

Progressive Modular Shelter for Asylum Seekers at the United States Southern Border

A Major Qualifying Project submitted to the faculty of

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Table of Contents

Table of Figures	3
Table of Tables	6
Acknowledgements	7
Abstract	8
1.0 Introduction	9
2.0 Background	10
2.1 Shelter Housing Design Parameters	10
2.1.1 Temperature	10
2.1.2 Rainfall and Flood Risk	11
2.1.4 Humidity	12
2.1.5 Transportation and Movement of Shelter	13
2.1.6 Consumer Parameters	14
2.1.7 Materials	14
3.0 Design Concept Development	15
3.1 Generation of Design Parameters and Specifications	15
3.2 Design Concept Generation and Selection	17
3.2.1 Initial Design Concepts	17
3.2.2 Design Selection	20
3.1.3 Further Development of the Beehive Train Car Design	23
4.0 Final Design Optimization and Assembly	25
4.1 Structural Design Decisions and Details	25
4.1.1 Sizing and Dimensions	25
4.1.2 Roof	26
4.1.3 Walls	28
4.1.4 Floor	29
4.1.5 Subfloor Support System	31
4.1.5 Interlock Mechanism	32
4.1.6 Leveling System	33
4.1.8 Interior Framing Support System	34
4.1.7 Other Systems	35

4.1.8 Layout and Housing Requirements	36
4.2 Overview of Step-by-Step Assembly of Shelter	37
5.0 Analysis and Verification	45
5.1 Finite Element Analysis (FEA)	45
5.1.1 Validation Through Hand Calculations	45
5.1.2 Mesh Convergence Analysis	47
5.1.3 Finite Element Analysis (FEA) Results	49
5.1.3.1 Material Choice	50
5.1.3.2 Loading Types for Each Subfloor Design	50
5.1.3.3 No Support Subfloor Analysis	51
5.1.3.4 Subfloor Support System New Configurations	52
5.1.3.5 Analysis of ANSYS Results for New Support Designs	54
5.1.3.6 Further Development and Analysis of Zelda Design	57
6.0 Conclusions	59
Bibliography	61
Appendix A: Preliminary Design Ideas	63
Appendix B: Finite Element Analysis (FEA) Method Verification through Hand Calculations	68
Appendix C: Specification Sheets for Materials	70
Appendix D: Finite Element Analysis (FEA) Subfloor System Data Results	72

Table of Figures

Figure 1: Weather Data for the Rio Grande Valley Region (National Park Service, 2019).....	11
Figure 2: Average Monthly Rainfall in Rio Grande Valley by Month (Weather Spark, 2019) ...	11
Figure 3: Map of Flood Risk Around Sector Location for Rio Grande Valley Region (National Weather Service, 2019).....	12
Figure 4: Humidity by Month Based on Dew Point for the Rio Grande Valley Region (Weather Spark, 2019).....	13
Figure 5: Federal Length and Width Requirements for Semi-Trailers (Federal Highway Administration, 2004).....	13
Figure 6: Beehive Shelter Design Sketch	18
Figure 7: Polar Express Car Design Sketch.....	19
Figure 8: Stackable Shelter Design Sketch.....	19
Figure 9: Drawer Shelter Design Sketch	20
Figure 10: Beehive Train Car Design Sketch	21
Figure 11: Stackable Drawer Design Sketch	22
Figure 12: Diagram of Initial Caster Chosen for Beehive Train Car Design (McMaster-Carr, 2013).....	23
Figure 13: Puzzle and Hinged Wall Panels for Beehive Puzzle Design.....	24
Figure 14: Floor and Wall Layers in Bed of Semi-Truck.....	26
Figure 15: Triangle Roof Component and Complete Roof of Beehive Shelter Design	27
Figure 16: Example of Corrugated Roof on a Cabin (Riverside Sheet Metal, 2019).....	27
Figure 17: PermaTherm Roof Panels Being Used in Industrial Setting (PermaTherm, 2019).....	28
Figure 18: Hinged Panels Folded Down.....	28
Figure 19: Hinged Panels Folded Up.....	29
Figure 20: Puzzle Wall Panel Isometric View	29
Figure 21: Floor Base Cutouts Showing Interlock Locations Where Only Similar Colors can be Connected at the Same Time	30
Figure 22: Coosa Composites Bluewater 26 Board. Reprinted from Boat Outfitters, by Coosa Composites, retrieved from https://www.boatoutfitters.com/coosa-composites-board-bluewater-26 , Copyright 2020 by Boat Outfitters	30
Figure 23: Aluminum I-Beam Diagram and Specifications for Subfloor System Connections (OnlineMetals, 2020)	31
Figure 24: Original Subfloor System.....	31
Figure 25: Subfloor Support System Design Ideas.....	32
Figure 26: Example of Interlock Connection Between Two Floor Assemblies	33
Figure 27: Diagram of Leveling Mount for Subfloor Support Pegs (McMaster-Carr, 2016)	34
Figure 28: Cross and Door Steel Frame Structures	35
Figure 29: Complete Steel Frame on Top of Floor Assembly without Hinged Walls to Show Steel Frame Individually.....	35

Figure 30: Puzzle Panel Door Frame and Door	36
Figure 31: Staircase Side View with Required Dimensions	37
Figure 32: Reinforced Zelda Subfloor Support System.....	38
Figure 33: Trapezoid Floor Section with Hinged Wall Panel.....	38
Figure 34: Triangle Section of Roof Panel	39
Figure 35: Threaded Levelers on the Subfloor Support System.....	39
Figure 36: Assembly of Two and Three Subfloor Support Systems	39
Figure 37: Process Steps for Additional I-Beams in Subfloor Support System	40
Figure 38: Process Steps to Assemble Hinged Walls on the Floor Base.....	40
Figure 39: Complete Floor Assembly Progress Check.....	41
Figure 40: Floor Assembly with Full Steel Frame and Hinged Wall Panels.....	41
Figure 41: Full Wall Assembly with Steel Frame Including one Door and Window Wall Panel	42
Figure 42: Progression of Triangle Roof Panel Assembly on Beehive Shelter	43
Figure 43: Full Assembly with Roof	43
Figure 44: Front and Back of Complete Shelter Assembly	44
Figure 45: Interlock Assembly Between Two and Three Floor Assemblies	44
Figure 46: Diagram of Simply Supported Beam	45
Figure 47: Total Deformation of Simply Supported Beam of the Max Deformation at the Center of -1.4603 mm.....	46
Figure 48: ANSYS Subfloor Constraints and Loads for Mesh Convergence Analysis; A Indicates the Distributed Load Being applied to the Top Face and B Indicates the Subfloor Design as a Fixed Support.....	47
Figure 49: Measured Deformation (Left) and Equivalent Von-Mises Stress (Right) for a 100 mm Mesh Size at the Center of the Triangle Subfloor Piece.....	48
Figure 50: Charts of Deformation (Left) and Equivalent Stress (Right) at the Center of the Triangle Structure for Different Mesh Sizes.....	49
Figure 51: New Material Entry for 7-Ply Marine Plywood in ANSYS Engineering Data.....	50
Figure 52: Example of Combined Loading Set Up where A is the Point Load Located in the Oval in the Center, B is the Fixed Support Underneath the Subfloor, and C is the Distributed Load Across the Top Triangle Face	51
Figure 53: Total Deformation Results for Original Subfloor Design with Point Load showing the Maximum Deformation at the Center Based on the Legend to the Left of the Triangle	51
Figure 54: Subfloor T-Support Structure.....	52
Figure 55: Subfloor Thirds Support Structure	53
Figure 56: Subfloor Zelda Support System	53
Figure 57: Subfloor Orthogonal Support System	54
Figure 58: Point Load Locations for New Subfloor Designs	54
Figure 59: Total Deformation (mm) Results for New Subfloor Designs Under Combined Loading Conditions; the Thirds Design has the Highest Deformation Compared to the Other Designs using the Legend to the Left	55

Figure 60: Chart of Safety Factor of All Designs with Industry Standard of 2 56
Figure 61: Maximum Stress of All Designs with Industry Standard of 1.3 56
Figure 62: Reinforced Zelda Subfloor Support System..... 57
Figure 63: Point Load Locations for Reinforced Zelda Subfloor System 57

Table of Tables

Table 1: Design Parameters and Specifications	16
Table 2: Final Shelter Design Ideas	17
Table 3: Design Matrix for Final Design Ideas	23
Table 4: Comparison of ANSYS and Excel Hand Calculation Results	47
Table 5: Mesh Convergence Final Results	48
Table 6: Results of Deformation Analysis for Original Subfloor System	52
Table 7: Final Result of Deformation for Reinforced Zelda Design	58

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Abstract

Due to a large backlog and influx of asylum seekers at the United States southern border, some sectors do not have enough capacity or resources to accommodate every individual. Tent camps and permanent structures such as churches are being currently used for overcapacity but do not provide a long-term solution. This project addressed the overcapacity situation by designing a sustainable, modular shelter that could be used by asylum seekers in a community environment. The shelter is a hexagon where the length of each side and height are 2.8 m and 2.4 m, respectively, and the floor is .75 m above the ground on a support system. The shelter is designed to accommodate four people along with required features including a door, windows, stairs. The interlock design between shelters allows multiple unit to be connected to create community bases and provide customized layouts based on the preference of the inhabitants.

1.0 Introduction

The goal of this Major Qualifying Project was to research, design, and analyze a shelter for detained asylum seekers at the United States southern border, specifically at the Rio Grande Valley sector. This project was done in conjunction with another Major Qualifying Project which developed a resource allocation tool for the defensive asylum process at the United States southern border. There is a large backlog of immigration cases that continues to build as more individuals arrive at the United States southern border. Along with analyzing the process flow, many asylum seekers need housing while they wait for their immigration case. However, due to the large numbers of individuals, some sectors are overcapacity and are not able to always provide adequate housing, and a temporary shelter would help with this issue.

Through research of natural disaster shelters, the differences between temporary and permanent shelter designs were found. A progressive shelter solution was pursued over a temporary shelter since a progressive shelter is intended for use of over 1 year. In addition, the shelters were designed to be modular so they can be oriented and customized based on the needs of the population. The primary goals were to design a shelter that could accommodate four people for longer than a year and can be connected for expansion to create communities for asylum seekers.

The final shelter is a hexagon footprint with a sealed interlock by having cuts in the floor base to connect two shelters. Once the shelters are in place, they will be permanent but additional shelters can still be adjoined on an open side of the interlock. The dimensions of the shelter are 2.8 m for each side and 2.4 m high. The shelter is also on a support system below the floor base that raises it an additional .75 m above the ground. Although this project does not consider all of the structural integrity pieces to ensure the shelter will survive, it is a possible design idea to be pursued for further development.

2.0 Background

Temporary housing and shelters are focused on disaster relief, but shelter solutions can also be developed to address overcapacity for asylum seekers at the United States southern border. The main difference is that disaster relief shelters are for short-term use of one to four months while shelter for asylum seekers may require housing for more than a year. There are four different types of disaster relief shelters: emergency shelters, temporary shelters, progressive shelters, and permanent housing. Progressive shelters are designed and built to be permanent and upgradeable in the future through altered structural components (Bashawri, 2014). These shelters are intended to be used for at least 2 years. The focus for this project will be on progressive shelters due to the need for consistent housing from overcapacity. Since the Rio Grande Valley sector has a large population of asylum seekers, this region will be the focus for environmental design parameters. In addition, consumer parameters are acknowledged based on FEMA regulations for emergency shelters.

2.1 Shelter Housing Design Parameters

The shelter designed for this project is intended for use near the United States southern border where many people are waiting for asylum hearings. Although this can apply to multiple regions along the Southern border, this project uses the climate data for the Rio Grande Valley region to represent one of the areas more prone to flood risk. As of February 2019, the Rio Grande Valley sector has an increasing population that accounts for “50% of all arrests along the entire Southwest border” (U.S. Customs and Border Protection, 2019). The shelters are designed for any season in this area, so environmental factors are addressed for year-round use.

2.1.1 Temperature

In the Rio Grande Valley region, the maximum and minimum temperatures for each month can be found in Figure 1. The minimum temperature is 32°F between December and January, but maximum for these months reach up to 69.9°F showing a possible large temperature change from day to day. The highest temperature is 100°F which occur in June and July. In relation to flood risk, river depth is also a factor, which is highest in October at 4.31 feet (National Park Service, 2019).

Month	Temperature Averages °F/°C		Precipitation (inches/mm)	River depth (feet/meters)
	Maximum	Minimum		
January	67.7 / 19.8	31.8 / -0.1	0.39 / 9.9	2.53 / 0.77
February	74.0 / 23.3	35.4 / 1.9	0.39 / 9.9	2.58 / 0.79
March	83.2 / 28.4	44.4 / 6.9	0.16 / 4.1	2.93 / 0.89
April	91.1 / 32.8	53.4 / 11.9	0.58 / 14.7	3.06 / 0.93
May	96.8 / 36.0	62.8 / 17.1	1.43 / 36.3	3.54 / 1.08
June	103.1 / 39.5	69.7 / 20.9	1.44 / 36.6	3.39 / 1.03
July	101.6 / 38.7	70.8 / 21.6	1.47 / 37.3	3.15 / 0.96
August	99.4 / 37.4	71.0 / 21.7	1.61 / 40.1	3.87 / 1.18
September	94.9 / 34.9	65.3 / 18.5	1.30 / 33.0	4.16 / 1.27
October	87.2 / 30.7	54.0 / 12.2	1.30 / 33.0	4.31 / 1.31
November	76.8 / 24.9	40.2 / 4.6	0.41 / 10.4	3.01 / 0.92
December	69.9 / 21.1	32.9 / 0.5	0.34 / 8.6	2.65 / 0.81

Figure 1: Weather Data for the Rio Grande Valley Region (National Park Service, 2019)

2.1.2 Rainfall and Flood Risk

The rainfall in the Rio Grande Valley region is not a pressing concern because the average yearly rainfall is only 10.82 inches. The highest rainfall occurs in May and September where the average monthly rainfall is 2.3 in. and 3.8 in, respectively (Weather Spark, 2019). Figure 2 below shows the average rainfall for each month based on data from 1950 to 2016.

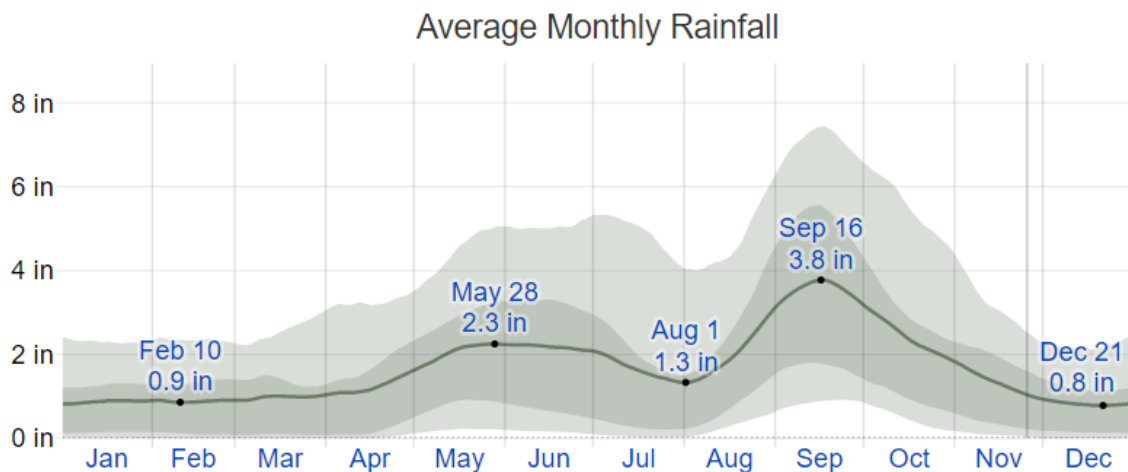


Figure 2: Average Monthly Rainfall in Rio Grande Valley by Month (Weather Spark, 2019)

While rainfall totals are low in the Rio Grande Valley region, there is a high flood risk due to surrounding rivers. A flood map was used to determine levels of risk for the area along the

southern border and can be seen in Figure 3 below. This map shows the Rio Grande Valley headquarters and the surrounding area. The zone shown in purple indicates a major flood risk for that area where the water level is 53 feet above sea level. The entire region has at least a mild flood risk with some areas near the border with major flood risk.

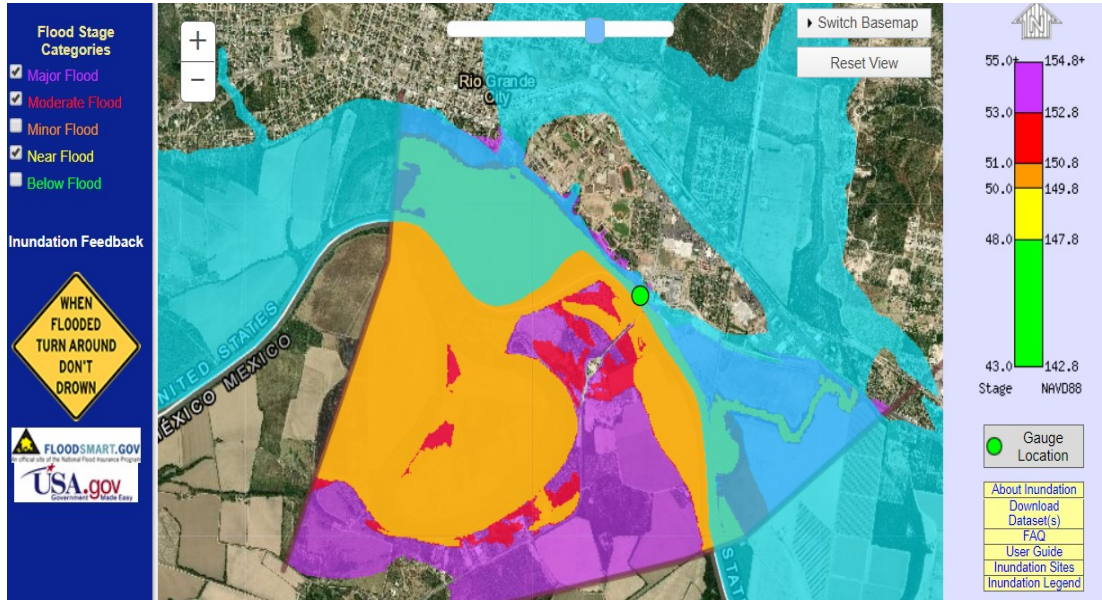


Figure 3: Map of Flood Risk Around Sector Location for Rio Grande Valley Region (National Weather Service, 2019)

2.1.4 Humidity

The humidity in the Rio Grande Valley region has a more humid period lasting for 8.4 months from March to November. The most humid period is from June to July where the dew point is between 65°F and 70°F (Weather Spark, 2019). For comfortable living conditions, the housing unit will need to maintain approximately 50% humidity which will become a challenge during the summer months (U.S. Environmental Protection Agency, 2017). Figure 4 shows the average humidity by month in the Rio Grande Valley region.

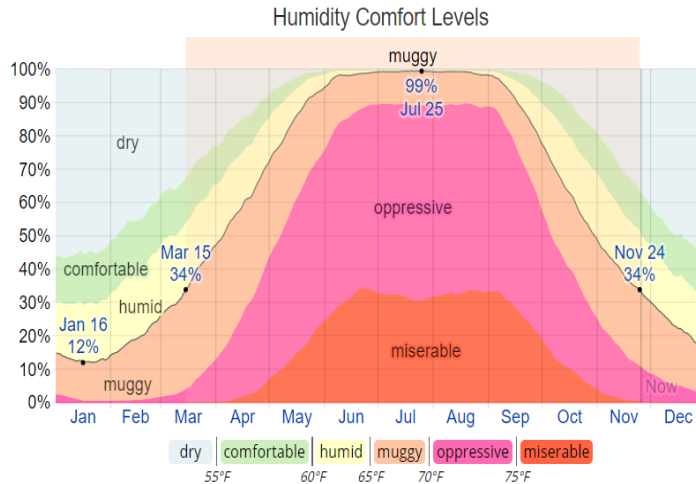


Figure 4: Humidity by Month Based on Dew Point for the Rio Grande Valley Region (Weather Spark, 2019)

2.1.5 Transportation and Movement of Shelter

The components of the shelter unit must be able to fit within dimension requirements for road transport. Air and sea travel will not be considered for shelter components for this project. When traveling on the road, the dimensions and weight of the shelter must comply with federal trucking requirements. In the United States, a standard semi-trailer dimensions to a width of 2.6 m (8.5 ft), a minimum length of 14.6 m (48 ft), and a height of 2.6 m (8.5 ft) (Federal Highway Administration, 2004). This can be seen in Figure 5 below showing the width and length requirements. Note that the length is a minimum since each state has a different length, but the maximum for the entire length is 65 feet by federal regulations.

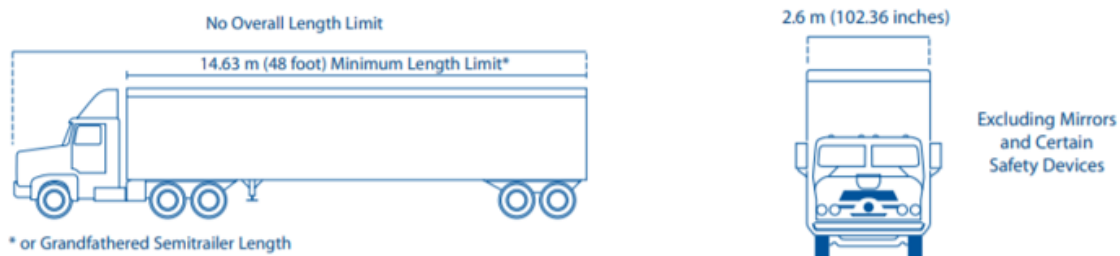


Figure 5: Federal Length and Width Requirements for Semi-Trailers (Federal Highway Administration, 2004)

Based on the large immigrant populations in the Rio Grande Valley area, one major challenge will be to transport and assemble the shelters efficiently. Once assembled, a shelter unit cannot be moved. Additionally, the roof of the shelter will require a crane to place each piece on top. The uneven terrain in the region is also a factor that is considered for the shelter design.

2.1.6 Consumer Parameters

Asylum seekers flee their country of origin to escape persecution or fear of persecution and travel hundreds of miles. One example of this occurred with the surge of refugees in the UK in 2015 from a civil war in Syria. The trauma from the war can cause physical and psychological effects for those fleeing and require dedicated support to recover (Quilter, 2015). Isabel Quilter (2015), a research analyst for the Social Care Institute for Excellence, gives advice on the social care practices for asylum seekers including, “non-discrimination and promotion of equality”, “decision-making that is timely and transparent”, and “a holistic approach”. These guidelines can apply to all countries accepting both asylum seekers and refugees.

To provide comfortable living conditions, the shelter should contain required house features including a toilet, sink, bathroom, food preparation area, and sleeping area. These should also have proper privacy to ensure the individuals feel comfortable and safe. A progressive housing unit must also provide an emergency exit along with a fire extinguisher. According to FEMA regulations, the floor space requirement for each person is 60 ft² (14 m²). There must also be sleeping areas for all occupants (FEMA 453, 2006).

2.1.7 Materials

The material used to build the shelter has a significant effect on the structure, assembly process, movement, and lifetime of the unit. The chosen material must give structural support and be able to withstand the environmental factors of the Rio Grande Valley region, especially in preventing mold from humidity and corrosion due to flooding. Corrosion and mold are closely considered for all panel and support system components discussed in Section 4.1.

3.0 Design Concept Development

3.1 Generation of Design Parameters and Specifications

Shelter ideas were developed based on the requirements for emergency shelters and the needs of the individuals who will use it. The design parameters were a set of characteristics to be included in the shelter. Once the parameters were decided, weights were assigned to each category based on the scale below:

- 5 = Required for product to be usable, but needs to be a unique design
- 4 = Highly recommended to be usable
- 3 = Moderately recommended for product to be usable but not required for proper function
- 2 = Not required for usable product but may be beneficial for better functionality
- 1 = Desired feature but not critical to design or functionality

This scoring system helped to determine which requirements were most important in developing the final design of the shelter unit. The design parameters are measurable by using the data provided in Section 2.1 to create specifications. These specifications were used to evaluate a design that could withstand environmental conditions and meet building codes. Table 1 shows the design parameters chosen along with their weight and specification.

Table 1: Design Parameters and Specifications

Req. ID	Design Parameter	Weight	Specification
1.1	The shelter must withstand temperature changes	5	<ul style="list-style-type: none"> - The shelter must withstand temperature of the Rio Grande Valley area with a maximum temperature of 105°F and a minimum of 32°F - The shelter will withstand temperature changes based on material selection and structural design
1.2	The shelter must withstand flood risks	5	<ul style="list-style-type: none"> - The shelter must withstand up to 3 feet of water if in a major flood risk area - The shelter should have a draining mechanism in cases of flooding
1.3	The shelter units must be able to interlock	5	<ul style="list-style-type: none"> - The units should have a coupler so units can be oriented and positioned in any direction
2.1	The shelter must withstand wind loading	4	<ul style="list-style-type: none"> - The structure should be able to withstand winds up to 20 mph for regular weather patterns - The structure will be tested for wind loading based on structural design and the material chosen
2.2	The shelter should have climate control	4	<ul style="list-style-type: none"> - The shelter should create an environment between 60 and 80°F and humidity between 40 and 50%
2.4	The shelter should be safe and secure and provide privacy	4	<ul style="list-style-type: none"> - The unit must provide adequate privacy along with fire extinguisher, locking system, smoke detector.
3.1	The shelter should have clean water	3	<ul style="list-style-type: none"> - The shelter needs the ability to connect to a clean water source or use a filtration system
3.2	The shelter should be lightweight	3	<ul style="list-style-type: none"> - The units need to be able to move freely on sandy terrain or have a light vehicle to help transport them
4.1	The shelter may have a waste management system	2	<ul style="list-style-type: none"> - The shelter should have a sanitary way of disposing waste
4.2	The shelter may be furnished	2	<ul style="list-style-type: none"> - The unit should have collapsible pieces of furniture that can be assembled easily
4.3	The shelter may be customized for different use	2	<ul style="list-style-type: none"> - Each unit can be furnished or supplied based on the typical rooms in a house including: bathroom, bedroom, kitchen

In addition to the priority weights assigned, the following definitions apply to completing the final design and are bolded in the Design Parameter column in Table 1:

- **Must** = denotes a requirement that is mandatory and would need to be verified or heavily noted in the final design
- **Should** = denotes a requirement that is highly preferred or necessary for basic living but will not be verified or analyzed heavily
- **May** = denotes a guideline or recommendation that is a goal to be addressed but will not be focused on

3.2 Design Concept Generation and Selection

3.2.1 Initial Design Concepts

After generation the design parameters and specifications displayed in Table 1 above, ten design ideas were created with these specifications in mind. Four final ideas were then selected for consideration and are described in Table 2. The additional six preliminary design ideas can be found in Appendix A.

Table 2: Final Shelter Design Ideas

Design Title	Description
Beehive Design	This design has a hexagonal base that is supported .75 m above the ground to address flooding. The interlock feature is a sliding door on four of the faces which can be extended if there is no connection or opened if two shelters are connected.
Polar Express Car Design	This design is a basic cube shape with a slanted roof for rainfall as well as wheels underneath the structure to easily move shelters together. The interlock connection uses a latch similar to a train car using a U-shaped latch.
Stackable Shelter Design	This design is a unit-based structure that can be customized to any length. The sections are hollowed rectangles that can be connected to desired length along with a back panel at the end. The sections are interlocked using a ball and socket that is pushed together and is airtight as to block any water from flooding.
Drawer Design	This design is a unit with a center structure that houses a smaller unit within it, which would then expand above the base unit. This design does not incorporate an interlock for multiple shelters, but the additional unit does provide more space for the same square footprint.

The Beehive Design is a hexagonal unit with sliding door connections on four of the six walls. The remaining two walls would already be a part of the assembly. The shelter unit is also .75 m above the ground on top of a support system. The interlock parameter is accomplished with a sliding door. These can also be closed in between connected shelters to address the privacy parameter. This design can be seen in Figure 6.

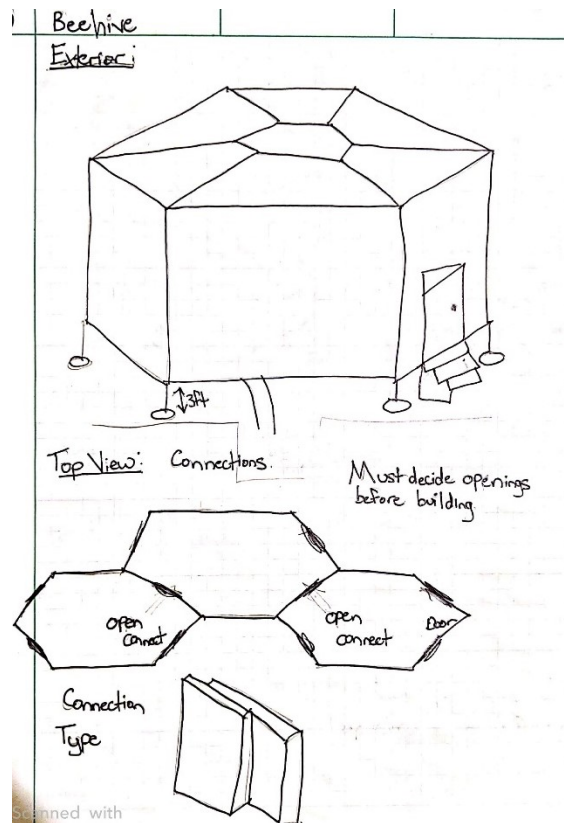


Figure 6: Beehive Shelter Design Sketch

Polar Express Car Design is a unit design with a simple cube structure with an interlock mechanism on the back and front of the shelter. The mechanism is similar to the connection between actual train cars that spring lock together along with a plastic frame that is zipped together. The shelters are also on locking wheels to allow for ease of mobility and easy interchange of connecting different shelters together in addressing the parameter for an interlock that is easily changed. However, these wheels are not good for the flood risk parameter and would be difficult in addressing the parameter of uneven terrain. This design can be seen in Figure 7.

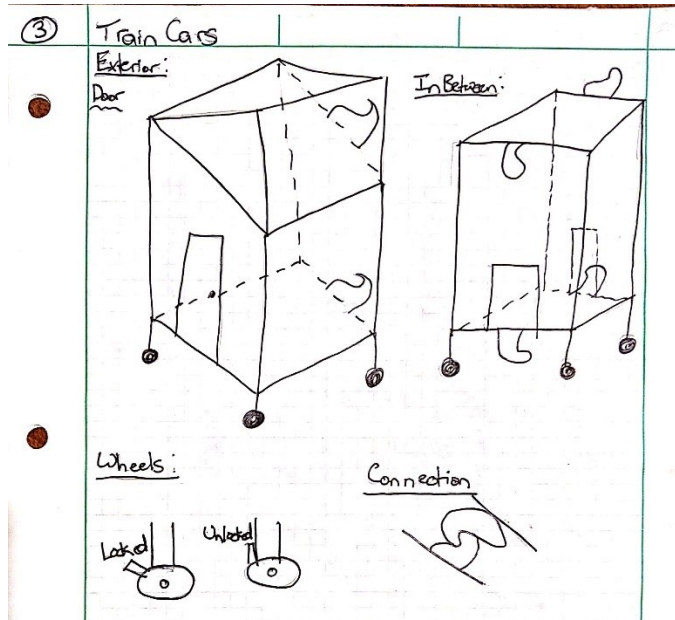


Figure 7: Polar Express Car Design Sketch

The Stackable Design is a unit constructed to a customizable length using framed middle frames along with end frames for the door and back of the shelter. Each section is connected using a sealed ball and socket mechanism that are pushed and locked together to address flood risk. The bottom legs of each shelter extend 1 foot off the ground along with large area feet to allow the structure to be level on uneven terrain. The minimum number of units would be two ends along with a center section in between. This design can be seen in Figure 8.

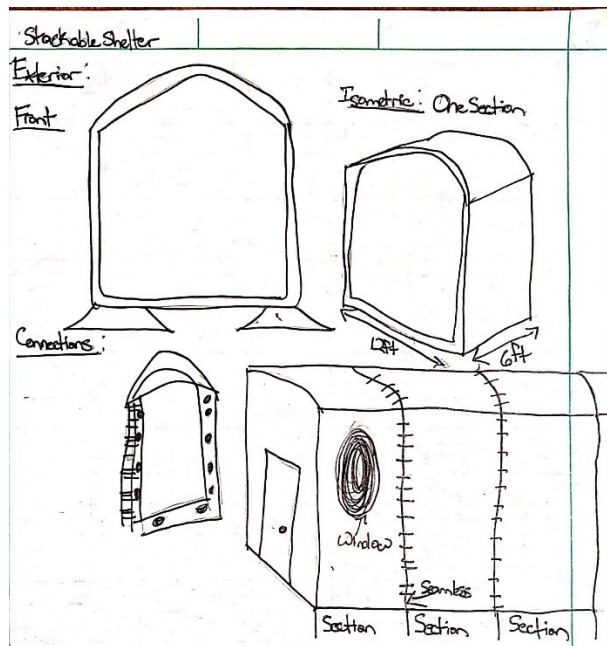


Figure 8: Stackable Shelter Design Sketch

The Drawer Design has a static unit that houses another smaller unit within it which would slide upward to create two separate floors. The smaller compartment walls and roof would already be assembled to reduce assembly time. The walls would have tracks to extend it upward along with a locking mechanism at the top. This design does not incorporate an interlock mechanism, but the additional layer provides more space in the same footprint. This design can be seen in Figure 9.

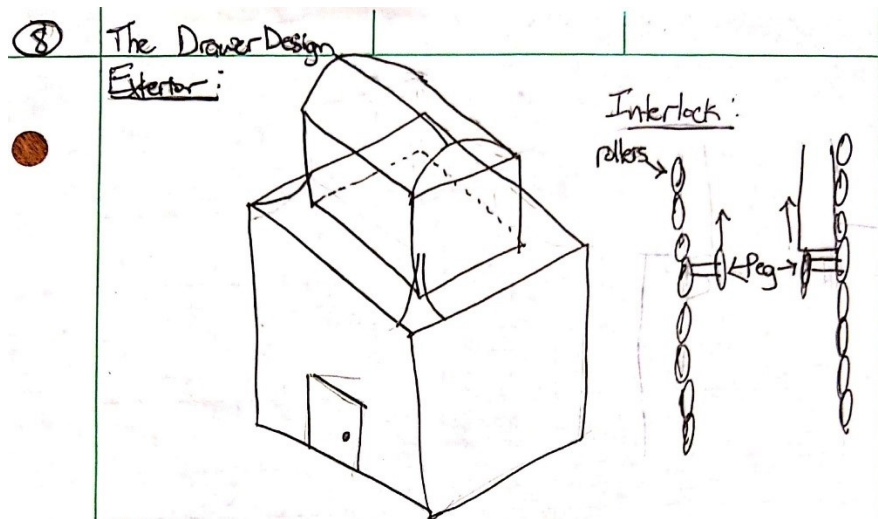


Figure 9: Drawer Shelter Design Sketch

3.2.2 Design Selection

Of the four designs described in Section 3.2.1, two final designs were created incorporating ideas from each. The first design was developed using ideas from both the Beehive Shelter and Polar Express Car Shelter, and the second design was developed using ideas from the Stackable Shelter and Drawer Shelter.

The Beehive Train Car Shelter was a unit that incorporates elements from the Beehive and Polar Express Car design ideas described in Table 2. The shelter is a hexagon like the Beehive design with four sides that can be interlocked. The other openings without the interlock ability act as a door or are closed off with a wall panel. The interlocking mechanism is similar to the Polar Express Car with a U-shaped connection and an accordion frame housing. The seal intends to address the temperature changes and flood risk parameters between the shelters. The units also include a .75 m gap between the shelter floor and ground to address the flood parameter with wheels at the end similar to the Polar Express Train Car. The new combined design can be seen below in Figure 10.

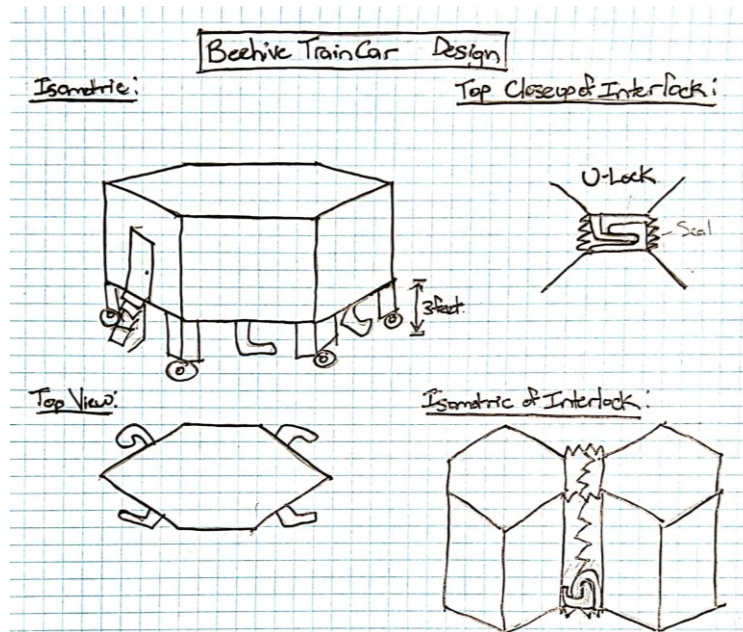


Figure 10: Beehive Train Car Design Sketch

The Stackable Drawer Design Shelter was a unit that combines elements from the Drawer Design and the Stackable Shelter ideas described in Table 2. The shelter shape resembles the Drawer Design where there is a permanent bottom floor unit that houses a smaller unit that is lifted and locked into place. The interlock mechanism from the Stackable Shelter of a ball and socket is incorporated to allow any length of shelters to connect, but this would create an open pocket between the shelters due to the rails to lift up the smaller compartment. This would do poorly in temperatures changes. This also incorporates a feature from the Stackable Shelter of providing a 1-foot gap between the ground and shelter floor to address flood risk and would have the same wide area feet for uneven terrain. The new combined design can be seen below in Figure 11.

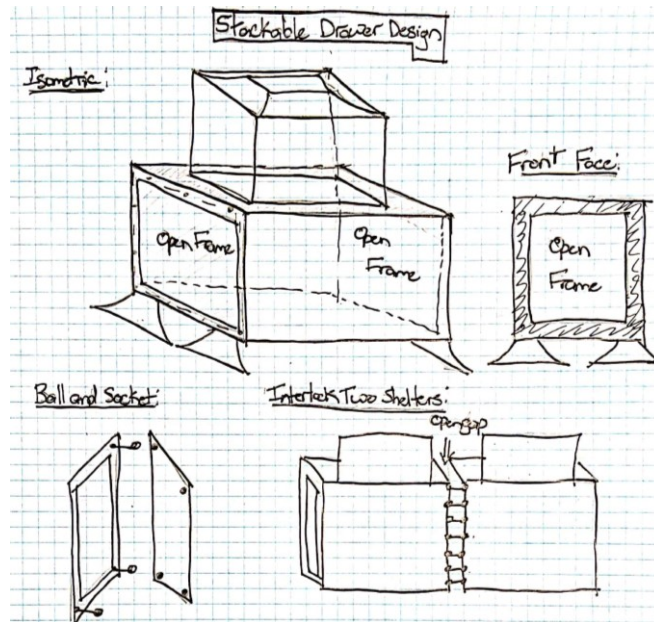


Figure 11: Stackable Drawer Design Sketch

The Beehive Train Car Design and the Stackable Drawer Design were the best solutions based on the ten original design ideas. Both of these ideas were compared using a decision matrix to evaluate their appropriateness compared to the design specifications and weights identified in Section 3.1. For each parameter, the designs were given an absolute ranking from 1-3. Designs that did not meet a specification received a rank of 1, and designs that effectively met a specification and defined it explicitly received a rank of 3. For example, the Stackable Drawer design receives a rank of 2 out of 3 for the interlock since it is able to interlock effectively but has an open pocket due to the required rails for the smaller compartment. This also results in a rank of 2 for the temperature changes for similar reasoning. Since the ranking is absolute, the designs can have the same score for one parameter. These rankings were multiplied by the weights assigned in Section 1.2. Table 3 presents the decision matrix used to select a final concept. Based on the results of the decision matrix, the Beehive Train Car was the chosen design.

Table 3: Design Matrix for Final Design Ideas

Design Parameter	Weight	Beehive Train Car Design		Stackable Drawer Design	
		Rank	Weighted Score	Rank	Weighted Score
The shelter must withstand temperature changes	5	3	15	2	10
The shelter must be able to withstand flood risks	5	3	15	3	15
The shelter units must be able to interclamp	5	3	15	2	10
The shelter must be able to withstand wind loading	4	2	8	2	8
The shelter should have climate control	4	2	8	2	8
The shelter should be safe and secure and provide privacy	4	2	8	3	12
The shelter should have clean water	3	2	6	2	6
The shelter should be lightweight	3	3	9	2	6
The shelter may have a waste management system	2	2	4	2	4
The shelter may be furnished	2	2	4	2	4
The shelter may be customized for different use (Bathroom, Bedroom, Kitchen)	2	2	4	3	6
Total		26	96	25	89

3.1.3 Further Development of the Beehive Train Car Design

The original Beehive Train Car Design is supported by caster wheels to allow mobility. After further research into casters for each of the six corners and center of the structure, the caster with the highest weight capacity each was only 400 lbs. which is not enough to support the entire structure. The caster found can be seen in Figure 12 below. Additionally, the mobility of the shelter could result in unwanted movement of the structure even when it is locked in place.

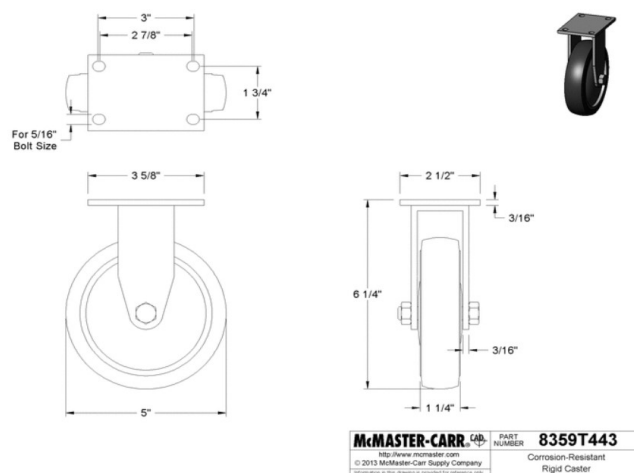


Figure 12: Diagram of Initial Caster Chosen for Beehive Train Car Design (McMaster-Carr, 2013)

To eliminate this issue, leveling feet were used to replace the casters under each of the seven pegs. These can withstand a larger weight capacity of up to 20,000 lbs. each. Additionally, this provides stability to the structure on uneven terrain since the height can be adjusted. In addition, the interlock mechanism was adjusted to accommodate the fact that shelter units now were not meant to easily roll and connect on the U-Shaped latch. This interlock design also required a separate fabric or plastic seal frame around the interlock which would create a pocket with less insulation. To eliminate this issue, the interlock mechanism was adjusted to resemble a puzzle piece configuration. The floors would be cut on four of the sides where half of the side would be cut off and could be connected together. The puzzle piece design is shown in Figure 13 below along with the hinged panel. Also due to this change, the name of the final design was changed to be the Beehive Puzzle design from this point forward.

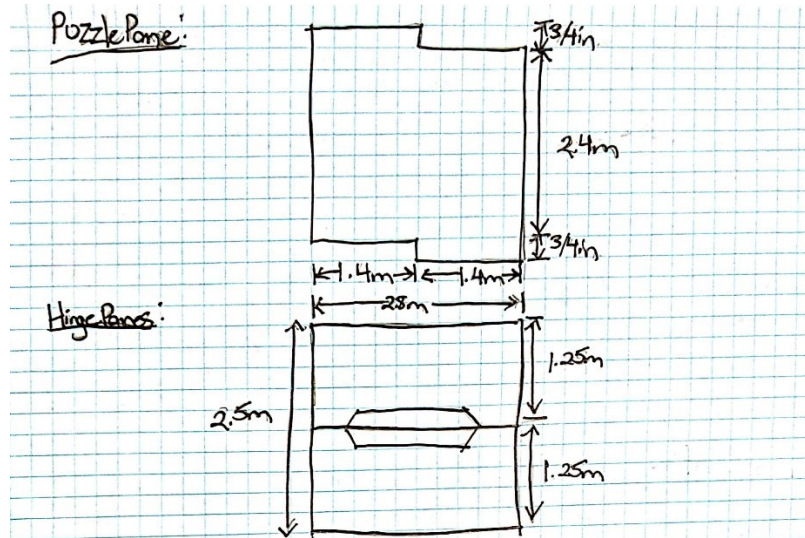


Figure 13: Puzzle and Hinged Wall Panels for Beehive Puzzle Design

4.0 Final Design Optimization and Assembly

This section describes decisions and additional details for components of the Beehive Puzzle shelter design as well as an assembly guide. These decisions were made to ensure structural integrity of each component including the roof, walls, floor, the interlock system, and additional support systems.

4.1 Structural Design Decisions and Details

After selecting the Beehive Puzzle design for further development, there were decisions made regarding the dimensions, material selection, the subfloor support system, interior framing, and the assembly process. These choices were driven by the need to develop a shelter that is modular and can be connected with others and withstand common loads.

4.1.1 Sizing and Dimensions

The required interior square footage dimensions were considered to determine an effective size of the shelter. The maximum exterior dimensions were restricted by federal shipping requirements. These requirements can be found in Section 2.1.5.

The floor, wall, and roof panels were designed to fit within the dimensions of the truck. The floor layer was made with half floor panels which also had two pre-attached hinged walls and could hold four floor panel assemblies in one layer with a height of 9 inches. The wall layer was made with six walls stacked side-by-side with a height of 4 inches. The roof layer can fit two on each of the floor panels so only six total panels in one layer. Using the height limit of 8.5 feet, six floor and wall panel layers could fit stacked on one truck which would provide 36 wall panels and 24 floor panels. The remaining hardware and subfloor would be on a separate truck. The diagram for sizing and be seen in Figure 14 below. This is a very rough estimate and only applies to the panel assemblies without the required hardware.

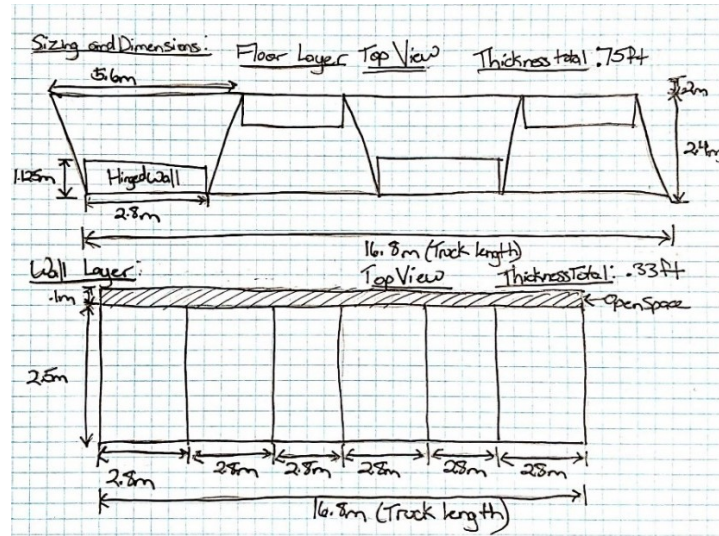


Figure 14: Floor and Wall Layers in Bed of Semi-Truck

The interior dimensions was sourced from section 1.7.1.2 of FEMA 453, *Safe Rooms and Shelters*, requirements stating that a shelter for long-term stay requires a minimum of 40 ft² (3.7 m²) of floor space per person (FEMA, 2006). The floor panel provides 160 ft² (14.87 m²) of floor space, so each unit has a capacity of four people.

4.1.2 Roof

The roof design consists of a hexagonal shape with angled triangular panels that are placed on top of the shelter assembly one at a time and attached to a center peg. Figure 15 shows the triangular component as well as the complete hexagonal roof. The roofing material must be custom cut and provide resistance against environmental factors including sunlight, temperature changes, and rainfall. Although a detailed analysis was not completed for the selection of the material, two materials were considered for this project by comparing their key features. The first material was corrugated steel roof panels. This material minimizes cost, can be purchased in large quantities, and is easy to assemble. The panels are resistant to rot but are not vulnerable to insects. The panels can also be treated to prevent algae growth. However, the panels do not provide any insulation, so an additional insulated frame needs to be applied which would make assembly more complex. Figure 16 shows a building with a corrugated steel roof.

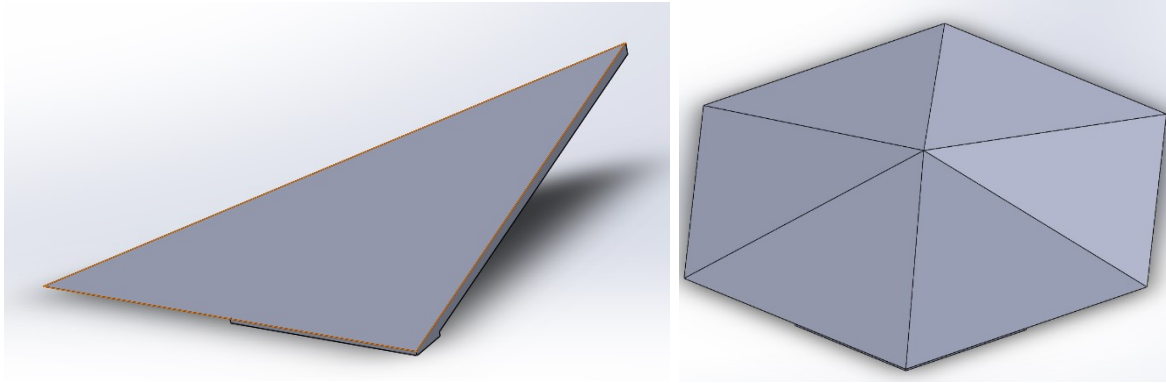


Figure 15: Triangle Roof Component and Complete Roof of Beehive Shelter Design



Figure 16: Example of Corrugated Roof on a Cabin (Riverside Sheet Metal, 2019)

The other roof material considered was PermaTherm insulated metal panels. These panels are constructed with a 4-in. (10.16-cm) layer of expanded polystyrene (EPS) reinforced with a sheet of 26-gauge galvanized steel on both sides. The EPS provides an insulation R-value of 16.68 and the steel provides a yield strength of 207 MPa. Since these panels need to be custom cut, the price per square foot estimate is \$6.50/ft² (PermaTherm Representative, personal communication, February 25, 2020). These panels also do not require any protective outer material, so they would be easier to assemble than the corrugated roof since the corrugated roof requires assembly of the roof and then the insulation layer separately. Figure 17 shows a roof equipped with PermaTherm panels. Due to better strength and insulation, the PermaTherm EPS panels were the chosen material to construct the roof.



Figure 17: PermaTherm Roof Panels Being Used in Industrial Setting (PermaTherm, 2019)

4.1.3 Walls

For this design, there are two types of walls. The first type is a hinged wall panel. These span half the height and are shipped as a pre-assembled component to one floor base half. This is done using a hinge that needs to be designed in the future to support the weight of the panel. Once upright, the hinged panels are supported by the internal steel frame. The initial panel assembly before setup can be seen in Figure 18 below. The final panel assembly can be seen in Figure 19 where both of the hinge panels are upright.

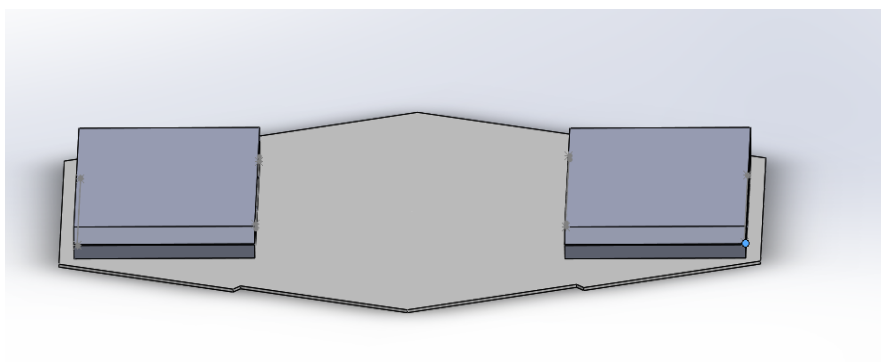


Figure 18: Hinged Panels Folded Down

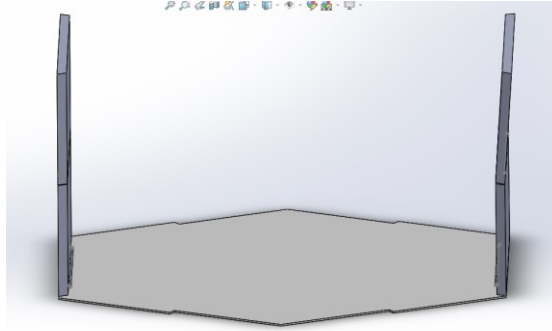


Figure 19: Hinged Panels Folded Up

The second type is the puzzle piece wall panel. These panels have slits going along half the length on the top and bottom of the panel to resemble the shape of the floor base. The puzzle piece panels can be seen in Figure 20 below. For material selection, the PermaTherm metal insulated panels were also used due to its insulation and strength as described for the roof.

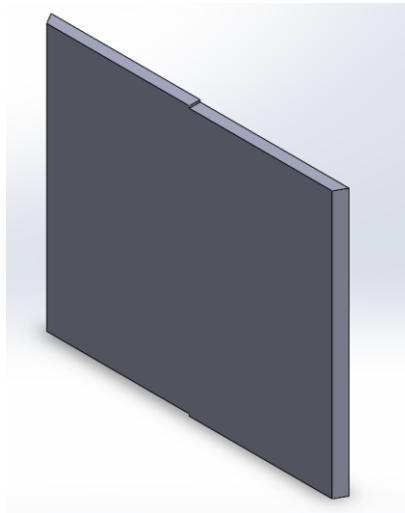


Figure 20: Puzzle Wall Panel Isometric View

4.1.4 Floor

The floor design incorporates the main portion of the puzzle piece interlock feature. This is done by removing half the length on four sides of the hexagon. This cutting sequence can be seen in Figure 21 below. This design allows for only two of the opposing sides to be interlocked at a time, where the same colors indicate where two interlocks can happen at the same time. In this case, two shelters can be connected to the green circles or two to the blue circles but not both at the same time.

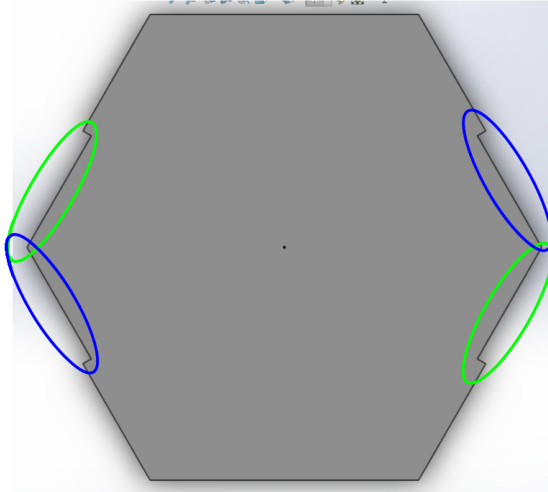


Figure 21: Floor Base Cutouts Showing Interlock Locations Where Only Similar Colors can be Connected at the Same Time

There were two options considered for the floor material. The first material was plywood as it is a common construction material for interior building. However, since these shelters will be in an external environment with high flood risk, the plywood would be prone to developing mold. Applying a resin or additional layer is possible but would require additional assembly steps.

The second material evaluated was Coosa Board, a polyurethane foam board reinforced with woven layers of fiberglass. This product is resistant to mold and is considered a replacement for plywood in applications with high moisture exposure. The chosen thickness was 0.75 in (20 mm) thick and can be mounted to floor studs. Coosa Board provides strength similar to marine plywood along with resistance to mold and a longer lifespan than regular plywood (Coosa Composites, 2019). Therefore, Coosa Board was the chosen material for the floor panels. Figure 22 shows the Coosa Board Bluewater 26 which is used for analysis in Section 5 below.



Figure 22: Coosa Composites Bluewater 26 Board. Reprinted from Boat Outfitters, by Coosa Composites, retrieved from <https://www.boatoutfitters.com/coosa-composites-board-bluewater-26>. Copyright 2020 by Boat Outfitters

4.1.5 Subfloor Support System

The Beehive Puzzle Design requires a subfloor support system that can withstand the weight of the structure along with the distributed load from furniture and point loads from humans inhabiting the shelter. The subfloor system was originally designed with aluminum I-beams around the perimeter and connecting to the center peg. The diagram of the I-beam and specifications provided through OnlineMetals can be seen in Figure 23 below. The original subfloor system can be seen in Figure 24 below.

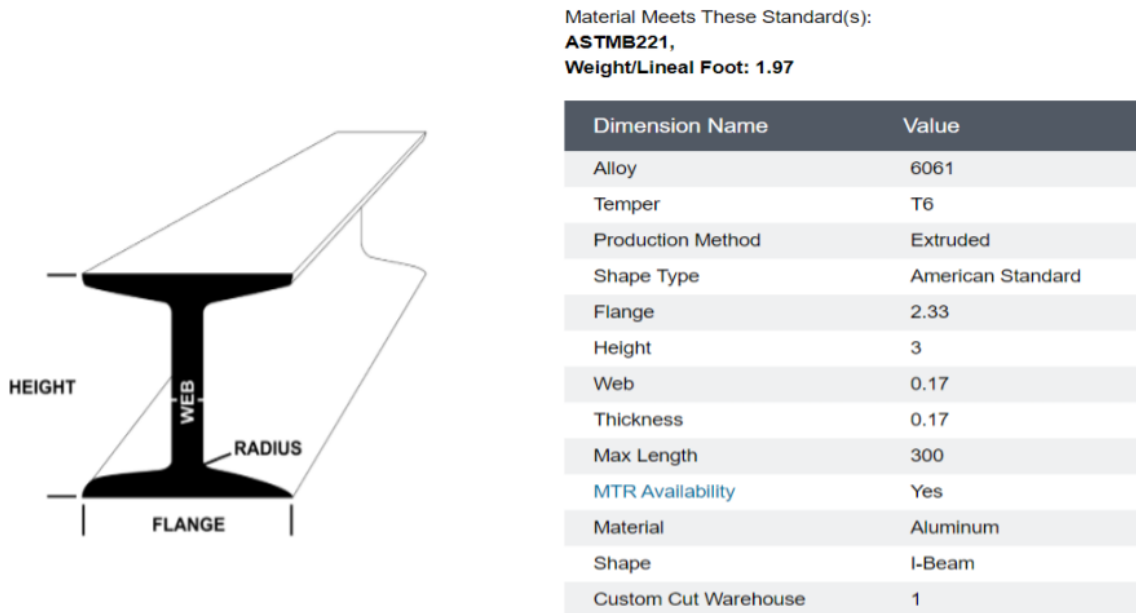


Figure 23: Aluminum I-Beam Diagram and Specifications for Subfloor System Connections (OnlineMetals, 2020)

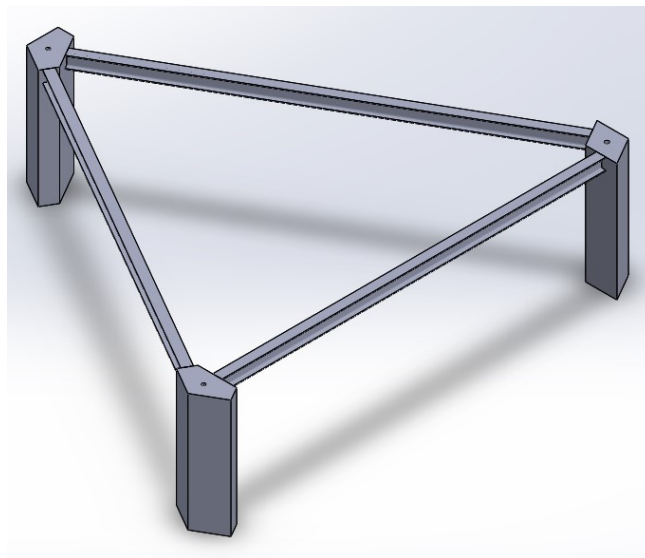


Figure 24: Original Subfloor System

Since the pegs and levelers raise the floor .75 m above the ground, this basic design would most likely not be able to withstand the weight of the structure. To address this, four additional designs were created to be tested for the described loading. The first design is the T-Support with a horizontal I-beam across the triangle and a vertical piece extending from the middle of the first new I-beam. The second design is the Thirds support system where an I-beam is extended from the midpoint of each of the triangle sides and attaches to an additional center peg. The third design is the Zelda support system that starts with a horizontal I-beam similar to the T-Support but then adds two extending from both sides of the first I-beam to the bottom I-beam. The fourth design is the Orthogonal support system that has I-beams extending perpendicular to each side of the triangle and meet at a large center peg. These designs can be seen in Figure 25 below.

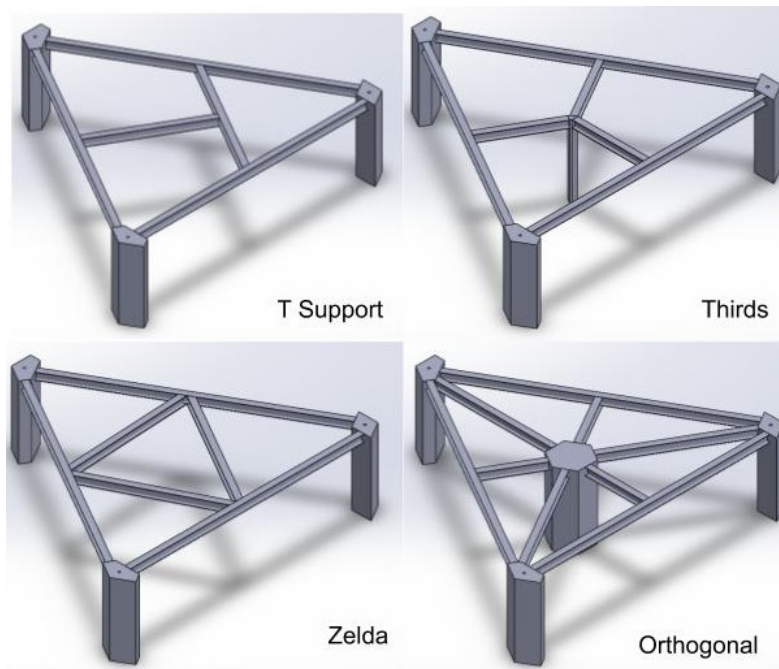


Figure 25: Subfloor Support System Design Ideas

4.1.5 Interlock Mechanism

The Puzzle Beehive Design has a puzzle interlock mechanism as the main component for allowing shelters to be connected to one another. The connection is made using a waterproof seal between the floor panels with both wall sides removed from each shelter. The interlock is then sealed on top of the shelter where the roof meets. The decision for how multiple shelters are connected must be decided before assembly as this connection is done before the walls are installed. One example of the connection organization can be seen in Figure 26 below.

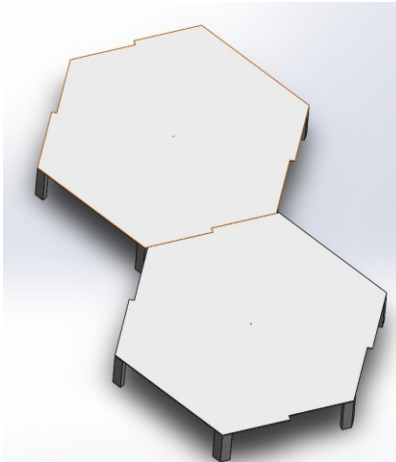


Figure 26: Example of Interlock Connection Between Two Floor Assemblies

4.1.6 Leveling System

The unit requires a leveling system to ensure that the interior floor surface is flat and that there is no unnecessary stress due to uneven terrain causing one peg to be much higher than another. This was achieved by mounting corrosion-resistant stainless-steel leveling feet to the bottom of each of the seven pegs. These leveling mounts have a weight capacity of 20,000 lbs. each and allow vertical adjustment during assembly. The specific leveling mount chosen leveling feet have a 20 mm diameter threaded screw that allows for height adjustment of up to 200 mm. The feet also can swivel on a ball bearing with a range of motion up to 7.5 degrees. Additional specifications can be found in Appendix C. The diagram of the leveling foot can be seen in Figure 27 below from the McMaster-Carr specification sheet in Appendix C.

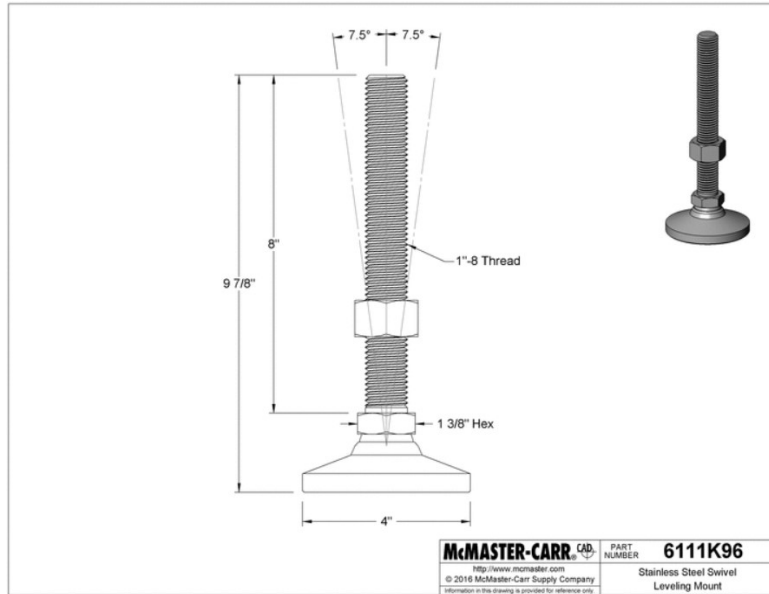


Figure 27: Diagram of Leveling Mount for Subfloor Support Pegs (McMaster-Carr, 2016)

4.1.8 Interior Framing Support System

Since the walls do not have enough strength to hold the roof, an interior framing system was constructed. It is important to note that this is only an initial design and no dimensions have been analyzed for the framing material. This framing system will be built on the inside of the structure before the walls are erected. There are two configurations to accommodate the doorway required either for entrance into the shelter or between two shelters through an interlocked piece. The base frames for both configurations can be seen below in Figure 28. These are bolted to the floor assembly and assembled next to each other with a gap of 60 degrees between each frame. There must be at least one door frame configuration for each shelter unit. The door configuration is used for either have an interlock, or the exterior door and the default configuration framing is used for all wall panels. In addition, a hexagonal center steel frame is used for connecting the roof assembly. A complete steel frame assembly on the floor base can be seen in Figure 29 below.

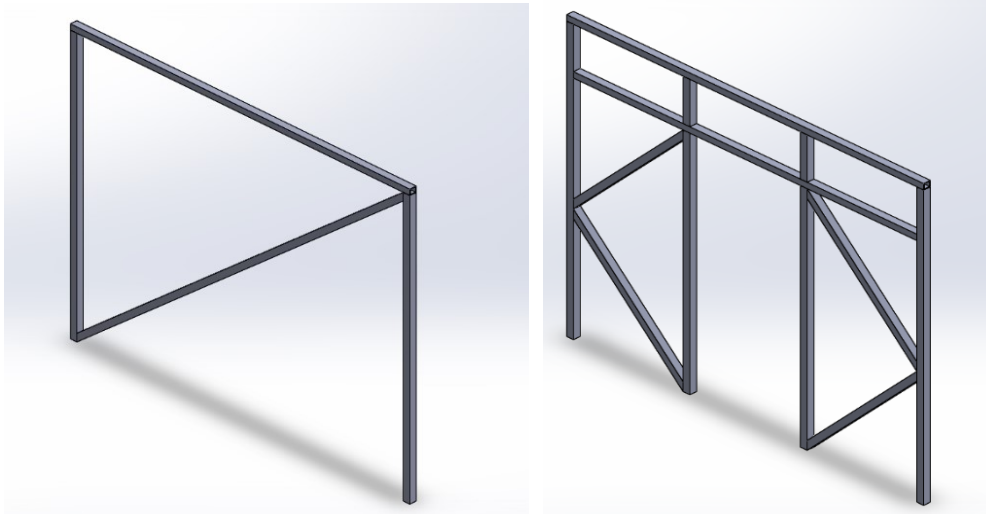


Figure 28: Cross and Door Steel Frame Structures

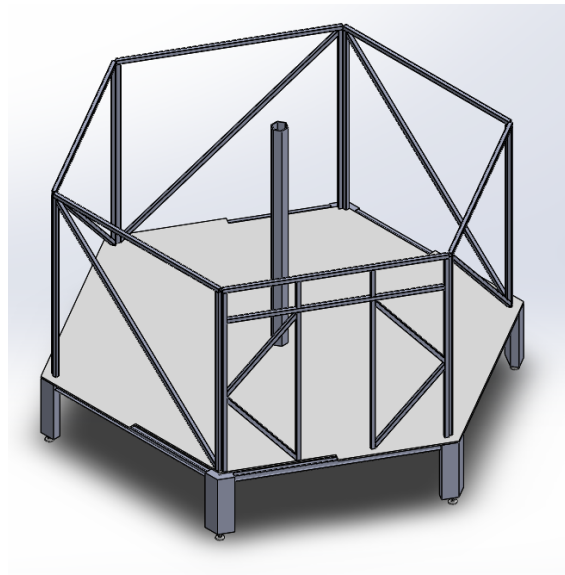


Figure 29: Complete Steel Frame on Top of Floor Assembly without Hinged Walls to Show Steel Frame Individually

4.1.7 Other Systems

Electricity, air ventilation, and plumbing systems will not be designed as part of this project. There is room for piping underneath the structure and could also incorporate a flood prevention system due to its height. The air handling can be done using a window air-conditioner as well installing a vent in the roof. For electricity, the design should be able to have room for electrical wiring, but this was not considered in this project.

4.1.8 Layout and Housing Requirements

The interior of the shelter must include basic living requirements for four people. This includes waste removal, plumbing, kitchen appliances (hotplate and refrigerator), and adequate space to sleep. This project did not include a floor plan to orient the placement of the required interior but does have the required square footage for four people.

The shelter also requires a door, windows, and stairs. A single 32 in. by 80 in. cut in one of the puzzle piece PermaTherm wall panels served as a door frame for the unit. This meets the width and height requirements for a common door for exterior entry and exit. The puzzle panel showing the door frame and door itself can be seen in Figure 30 below.



Figure 30: Puzzle Panel Door Frame and Door

Two 12 in. by 36 in. windows were cut into one of the puzzle panels on the opposite side of the door. These can also be present for the hinged walls, but the windowpanes need to be installed as part of assembly on site (Ringer Windows, 2020). Finally, stairs were designed based on 1009.4.2 Riser Height and Tread Depth Code. The dimensions of the stair assembly can be seen in Figure 31 below. A handrail also had to be installed to meet these similar standards which had a height of 36 in. (.915 m), and a width of 3.5 in (89 mm) (IBC, 2012).

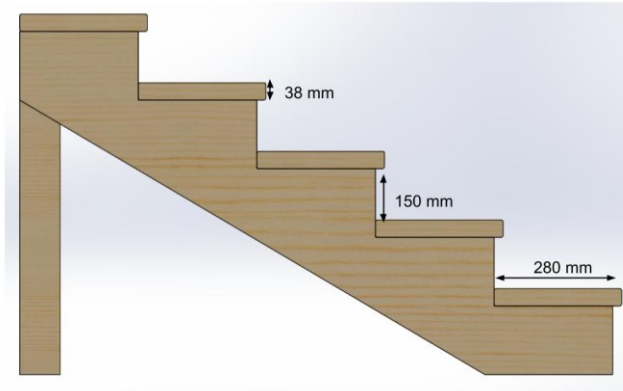


Figure 31: Staircase Side View with Required Dimensions

4.2 Overview of Step-by-Step Assembly of Shelter

When arriving at a site, the shelter has pieces that need to be assembled with minimal machinery and basic mechanical tools. This section describes the logical steps in order to assemble one modular shelter as well as instructions for interlocking two floor assemblies. These instructions only provide details for the components analyzed and is not adequate to completely assemble this shelter. Each assembly consists of the following pieces:

- Seven (7) Leveling Mounts
- Three (3) Triangle Subfloor Supports (See Figure 32)
 - Two (2) side pegs
 - One (1) third center peg
 - All I-beam connections
- Additional I-Beams for subfloor supports
- Two (2) Trapezoid Floor Sections (See Figure 33)
 - Trapezoid Floor Section
 - Four (4) Hinge Wall Half Panels
- Four (4) Puzzle Wall Panels
- Six (6) Triangle Roof Panels (See Figure 34)
- Square Frame Steel Beams
 - Basic Cross Frame
 - Door Frame (For Exterior Door and Interlock Panels)

- Door, Stairs, and Windowpanes
- Required hardware (Note: for this project, most hardware was not considered and assumed to be a part of the assembly. Although hardware is considered, there are not detailed instructions for this part of the assembly.)

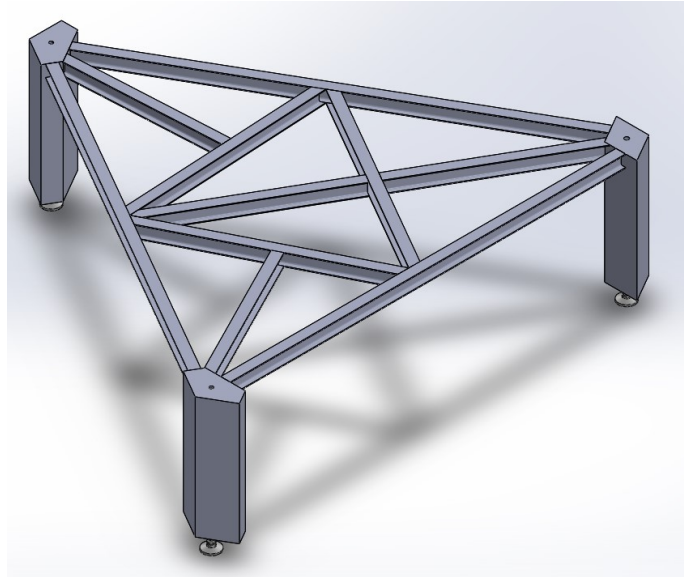


Figure 32: Reinforced Zelda Subfloor Support System

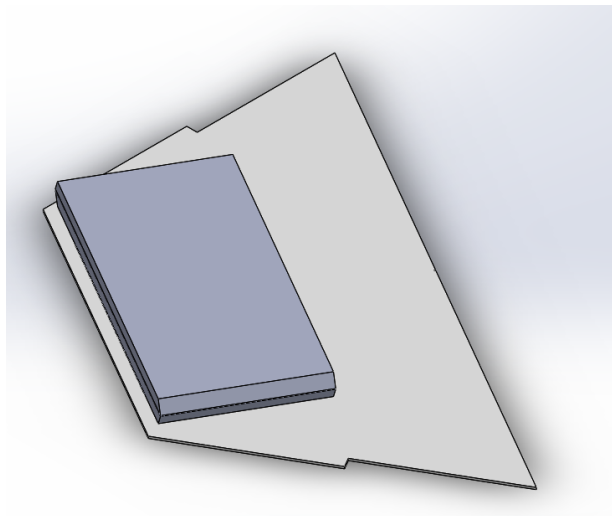


Figure 33: Trapezoid Floor Section with Hinged Wall Panel

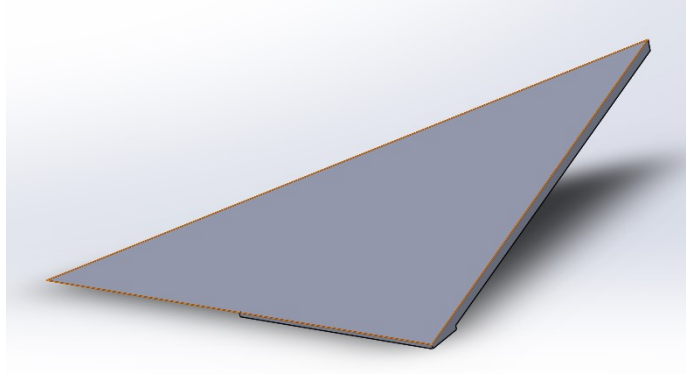


Figure 34: Triangle Section of Roof Panel

The first step is to thread the leveling mounts on the bottom of each of the pegs in the Triangle Subfloor Supports. Once threaded, they will look similar to the model in Figure 35 below.

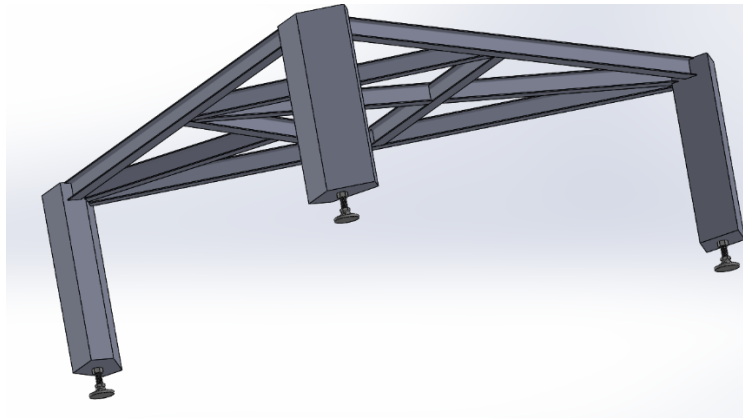


Figure 35: Threaded Levelers on the Subfloor Support System

Once three of the subfloor supports have been threaded, attach the three of them using necessary hardware at the center peg to form a hexagon. Each step of attaching two together and then three together is seen in Figure 36 below.

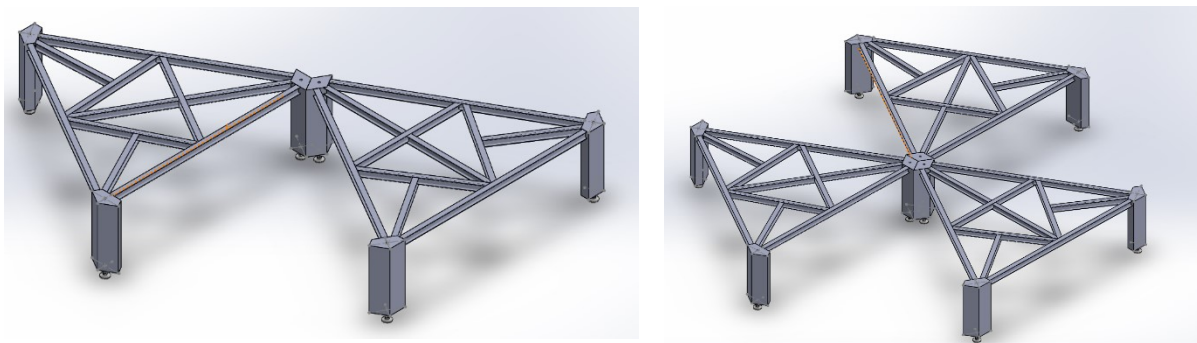


Figure 36: Assembly of Two and Three Subfloor Support Systems

Once the three are together and level, connect the additional I-beams to match the shape constructed in each of the triangle subfloor supports using a bolt and bracket setup. The progress steps for adding each set of additional I-beams can be seen in Figure 37.

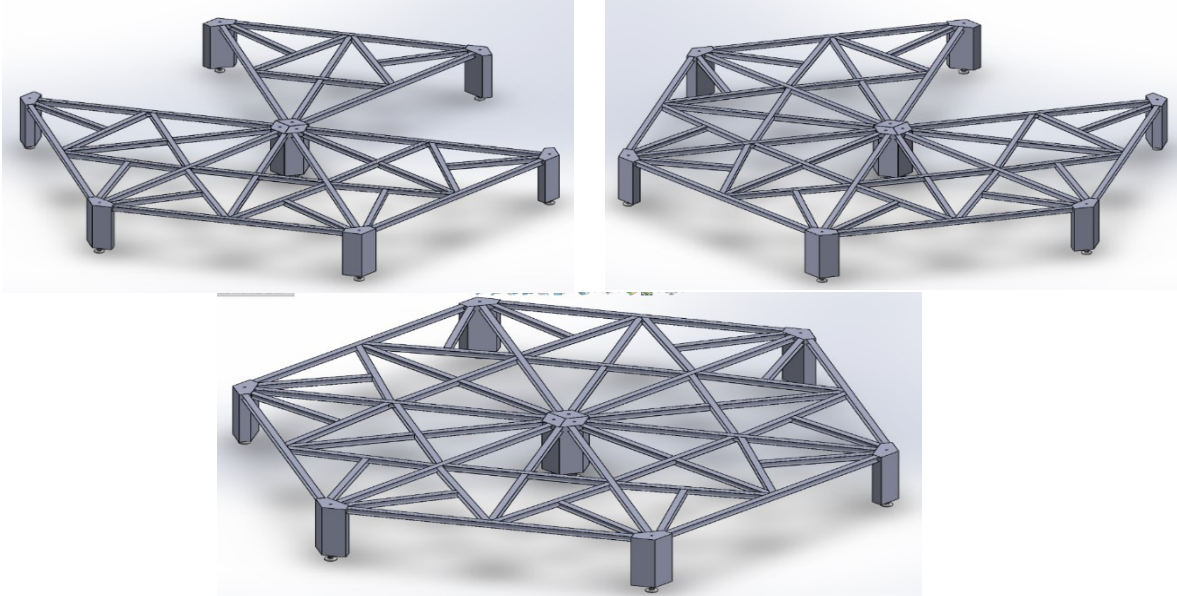


Figure 37: Process Steps for Additional I-Beams in Subfloor Support System

The next step is to place the two trapezoid floor panels with the hinged walls attached on top of the subfloor system just built. Attach the floor assembly using provided hardware to the subfloor system. Next, open both of the hinged walls attached to the floor panel and lock into place. Figure 38 shows the process from opening one and then both hinged wall panels.

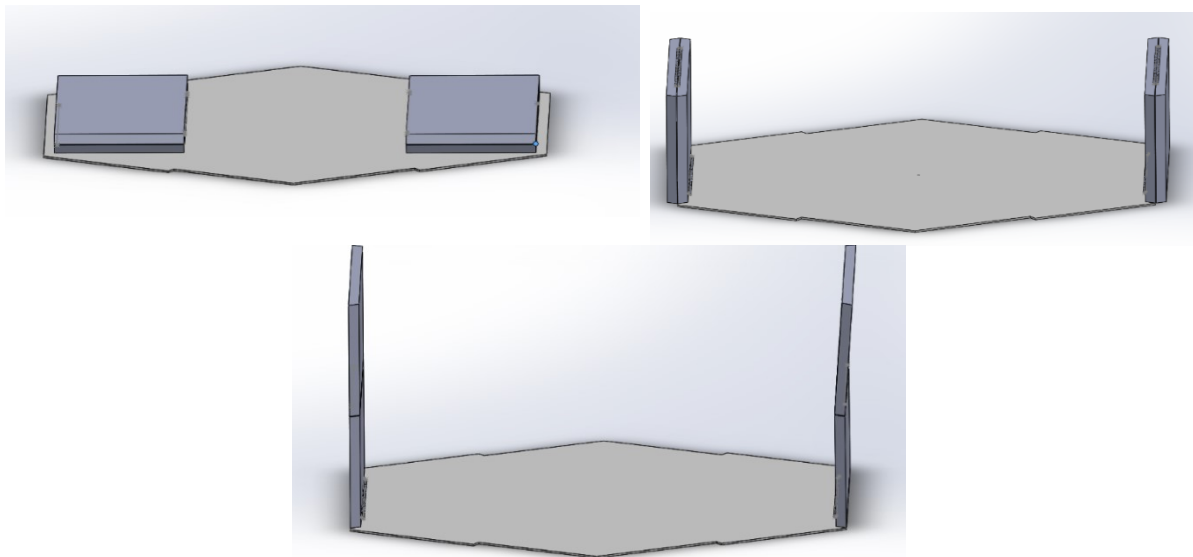


Figure 38: Process Steps to Assemble Hinged Walls on the Floor Base

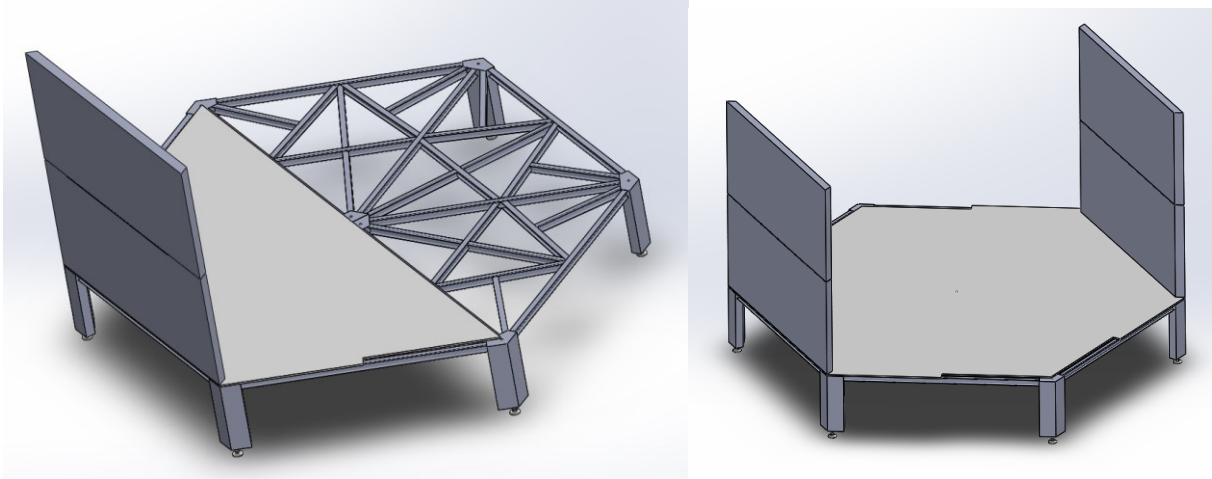


Figure 39: Complete Floor Assembly Progress Check

Figure 39 above shows the progression from attaching each half of the floor to the subfloor support system. Next, the steel frames are built based on whether a door or default configuration is needed. For this assembly, there will only be one door steel frame for the exterior door. The frames are assembled in Figure 40 below. This figure also shows where the exterior door puzzle panel will have to go based on the steel frame used.

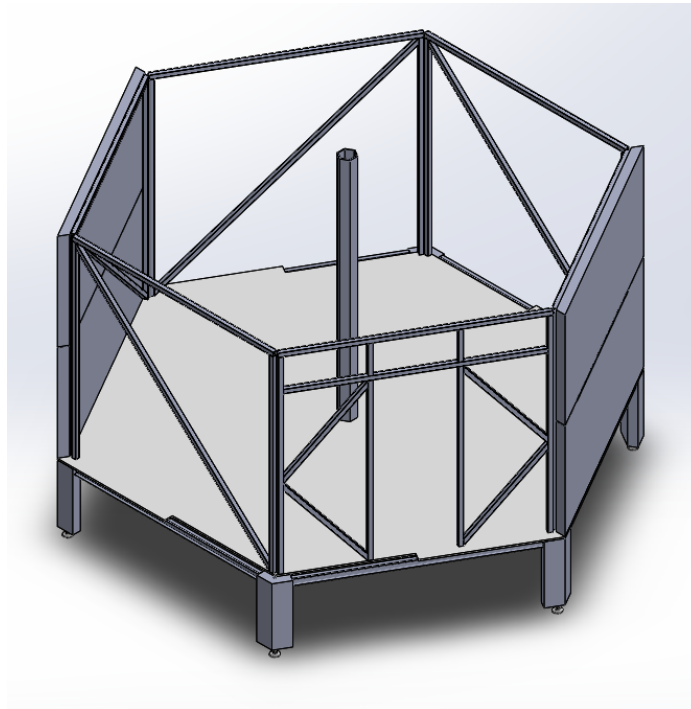


Figure 40: Floor Assembly with Full Steel Frame and Hinged Wall Panels

The remaining four walls are then mounted to the assembly. This assembly also includes a puzzle panel with windows as can be seen in Figure 41 below.

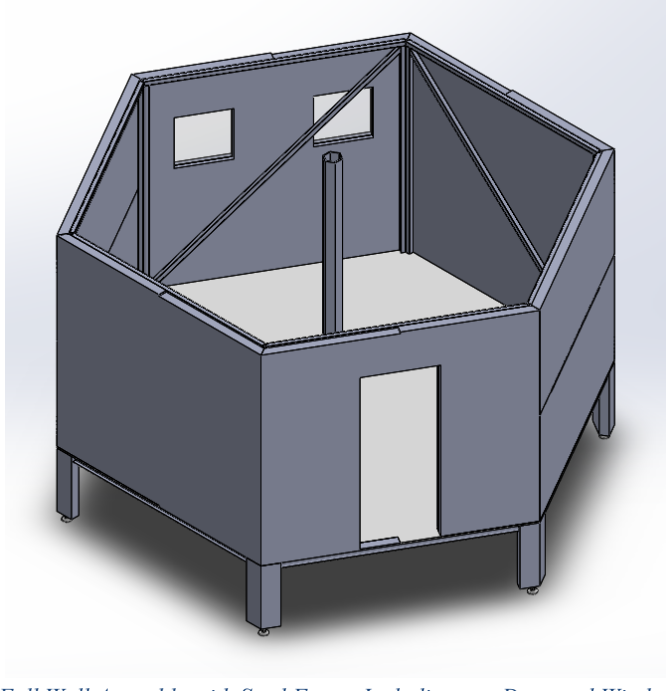


Figure 41: Full Wall Assembly with Steel Frame Including one Door and Window Wall Panel

Next, the triangle roof panels are placed on top of the wall assembly using a crane. The triangle comes in contact with the wall frame and the center peg and is attached using supplied hardware. The progression of adding the triangle roof panels can be seen in Figure 42 below.

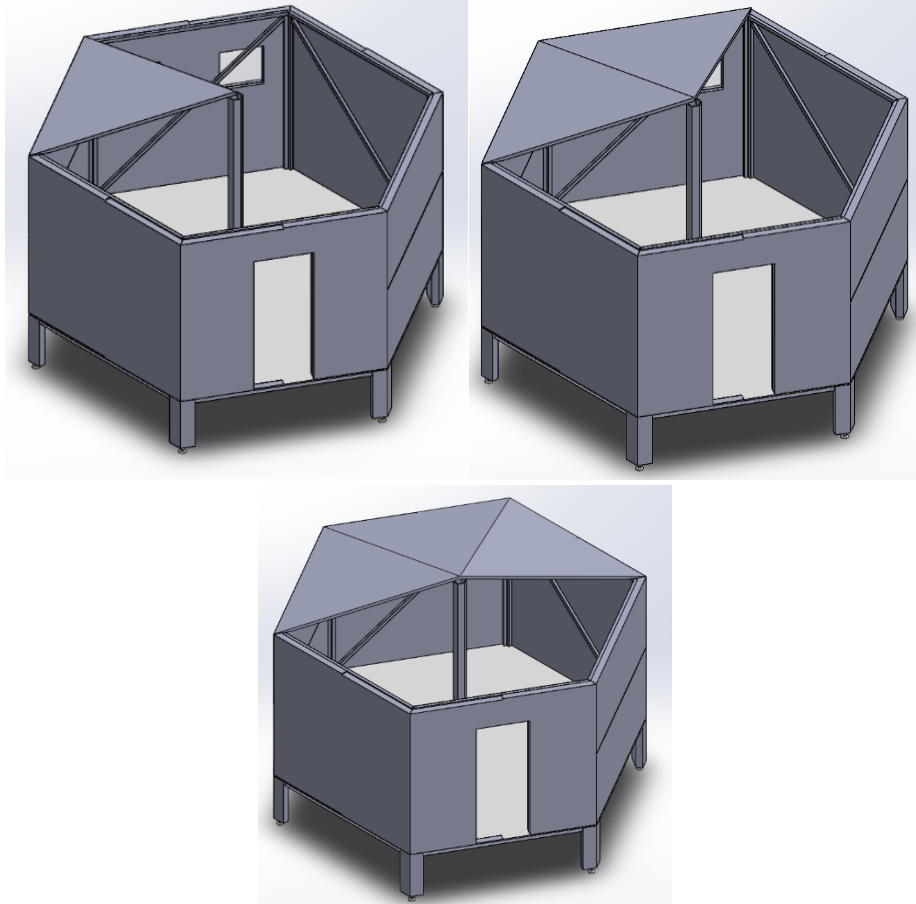


Figure 42: Progression of Triangle Roof Panel Assembly on Beehive Shelter

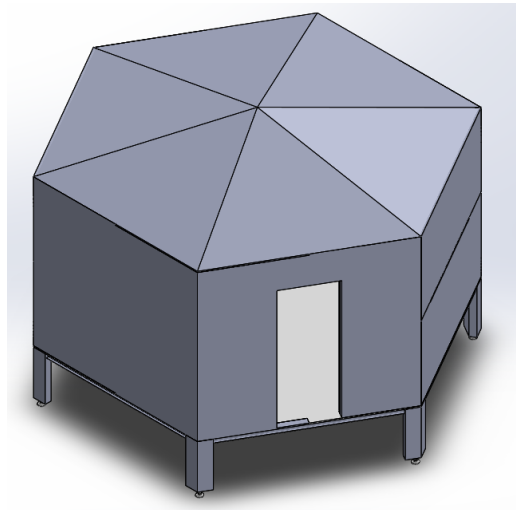


Figure 43: Full Assembly with Roof

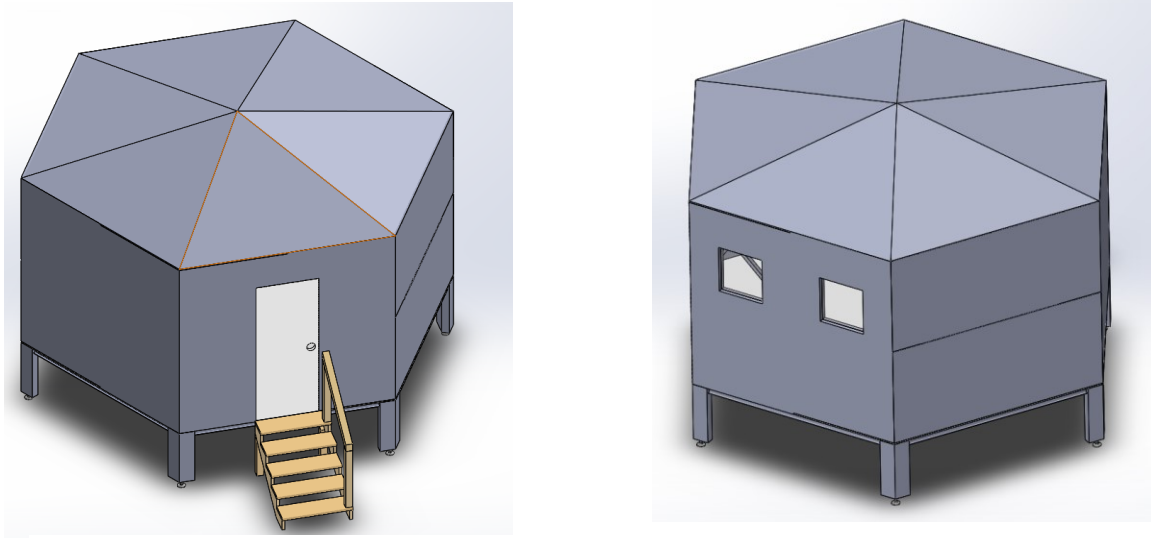


Figure 44: Front and Back of Complete Shelter Assembly

Finally, the door, windows, and staircase are added to the assembly using the provided hardware. Once all of these are added, the shelter is complete as can be seen in Figure 44 above.

For adding an interlocked portion, the process for assembly is very similar. The same procedure is followed when both of the subfloor systems are built with the floor panels on top. The two are attached using provided hardware as can be seen in Figure 45 below. Then, the remaining assembly steps are followed.

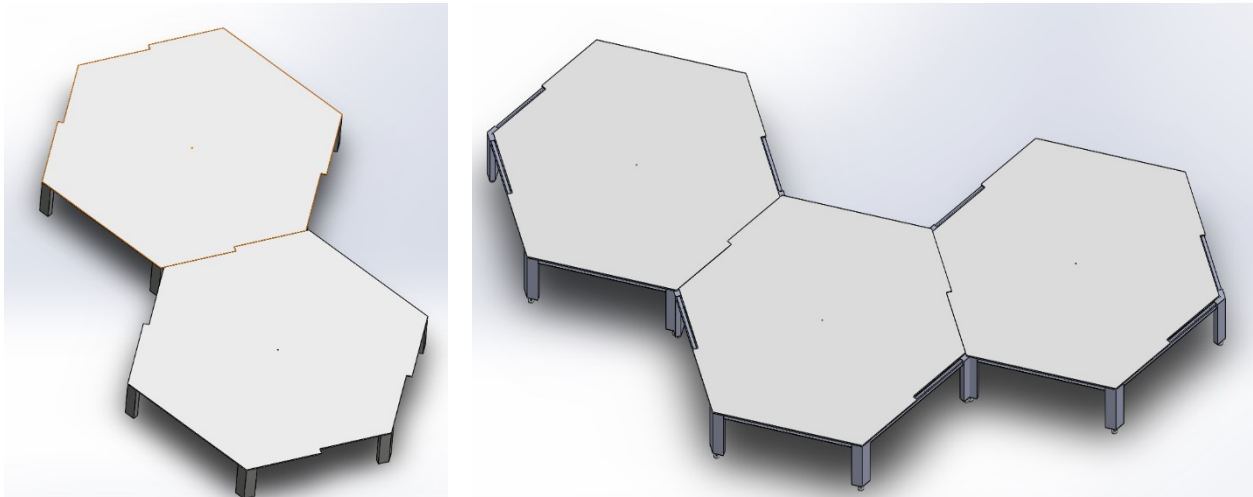


Figure 45: Interlock Assembly Between Two and Three Floor Assemblies

5.0 Analysis and Verification

5.1 Finite Element Analysis (FEA)

The finite element analysis (FEA) software ANSYS was used for evaluation to ensure structural integrity of the subfloor system based on equivalent stress and deformation failure criteria. ANSYS outputs stress and deformation results for a total distribution points across the entire model which are referred to as nodes. The FEA methods used in ANSYS were first validated through hand calculations. Then, the proper mesh sizing was found through a manual convergence study. Finally, results for equivalent stress and deformation for the actual subfloor models were obtained and compared to industry standards for construction safety factors.

5.1.1 Validation Through Hand Calculations

To verify the accuracy of the modeling techniques and loading conditions, a simply supported beam was subjected to bending via a distributed load in ANSYS. The results were then compared to hand calculations completed using Microsoft Excel software.

The calculation was performed by modeling a 40 mm x 40 mm x 1000 mm square steel beam as a simply supported beam. The supports for this beam were a pin at the left end and a roller at the right end. This can be seen in Figure 46 below.

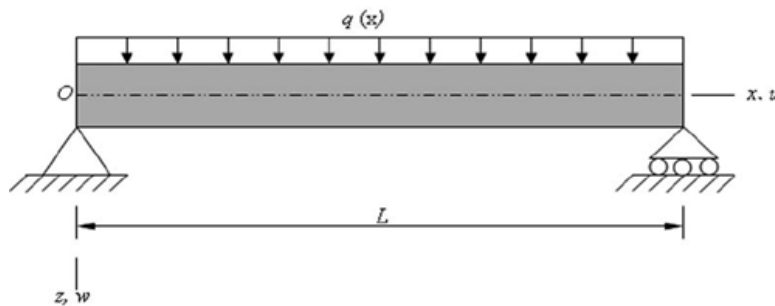


Figure 46: Diagram of Simply Supported Beam

A distributed load is applied along the beam with a value of 5 N/mm. The first calculated value was the maximum bending stress using the following two equations where the maximum moment is found followed by the bending stress:

$$M_{max} = M\left(\frac{L}{2}\right) = -\frac{FL^2}{8}$$

Where M is the maximum moment occurring at the center of the beam, F is the distributed load (N/mm), and L is the length of the beam. The formula to find the bending stress is below and was used for hand calculations:

$$\sigma_{max} = |M_{max}| * \frac{c}{I} = \left| \frac{FL^2}{8Z} \right|$$

Where σ_{max} is the maximum normal stress due to bending (MPa), M_{max} is the moment along the beam at the center of the length (N*mm), c is the distance from the neutral axis to the edge in the cross section (mm), I is the moment of inertia (mm⁴), and Z is the section modulus (mm³).

The second calculated value was the maximum deformation occurring at the center of the length of the beam using the following equation for maximum deformation:

$$w_{max} = w \left(\frac{L}{2} \right) = \frac{5FL^4}{384EI}$$

Where w_{max} is the maximum deformation occurring at the center of the length (mm), F is the distributed load (N/mm), E is the Young's Modulus of the material (N/mm²), and I is the moment of inertia (mm⁴). These calculations assume that the stresses and loads are evenly distributed and utilize a mesh sizing 20 mm squares along the surface area. The hand calculations evaluate a 3D model of the beam similar to the model developed in ANSYS with a fixed support on the left and right edge and the force load distributed on the top face. The results of total deformation can be seen in Figure 47 below. The full calculations can be found in Appendix B.

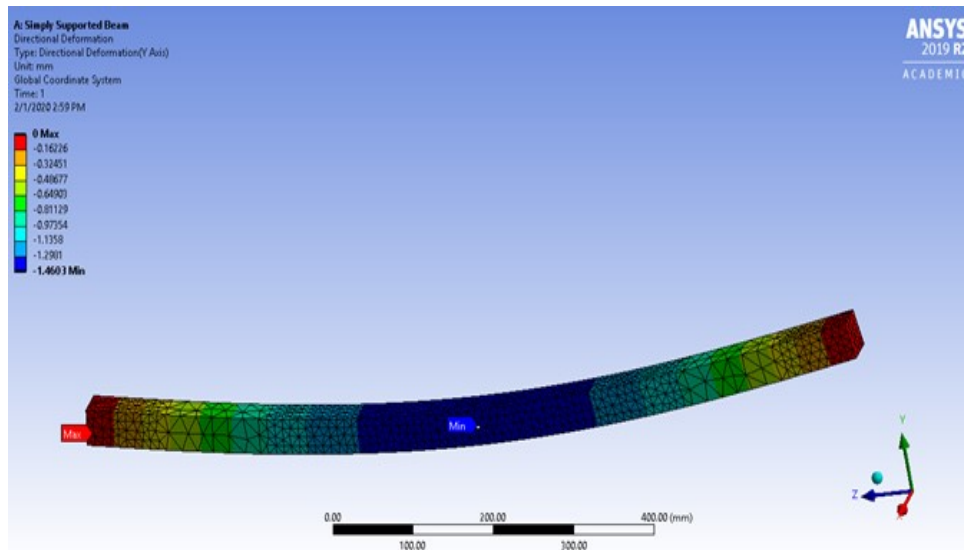


Figure 47: Total Deformation of Simply Supported Beam of the Max Deformation at the Center of -1.4603 mm

The comparison of the maximum bending stress and maximum deformation values in Table 4 shows the comparison of ANSYS and Excel results. Based on the low percent error between the values, the conclusion was that the values were similar to validate the accuracy of ANSYS modeling for Finite Element Analysis (FEA).

Table 4: Comparison of ANSYS and Excel Hand Calculation Results

Resulting Value	ANSYS	Theoretical Calculation	Percent Error, %
Maximum Bending Stress, MPa	58.626	58.594	.055
Maximum Deformation, mm	-1.460	-1.453	.479

5.1.2 Mesh Convergence Analysis

A mesh convergence analysis was performed for the FEA analysis for the subfloor support system to ensure the accuracy of the model within ANSYS. There were multiple instances of the same analysis performed on the basic subfloor support with a decrease in the mesh size for each iteration. The triangle section of a subfloor component was modeled in ANSYS, fixed on the bottom supports and at all three edges with a distributed load of 11,000 N applied normal to the top face. Figure 48 shows the applied setup to the original triangle subfloor system.

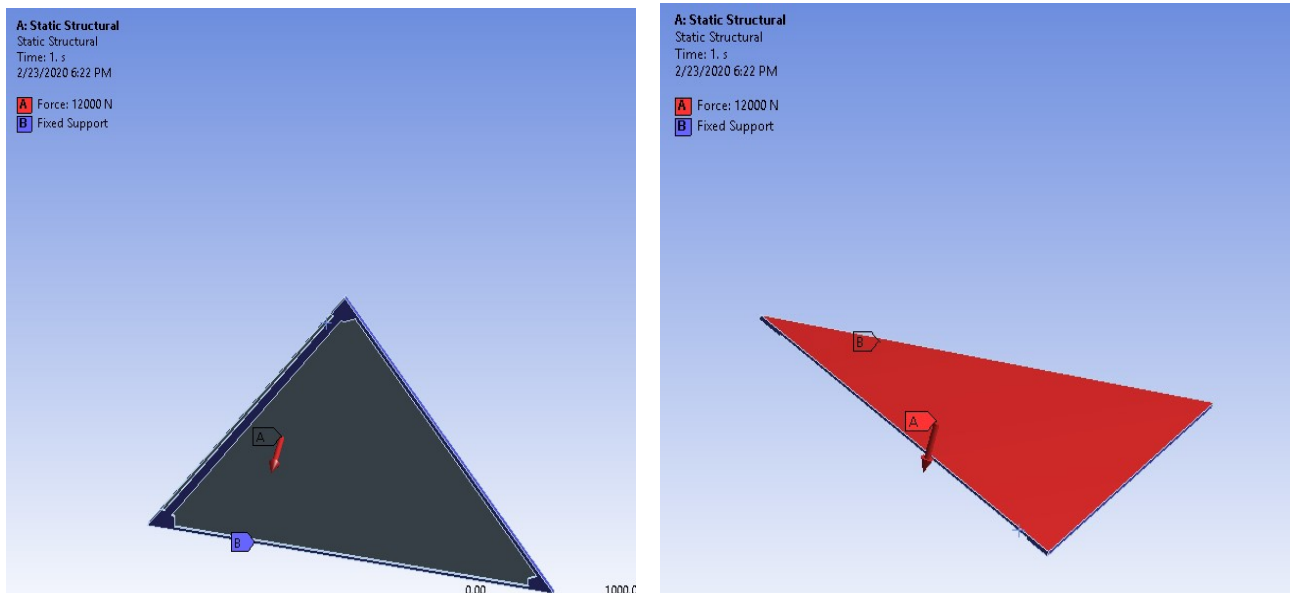


Figure 48: ANSYS Subfloor Constraints and Loads for Mesh Convergence Analysis; A Indicates the Distributed Load Being applied to the Top Face and B Indicates the Subfloor Design as a Fixed Support

For the analysis, the deformation and equivalent stress in the panel were investigated in the same locations. Using a probe, one stress value and one deformation value were evaluated at the center of the triangle structure. These locations can be seen in Figure 49, where the panel has a mesh size of 100 mm as the lines on top of each of the diagrams show.

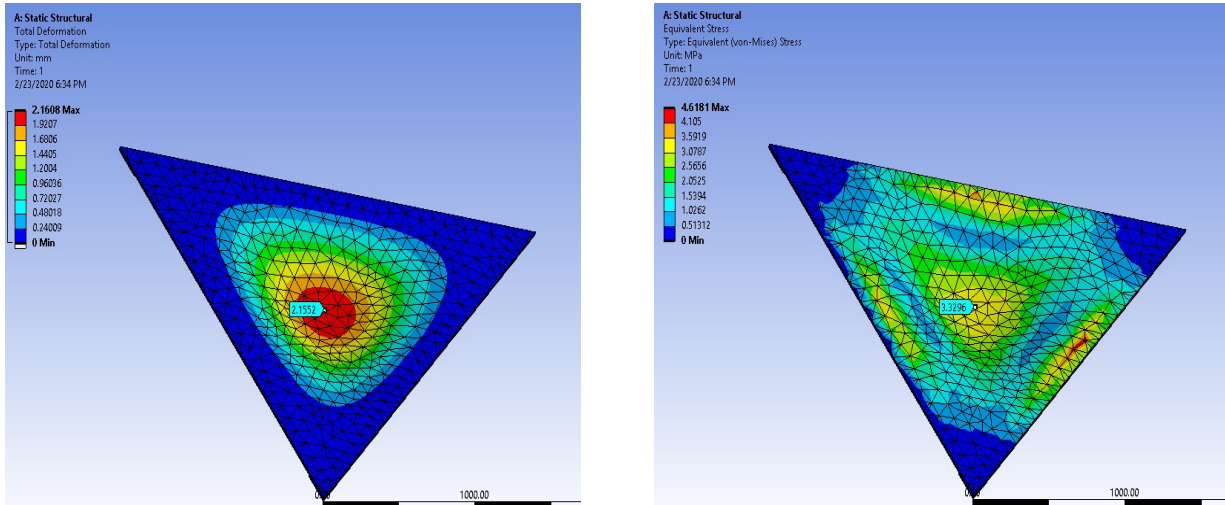


Figure 49: Measured Deformation (Left) and Equivalent Von-Mises Stress (Right) for a 100 mm Mesh Size at the Center of the Triangle Subfloor Piece

These two values were inspected as the mesh ranged from 200 mm to 4 mm. The results of the convergence analysis can be seen in Table 5 and Figure 50. The percent error between 200 mm and 150 mm is 55.90% while the percent error between 5 mm and 4 mm is .030% showing that the percent error between mesh sizes is reducing significantly at this point. Based on the mesh convergence analysis, a mesh size of 5 mm was selected for the subfloor support structures due to the low percent error.

Table 5: Mesh Convergence Final Results

Mesh Size (mm)	Deformation Center (mm)	Stress Center (MPa)
200	1.9691	0.8764
150	4.4649	2.0348
100	6.7999	2.6774
75	6.9433	2.7814
50	7.2978	2.8690
25	7.5965	2.9030
15	7.8246	2.9823
10	7.8925	2.9821
5	7.8472	3.0025
4	7.8795	3.0034

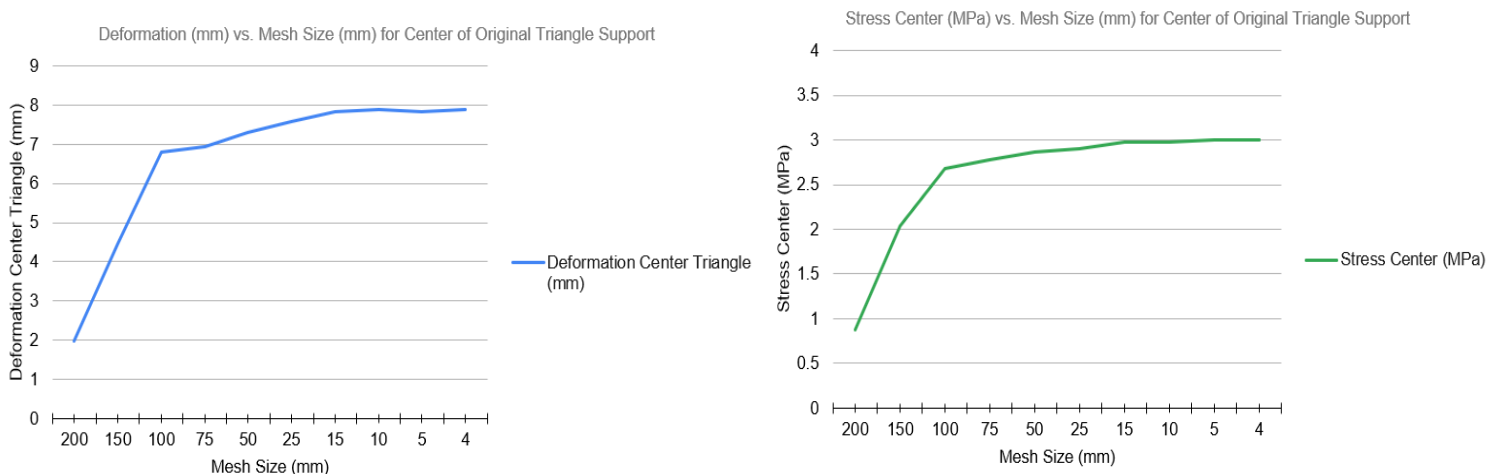


Figure 50: Charts of Deformation (Left) and Equivalent Stress (Right) at the Center of the Triangle Structure for Different Mesh Sizes

5.1.3 Finite Element Analysis (FEA) Results

The Coosa Board Bluewater 26 floor panel was analyzed for structural stability above the triangle support system. For this analysis, FEA analysis was performed on a triangular floor panel of the .75 in (20 mm) Coosa Board along with extruded bodies below the panel for fixed supports based on the subfloor design. After initial analysis on the first subfloor, further designs were created and analyzed in a similar fashion to choose the most ideal for the shelter design. Coosa Composites also advises having 12-14 in. studs between the subfloor and the Coosa Board (Coosa Composites, 2019). The addition of studs was not considered but would provide more strength than this analysis shows.

The Coosa Board Bluewater 26 has a limiting deformation of $L/d = 16$ where L is the thickness of the board of and d is the maximum deformation, which allows for 1.125 mm deformation for a 0.75 in. (20 mm) thick panel (see specifications sheet in Appendix C). This is compared with the maximum deformation in each load case. The application of this material was chosen to be “for use with reliable materials where loading and environmental conditions are not severe” (EngineeringToolBox, 2020). This corresponds to a safety factor of 2, so this is the industry standard the subfloor system must meet to be considered safe.

Additionally, the maximum equivalent stress (MPa) is compared to the core strength of the Coosa Board panel which is 3.65 MPa as found in the specification sheet. In general, there is a linear connection between load and stress, so the safety factor would be considered the same

(EngineeringToolBox, 2020). However, the safety factor requirement is reduced to 1.3 for the maximum stress since the FEA analysis includes all possible stresses and this linear connection generally applies to normal stress and shear stress individually.

5.1.3.1 Material Choice

Due to the limited data for Coosa Board strength and compatibility with ANSYS, the material used for this analysis was 7-Ply Marine Plywood. The lead engineer Eddie Sabol at Coosa Composites advised that the strength of the material is very similar to that of this marine plywood (E. Sabol, personal interview, February 21, 2020). The data for marine plywood was obtained from CES Edupak. The material entry into ANSYS can be seen in Figure 51 below.

Properties of Outline Row 3: Marine Plywood (7-Ply)				
	A	B	C	D
1	Property	Value	Unit	
2	Material Field Variables	Table		
3	Density	0.0253	lb in ⁻³	
4	Isotropic Elasticity			
5	Derive from	Young's Modulus and P...		
6	Young's Modulus	8.27E+05	psi	
7	Poisson's Ratio	0.245		
8	Bulk Modulus	3.7268E+09	Pa	
9	Shear Modulus	2.2899E+09	Pa	

Figure 51: New Material Entry for 7-Ply Marine Plywood in ANSYS Engineering Data

5.1.3.2 Loading Types for Each Subfloor Design

Two different load types were applied during the FEA process. The first was a distributed load of 11,000 N (2,472 lbs.) across the triangle section to simulate one sixth of the weight of the structure as well as furniture inside the shelter. The second is a point load of 890 N (200 lbs.) to simulate a person stepping on a vulnerable part of the structure. Finally, the panel is tested with both of these loads combined. The locations for the point loads are then placed in the center of areas that do not have support beams. The fixed support constraints are applied on the subfloor structure under the triangle and on the three edges of the triangle. An example of the combined loading can be seen in Figure 52 below.

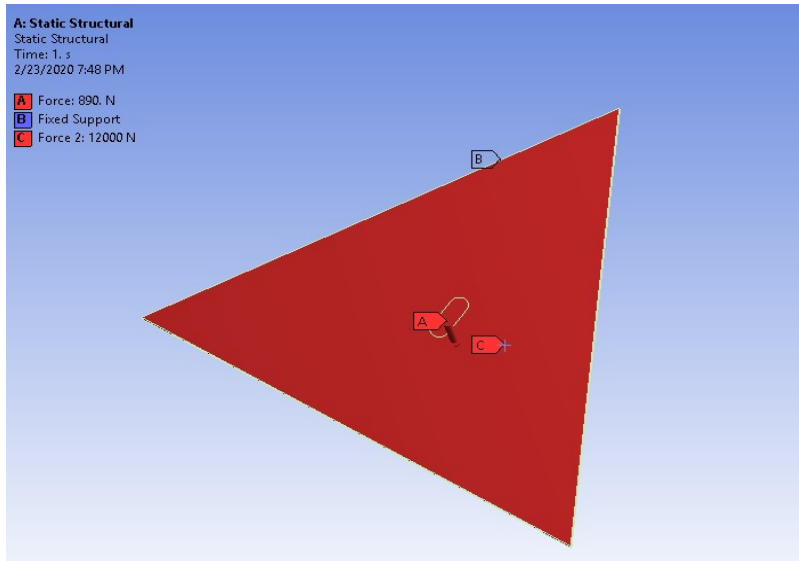


Figure 52: Example of Combined Loading Set Up where A is the Point Load Located in the Oval in the Center, B is the Fixed Support Underneath the Subfloor, and C is the Distributed Load Across the Top Triangle Face

5.1.3.3 No Support Subfloor Analysis

The initial design with only external beam supports was analyzed to determine baseline stress and deflection values. For each of the distributed load, point load, and the combined load, the design did not withstand the requirements. An example of the total deformation output for point load can be seen in Figure 53 below. The results compared to the requirements above indicate that the values were extremely high and would not create a safe structure. These results can be seen in Table 6 below.

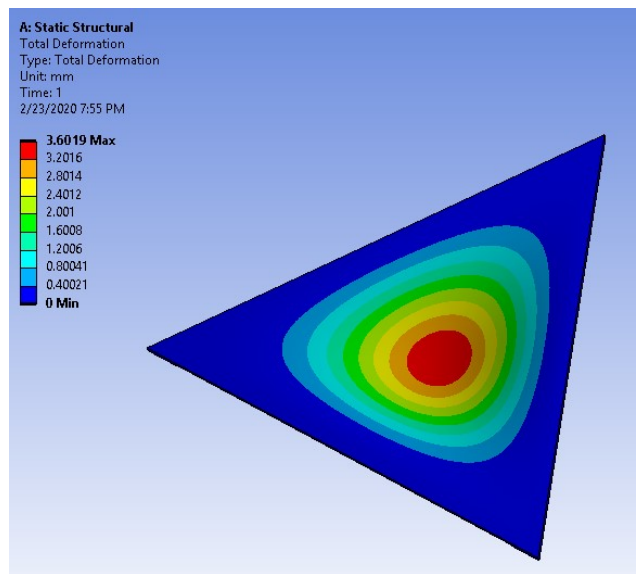


Figure 53: Total Deformation Results for Original Subfloor Design with Point Load showing the Maximum Deformation at the Center Based on the Legend to the Left of the Triangle

Table 6: Results of Deformation Analysis for Original Subfloor System

Design Type	Trial Number	Load Type	Load Amount	Max Deformation (mm)	Safety Factor	Max Stress (MPa)	Core Strength (MPa)	Safety Factor
No Support	1	Distributed	11000 N	7.9545	0.149	7.1261	3.65	0.512
No Support	2	Point	890 N	3.4906	0.340	3.0624	3.65	1.192
No Support	3	Combo	11000 N (Dis), 890 N (Point)	11.1640	0.106	9.0127	3.65	0.405

5.1.3.4 Subfloor Support System New Configurations

Since the original subfloor design did not meet any of the requirements, four additional support designs were generated utilizing both I-beams and some of which added an additional peg in the center. The first design was called the T-Support Design which added a horizontal I-beam along with a vertical one stemming down from the horizontal to form a “T” shape. The subfloor design can be seen in Figure 54 below.

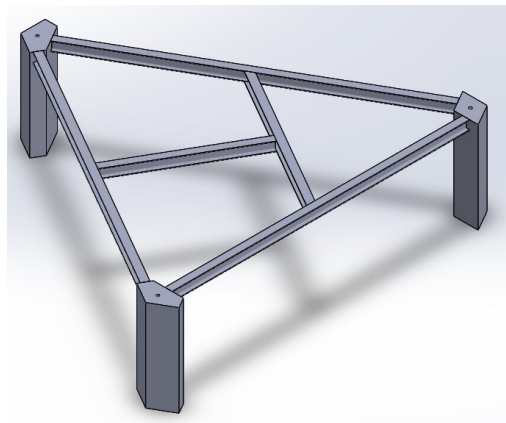


Figure 54: Subfloor T-Support Structure

The Thirds Design had additional I-beams extended from the midpoint of every triangle side and meeting at an additional small peg in the center. This design seems to provide similar support as the T Support design but with the additional complication of another center peg. This subfloor design can be seen in Figure 55 below.

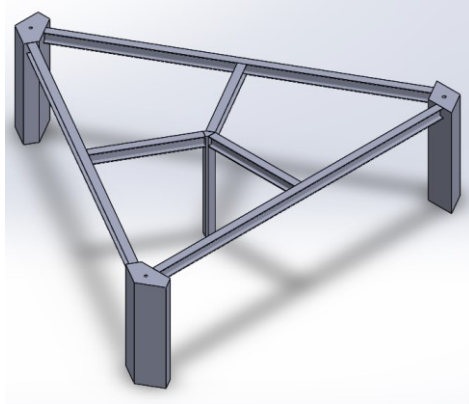


Figure 55: Subfloor Thirds Support Structure

The Zelda Design began with a horizontal I-beam similar to the T-Support Design but then two extending from the bottom of either side of the horizontal beam to the midpoint of the bottom triangle beam. This formed all triangles throughout the interior of the subfloor. This design can be seen in Figure 56 below.

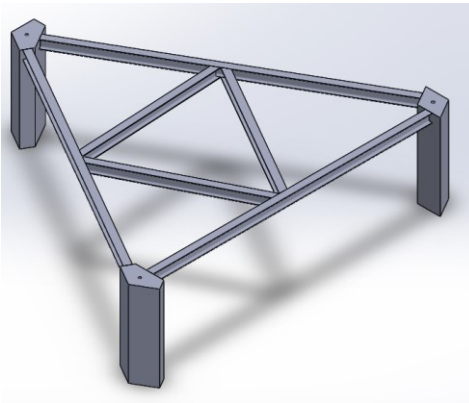


Figure 56: Subfloor Zelda Support System

The Orthogonal Design was the last and most complex design created for this iteration and is supported by I-beams extending from each of the perpendicular points of the three sides of the triangle. Due to the overlap of I-beams, a large center peg was added for the I-beams to connect to and created a total of six additional I-beams. This design can be seen in Figure 57 below.

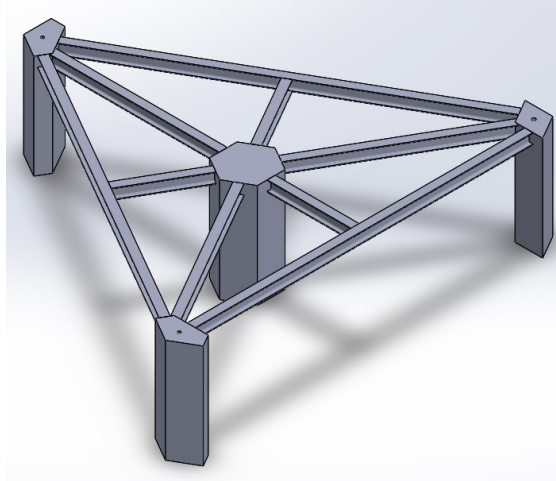


Figure 57: Subfloor Orthogonal Support System

Before analyzing each of the support systems, the point load locations were identified based on the criteria described above stating to place them in the center of areas with no support. The point load locations for each design can be seen in Figure 58 below for each of the new designs.

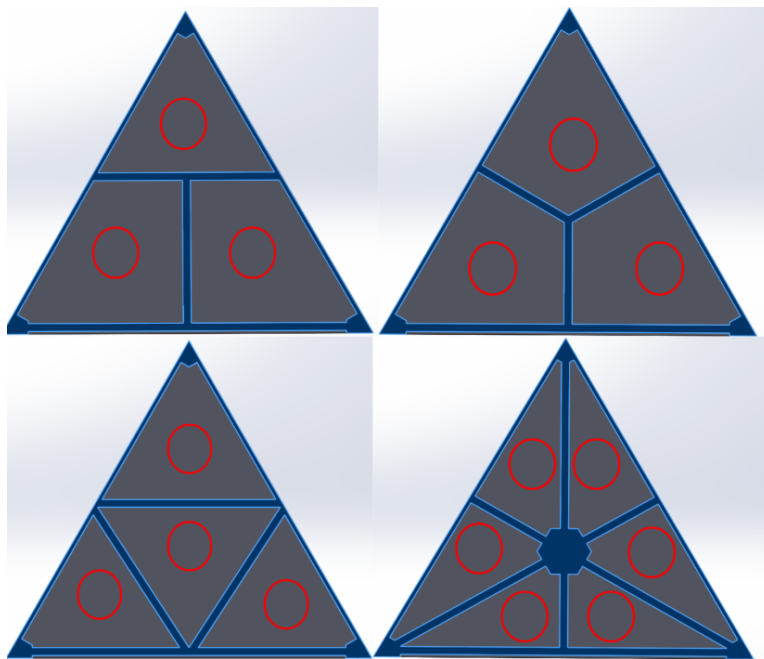


Figure 58: Point Load Locations for New Subfloor Designs

5.1.3.5 Analysis of ANSYS Results for New Support Designs

Each of the four design ideas described above were then analyzed to find the maximum deformation and stress based on the load types described above. Each was then compared to the requirements for safety factor as well as core strength of the Coosa Board to determine whether

or not they could be viable solutions. Figures 59 shows the total deformation (mm) results for all new subfloor designs under the combined loading conditions. Note that these are compared using the same legend scale. The resulting aggregate data can be found in Appendix D.

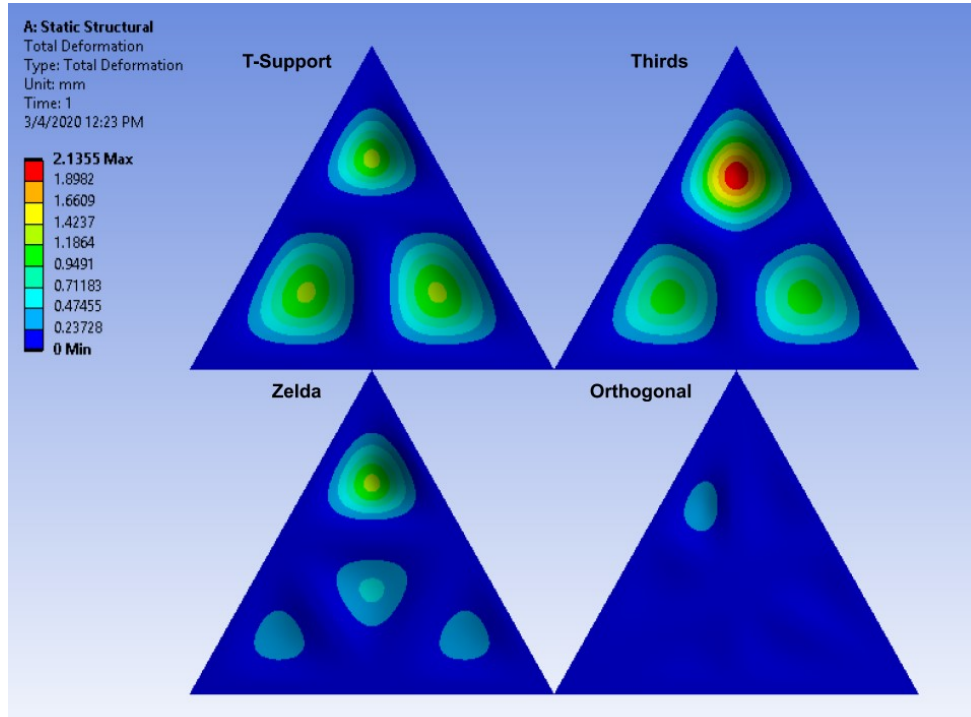


Figure 59: Total Deformation (mm) Results for New Subfloor Designs Under Combined Loading Conditions; the Thirds Design has the Highest Deformation Compared to the Other Designs using the Legend to the Left

Comparing the safety factor for deformation and stress to the industry standards set above, it was found that the Orthogonal Design met the criteria while the Zelda, Thirds, and T-Support Design did not. Since the combined loading always created the highest stress and deformation for each design individually, these are compared in Figure 60 and 61 below. The data results for other loads can be found in Appendix D. To meet the criteria, the design must be above the red line which indicates the industry standard safety factor.

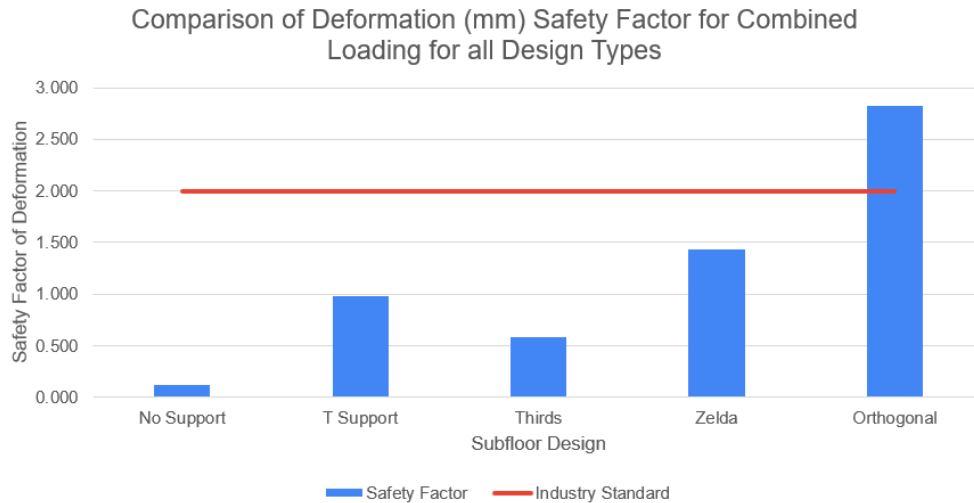


Figure 60: Chart of Safety Factor of All Designs with Industry Standard of 2

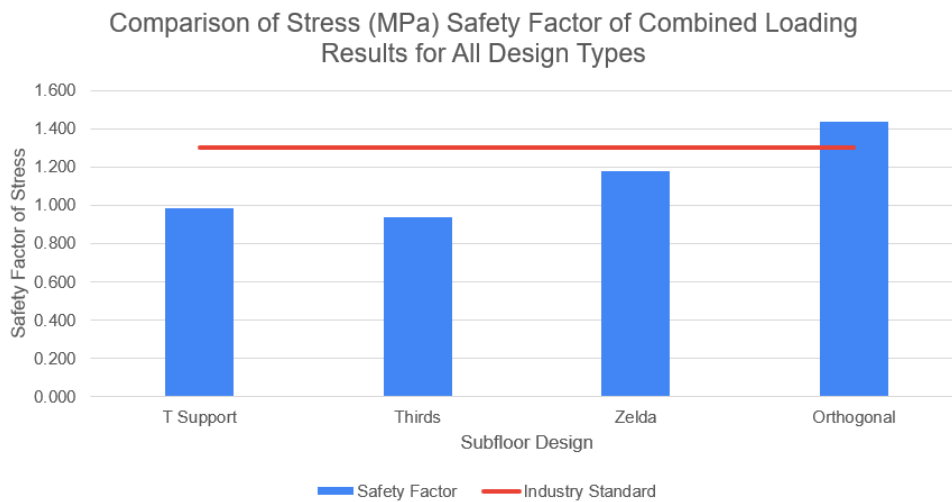


Figure 61: Maximum Stress of All Designs with Industry Standard of 1.3

Based on the graphs and the results above, it appears that the Orthogonal Design is the only one that would be considered viable. However, this solution involves a lot of extra assembly along with the added variability of an additional large peg. The Zelda Design was also considered a possible solution even though the combined loading safety factor for deformation was 1.3 which is below the requirement of 2. However, the Zelda design is simpler to assemble and would not require an additional peg. In conclusion, the Zelda design is the preferred choice out of all of the designs analyzed above due to its ease of assembly and close to meeting the requirements, but still must be improved to meet the requirements.

5.1.3.6 Further Development and Analysis of Zelda Design

To improve the Zelda design, four additional I-beams were added that bisected each of the four inner triangles of the design. Although this would require more assembly, it does provide more structural integrity overall. The subfloor system for the Reinforced Zelda Design can be seen in Figure 62 below.

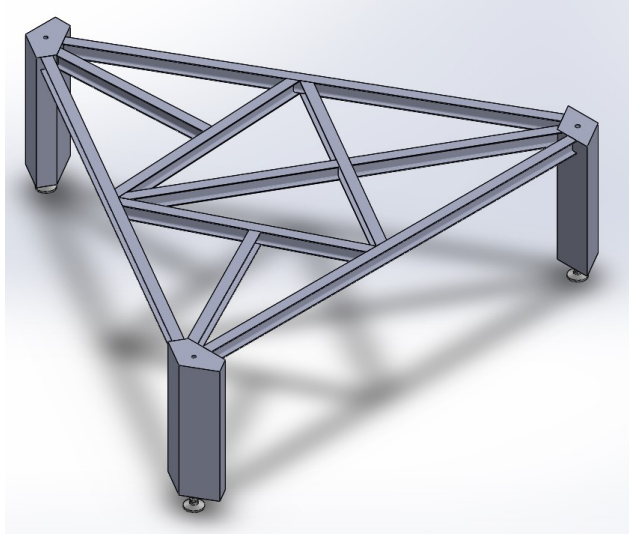


Figure 62: Reinforced Zelda Subfloor Support System

A similar procedure for analysis was conducted on this design. Figure 63 shows the location of the possible point loads in the center of the open areas. Additionally, the final results for deformation (mm) and Maximum Stress (MPa) can be seen in Table 8 below.

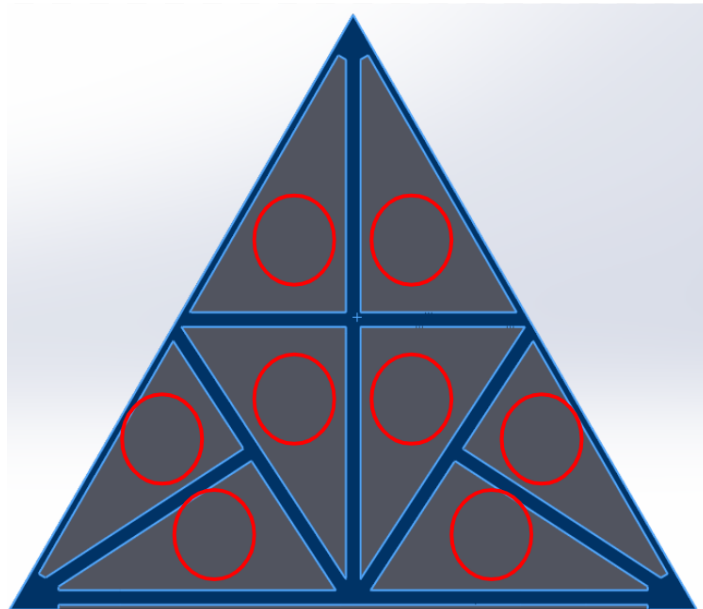


Figure 63: Point Load Locations for Reinforced Zelda Subfloor System

Table 7: Final Result of Deformation for Reinforced Zelda Design

Design Type	Trial Number	Load Type	Load Amount	Max Deformation (mm)	Safety Factor	Max Stress (MPa)	Core Strength (MPa)	Safety Factor
Zelda Reinforced	1	Distributed	11000 N	0.08887	14.065	0.6503	3.65	5.613
Zelda Reinforced	2	Point Load (Bottom)	890 N	0.07512	16.641	1.3714	3.65	2.662
Zelda Reinforced	3	Combo	11000 N (Dis), 890 N (Point)	0.12404	10.077	1.7778	3.65	2.053

The safety factors for each of the loads are well above the requirement of 2 for deformation and above 1 for stress. This is important if loads with higher force or more points loads are applied to the floor. One case this analysis did not identify is having four-point loads to simulate having the four people in the shelter at one time. Based on the final results above, the Reinforced Zelda Design passes all of the requirements for safety factor of deformation and stress for each load type. This was the final subfloor system chosen for the Beehive Puzzle Shelter Design.

6.0 Conclusions

Through research, design, and analysis, this project provided initial design ideas for a housing solution for situations of overcapacity at sectors at the United States southern border. Unlike many facilities that put many people in one permanent structure or in tents surrounding the area, this shelter design can be used by multiple families and provides privacy in a semi-permanent structure. The interlock system helps create small community environments that are safe and still allow enough space for each individual. Upon delivery of materials, the assembly of the shelter does require some significant effort but will be a progressive structure that will stay for multiple years. Over time, these shelters can be used or remain vacant while still having structural integrity. The CAD model helped to visualize and validate the structural integrity of the floor system through analysis methods in Chapter 5. It also shows how an interlock system can allow for some variability in the number of shelters that can be connected and allow for customization based on the larger population present at a certain sector. For example, if most asylum seekers are Unaccompanied Alien Children, then the shelters can be constructed with more attached.

Although analysis was employed for the subfloor system of the shelter, many of the aspects still require additional analysis to confirm structural integrity. Additionally, the assembly of the shelter has not been fully analyzed or tested. For the analysis of the subfloor support system, only static loading was tested through results of deformation and equivalent stress. Future analyses for dynamic loading should be done on this system before implementation. Some types of tests to be conducted might include testing for vibrations or oscillations due to wind. Using the ANSYS software package, tests for resonant frequency and vibrations should be conducted.

To test and develop the design further, prototyping would also need to be done. This will aid in understanding what can actually be physically manufactured compared to the computer-generated models and results. This process would start with a scaled down prototype to confirm assembly of the product. Then, a full-scale model can be manufactured to see if assembly is possible and to understand what limitations the shelter would have compared to the CAD model. These models would go through design of experiments for each component (subfloor, walls, steel frame, roof assembly) as well as the structure as a whole. Design of experiments aims to describe and interpret controlled testing to evaluate what is causing those test results. Also, a full

cost analysis of all the components should be done to show this is a cost-effective solution over the current system at the United States southern border.

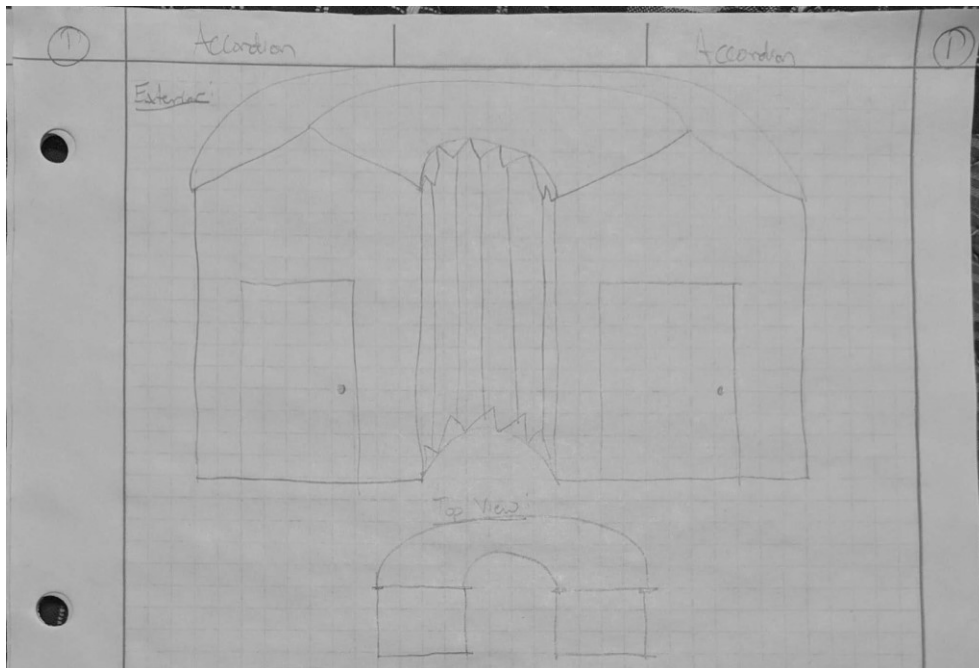
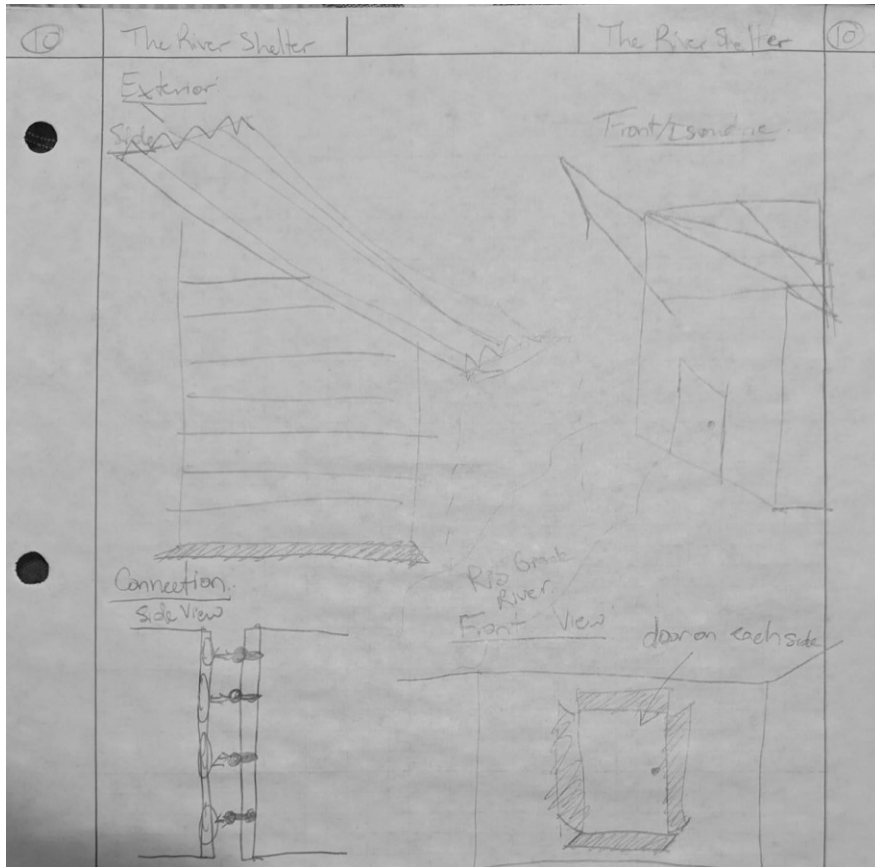
Overall, this project provided a progressive potential solution for a shelter for asylum seekers and could also be used at other sectors for help with overcapacity. Although there is still more work required to consider this idea for implementation, this project provides a starting point. This project provides general analysis for the shelter system as a whole and one detailed analysis for the subfloor system, so it will need significant additional analysis and experimenting before it can be considered a viable solution.

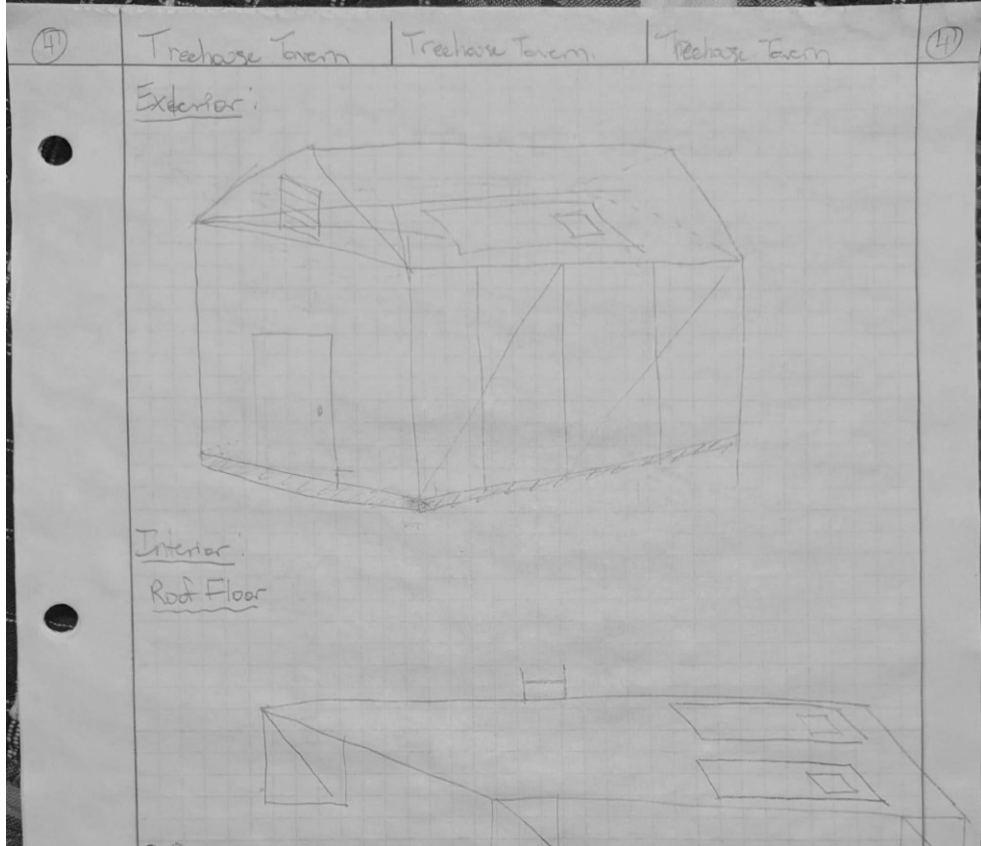
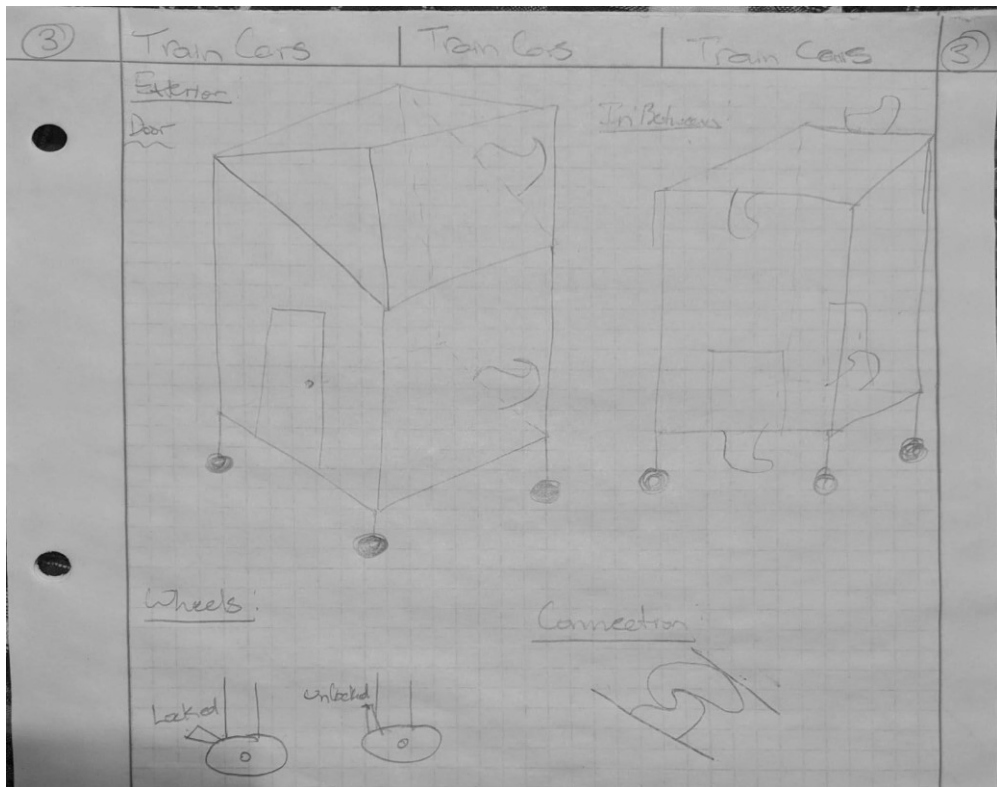
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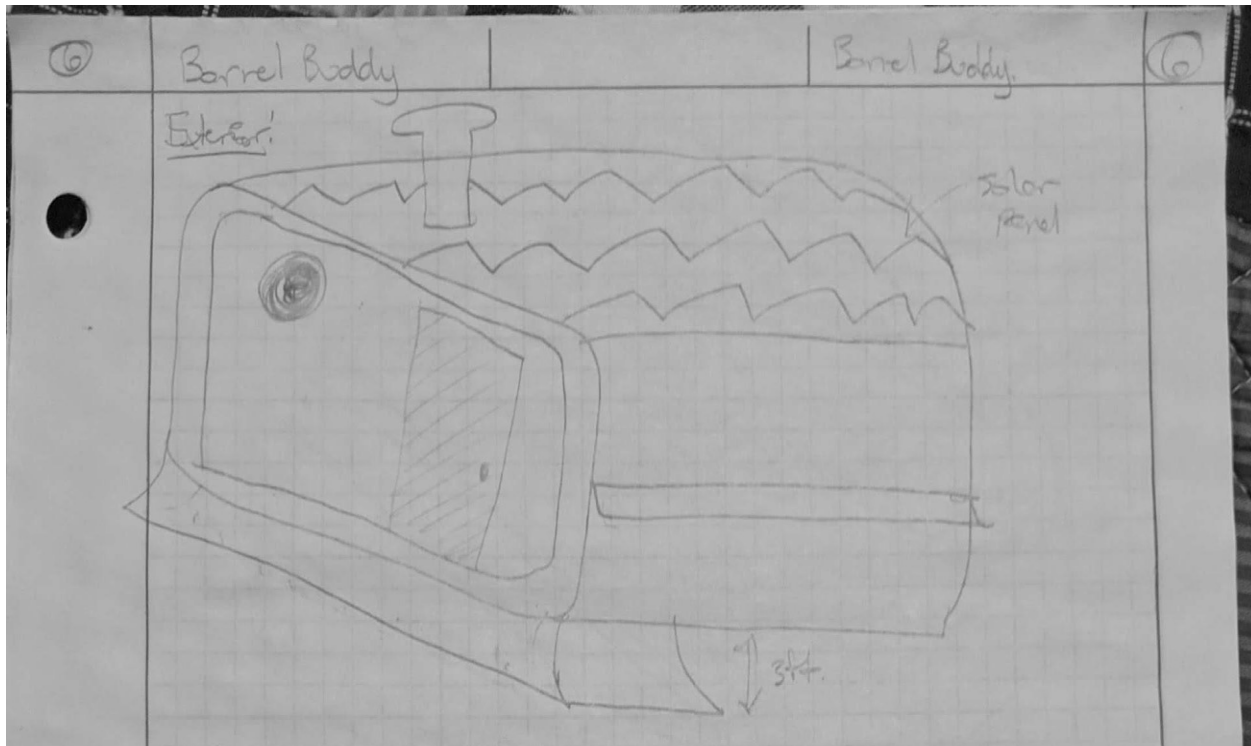
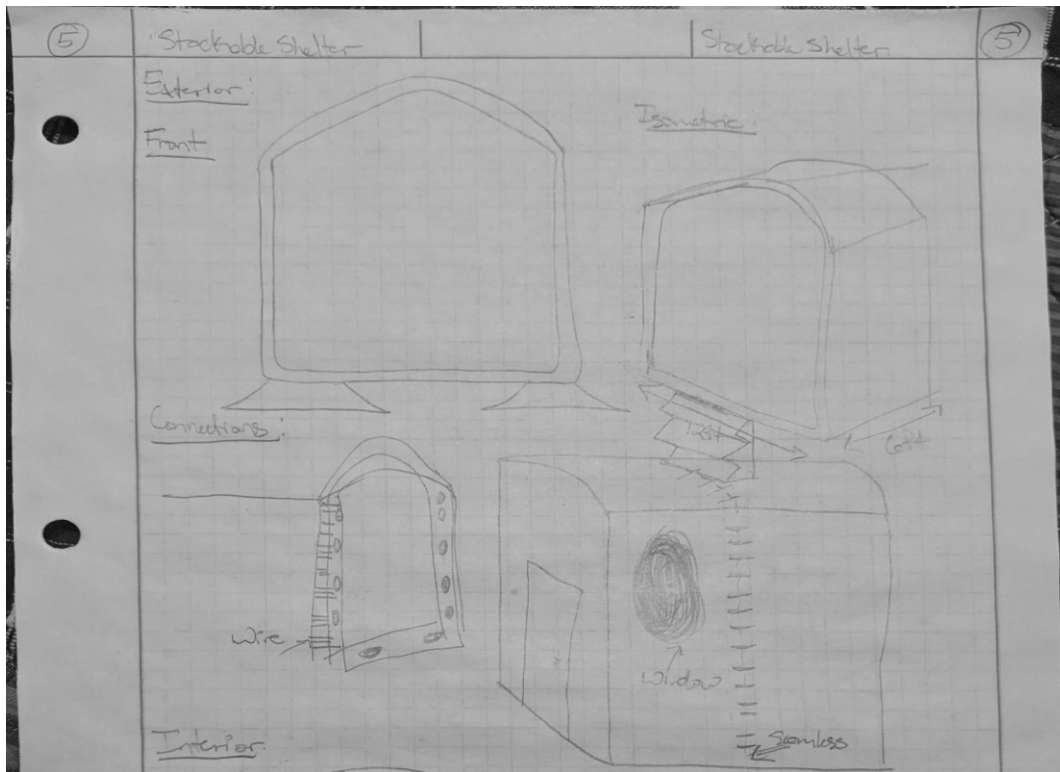
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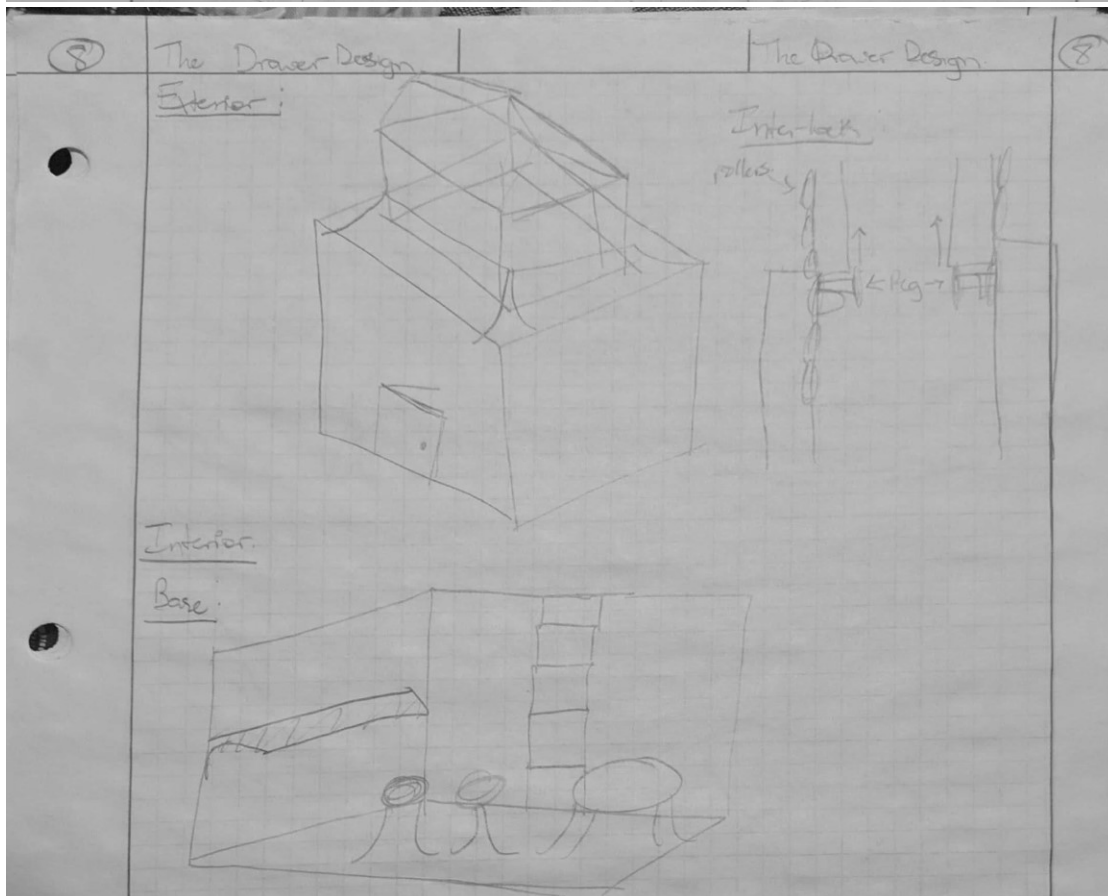
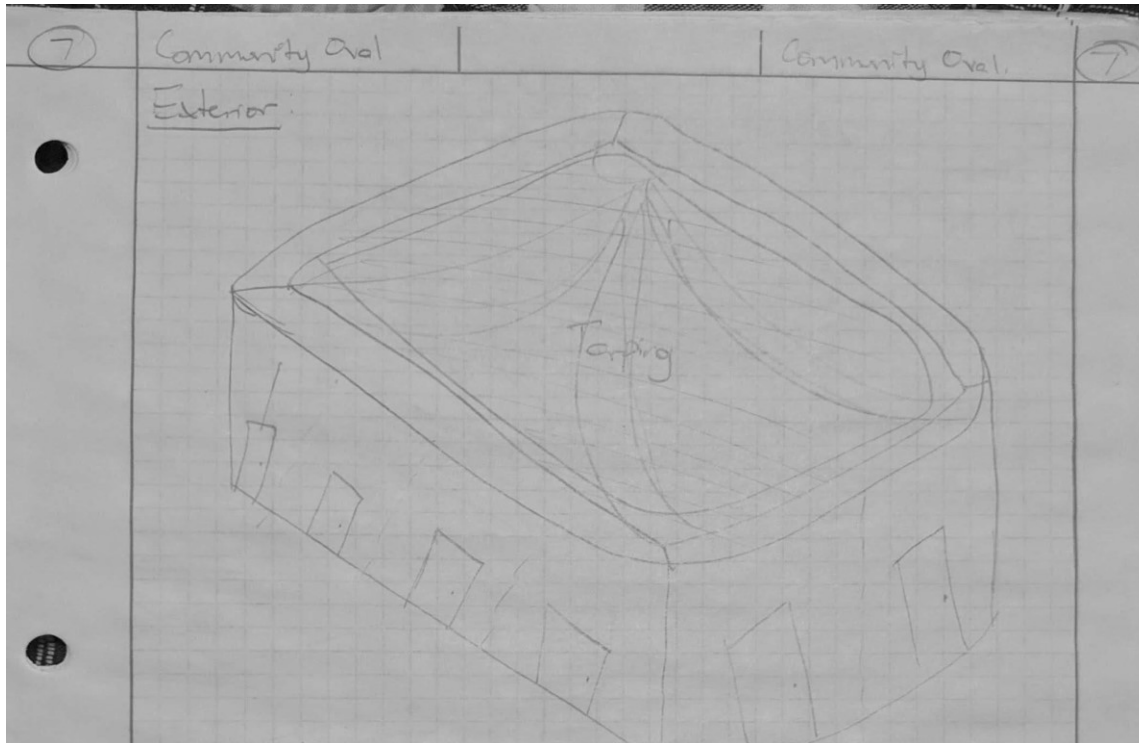
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Appendix A: Preliminary Design Ideas









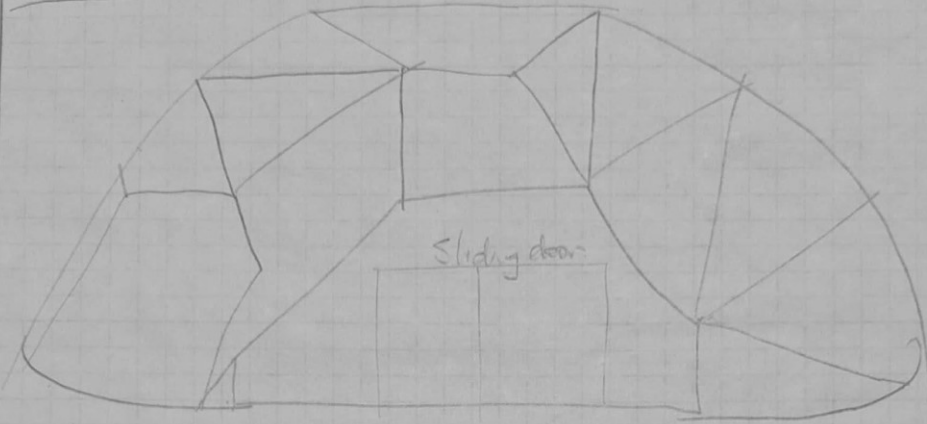
9

The Geodome

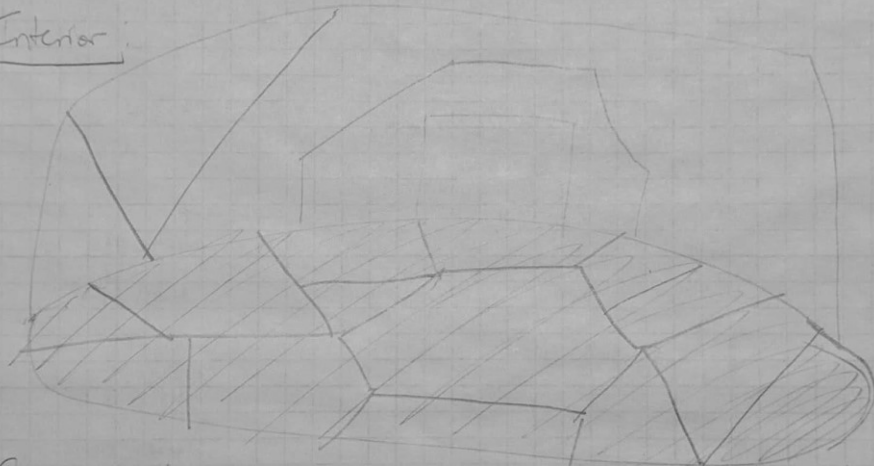
The Geodome

9

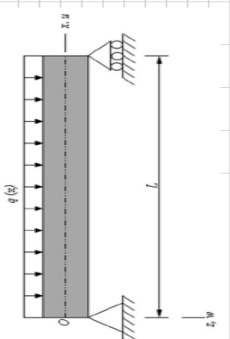
Exterior:



Interior:

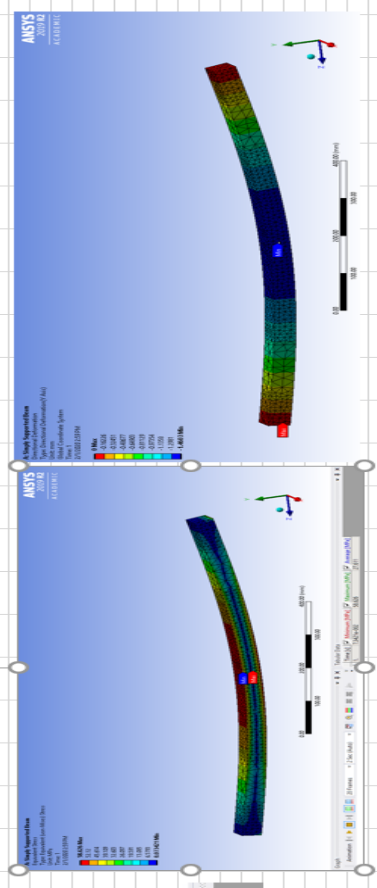


Appendix B: Finite Element Analysis (FEA) Method Verification through Hand Calculations



$a = 40 \text{ mm}$
 $c = \frac{dZ}{2}$
 $I = \text{Moment of Inertia } 172 \cdot a^4$
 $Z = \frac{a^3}{36}$

Mesh Division
 Branchion For
 MIE MUP Asylum Process at the U.S. Southern Border
 Professor Trapp and Professor Wodni-Schwartz



The results show that the ANSYS results for bending stress and deformation are close to what is calculated by hand. These values can be adjusted in the spreadsheet to show different representations based on material and

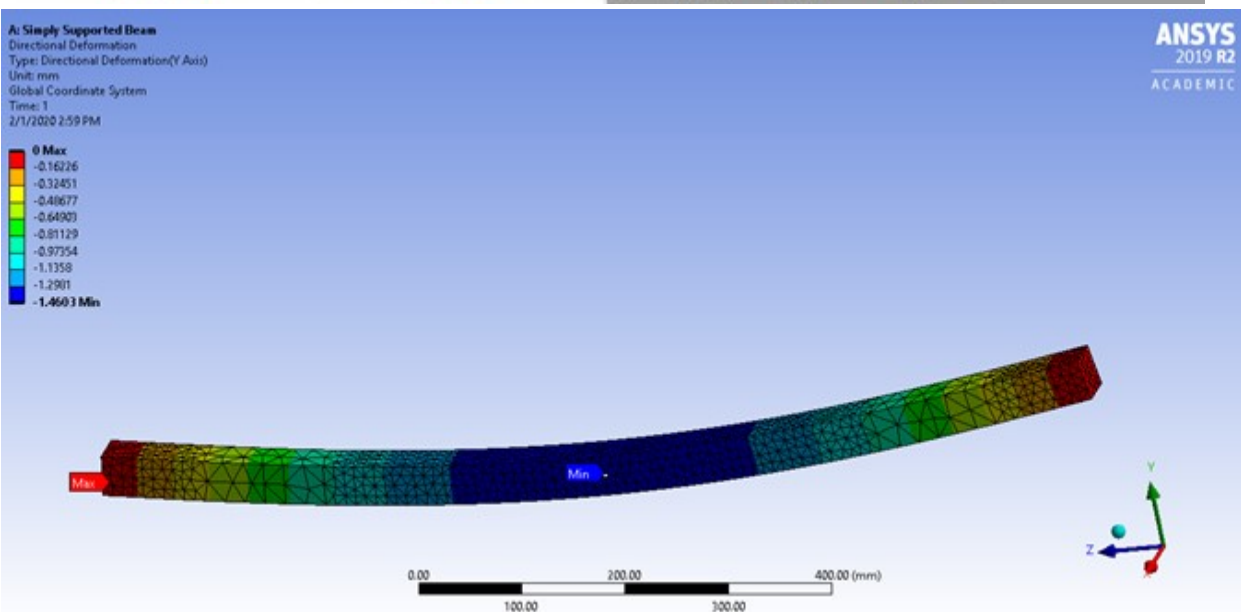
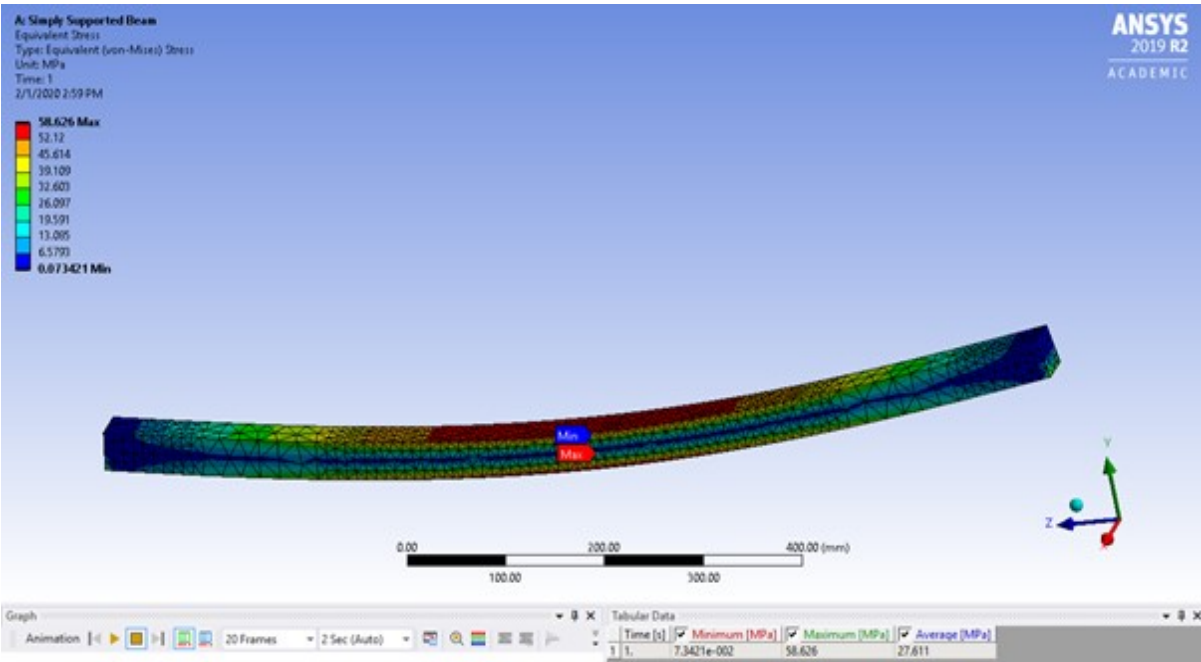
22	Moment and Maximum Bending Stress:	
23	$M_{max} = M\left(\frac{L}{2}\right) = \frac{pL^2}{8} = 62500 \text{ N}\cdot\text{mm}$	
26	$\sigma_{max} = \frac{M_{max} \cdot c}{I} = \frac{62500 \cdot \frac{40}{2}}{172 \cdot 40^4} = 59.9398 \text{ Mpa}$	
29	ANSYS Result	59.63 Mpa
32	Max Deformation:	
36	$w(x) = -\frac{px^2}{24EI} (L^2 - 2x^2 + x^3)$	
37	$w_{max} = w\left(\frac{L}{2}\right) = \frac{5pL^4}{384EI} = -1.632 \text{ mm}$	
38	ANSYS Result	-1.46 mm

Tabular Data

Time [s]	Minimum [MPa]	Maximum [MPa]	Average [MPa]
1.1	-7.821e-002	58.626	27.811

Tabular Data

Time [s]	Minimum [mm]	Maximum [mm]	Average [mm]
1.1	-1.4693	0	-0.9339



Appendix C: Specification Sheets for Materials



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 Pelham, AL 35124
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	Density	Core Shear		Core Compressive		Flatwise Tensile	Flexural Properties	
	ASTM C271	ASTM C273		ASTM C365		ASTM C297	ASTM D790	
	(lb/ft ³) / (kg/m ³)	Strength (psi) / (MPa)	Modulus (psi) / (MPa)	Strength (psi) / (MPa)	Modulus (psi) / (MPa)	Strength (psi) / (MPa)	Strength (psi) / (MPa)	Modulus (psi) / (MPa)
Bluewater 20								
0.50" / 12 mm	20 / 320	410 / 2.83	3,640 / 25.10	510 / 3.52	9,150 / 63.09	380 / 2.62	3,860 / 26.61	188,700 / 1,301.04
0.75" / 20 mm	20 / 320	420 / 2.90	4,660 / 32.13	410 / 2.83	7,270 / 50.12	440 / 3.03	2,830 / 19.51	166,000 / 1,144.53
1.50" / 38 mm	20 / 320	500 / 3.45	6,360 / 43.65	660 / 4.55	19,460 / 134.17	570 / 3.93	2,750 / 18.96	135,000 / 930.79
Bluewater 26								
0.50" / 12 mm	26 / 416	550 / 3.79	2,050 / 14.13	800 / 5.52	13,980 / 96.39	690 / 4.76	5,260 / 36.27	265,300 / 1,829.18
0.75" / 20 mm	26 / 416	530 / 3.65	4,220 / 29.10	820 / 5.65	11,810 / 81.43	480 / 3.31	4,960 / 34.20	242,900 / 1,674.74
1.50" / 38 mm	26 / 416	520 / 3.59	6,300 / 43.44	1,060 / 7.31	31,050 / 214.08	510 / 3.52	4,010 / 27.65	215,100 / 1,483.06
Nautical 15								
0.50" / 12 mm	15 / 240	410 / 2.83	2,680 / 18.48	400 / 2.76	7,130 / 49.16	340 / 2.34	2,220 / 15.31	83,900 / 578.47
Nautical 20								
0.50" / 12 mm	20 / 320	450 / 3.10	2,970 / 20.48	600 / 4.14	13,340 / 91.98	600 / 4.14	2,700 / 18.62	91,700 / 632.25
0.75" / 20 mm	20 / 320	510 / 3.52	3,740 / 25.79	740 / 5.10	15,710 / 108.32	630 / 4.34	2,430 / 16.75	71,800 / 495.04
1.50" / 38 mm	20 / 320	420 / 2.90	5,220 / 35.99	530 / 3.65	19,339 / 133.34	420 / 2.90	2,310 / 15.93	75,200 / 518.49
Nautical 24								
0.50" / 12 mm	24 / 384	650 / 4.48	3,990 / 27.51	980 / 6.76	16,830 / 116.04	550 / 3.79	3,430 / 23.65	114,700 / 790.33
0.75" / 20 mm	24 / 384	630 / 4.34	5,630 / 38.82	630 / 4.34	9,330 / 64.33	660 / 4.55	2,910 / 20.06	99,100 / 683.27

*ASTM D790 - 3 point Bending, L/d=16/1

Important! The information and data presented herein are based upon information reasonably available to Coosa Composites, LLC from independent testing labs at the time of publication and are presented in good faith, but are not to be construed as guarantees or warranties, express or implied, regarding performance, results are to be obtained from use, comprehensiveness, and merchantability. You should thoroughly test any application, and independently determine satisfactory performance before commercialization or use.

Revised April 2012

Plywood (7 ply, beech), perp. to face layer

Datasheet view: All attributes  Show/Hide

Hybrids: composites, foams, honeycombs, natural materials > Composites > Natural material composites > Wood > Plywood > Transverse >

General information

Designation

Plywood (7ply,T)




Typical uses

Aerospace components, automotive components, furniture, building and construction, marine and boat building, packaging, musical instruments, modeling.

Composition overview

Compositional summary

Cellulose/Hemicellulose/Lignin/12%H2O/Adhesive

Material family		Natural
Base material		Wood (composite)
Renewable content		100 %

Composition detail (polymers and natural materials)

Wood		100 %
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Price

Price		* 0.249	- 0.277	USD/lb
Price per unit volume		* 10.9	- 13.8	USD/ft^3

Physical properties

Density		0.0253	- 0.0289	lb/in^3
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Mechanical properties

Young's modulus		0.551	- 0.827	10^6 psi
Specific stiffness		1.69e6	- 2.57e6	lbf.ft/lb
Yield strength (elastic limit)		* 1.17	- 1.44	ksi
Tensile strength		5.08	- 7.98	ksi
Specific strength		* 3.55e3	- 4.52e3	lbf.ft/lb
Elongation		* 2.49	- 3.04	% strain
Compressive strength		* 3.05	- 4.5	ksi
Flexural modulus		0.551	- 0.754	10^6 psi
Flexural strength (modulus of rupture)		5.08	- 7.98	ksi
Shear modulus		0.029	- 0.0435	10^6 psi
Shear strength		0.435	- 0.725	ksi
Bulk modulus		* 0.258	- 0.386	10^6 psi
Poisson's ratio		0.2	- 0.3	
Shape factor		5.6		
Hardness - Brinell		26.4	- 32.3	HB
Elastic stored energy (springs)		0.0795	- 0.137	ft.lbf/in^3
Fatigue strength at 10^7 cycles		* 1.71	- 2.1	ksi
Differential shrinkage (radial)		0.01	- 0.03	%
Differential shrinkage (tangential)		0.2	- 0.4	%
Work to maximum strength		0.612	- 0.748	ft.lbf/in^3

Impact & fracture properties

Fracture toughness		* 0.455	- 0.91	ksi.in^0.5
Toughness (G)		0.0275	- 0.0952	ft.lbf/in^2

Thermal properties

Glass temperature		171	- 216	°F
Maximum service temperature		248	- 284	°F
Minimum service temperature		* -99.4	- -9.4	°F
Thermal conductivity		* 0.0693	- 0.0867	BTU/hr.ft.°F
Specific heat capacity		0.396	- 0.408	BTU/lb.°F
Thermal expansion coefficient		* 3.33	- 4.44	µstrain/°F
Thermal shock resistance		* 419	- 678	°F
Thermal distortion resistance		* 1.68e4	- 2.4e4	BTU/hr.ft

Appendix D: Finite Element Analysis (FEA) Subfloor System Data Results

Deformation:

Design Type	Trial Number	Load Type	Load Amount	Max Deformation (mm)	Safety Factor	Industry Standard
No Support	1	Distributed	11000 N	7.9545	0.157	2
No Support	2	Point Load	890 N	3.4906	0.358	2
No Support	3	Combo	11000 N (Dis), 890 N (Point)	11.164	0.112	2
T Support	1	Distributed	11000 N	1.2236	1.022	2
T Support	2	Point Load (Bottom)	890 N	0.8945	1.397	2
T Support	3	Point Load (Top)	890 N	0.80934	1.544	2
T Support	4	Combo	11000 N (Dis), 890 N (Point)	1.2748	0.981	2
Thirds	1	Distributed	11000 N	1.0767	1.161	2
Thirds	2	Point Load (Bottom)	890 N	1.222	1.023	2
Thirds	3	Point Load (Top)	890 N	1.2014	1.040	2
Thirds	4	Combo	11000 N (Dis), 890 N (Point)	2.1313	0.586	2
Zelda	1	Distributed	11000 N	0.5429	2.302	2
Zelda	2	Point Load (Bottom)	890 N	0.49017	2.550	2
Zelda	3	Point Load (Top)	890 N	0.80797	1.547	2
Zelda	4	Combo	11000 N (Dis), 890 N (Point)	0.87279	1.432	2
Orthogonal	1	Distributed	11000 N	0.14358	8.706	2
Orthogonal	2	Point Load (Bottom)	890 N	0.30463	4.103	2
Orthogonal	3	Point Load (Middle)	890 N	0.37191	3.361	2
Orthogonal	4	Point Load (Top)	890 N	0.33948	3.682	2
Orthogonal	5	Combo	11000 N (Dis), 890 N (Point)	0.44224	2.827	2

Stress:

Design Type	Trial Number	Load Type	Load Amount	Max Equivalent Stress (MPa)	Core Strength (MPa)	Safety Factor	Industry Standard
No Support	1	Distributed	11000 N	7.1261	3.65	0.512	1.3
No Support	2	Point Load	890 N	3.0624	3.65	1.192	1.3
No Support	3	Combo	11000 N (Dis), 890 N (Point)	9.0127	3.65	0.405	1.3
T Support	1	Distributed	11000 N	2.6582	3.65	1.373	1.3
T Support	2	Point Load	890 N	2.3255	3.65	1.570	1.3
T Support	3	Point Load	890 N	2.1699	3.65	1.682	1.3
T Support	4	Combo	11000 N (Dis), 890 N (Point)	3.7104	3.65	0.984	1.3
Thirds	1	Distributed	11000 N	2.4922	3.65	1.465	1.3
Thirds	2	Point Load (Bottom)	890 N	2.3535	3.65	1.551	1.3
Thirds	3	Point Load (Top)	890 N	2.3549	3.65	1.550	1.3
Thirds	4	Combo	11000 N (Dis), 890 N (Point)	3.9001	3.65	0.936	1.3
Zelda	1	Distributed	11000 N	1.7635	3.65	2.070	1.3
Zelda	2	Point Load (Bottom)	890 N	1.976	3.65	1.847	1.3
Zelda	3	Point Load (Top)	890 N	2.0748	3.65	1.759	1.3
Zelda	4	Combo	11000 N (Dis), 890 N (Point)	3.0938	3.65	1.180	1.3
Orthogonal	1	Distributed	11000 N	0.87034	3.65	4.194	1.3
Orthogonal	2	Point Load (Bottom)	890 N	1.649	3.65	2.213	1.3
Orthogonal	3	Point (Middle)	890 N	1.8551	3.65	1.968	1.3
Orthogonal	4	Point (Top)	890 N	1.9225	3.65	1.899	1.3
Orthogonal	5	Combo	11000 N (Dis), 890 N (Point)	2.5387	3.65	1.438	1.3