sandwiched in between the smaller **0.735m** extrusions. Screw tight.

d. Connect the door to the door frame by dropping 2 drop-in T-nuts into the left side of the door frame extrusion.
e. Place a butt hinge flat on the outside of the door frame and screw it into the T-nust using 2 screws and a hex key/Allen wrench.
f. Repeat steps e and f for the second butt hinge.
g. Next, place 2 more drop-in T-nuts in the door extrusion and line them up with the secured butt hinges. Use 2 screws and a hex key/Allen wrench to fully join the door to the door frame.
h. Repeat step g for the second butt hinge so that the door is fully attached and complete.

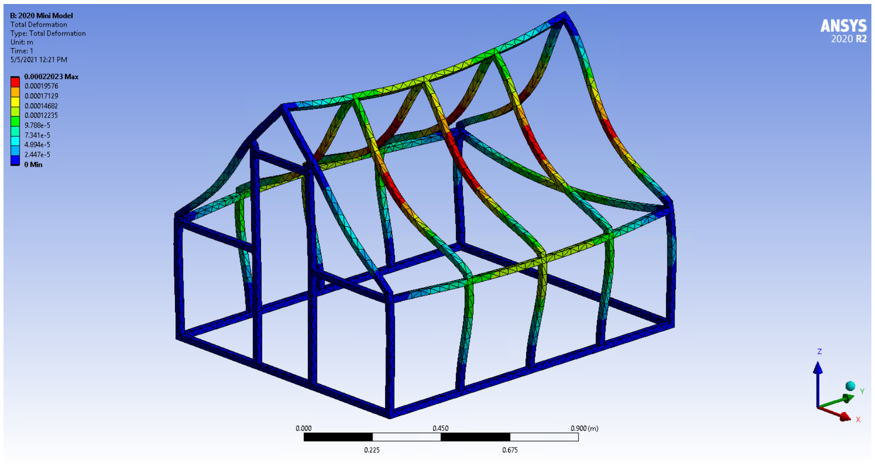


i. For the door handle, place 2 drop-in T-nuts into the right side of the door, put the door handle in position, and screw it in place with 2 screws and a hex key/Allen wrench. It might be easier to place the T-nuts in one at a time instead of both at once.

14. Wiggle wire & polyethylene
    a. Attach wiggle wire rail to the parts of the frame highlighted below with the 1” self tapping screws. The screws should be spaced about 12 to 18 inches apart.

    b. Lay the polyethylene on top of the area you want covered and insert the wiggle wire into the rail.

Appendix D - Testing Strain



B: 2020 Mini Model
Total Deformation
Type: Total Deformation
Unit: m
Time: 1
5/5/2021 12:21 PM

MICRO-MEASUREMENTS
FOR COMPLETE TECHNICAL DATA, VISIT WWW.VISHAYPG.COM

GRID RESISTANCE IN OHMS
120.0±0.3%

TC OF GAGE FACTOR, %/100°C
(+1.8±0.2)

GRID	GAGE FACTOR @ 24°C	TRANSVERSE SENSITIVITY
1	2.085±0.5%	(+0.9±0.2)%
2		
3		
NOM		

THERMAL OUTPUT COEFFICIENTS FOR 2024-T4 ALUMINUM @ G.F. OF 2.00

ORDER	FAHRENHEIT	CELSIUS
0	-1.16E+2	-3.81E+1
1	+3.23E+0	+3.05E+0
2	-2.67E-2	-6.90E-2
3	+5.66E-5	+3.30E-4
4		
5		

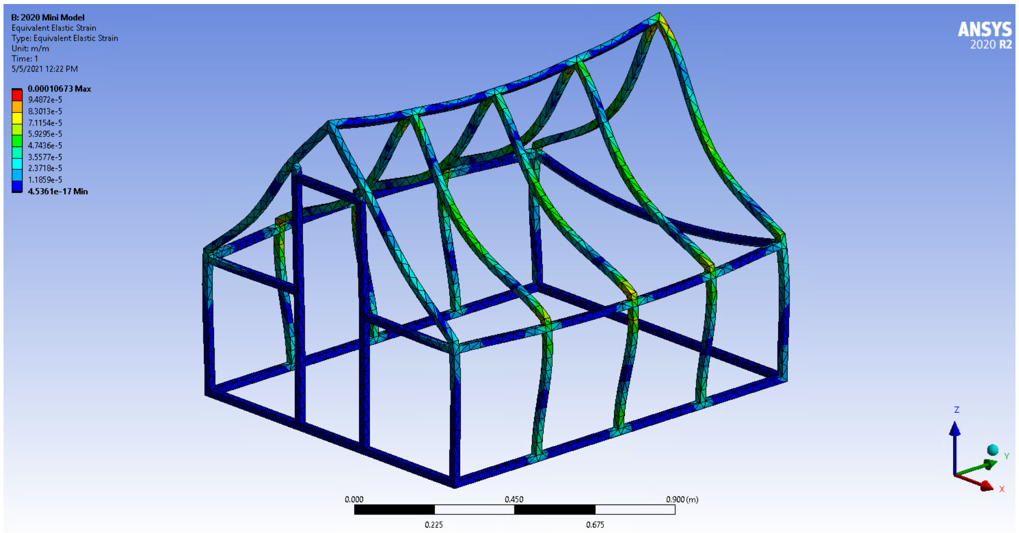
FOIL LOT NUMBER
A108AF507

WORK ORDER NUMBER
01220314
35079137

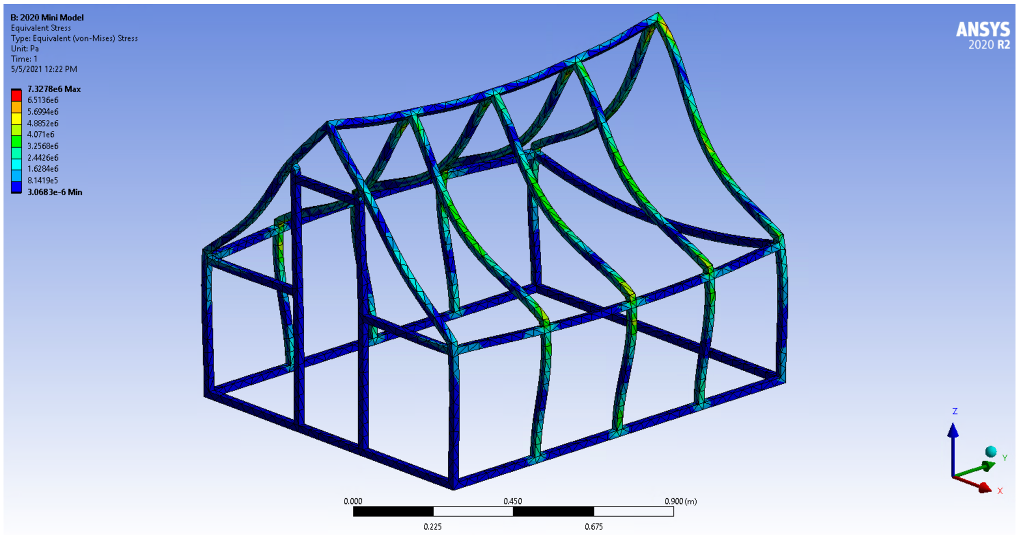
ITEM CODE	QTY 1 PK	CODE	RoHS COMPLIANT
MMF006836	(10 pcs)	201936US	

COUNTRY OF ORIGIN USA

CEA-13-240UZ-120



B: 2020 Mini Model
Equivalent Elastic Strain
Type: Equivalent Elastic Strain
Unit: m/m
Time: 1
5/5/2021 12:22 PM



B: 2020 Mini Model
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: Pa
Time: 1
5/5/2021 12:22 PM

Weight (lb)	Output Voltage (V)	Strain (m/m)	Tensile Stress (MPa)
16.61663379	0	0	0
33.23326758	-0.00012	0.00004604537565	3.221887025
49.84990138	-0.00012	0.00004604537565	3.221887025
66.46653517	-0.00012	0.00004604537565	3.221887025
83.08316896	-0.00012	0.00004604537565	3.221887025
99.69980275	-0.00012	0.00004604537565	3.221887025
116.3164365	-0.00025	0.00009593285468	6.712613707
132.9330703	-0.00025	0.00009593285468	6.712613707
149.5497041	-0.00037	0.00014198744100	9.935145222
166.1663379	-0.00050	0.00019188489976	13.42657021
195	-0.00055	0.0002110776121	14.76952268
245	-0.00088	0.0003377687747	23.6343567
295	-0.00100	0.0003838465842	26.85851319
345	-0.00125	0.0004798562351	33.57650048
395	-0.00137	0.0005259476918	36.80161189
445	-0.00175	0.000671933183	47.01650868