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Sustainable Roof Systems: Design Report

J. Brown
Trinity University

A. Freeland
Trinity University

J. Zangirolami
Trinity University

K. Ogba
Trinity University

K. Golmon
Trinity University

See next page for additional authors

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Authors

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Design Report

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Sustainable Roof Systems

J. Brown, A. Freeland, J. Zangirolami, K. Ogba, K. Golmon, J.H. Hakim, J. Hammon
Dr. D. Glawe, Faculty Advisor
Professor K. Drennan, Industry Consultant

This report describes the design of a prefabricated sustainable roof system for LionForce Systems. While being economical, environmentally sustainable, aesthetically pleasing, and easy to assemble on site, the design includes a sturdy and durable roof-to-wall joint that minimizes waste, insulates the interior, and locks out moisture. In addition, the design facilitates a 20-foot unsupported roof span and a 4-foot overhang beyond the exterior wall, with allowances for variation in roof pitch. The roof-to-wall joint was successfully designed and prototyped with less than half the $1200 allowable budget using galvanized steel with Expanded Polystyrene (EPS) insulation.

Executive Summary

LionForce Systems, a panelized pre-fabricated home construction company, requested the design of a system to create a structural and environmental seal between roof and wall panels of homes, increase unsupported roof span from 14 to 20 ft, and support an overhang of 4 instead of 2 ft. A successful design is structurally sound, impenetrable by moisture, critters, and air, and allows roof pitches from 2/12 to 8/12. Roof pitch is the ratio of vertical height to horizontal span.

To improve LionForce's product, a steel roof-to-wall joint in an L-shape was designed and prototyped. The L sits on the wall panel, and both extremes are in contact with the roof, providing structural support and an environmental seal. The L joint is filled with pre-cut expanded polystyrene (EPS), which LionForce currently uses. Load analysis showed that the joint's structural steel supports 189 lbs of requisite load per panel without buckling or yielding. Thermal analysis led to perforations in the structural steel to reduce thermal bridging through the joint, improving thermal performance and energy efficiency. Joint production costs $8.48 per 4 ft joint.

The proposed 6 in. thick Transcon roof panel experiences a pitch-dependent maximum bending moment of 187 to 217 lb_f-in, just above the L with a 20-ft span. The requisite load is the roof's weight plus a dead load, per code. The pitch-dependent maximum stress in the roof panel's structural steel is 28 to 32 psi. This is below the structural steel's yield stress, so the 6 in. thick Transcon panel is within code. From thermal analysis, delta studs or cut-outs in the joint's bottom are recommended to prevent thermal bridging through the steel.

An external bracket support is recommended to support the 4-ft overhang past the exterior wall. Design criteria prohibit external structures, but this is the best functional solution. Calculations of a 2 ft by 3 ft support bracket show that a bracket supports the overhang.

Out of a $1200 budget, $551 was spent on traveling and material for many prototypes, including designs that were abandoned. In order to assure a tight fit and adequate compliance with Transcon and ABT panels, both companies' panels were assembled for a fit test with the system.

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1 Introduction

LionForce Systems has developed a highly-innovative, pre-fabricated approach to residential construction. In the LionForce version of pre-fabricated construction, roof and wall panels are created in factories according to design specifications and shipped to construction sites for assembly. This detailed, systematic method of home building reduces on-site waste and streamlines the construction process while creating a highly green and energy efficient final product.

LionForce's homes utilize highly efficient and durable panels, but the joint between the wall and roof panels does not have an effective pre-fabricated seal or structural support component. No current system exists at this time to secure the roof-to-wall joint. Instead, the roof panel is simply placed on top of the wall panel, and the joint is sealed using either a foamed-in-place insulation called Icynene or an alternative soy-based foam injection insulation, depending on budget. Neither Icynene nor its soy-based counterpart is an eco-friendly material according to LionForce Systems' goals and standards, because their use creates an excess of construction site waste (Icynene Insulation System). A more efficient system would inject or pre-cut only the amount of insulation necessary. The current system also places excess stress on the outside edge of the wall when a pitched roof is installed. A pitched roof is one that is placed at an angle with the horizontal plane, as opposed to a flat roof that is perpendicular to the walls. Roof pitch is defined as the ratio of the roof's vertical rise to its horizontal distance, like the slope of a line. In addition, the current roof panel construction system used by LionForce Systems only allows for 14 feet of roof span with a 2-foot overhang. The roof span refers to the unsupported portion of roof between load-bearing walls in the house. The overhang refers to the portion of each roof panel that extends beyond the outside wall of the house. This extension provides shade for windows in order to reduce cooling costs and save energy during the summer. It also shields the surface of the house from precipitation and direct sunlight, which can damage walls over time.

In order to improve LionForce's home construction product, a roof-to-wall joint was desired which would alleviate stress on the outer edge of the wall and create a tight environmental and thermal seal at the joint. Additionally, LionForce requested a design that would support up to 4 feet of overhang beyond the outside wall and allow for a roof span of at least 20 feet. The roof span and overhang should be maintained around all corners of the house. While increasing the external overhang and roof span are ideal goals, it is essential that the design allow for variation in roof pitch from 2/12 to 8/12 (corresponding to 2 feet or 8 feet, respectively, of height per every 12 feet of horizontal distance). It would also be an additional benefit if the design could maintain useable space within the joint for the networking of electrical systems. The design is considered successful if it creates a durable roof and joint system that minimizes waste, is structurally sound, insulates the interior, locks out moisture, is easy to implement, and is environmentally sustainable and aesthetically pleasing. All of these objectives must be met in a cost effective design that is in accordance with building codes and standards.

2 Design Overview

As previously mentioned, Lionforce Systems is pursuing three objectives to improve its prefabricated roof system. The primary objective was to design an effective roof-to-wall joint that could be implemented in a prefabricated home. With this main objective and the additional objectives of extending roof span and external overhang in mind, a basic L-shaped joint was constructed. An overview diagram of the final design is shown in Figure 1.

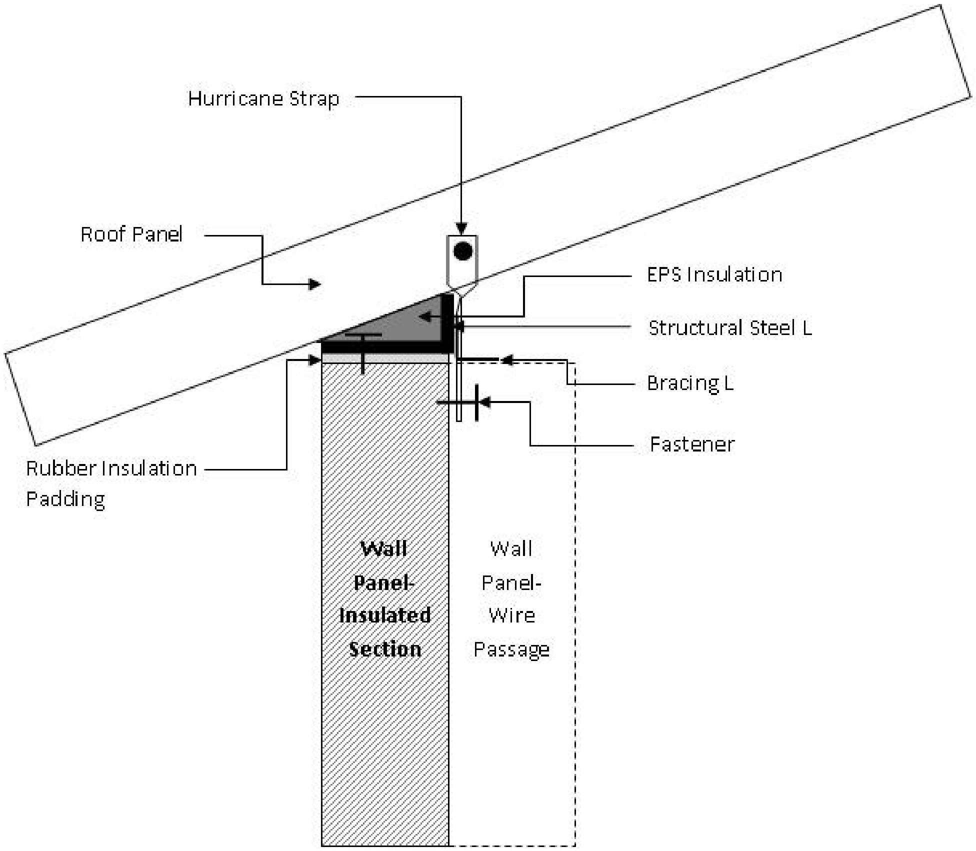


Figure 1: Full Design Overview

In this figure, an Accelerated Building Technologies (ABT) panel is shown as the supporting wall, and a Transcon panel is used for the roof. The dotted lines to the right of the insulated section represent the empty space between struts that extends every 4 feet. The design leaves this space empty so it can be used for electrical wiring. The simple L-shaped joint can be seen in bold black, and EPS Insulation appears as dark gray inside of the triangle. A thin layer of insulation is used for padding between the L-shaped joint and the wall panel in order to compensate for any bending or warping in the steel that may cause an uneven interface between the wall panel and the bottom of the joint. A bracing L bracket and a hurricane strap provide further structural integrity in the joint. These components will be described in further detail in Sections **3.2.1 and 3.2.3.**

The objective of extending the overhang to 4 feet was presented to the team with secondary importance in relation to creating structural stability and impregnability in the roof-to-wall junction. LionForce Systems provided this secondary objective in hopes that the team could resolve the issue. The design criteria was to extend the overhang to 4 feet without using external support, as it would change their branded aesthetic, and without greatly increasing the material amount or cost of their panels. LionForce would like to adhere to their signature look, and they are also wary of increasing the costs in an already expensive process. On top of increasing material costs, the use of more metal framework in panels would increase the transfer of heat through the roof and increase the load which wall panels and any joint system must support. After researching, discussing the dilemma with experts from LionForce, ABT, and Transcon, and performing calculations, the group determined that a 4-foot unsupported overhang was not feasible within the given constraints. The objective was not abandoned altogether. Instead, a functional option was proposed to integrate support brackets onto the exterior of homes to support the extra weight of the overhang as seen in Figure 2.

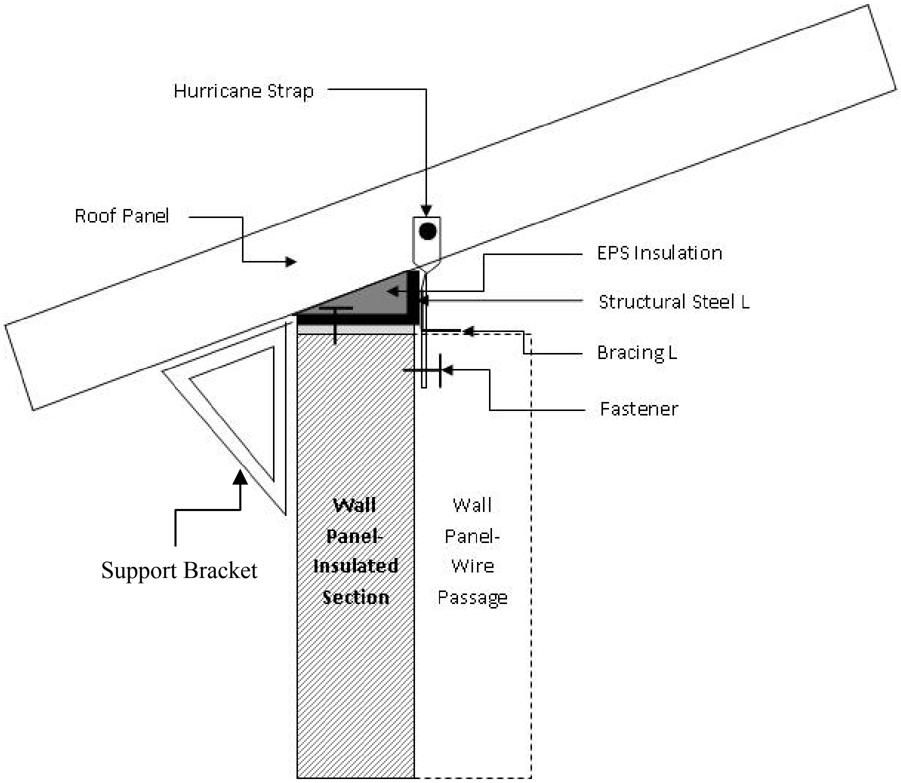
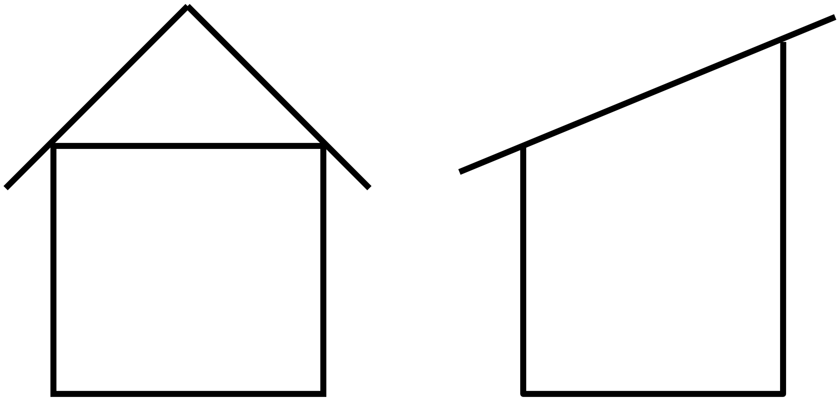


Figure 2: Overhang with External Support Bracket

The addition of external support brackets is not in compliance with the initial aesthetic design preferences set by Lionforce but was deemed necessary to meet structural requirements. This approach was chosen after multiple consultations were made with highly trained engineers who specialize in prefabricated roof designs.

Another challenge was to achieve an unsupported roof span of 20 feet in the pre-fabricated home. A reduction in the current width between load-bearing struts in Transcon roof panels would enable an increase in roof span. Furthermore, changing the overall design configuration of panels from a shed style roof to a gable style would increase the allowable roof span. In a gable style roof, two roof panels meet at the highest point of a house, creating an apex. With this more typical design, a traditional pointed roof is created. Shed style roofs are comprised of only one slanted roof panel, which spans across two walls that differ in height. Basic diagrams of these two roof formations can be seen in Figure 3.



Gable Roof

Shed Roof

Figure 3: Gable and Shed Roof Configurations

The recommendations for roof panel width and configuration are explained in further detail in Section 3.3 of Subsystem Designs.

3 Subsystem Designs

The various design aspects of this project are presented below, including pre-fabricated panels, the roof-to-wall joint, span, and overhang.

3.1 Pre-fabricated Panels

In each panel, a 12-gage steel frame sandwiches molded Expanded Polystyrene (EPS), which acts as insulation to create a thermal barrier, thereby minimizing the conduction of heat through walls. This barrier creates a durable seal with exceptional insulation and resistance to insects, moisture, and airflow. LionForce Systems currently uses panels that are provided by Accelerated Building Technologies (ABT). They are also considering the use of panels produced by Transcon Steel. Both of these vendors use the same basic materials in different configurations to produce panels with similar thermal and structural performance. Transcon panels are rated for use as both roof and wall components with identical dimensions and configurations. They also provide flexibility to the user in selecting the thickness, length, and width of each panel as well as the distance between load-bearing studs. ABT panels are rated only for use as wall panels and provide less flexibility with respect to the dimensional and strut-spacing aspects of panel design (Accelerated Building Technologies). ABT panels are constructed in 8-foot sections with structural studs located 2 feet inwards on each end so that all studs are 4 feet apart throughout the span of any wall. Although this complicates design in terms of dimensional flexibility, it also provides ABT with a thermal advantage over Transcon panels. This is because Transcon panels must interface with each other stud-to-stud, creating a large area of steel-to-steel contact, which facilitates thermal bridging. ABT panels, on the other hand, link through male and female match-ups in the insulation, so that a tight seal is created without increasing heat transfer, as shown in Figure 4.

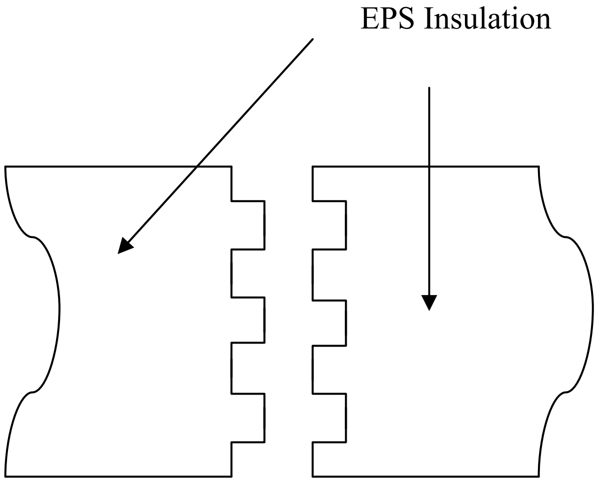


Figure 4: ABT Interface between Wall Panels Top View

The exterior portion of ABT panels is comprised of both insulation and steel framing densely packed together without air gaps. The steel studs which provide structural integrity to the panel extend inwards beyond the insulation, creating 4-foot empty spaces between studs. This empty space between struts, which can be used for electrical wiring, is shown in Figure 5, a diagram of a basic ABT panel.

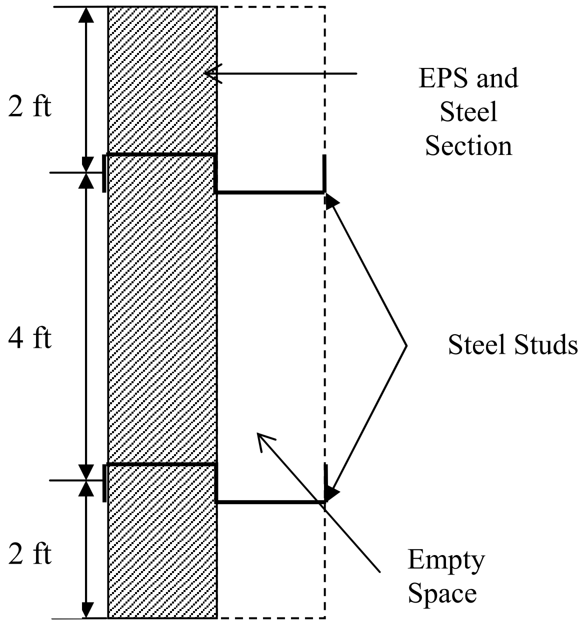


Figure 5: Cross-Sectional View From Above of an ABT Panel

Both companies place a U-shaped steel track along the top of their wall panels (Figure 6). Transcon also places these tracks on the bottom of their panels.

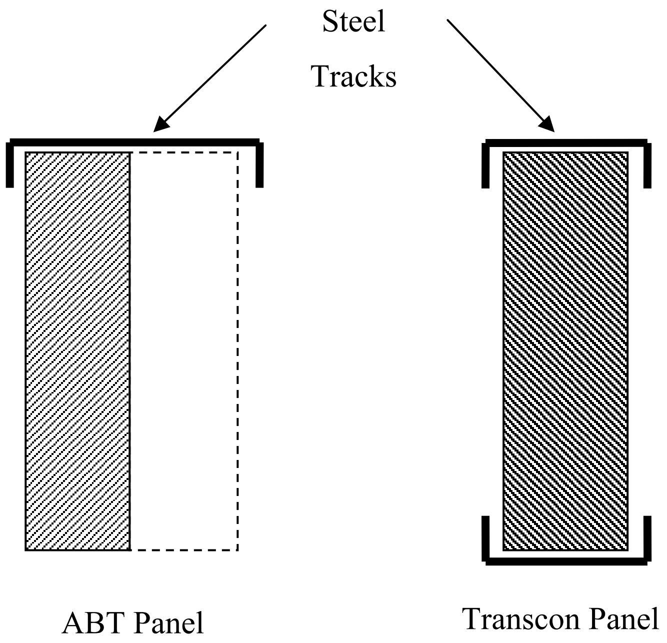


Figure 6: Diagram of Steel Tracks on Both Panels

LionForce Systems has a working relationship with ABT and is accustomed to using their panels, but may consider the integration of Transcon panels for the roof portion of their operation. Both of these companies offer panels which perform exceptionally well as thermal, energy, and moisture seals in residential homes.

3.2 Roof-to-Wall Joint

Two issues are addressed in the design of the roof-to-wall joint: structural integrity and thermal insulation. The joint must alleviate stress on the outer edge of the wall panel, and it must seal off any gaps which would facilitate air and moisture penetration. Specific aspects of the design are discussed in the following sections.

3.2.1 Structure

The basic L shape of the roof-to-wall joint design, as seen in Figure 1, was chosen for its simplicity, manufacturability, cost, structurally stability and thermal properties. This roof-to-wall joint is comprised of an outer 12-gage steel casing and an inner filling of molded Expanded Polystyrene (EPS). The roof-to-wall joint distributes the load of the roof panel to two points instead of one, thereby reducing the stress concentration on the outer edge of the wall. Figure D-1 in the appendix shows a detailed computer aided design (CAD) drawing of the roof-to-wall steel joint. Figure D-2 in the appendix shows stress concentration levels on the roof-to-wall joint.

The L-shape of the roof-to-wall joint is designed so that the bottom rests flat against the wall while the tip of the vertical element makes contact with the slanted roof. This part can be manufactured and installed for a roof pitch range of 2/12 to 8/12 by simply changing the height of the vertical portion. A bracing L bracket was added for additional support, as shown previously in Fig. 1.

3.2.2 Thermal Properties

From preliminary research, molded EPS was seen as the best pre-fabricated insulating material available. Since LionForce already uses EPS, it is also ideal for incorporation into their pre-existing product. EPS integrated with a structural steel frame form a lightweight mold and water-resistant design that greatly minimizes waste and reduces environmental impact at the construction site.

To minimize thermal bridging between the interior and exterior of the house through the structural steel frame, delta studs (or similar cut-outs) are recommended for the horizontal component of the L-joint. Delta studs are created by cutting out material from metal in order create a disjointed pathway for heat to traverse. These gaps will impede the flow of heat through the roof-to-wall joint, thereby increasing the R-value of the house. An R-value is a measure of a material's thermal resistance, defined as the ratio of the temperature difference across an insulator to the heat flux through it. A larger R-value is attributed to a house which transfers less heat in or out and therefore exhibits high energy efficiency throughout the home. The EPS that fills the joint will further insulate the system. EPS has an R-value of 4.5 as compared to the the R-value of structural steel, which is practically negligible. The high R-value of EPS means that it will be effective in reducing heat flow through the panel. The sheet metal of the joint and the wall panel will not align well if the metal is warped slightly. In order to resolve this issue, and improve thermal insulation at the joint, a layer of foam is inserted between the panel and joint. Thin, flexible closed-cell foam is recommended for this layer. During prototyping, gray Volara polyolefin foam was used, and it performed well.

3.2.3 Fasteners and Connections

The roof-to-wall joint is fastened to the wall panel with a self-drilling screw. This screw is represented by a bold "T" shape in Figure 7 (expanded from Figure 1, the overall design view).

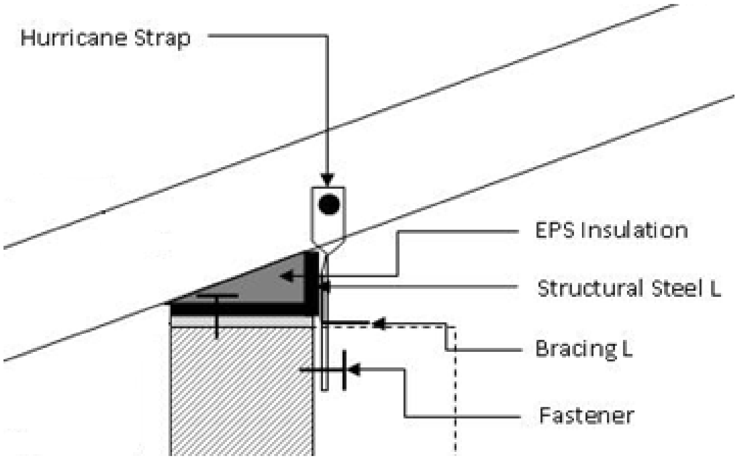


Figure 7: Cut-Out Close-Up View of L-Shaped Joint

This fastener penetrates through the steel of the joint, the thin layer of insulation, and the steel stud in the panel in order to hold the joint to the wall. The joint will be attached to the wall panel prior to transport to the construction site in order to reduce on-site waste and streamline construction. Another self-drilling screw secures a hurricane strap to the roof panel. This hurricane strap attaches directly to the wall panel with a third self-drilling screw, labelled as a

"Fastener" in the diagram. The purpose of the hurricane strap is to attach the roof panel directly to the interior of the wall studs in order to hold the roof panel in place in case of wind loads that may lift it from the house. If a Transcon panel is used for the wall component of a home, the fastener will attach directly to the steel/EPS frame of the panel as shown in Figure 7. However, if an ABT panel is used, the hurricane strap will actually be attached just inside the empty passage section, represented by the dotted line, since studs will extend to that point. This small variation will be easy to adjust during the design process. Since the fasteners are all self-drilling screws, this attachment system does not require pre-drilling, so the required labor time during both the manufacturing and construction is minimized.

3.3 Roof Span

In order to increase the unsupported roof span to 20 feet, it is recommended to narrow the width of the roof panels. Each component of the steel frame will then support a smaller load, and length may be increased without bending or complete failure. A diagram of a Transcon Panel is shown in Figure 8.

Figure 8: Transcon Panel, from (Transcon Steel)

Furthermore, changing the roof configuration from shed to gable will enable a larger roof span. A shed roof design has a vertical support force at each wall section. A gable roof has similar wall supports, but also provides each roof panel with a resistive force from the opposing roof panel (Figure 9).

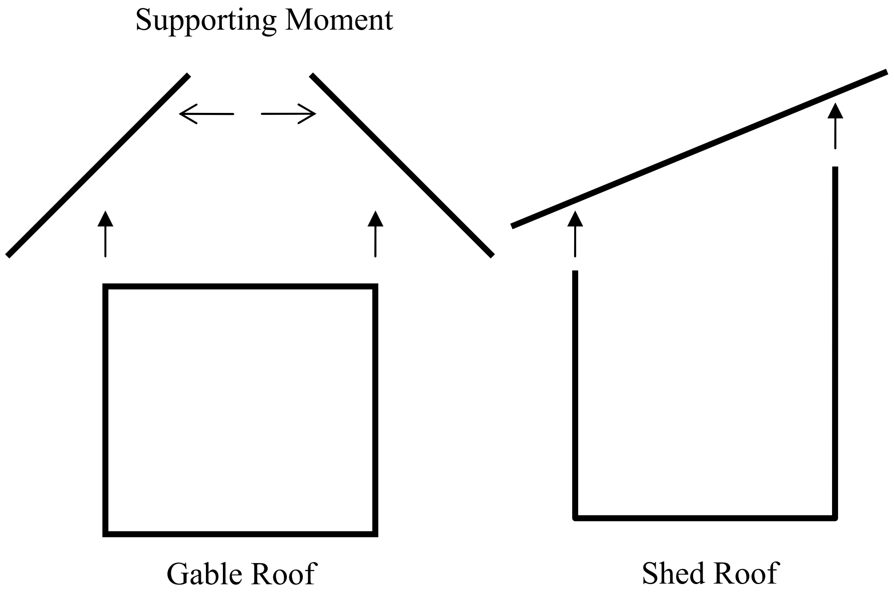


Figure 9: Gable and Shed Roof Supporting Forces

The gable roof configuration would require Lionforce to adjust their current roof panels in order to facilitate a double-sided roof with an apex. The highest point of each roof panel would have to be bevelled in order to create a point. Bevelling refers to the shaping of an edge so that it forms an angle other than a right angle. In the gable style, both roof panels support each other at the apex, thereby reducing the load on the walls, and allowing for an increased roof span. Both the gable and shed style roof are feasible designs, but achieving a 20-foot unsupported span with a shed roof would require a decreasd roof panel width. Further analysis on roof span is performed in Section 4.3.

4 Computational Methods and Results

Due to the nature of this design, preliminary testing is difficult to implement without incurring extensive costs, so it is important that mathematical models of the design be constructed to determine the plausibility of solutions. This modeling offers a general understanding of the forces and heat dissipation involved.

4.1 Pro-Mechanica Model Results

Pro-Mechanica was used to test and verify the various stress concentrations that occur in the roof-to-wall joint, and demonstrate how a constant uniform load would affect the roof-to-wall joint over time. Figure D-2 in the appendix shows five different results and simulations of the roof-to-wall joint acquired by Pro-Mechanica. The results are interpreted through a Strain Energy Convergence graph, Deformation Convergence graph and Von Mises Convergence graph, which are further described in the appendix.

In the model, the roof load of 250 lb was uniformly distributed across the top edges of the joint. The applied load is comprised of the weight of the Transcon roof panel plus the dead load required by the International Building Code. Using this load, a precise model analysis was done in Pro-Mechanica to determine the maximum stress in the roof-to-wall joint. The strain energy convergence and the deformation energy values are proportional to each other, which indicates that an increase in strain energy will most likely cause the roof-to-wall joint to deform rapidly. With the exception of the Von Mises Convergence Graph, the solutions are virtually unchanged. The Pro-Mechanica results show that the implementation of a bracing L-bracket is adequate to support the roof-to-wall joint.

4.2 Overhang Support Bracket

Originally, LionForce asked for a 4-foot overhang with no external support structures and little additional cost. The original joint design therefore included an extension built into the joint that would continue from the wall until the edge of the overhang. This extension would be flush with the lower side of the roof panel overhang. However, calculations performed on this design showed that it was insufficient to support the required weight. An external support bracket system was then analyzed to support the overhang at a fixed interval along the side of the house. The fixed interval was chosen to match up with the structural steel studs in the wall panel. This input variable is reflected in 'panel width' for these calculations, shown in Table E-1 of the appendix. The full diagram of the joint design including the support bracket was introduced previously in Fig. 2. The entire weight of the 20 foot roof span and 4 foot overhang is assumed to be evenly distributed across the wall and external support brace.

Figure 10 shows the free body diagram for the overhang support bracket including only external forces on the bracket. Parameter W results from the distributed weight of the roof including the required dead load. F_1 and F_2 are anchoring forces at distances d_1 and d_2 from the bottom of the bracket, respectively. Parameter N represents the normal force of the wall on the brace, and d_N is the distance from the bottom of the brace to the location of the normal force. For the calculations performed, it was assumed that the two anchor bolts were located at points A and B.

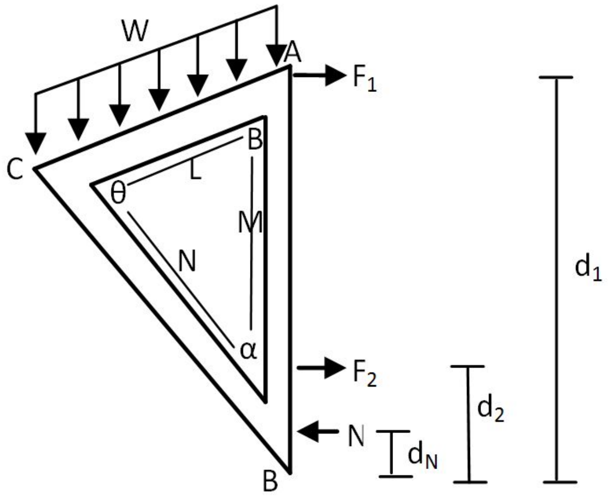


Figure 10: General External free body diagram of overhang support bracket

Figure 11 shows the external forces F_1 and F_2 and N on the bracket resolved into their x and y components. N is considered included in the F_1 and F_2 forces. The variable O_L stands for overhang length.

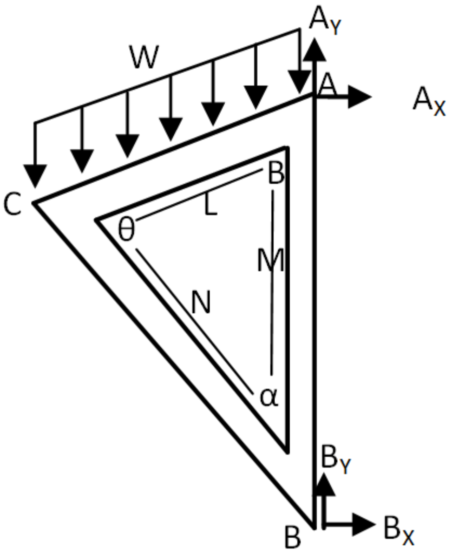


Figure 11: Simplified External FBD of overhang support resolved into x and y components

The bracket in Figure 11 was analyzed by setting the sum of the forces in the y direction equal to zero (Eq. 1), the sum of the forces in the x direction equal to zero (Eq. 2), and the sum of the moments about point A equal to zero (Eq. 3), since the truss is in static equilibrium. The resulting calculations are shown in Table E-1 of the appendix.

$$A_Y + B_Y = wO_L \tag{1}$$

$$A_X = -B_X \tag{2}$$

$$\sum M_A = \frac{wO_L}{2}(O_L sin\beta) + MB_X = 0 \tag{3}$$

The results show that vertical anchor forces A_y and B_y must support 2832 lbs between them (Table E-1). Additionally, each bolt must be capable of handling this force on its own, in order to prepare for a worst case scenario in which the bolts are accidentally installed so only one of the bolts carries the entire vertical load of the overhang.

A free body diagram for the internal forces on the top member of the support bracket is shown in Figure 12. This free body diagram was used to determine F_{BC}, the compression force in the critical member.

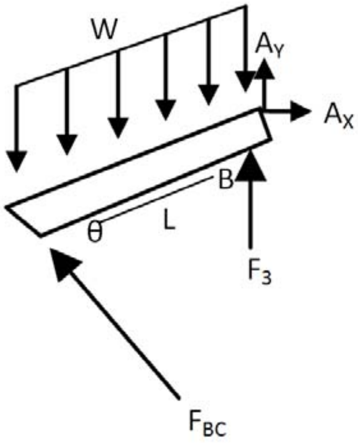


Figure 12: Internal free body diagram for member AC of overhang support bracket

Figure 12 was analyzed using the same statics equations as were used for Fig. 11. The sum of moments equation for Fig. 12 is shown in Eq. 4.

$$\sum M_A = wO_L\left(\frac{O_L \sin\beta}{2}\right) - LF_{BC}\sin(\theta) = 0 \tag{4}$$

A spreadsheet was made to determine the dimensions and resulting forces on the support bracket based on inputs of L, M, and roof pitch (Figure 11). An example calculation using a roof pitch of 8/12, a dead load of 30.525 lb/ft^2, L as 2 feet, and M as 3 feet yields a compression force of 2377 lbs in member BC (Table E-1).

The minimum cross sectional area for member BC was found based on the yield stress of structural steel using Eq. 5. F is the compression force previously found for member BC.

$$\sigma_{ys} = \frac{F}{A} \tag{5}$$

The minimum cross sectional area of a rectangular rod is 0.032 in^2 using the forces resulting from the calculations in Table E-1. The joint was modeled by a pinned-pinned column (Eq. 6), and a fixed-fixed column (Eq. 7).

$$P_{cr} = \frac{\pi^2 EI}{L^2} \tag{6}$$

$$P_{cr} = \frac{\pi^2 EI}{4L^2} \tag{7}$$

The moment of inertia, I, for a pinned-pinned column was found to be 0.002427 in^4, and I for a fixed-fixed column is 6.067x10^-5 (Table E-2). Using these moments of inertia and assuming a square cross section, the minimum cross sectional area for the pinned-pinned column is 0.232 in^2, and 0.165 in^2 for the fixed-fixed column, based on Eq. 8.

$$I = \frac{bh^3}{12} \tag{8}$$

Based on these calculations, it is recommended to use a rod with a rectangular cross-section of 0.5 in by 0.5 in for steel member BC to satisfy both the minimum cross sectional area and the minimum moment of inertia requirements. Other cross sectional areas should be considered in the final design to optimize for lower material costs.

4.3 Span Calculations

Calculations were performed on the span of the roof to determine the load that a joint system would need to support. First, a piece of a roof panel was measured and weighed. Using these measurements, the density of a panel was found to be 0.004825 lbs/in^3. These calculations are detailed in Table F-1 of the appendix. Using the resulting value for panel density and assuming a consistent relationship between the amount of steel and EPS insulation throughout panels, calculations were performed to attain the load that roof panels place on the joint or roof panel.

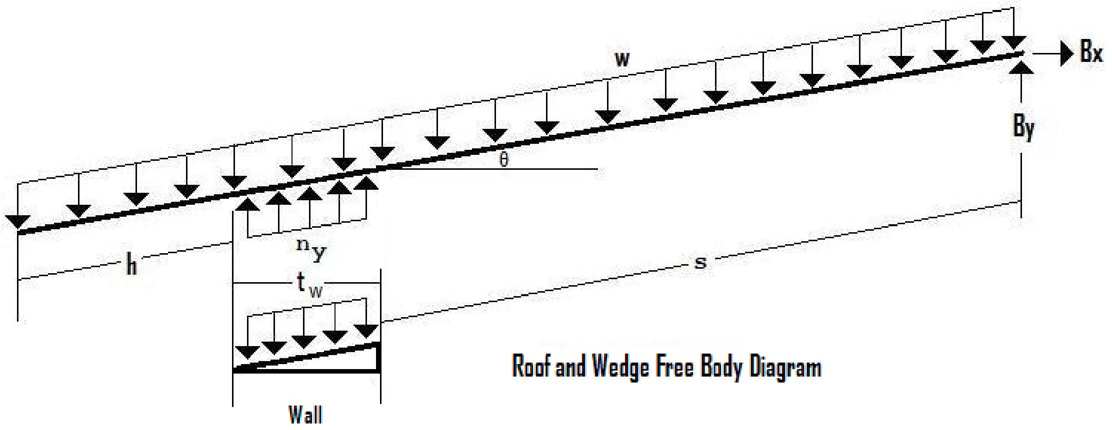


Figure 13: Free Body Diagram Analysis of Roof Panels

Figure 13 shows the distributed weight of the roof supported by a simple wedge shape, which is pulled away from the roof panel for clarity purposes. Statics analysis of the roof panel system shown in Figure 13 equates the sum of the forces on the panel to zero. The results show that with the typical Transcon dimensions of 6-in thick panels that are 2-feet wide between studs and an overall roof span of 24 feet including overhang, the supporting joint system is subjected to 189 lbs_f. These calculations are detailed in Table F-3 of the appendix.

The International Building Code states that the required live load that a roof must support per this specific assembly is between 27.5 and 30.5 psf (0.19 and 0.21 psi), depending on roof pitch (International Code Council, 2009). The lower end of this range applies to an 8:12 pitch and the upper end applies to a 2:12 pitch. The load was determined based on the roof material, the pitch, and the tributary area (the span length multiplied by the width of the panel). The deflection limit is based on the span of the roof, L, and the type of ceiling attached to the roof (Table 1).

Table 1: Deflection limits for various ceiling materials (International Code Council, 2009).

Ceiling	**Deflection**
Plaster ceiling	L/360
Non-plaster ceiling	L/240
No ceiling	L/180

Calculations regarding the span of the roof were performed using a two-dimensional coordinate system with the vertical axis perpendicular to the pitch of the roof (Figure 14 and Figure 15). The panel was treated as if the foam had no load bearing capabilities, so that only the outer steel frame was accounted for. This affected the area moment of inertia and the cross sectional area of the panel. Two different roof configurations were analyzed. These are gable (Fig. 14) and shed roof styles (Fig. 15).

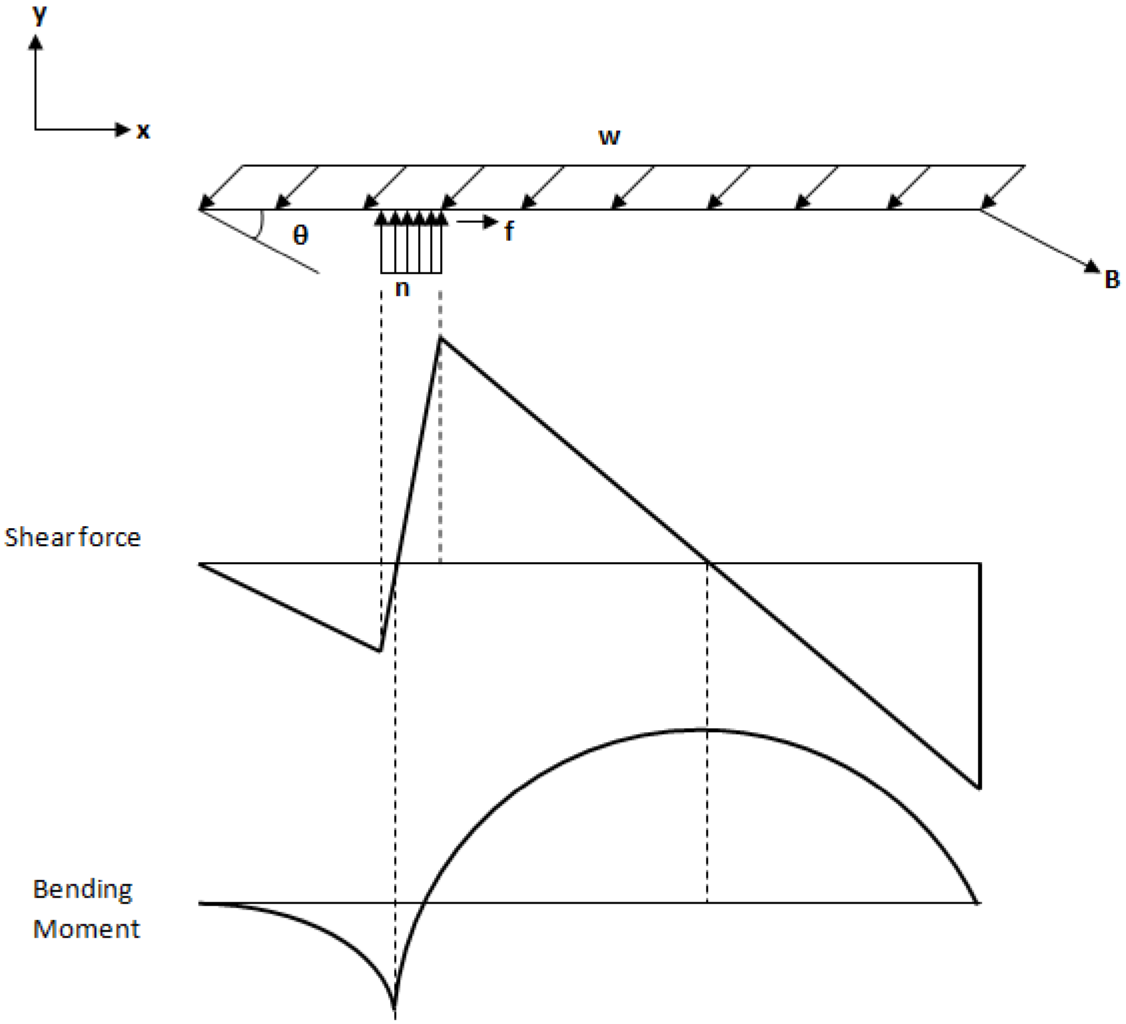


Figure 14: Shear stress and moment diagram of gable roof panel in horizontal coordinate system.

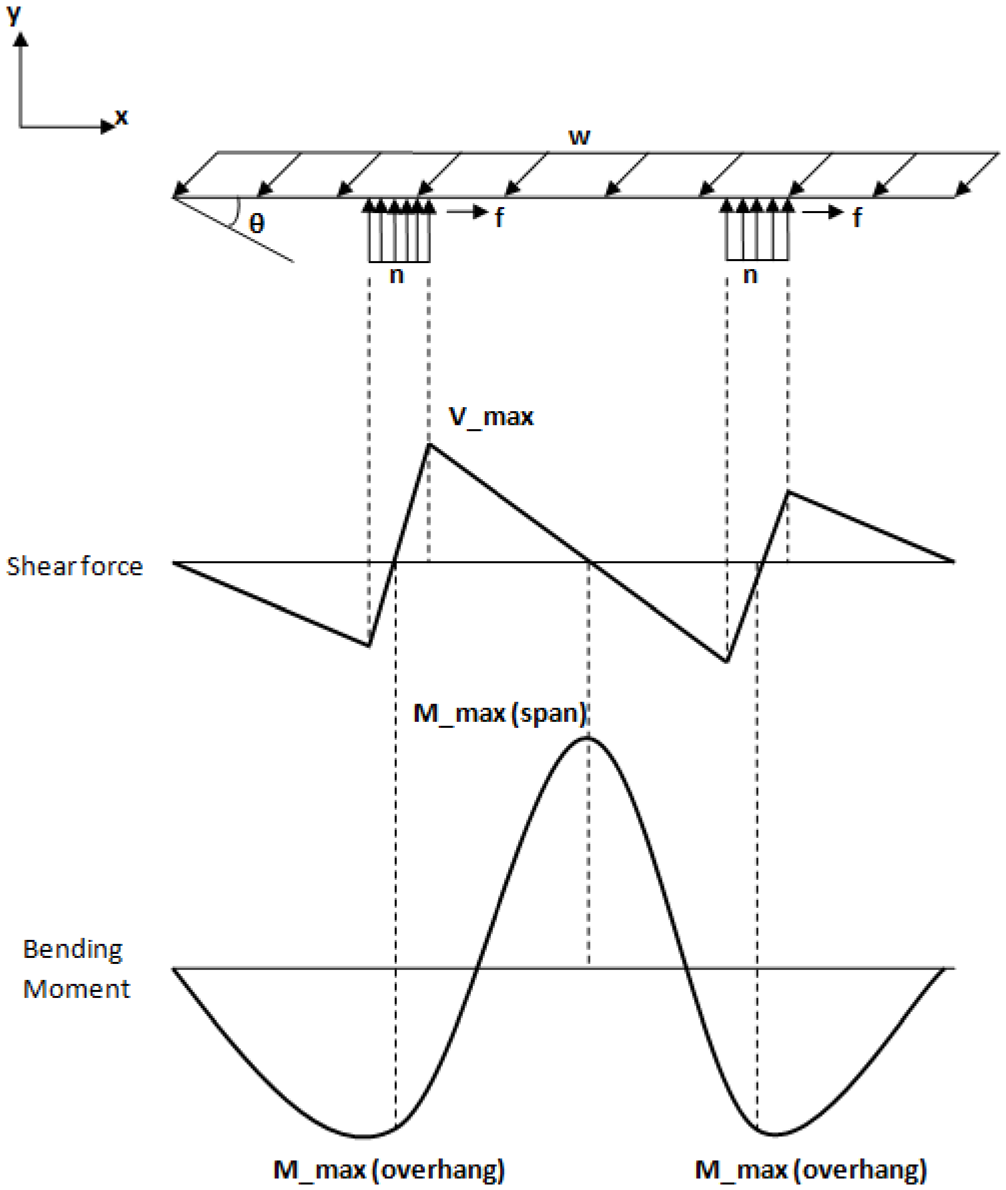


Figure 15: Shear stress and moment diagram of shed roof panel in horizontal coordinate system.

The weight of the roof was considered an evenly distributed load across its span. The live roof load required by code was also treated as an evenly distributed load, so these forces were added together and treated as one. Two other forces were taken into consideration in these calculations. In the shed configuration, two normal support forces at the walls were considered. In the gable configuration, the normal support force at one wall and the support force at the apex of the roof were considered. The normal force, n, was treated as an evenly distributed load over the span of the wedge, and the support force, B, was treated as a point load acting. In the shed roof configuration, two fastener forces in the roof-to-wall joints were also considered in calculations. This was done because in the gable roof, the vertical component of the support force at the apex would require an equal and opposite reaction from the opposing roof panel. Because the two roof panels are symmetrical, the upward pointing force must be equal to the downward pointing force, which is only possible if the force is zero. For the shed roof, it was assumed that the normal forces from the two wedges were equal, and the fastener forces at each wedge were also equal.

The values of the forces shown in Figure 14 and Figure 15 were determined from equilibrium calculations. Mechanics of materials analysis was used to generate shear force and bending moment diagrams in order to determine the maximum moment endured by the roof panel and the stress resulting from that moment (Figure 14 and Figure 15). These calculations can be found in Tables F-2 and F-3 of the appendix.

This analysis shows the stress and moment endured by the roof panel for various thicknesses, pitches, and spans. The maximum moment experienced by the roof due to the overhang occurs at a location just inward from the outer edge of the wedge (i.e. the end with the overhang) and in contact with the wedge. This distance is dependent upon the length of the overhang and the difference between the weight of the roof and the normal force supporting it. The maximum moment due to the overhang ranges from 5,558 lb_f-in for an 8/12 pitch, gable roof, to 6,588 lb_f-in for a 2/12 pitch, gable roof. The stress experienced by the roof panel at this point ranges from 750 psi to 883 psi, increasing with pitch. The maximum moment on a gable roof that is caused by the span occurs a few inches from the center, towards the apex. It is most dependent on the value of the anchor force. The moment ranges from 24,600 lb_f-in to 29,200 lb_f-in, decreasing with pitch. The resulting stresses from this moment range from 3,300 psi to 3,910 psi.

For the shed roof, the maximum moment due to the overhang occurs in almost the same place as it did in the gable roof. It is defined by the same parameters, but those parameters vary due to the configuration of the roof. The values of this moment ranged from 5,560 lb_f-in to 6,592 lb_f-in. The resulting stresses ranged from 750 psi to 883 psi. The maximum moment on a shed roof that is caused by the span occurs about halfway through the span of the panel as well. It ranges from 33,600 lb_f-in to 39,800 lb_f-in. The stresses incurred by this moment range from 4,490 psi to 5,320 psi.

When the thickness of the roof panel is decreased from 6 to 4 inches, the stress caused by the span of the roof decreases by almost a factor of 2. As the thickness increases, so does the inertia of the panel, which decreases the stress. This increase in thickness changes the weight of the panel by a factor of 1.5. Other methods of significantly decreasing the stress are increasing the gauge of the steel and the frequency of metal studs in the panels. Between the shed and gable roof configurations, there is little difference in the stresses caused by the overhang. The gable roof does offer more strength in its span, as it incurs much less stress, even though only one side of the roof panel was analyzed.

The stresses endured by the roof panel are far less than the yield stress of steel (between 25 and 200 ksi) (Engineer's Edge, 2010) and the maximum stress resulting from the deflection limits (83 to 167 ksi) stated by the code (Table F-2 and F-3). The maximum allowable stress was determined by multiplying the maximum allowable strain by the modulus of elasticity of alloyed steel (30 x 10^6 psi) (Engineer's Edge, 2010). The maximum allowable strain was determined by dividing the maximum deflections dictated by the code (
Table **1**) by the desired roof span.

4.4 Thermal Value

Energy efficiency is both a LionForce Systems goal and a roof system design constraint. One objective of the design is to maintain or improve the current R-Value of the home. The R-value measures thermal resistance, as mentioned previously. Heat is gained primarily through rooftops because they are the most exposed part of the house to the sun's rays. The current roof system uses ABT roof panels (same as wall panels), which have an additional air cavity. The air cavity serves as a channel for electrical wiring, but also doubles the amount of steel in the roof system. Heat is transferred into the house through the steel in these panels. The majority of the heat that the exterior roof is exposed to is mitigated by the EPS insulation, while a smaller percentage is transferred through the metal studs. Light gauge steel has a much lower R-value than EPS insulation, so the steel creates a thermal bridge and reduces the overall thermal efficiency of the panel by allowing more heat transfer through the structure. Properly oriented, the ABT panel could still provide a thermal seal. The Transcon panel eliminates the ABT air cavity section, which allows for flexibility in panel design, but provides less storage for electrical wiring. To further reduce the amount of steel in the panel a Delta stud may be used in lieu of a typical solid C-stud. Delta studs eliminate excess steel by removing portions of the stud in a truss-like pattern (Fig. G-1). This pattern maintains the structural load bearing properties of the panel while increasing its thermal efficiency.

The total R-value of the roof panel was calculated for both a standard C-stud and the Delta stud. This was calculated to show the overall decrease in thermal bridging due to the use of the Delta stud. A typical Delta stud reduces the thermal transference by 75% when compared to the solid C-stud used in standard construction (Transcon Steel).

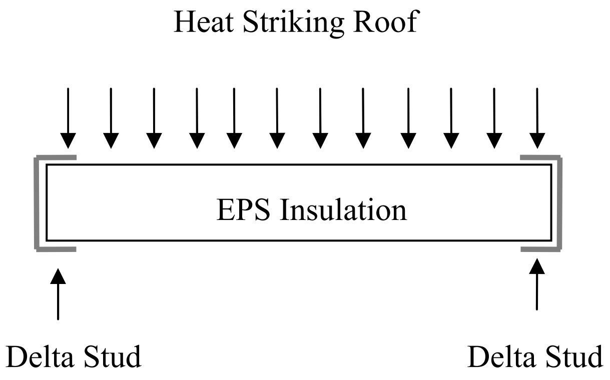


Figure 16: Free Body Diagram Analysis of Roof Panels

EPS insulation was used in both the C-stud and Delta stud systems. Standard R-values for both the steel and EPS were provided (Figure 16). The system can be represented as a resistive network in which, the insulation (R_{EPS}) and studs (R_{STUD}) are considered in parallel:

$$\frac{1}{Rtotal} = \frac{1}{Reps} \cdot Aeps + \frac{1}{Rstud} \cdot Astud \tag{9}$$

Area percentages were calculated to take into account the vast difference in the amount of heat striking the EPS (A_{EPS}) versus the steel (A_{STUD}). Area percentages were used to weight the R-values accordingly. The results show a 16% increase in the R-value (R_{TOTAL}) of the panel when using the Delta stud versus the C-stud. R value calculations for the current roof panel can be seen in Table 2.

Table 2: Results of Roof Panel R-Value Calculations

Total R-Value of Panel	
Trancon Delta Stud	2.24
Typical C-Stud	1.63

Using the calculated R-value of the Delta stud roof panel a mock roof was modeled to calculate the total R-value of the composite roof system. The composite roof system includes all layers in a complete roof assembly (Figure 17).

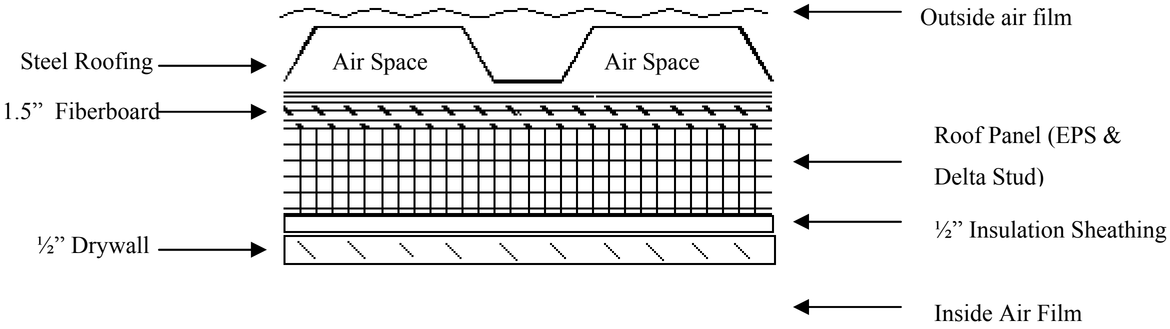


Figure 17: Mock Roof Assembly

Industry standard roof assemblies and the LionForce system assembly were considered when creating the composite roof system. The method for calculating the composite roof thermal values is similar to the panel R-value calculation. The system is set up as a resistive network in series, where the material R-values are simply summed. R-values used are based on the material depth. The sum of material sections provides the total R-value.

According to the current ASHRAE code (90.1), the standard R-value of a roof system in Zone 2 (Southern Texas) requires a minimum R-20 for sustainable buildings (Polyisocyanurate Insulation Manufacturers Association (PIMA)). The roof system calculation with a 4-inch thick panel resulted in an R-value of 17.87 (Appendix C). The R-value calculated is slightly lower than the sustainable building code. Steel roofs are typically used on LionForce Systems homes. Although this provides an extremely low R-value, the beneficial reflective properties of steel were not taken into account in the system calculations. The thermal reflectivity of steel has been shown to increase energy efficiency by reflecting heat, thus reducing the interior heat gain. Use of a steel deck could also better utilize the air space to increase the overall energy efficiency of the roof system. Increasing the depth of the roof panel, both steel and EPS insulation, by an inch (to a 5-inch thick panel) provides an R-value of 20, which complies with the industry standard.

These differing results show the array of options for roof design. Varying other layer thicknesses or the use of an additional insulating thermal layer provide other possibilities for producing the required thermal resistance. Material usage and load bearing issues should be considered when adjusting for thermal specifications. Currently a new ASHRAE code (189) has been proposed that will increase the R-value in Zone 2 to 25. The options presented above provide solutions to increasing the R-value of the current roof system to maintain code compliant roofs with the continually changing building standards.

4.5 *Critical Load Calculation*

As shown in Figure 18 the roof-to-wall joint will be compressed by the weight of the roof panel and other roofing materials used.

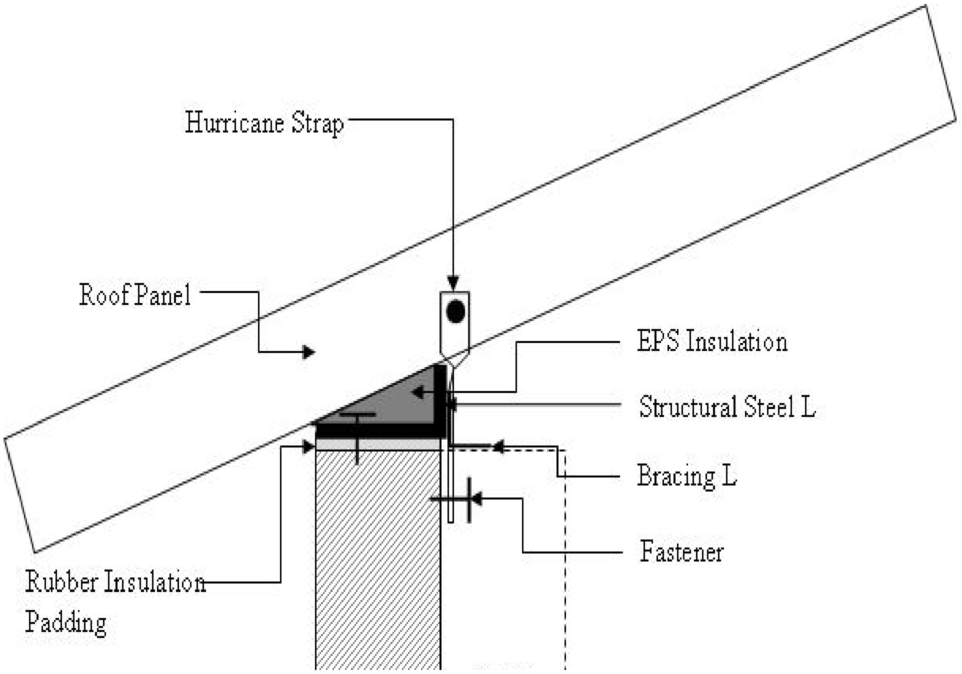


Figure 18: Free Body Diagram Analysis of Roof Panels

The vertical portion, or height, of the L-shaped joint is subject to buckling, whereas the horizontal portion is flush with the top of the wall section. The critical load values for buckling of the vertical portion of the wedge were calculated for a roof pitch range of 8/12 to 2/12, which correspond to the desired roof pitches for LionForce design. Using the material properties of common 12 gauge steel and the height of the vertical portion of the joint as inputs, the critical load that will cause buckling was calculated to be 179 lb_f for an 8/12 roof pitch (Appendix H). This value is greater than the load calculated for the weight of the roof panel 122 lb_f (Table F-1). As the height of the wedge is decreased, the critical load required for buckling increases exponentially. Therefore, lower roof pitches will have increased strength to prevent buckling. For both the 2/12 and 8/12 pitches, the wedge will withstand the buckling force applied, however, deflection may occur. An additional L-bracket in the design will help resist deflection.

4.6 Physical Fit Test

In order to verify physical compliance, panels from both companies (ABT and Transcon) were used to perform a physical 'fit test.' In this test, small portions of roof and wall panels were assembled with the joint to verify functionality and ease of assembly. The test showed that the joint fit well with both Transcon panels and ABT panels, which were used as wall components during the test. Figure 19 shows the joint fastened to an ABT wall panel.

Figure 19: L-Joint fastened to ABT Panel During Fit Test

In this picture, the bracing L-bracket can be seen bracing the vertical section of the joint. It is also evident that a good interface is made with the thin closed-cell foam that sits between the L-joint and that ABT panel track. In Figure 20, the complete assembly with a Transcon roof panel is shown. The hurricane straps can be seen connecting the Transcon roof panel directly to the stud on the ABT wall panel. The expected placement of the hurricane strap onto the outer edge of the ABT studs, distant from the foam, played out according to plan. What was not expected during testing was the misalignment of studs between ABT and Transcon Panels. ABT studs are positioned 2 feet inward from the end of each panel, but Transcon panels have studs on each end. In order to ensure a structural link between wall and roof panels, these studs must be lined up to facilitate connecting the two structural supports. When the studs are lined up, the ABT and Transcon panels are staggered, as shown in Fig. 20.

Figure 20: Assembly of L-Joint with Transcon Roof and ABT Wall Panel During Fit Test

5 Budget Analysis

LionForce Systems is a new company that is slowly emerging into the home building industry. It is focused not only on creating a prefabricated eco-friendly home but also on customizing the home to the specific requests of each customer. Their innovative process of building homes allows the customer to virtually add any modifications they desire within technical reason.

Table C-1 in the appendix breaks down the cost of constructing one 4-foot long joint. The total cost estimate comes out to $8.48, but this approximation is considered an extreme over-estimation. Prototyping materials were purchased in bulk without consideration for per unit price, so rough estimates were made based on total cost and percent used. All numbers were rounded up to produce a worst case scenario. In addition, the purchase of materials in bulk during home construction would drastically reduce this price during implementation by LionForce Systems.

Table C-2 details the costs related to the construction of an entire home using ABT wall and Transcon roof panels connected with the L-shaped joint design. The total in this table comes out to a little over $27,000. The objective of this cost analysis is to demonstrate that this panel system would be economically viable. The costs are again considered high estimates. However, investing under $30,000 on the framing of an entire home with green building techniques is competitive. An extremely inexpensive, straw bale home was priced at $17,095 to frame an entire home (Owens, 2008). With this being the lowest end of pricing, the LionForce method is competitive in the green market, which operates at a considerably higher price than standard or traditional construction. Buyers save on long-term expenses, energy costs, and government subsidies. Price is also often not the main motivator in entering green home construction.

LionForce Systems has constructed two pre-fabricated homes, called Trumbo 1 and Trumbo 2. Through the construction of these homes, significant progress was made towards a greater understanding of the benefits and risks associated with the use of steel and EPS. Changing materials at this point would waste the time, material, and labor investment in these two homes as well as the expertise LionForce personnel worked so hard to attain. Investors in innovative green products develop loyalty over time when they observe consistent results. For these reasons, it is ideal that the design is comprised of materials that LionForce currently uses.

Costs related to the manufacturing of steel will be minimized by creating the simplest design possible. Each additional bend or frame change adds steps to the creation process and incurs even more costs. Since manufacturing for steel is more complex than the manufacturing for EPS, major cost minimization is going to stem from this portion of the design. Therefore, the simple L-shape, with one single bend and minimal steel, is ideal for cost minimization with regards to steel.

As mentioned previously, the material cost of EPS will have a small impact on overall design cost. EPS is purchased in blocks and, in comparison to steel, can be easily cut and shaped. Additionally, the L-joint design does not change the makeup of the wall and roof panels in which most of the EPS is placed. However, there is still an opportunity for cost reduction. Removal of EPS from the overhang section of roof panels would cut back on material costs. The purpose of the insulation is to create a thermal barrier between the house and its surroundings. Insulation in the overhang, which is external to the house, has no added value.

EPS is in large part a product of the petroleum industry, so oil prices will play a role in its price. However, the benefits of EPS versus traditional insulation would outweigh fluctuations in oil prices. EPS usage also fits more in line with LionForce’s need to provide the best insulation possible. Some alternatives to EPS exist, but they are not yet at the level of technological sophistication that EPS has reached, so their use would incur the risk of an unfamiliar material.

Conclusions and Recommendations

This design is a product of its various subsystems, thus its success is dependent on the success of each of the subsystems in performing their respective functions. Analysis of these subsystems was based on thermal and structural calculations that incorporate a variety of assumptions. The calculations showed that the roof-to-wall joint satisfied design criteria, and the 20-foot span is feasible. The 4-foot overhang turned out to be unrealistic within LionForce's desired constraints, but an external bracket support system is recommended which could successfully support the load of an external overhang. The biggest issue with the overhang is that it puts a large amount of stress on the roof panel, especially around corners. LionForce did not want the addition of any external supports to the house, but this is the cheapest feasible solution.

Thermal analysis showed that the designed roof-to-wall joint will not transfer excessive heat in or out of the joint. This is due to the foam (inside the wedge and on top of the wall panel) and the cut outs or delta studs in the base of the L-shape (to limit thermal bridging). The critical load analysis proved that the vertical component of the L-joint will not buckle under the force of the roof (including a live load, per code). The analysis of the span indicated that a 20-foot span is possible using both a shed and gable style roof system.

The stresses calculated regarding the span show that a 20 foot span is indeed viable using a 6 inch thick Transcon panel that is 24 inches wide. The gauge of the steel should be at least 12. The stresses caused by the span were well within the limits of any type of steel, thus this system is mechanically suitable as a roofing configuration. The use of Transcon panels for the roof is important for the increase of span. Transcon panels are much lighter than the ABT panels previously used. The thickness of the roof panel may be varied in order to allow for different spans.

The design was completed successfully under budget, using only $551 out of a $1200 budget. The vast majority of these expenses were spent on the prototyping of wrong turns and traveling expenses that would not be necessary in replication of the ultimate design. In order to recreate a single 4 foot length of joint (corresponding to a 4 foot width between trusses), it would cost $8.84, according to generous estimates of all individual part costs. The joint has proven to be an economically feasible design that was arrived at with less than half of our resources. Throughout the semester, the hours spent on the project reflected an economic use of time. All group members spent between 7 and 10 hours average weekly on the project, which is a reasonable amount of man hours for the task.

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A Final Budget Spreadsheet

Date	Sponsor	Description		Status	Budgeted Amount	Actual Amount	Notes
9/2/2009	Engr Dept	Senior Design Project Allotment			$1,200	$1,200	
Total Income					$1,200	$1,200	

Expenses							**Status (Check one)**				
Date	**Vendor**	**Item Description**	**PO #**	**Status (Planned/ Pending/ Cleared)**	**Budgeted Amount**	**Actual Amount**	**Internal**	**Dept Purchase Order**	**PCARD**	**Reimburse-ment**	**Notes**
Feb											
11/13/2009	Westbrook Metals	2 Galvanized Steel sheets	3183413	Cleared	$50	$50		x			
11/16/2009	San Antonio Foam Fabricators	EPS insulation		Cleared	$22	$22				x	
2/5/2010	White Cap Construction Supply	self-drilling screws		Cleared		$2.15				x	Unplanned
2/5/2010	San Antonio Foam Fabricators	Insulation foam for joint + adhesive		Cleared		$50.89				x	Unplanned
2/10/2010	Amazon.com	IBC book		Cleared		$102.31		x			Unplanned
2/16/2010	ABT	Wall Panel		Planned	$100	$0					Donated
2/16/2010	Transcon	Roof Panel		Planned	$72.80	$0.00		x			Donated
2/16/2010	Lowes	Fasteners		Planned	$30	$0				x	Canceled
2/16/2010	Lowes	Insulation		Planned	$50	$0				x	Canceled
3/1/2010	White Cap/Simpson Strong Tie	hurricane straps & L-brackets		Cleared	-	$69.47					Unplanned
4/10/2010	Travel Expenses for Panel Retrieval	Food, mileage	3183485	Cleared	$60.00	$253.79				x	
4/10/2010	ABT	Screws		Cleared	$10.00	$0.00					Donated
4/27/2010	Kinkos	Final Report Binding and Printing		Planned	$22.41	0					Dept Fundings
Total Expenses					$417	$551					

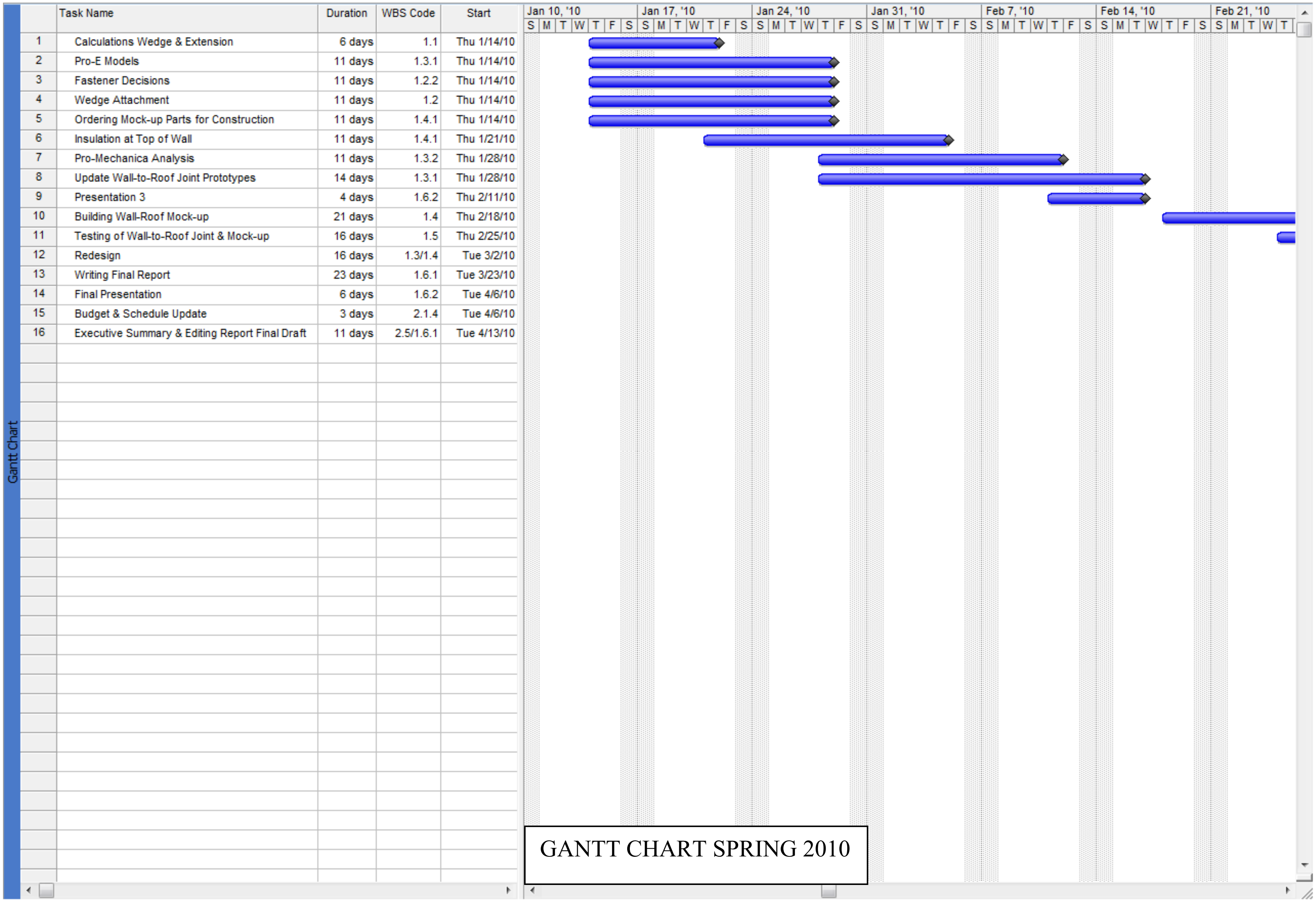
	Budgeted	Actual
Budget Remaining	$782.71	$649.31

Notes:

* Many planned items were given as donations.

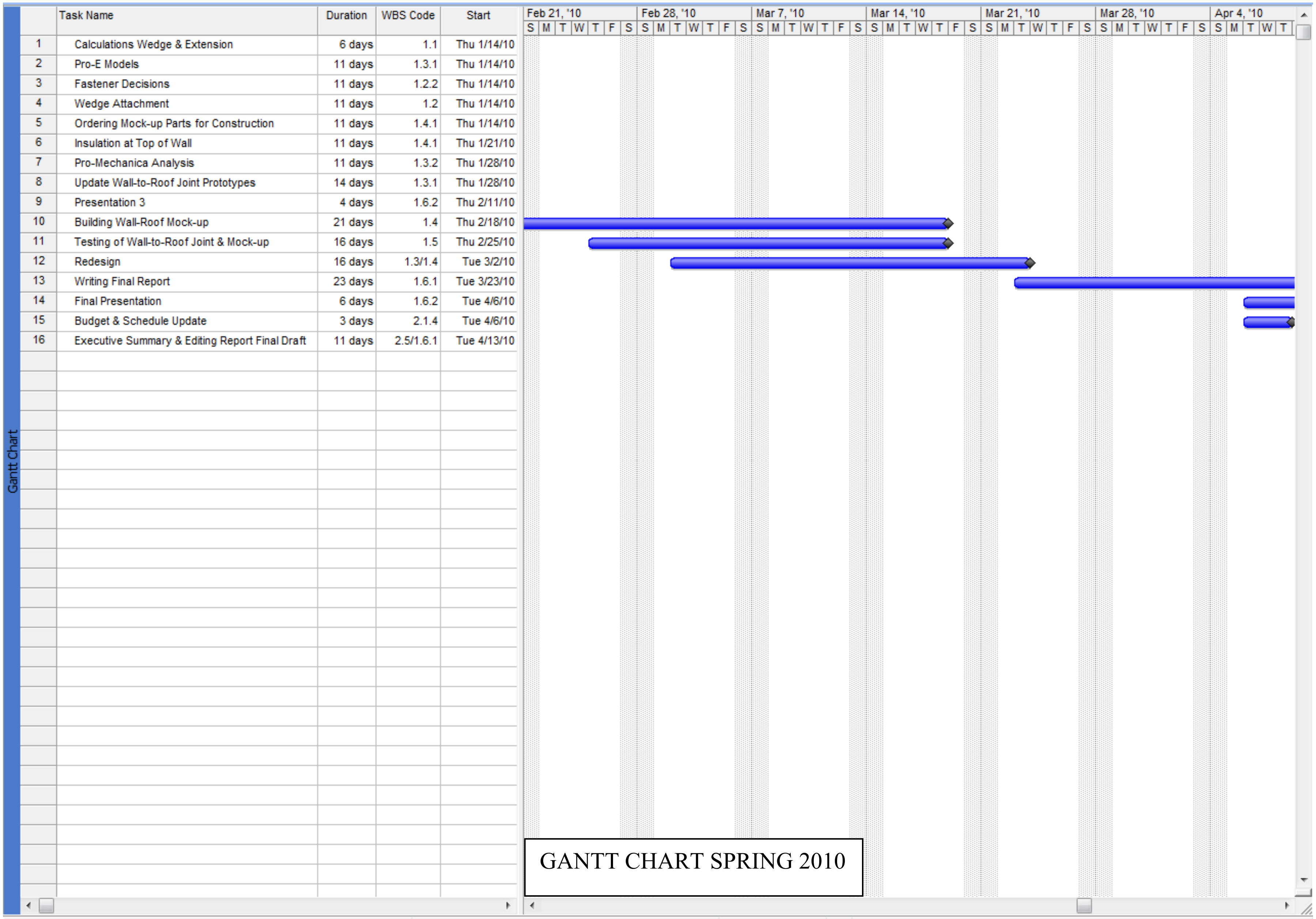
B Final WBS and Schedule

1. Project Work
    - 1.1. Hand Calculations
        - 1.1.1. Wedge with extension
        - 1.1.2. Span/Overhang
        - 1.1.3. Thermal
    - 1.2. Research
        - 1.2.1. Building Codes
        - 1.2.2. Fasteners
    - 1.3. Computer Modeling
        - 1.3.1. Pro Engineer CAD drawings
        - 1.3.2. Pro Mechanica CAD drawing
    - 1.4. Physical Prototyping
        - 1.4.1. Ordering parts/Shopping
        - 1.4.2. Joint
        - 1.4.3. Span/Overhang
    - 1.5. Physical Testing
    - 1.6. Documentation
        - 1.6.1. Design Report
        - 1.6.2. Presentation
2. Administration
    - 2.1. Planning
        - 2.1.1. Agenda setting (Group Leader)
        - 2.1.2. Group email correspondence
        - 2.1.3. Meeting minutes
        - 2.1.4. Budget
    - 2.2. Project Management
        - 2.2.1. Monthly Management Reviews
        - 2.2.2. One-on-ones with Dr. K. Nickels (Progress Reports)
        - 2.2.3. Meeting with Dr. D. Glawe
    - 2.3. Self-Peer Evaluations
    - 2.4. Group Meetings
    - 2.5. Executive Summary
3. Course Content (Non-Project
    - 3.1. 2:10 General Meetings
    - 3.2. Reading/Other Homework
    - 3.3. Studying
    - 3.4. In-Class Time



	Task Name	Duration	WBS Code	Start
1	Calculations Wedge & Extension	6 days	1.1	Thu 1/14/10
2	Pro-E Models	11 days	1.3.1	Thu 1/14/10
3	Fastener Decisions	11 days	1.2.2	Thu 1/14/10
4	Wedge Attachment	11 days	1.2	Thu 1/14/10
5	Ordering Mock-up Parts for Construction	11 days	1.4.1	Thu 1/14/10
6	Insulation at Top of Wall	11 days	1.4.1	Thu 1/21/10
7	Pro-Mechanica Analysis	11 days	1.3.2	Thu 1/28/10
8	Update Wall-to-Roof Joint Prototypes	14 days	1.3.1	Thu 1/28/10
9	Presentation 3	4 days	1.6.2	Thu 2/11/10
10	Building Wall-Roof Mock-up	21 days	1.4	Thu 2/18/10
11	Testing of Wall-to-Roof Joint & Mock-up	16 days	1.5	Thu 2/25/10
12	Redesign	16 days	1.3/1.4	Tue 3/2/10
13	Writing Final Report	23 days	1.6.1	Tue 3/23/10
14	Final Presentation	6 days	1.6.2	Tue 4/6/10
15	Budget & Schedule Update	3 days	2.1.4	Tue 4/6/10
16	Executive Summary & Editing Report Final Draft	11 days	2.5/1.6.1	Tue 4/13/10

GANTT CHART SPRING 2010



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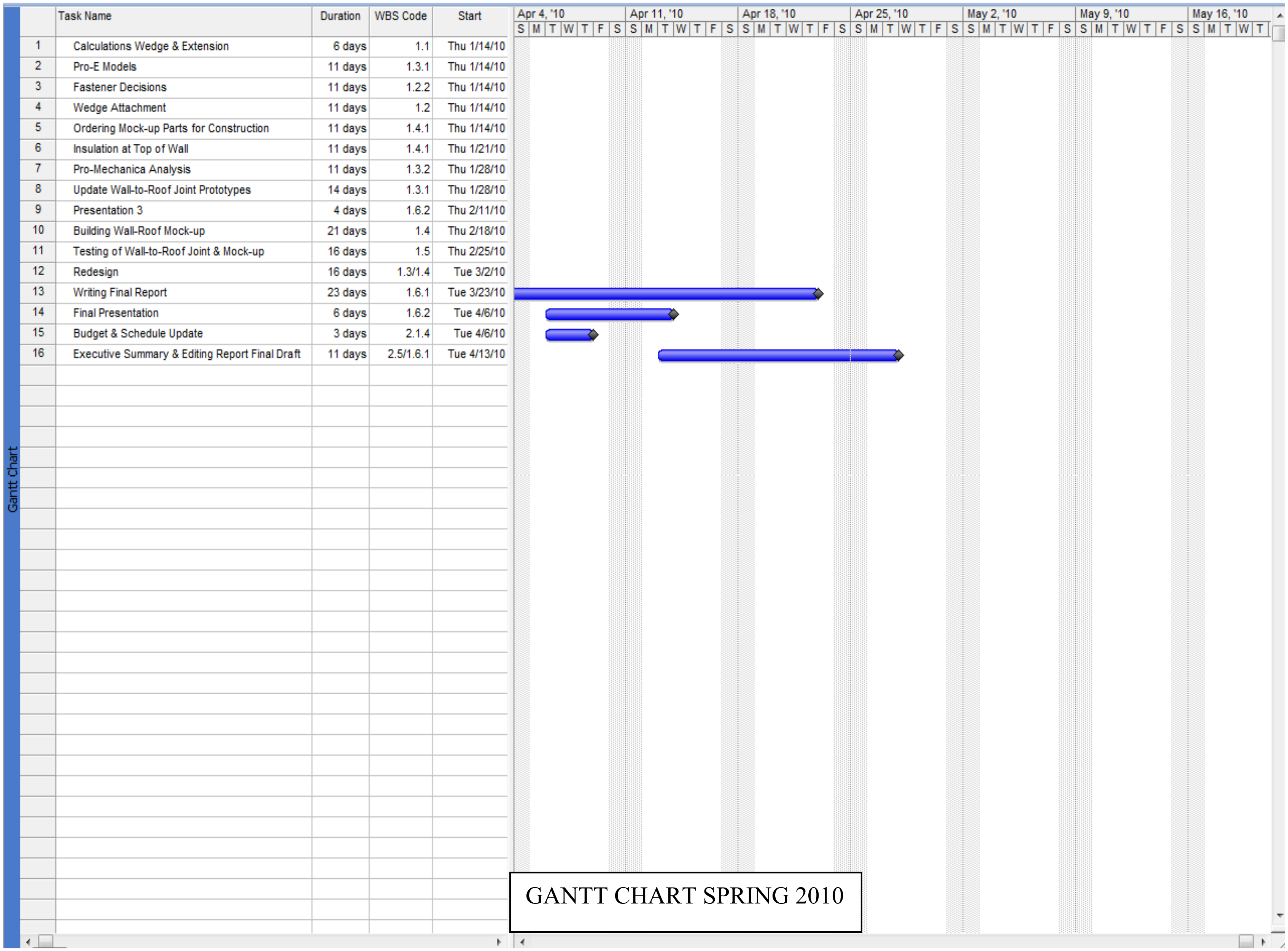
GANTT CHART SPRING 2010



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12	Redesign	16 days	1.3/1.4	Tue 3/2/10
13	Writing Final Report	23 days	1.6.1	Tue 3/23/10
14	Final Presentation	6 days	1.6.2	Tue 4/6/10
15	Budget & Schedule Update	3 days	2.1.4	Tue 4/6/10
16	Executive Summary & Editing Report Final Draft	11 days	2.5/1.6.1	Tue 4/13/10

GANTT CHART SPRING 2010

C Cost Analysis

This section includes material costs for panels, straps, and fasteners for multiple pre-fabricated construction suppliers.

Table C- 1: Bill of Materials and List of Venders

Item Description	**Vendor**	**Approximate Item Cost**
Galvanized steel sheets	Westbrook Metals	$4.00
EPS Insulation	San Antonio Foam Fabricators	$0.46
Self-Drilling Screws	White Cap Construction Supply	$0.02
Hurricane Straps & L-brackets	White Cap/Simpson Strong Tie	$2.00
Insulation	Lowes	$2.00
Total:		$8.48

Table C- 2: Material Cost per Square ft. and per Home

ITEM	**Supplier/Sub**	**UNIT**		**Multiplier**	**Material Cost Per Home**
Panels and Associated Costs	ABT wall panels	ft^2	$ 8.50	2,448 ft^2	$20,808.00
	Basic Panel Cost Breakdown				
*	EPS* (Per Panel)	ft^2	$ 1.45	1,260 ft^2	$1,827.00
*	Steel** (Per Panel)	ft^2	$ 1.10	1,260 ft^2	$1,386.00
	Transcon roof panels 3.5" 18 ga. 24" oc	ft^2	$ 4.55	560 ft^2	$2,548.00
	Transcon Roof Fasteners	ft^2	$ 0.15	560 ft^2	$84.00
	Transcon Roof Fascia Cap (10" x 2 bend x 20ga) (1)	per 10' stick	$ 18.23	30.6	$557.84
	Basic Panel Cost Breakdown				
*	EPS* (Per Panel)	ft^2	$ 1.45	1,260 ft^2	$1,827
*	Steel** (Per Panel)	ft^2	$ 0.80	1,260 ft^2	$1,008.00
	Misc: Shipping Costs to San Antonio	Per home	$ 500.00	NA	$500.00
	Basic Joint Cost				
	Joint	Per 4 ft wall span	$ 8.48	306 ft	$2,594.88
Total Cost			**$ 539.91**		**$27,092.72**

Note: Total Costs are only approximations. Technical information was provided from the original LionForce home. Per home material costs were figured by multiplying the unit costs by their respective multipliers. '*' indicates items that were not factored into total cost (due to redundancy).

Table C- 3: Multipliers and Their Explanations for Material Cost Calculations

Multiplier	Explanation
1,260 ft^2	ABTspecs stated to use this multiplier
2,448 ft^2	Square footage of wall in first LionForce home
560 ft^2	Square footage of roof in first LionForce home
30.6	Perimeter of first LionForce home divided by 10-ft sections
306 ft	Perimeter of first LionForce home

Note: All the data comes from primary sources (ABT pricing from LionForce sent by Dr. Kimberley Drennan of LionForce Systems; Transcon Steel from Mr. Geoff Jennings, President of Transcon). **Cost estimates based on Transcon roof panels and ABT wall panels.**

Table C- 4: Transcon Steel Panel Pricing

Component Description	Cost
Roof panel: 6” thick, 24” oc spacing, 20 ga.	$5.77 per square foot
Fasteners: #10 x 7” Phillips Coated Roof Grip	$0.15 per square foot of roof
Fascia Cap: 10” x 2 bend x 20ga. Fascia Cap	$18.23 per 10’ stick
Shipping to San Antonio	Approx. $500 with a max of 4,500 square ft per truck for 6” thick panels

D CAD Drawings

This section includes a collection of Pro-E models of the Roof-to-Wall Joint, pictures of the physical joint prototype, and other various panel, connection detail, and roof support figures.

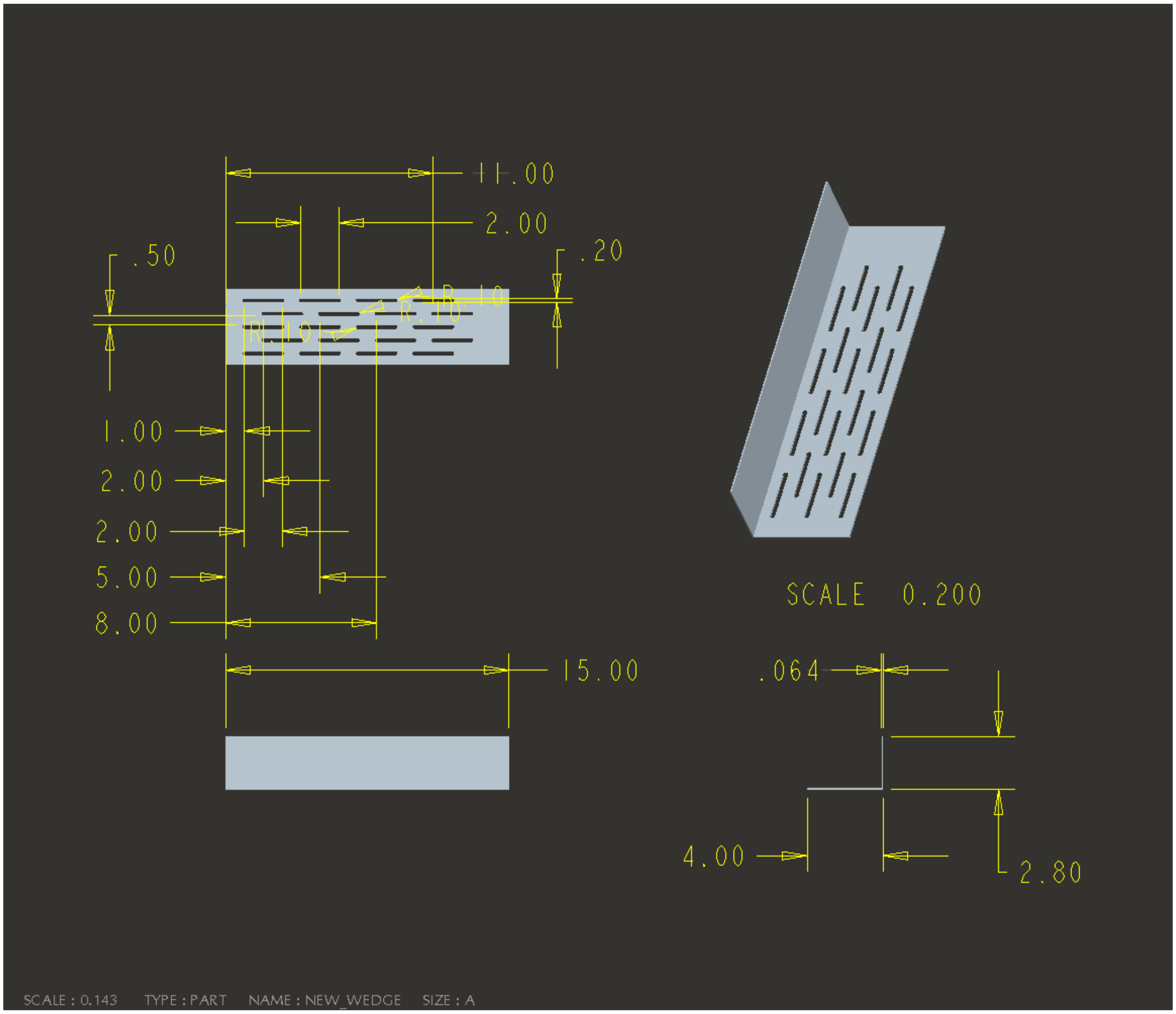


Figure D- 1: Roof-to-Wall Joint CAD Model

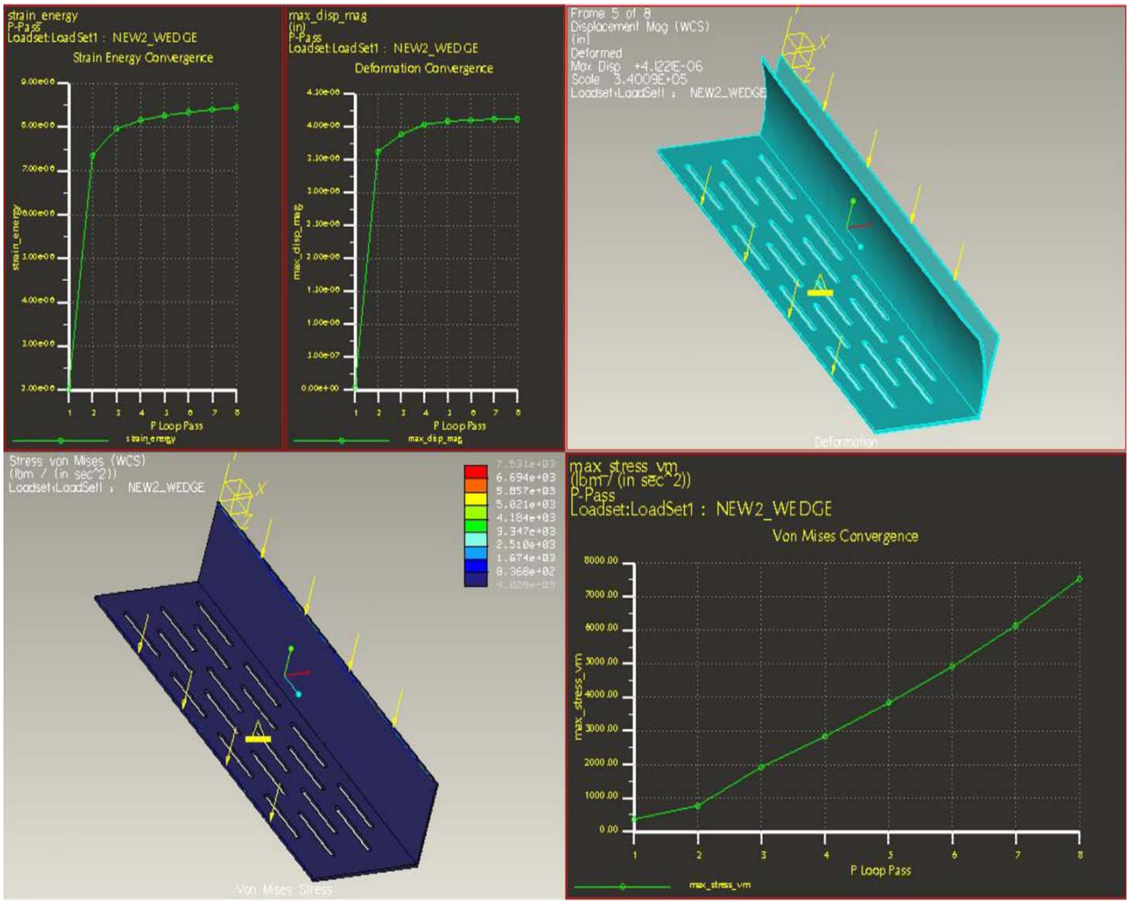


Figure D- 2: Roof-to-Wall Joint Pro-Mechanica CAD Results

The **Strain Energy Convergence Graph** in the upper left-hand corner shows the strain energy in the joint over time. Time on the x-axis is labeled as a "P Loop Pass," because these results are in simulations form.

The **Deformation Convergence Graph** to the right of the strain energy convergence graph shows the maximum deformation in the vertical member of the joint over time.

The **Von Mises Convergence Graph** in the lower right-hand corner shows the maximum stress in the joint over time.

The figure in the upper right-hand corner is the fifth frame simulation done in Pro-Mechanica of deformation in the roof-to-wall joint.

The figure in the lower left-hand corner is a color-coded depiction of stress concentrations in the joint. The dark blue color of the joint shows areas that are experiencing safe stress levels. A red color would pinpoint an area experiencing dangerous stress levels.

E Overhang Calculations

This section presents calculations for an external overhang support bracket. Figures E-1 through E-2 were already presented and discussed in the main body of the report. They are reproduced here so the reader can better understand the full calculations which are presented in this section without referring to the main report.

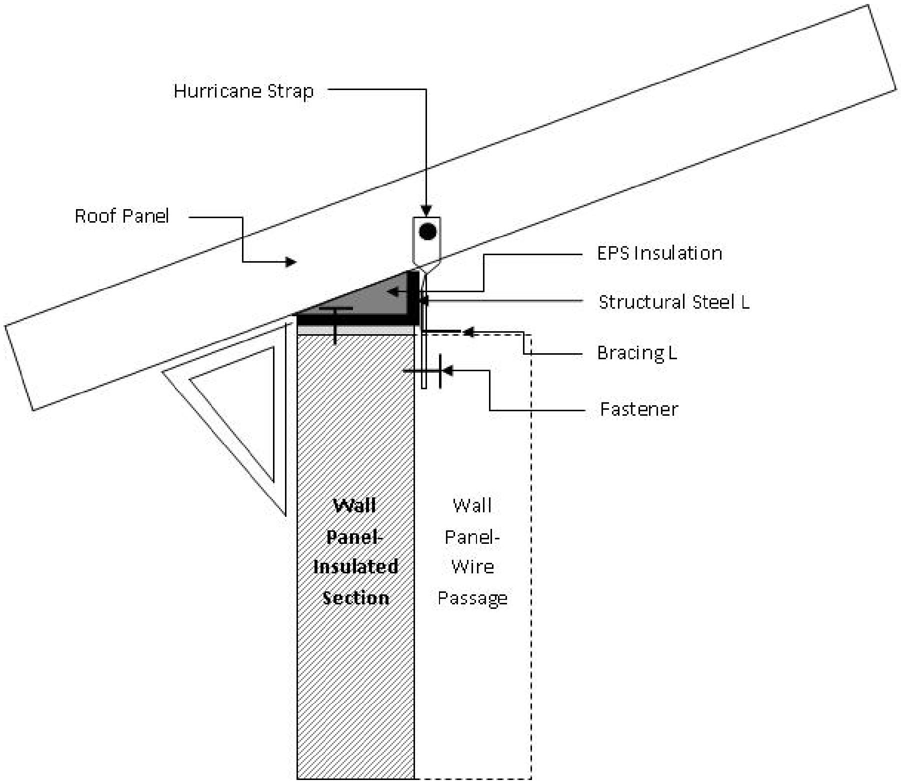


Figure E- 1: Overhang with Support Bracket

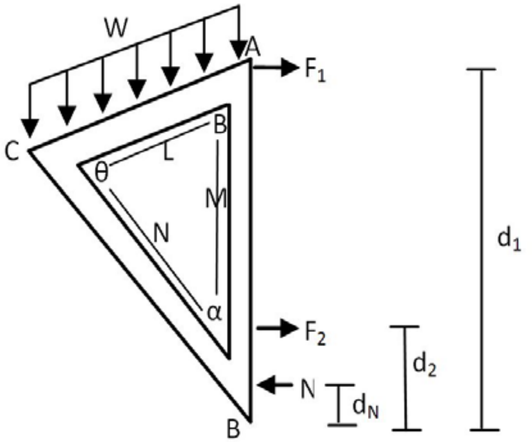


Figure E- 2: General External free body diagram of overhang support bracket

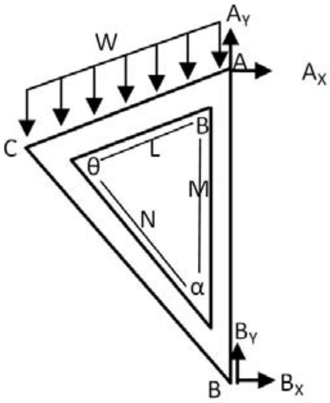


Figure E- 3: Simplified External FBD of overhang support resolved into components

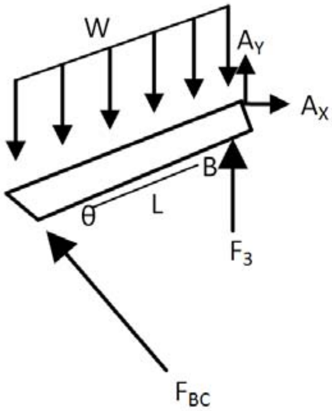


Figure E- 4: Internal free body diagram for member AC of overhang support bracket

Table E- 1: Calculations on External Overhang Support

Assumptions:			
d1 = m			
d2 = 0			
N = 0 or m, and is combined or considered by F1 and F2 values			
Given Values:	Specific weight of roof panel, gamma	0.004825	(lb/in^3)
-		<u>ft</u>	<u>inches</u>
	Wall width	0.5	6
	span length	20	240
	Overhang length, O_L	4	48
	Roof panel thickness	0.333	4
	Roof panel width	4	48
	Safety factor load	30.525	(lb/ft^2)
Input Variables:	W, weight of roof (lb)	273.9	
	weight of roof including safety factor (lb)	3282.0	
	Roof pitch	0.667	
Chosen Variables:	L, length of top support (ft)	2	
	M, length of vertical member (ft)	3	
Calculations:			
External FBD:	$\sum M_Z = \frac{wO_L}{2}(O_L \sin\beta) + MB_X = 0$		
	$\sum F_X = 0$		
	$A_X = -B_X$		
	$A_Y + B_Y = wO_L$		
Internal FBD:	$\sum M_A = wO_L\left(\frac{O_L \sin\beta}{2}\right) - LF_{BC}\sin(\theta) = 0$		
Outputs:	w (lb/ft) for panel width used	59.1	
	w including safety factor(lb/ft)	707.9	
Results:		<u>Radians</u>	<u>Degrees</u>
	Beta, roof pitch	0.98	56.31
	Alpha, bottom angle	0.72	41.35
	Theta, outside angle	1.44	82.34
	N, length of critical member (ft)	2.52	
	Bx, anchor force to right at bottom, lb	-1571	
	Ax, anchor force to right at top, lb	1571	
	By, anchor force up at bottom, lb (worse case)	2832	
	Ay, anchor force up at top, lb (worse case)	2832	
	F_{BC}, compression force in critical member (lb)	2377	

Table E- 2: Bending and Buckling Calculations in Critical Member of Support Bracket

Given Values			
Structural Steel	Modulus of elasticity, E	30000000	psi
	Yield stress, σ_{ys}	75000	psi
Calculations:	$\sigma_{ys} = \frac{F}{A}$		
Buckling			
pinned-pinned:	$P_{cr} = \frac{\pi^2 EI}{L^2}$	$I = \frac{bh^3}{12}$	
fixed-fixed:	$P_{cr} = \frac{\pi^2 EI}{4L^2}$		
Results:			
	Moment of Inertia, I for pinned-pinned	0.0002427	in^4
	Moment of Inertia, I for fixed-fixed	6.067E-05	in^4
	Cross-sectional area, A	0.0316967	in^2

F Span Calculations

The load calculations to provide an expanded internal span for the final design are provided in this section.

Variable definitions:

I = 2nd moment of area/ area moment of inertia (in^4)

P = weight of roof panel (lbs)

L_r = Live roof load, per code. (psi)

w = width of roof panel (in)

l = length of roof panel (in)

h = length of overhang (in)

θ = angle made by the roof panel with the horizontal; pitch of roof (deg)

B = Anchor force at the apex of the roof (lbs)

n = normal force provided by the wedge (lb/in)

M_{max} = maximum moment endured by roof panel (lb-in)

σ_{total} = stress endured by roof panel (psi)

t_w = thickness of wedge (in)

f=force of friction of anchor/fastener

V_{max}=maximum shear force endured by panel (lb)

Table F- 1: Calculations on Sample for Density

Calculations on Sample for Weight per Unit Volume

Assumptions:

1) The ratio of steel to EPS in panel sample is consistent between all full-sized panels

Measured Values: Dimensions of Sample

Sample Dimensions:		
Weight (W)	5.5	lbs
Length (l)	19	in
Width (w)	15	in
Thickness (t)	4	in

Calculations: Panel Weight Density (ρ)

Weight Density Equation

$$\boxed{\rho = \frac{W}{l * w * t}}$$

Results:

Panel Weight Density		
Density	0.004825	lbs/in^3

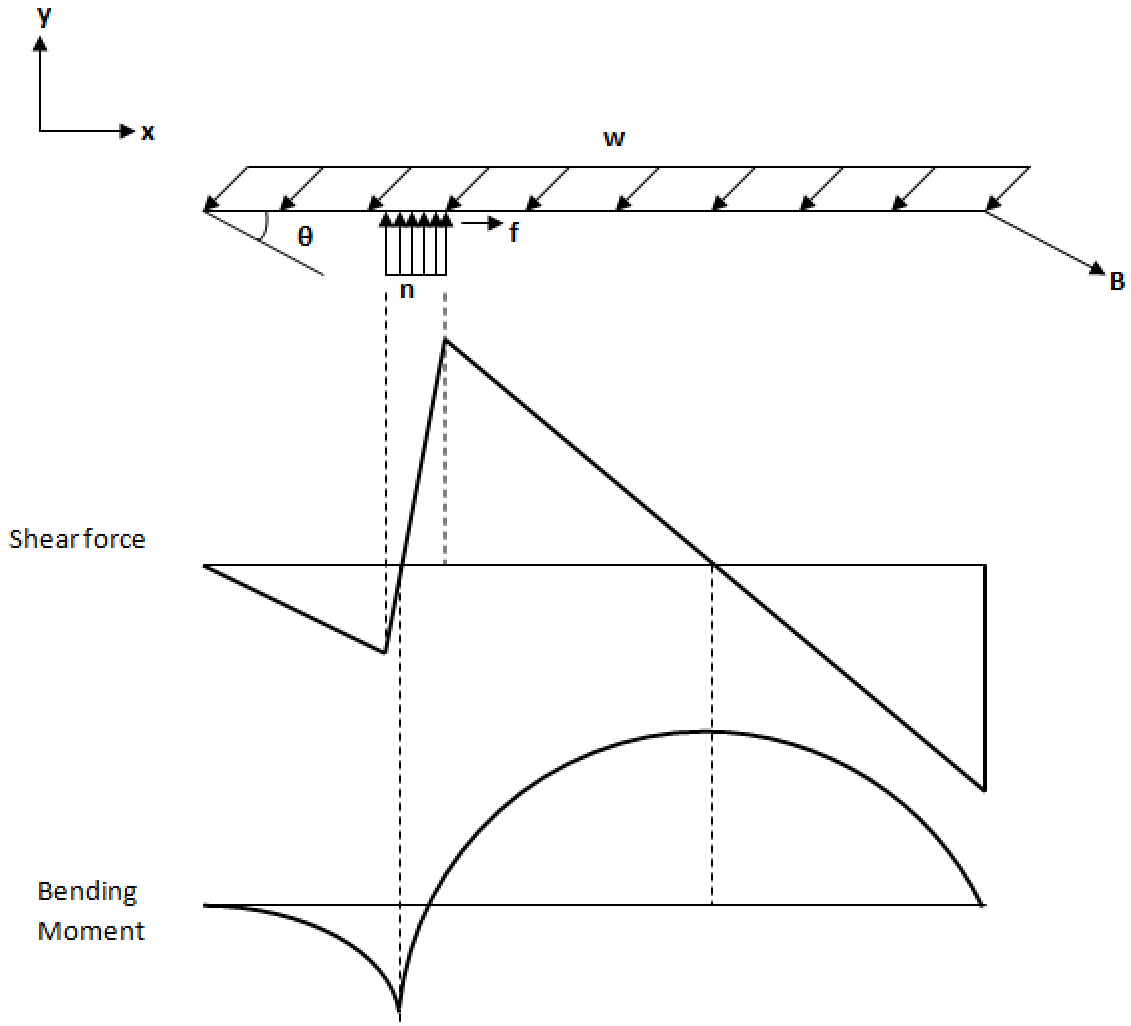


Figure F- 1: Shear force and bending moment diagram of the gable roof panel in horizontal coordinate system.

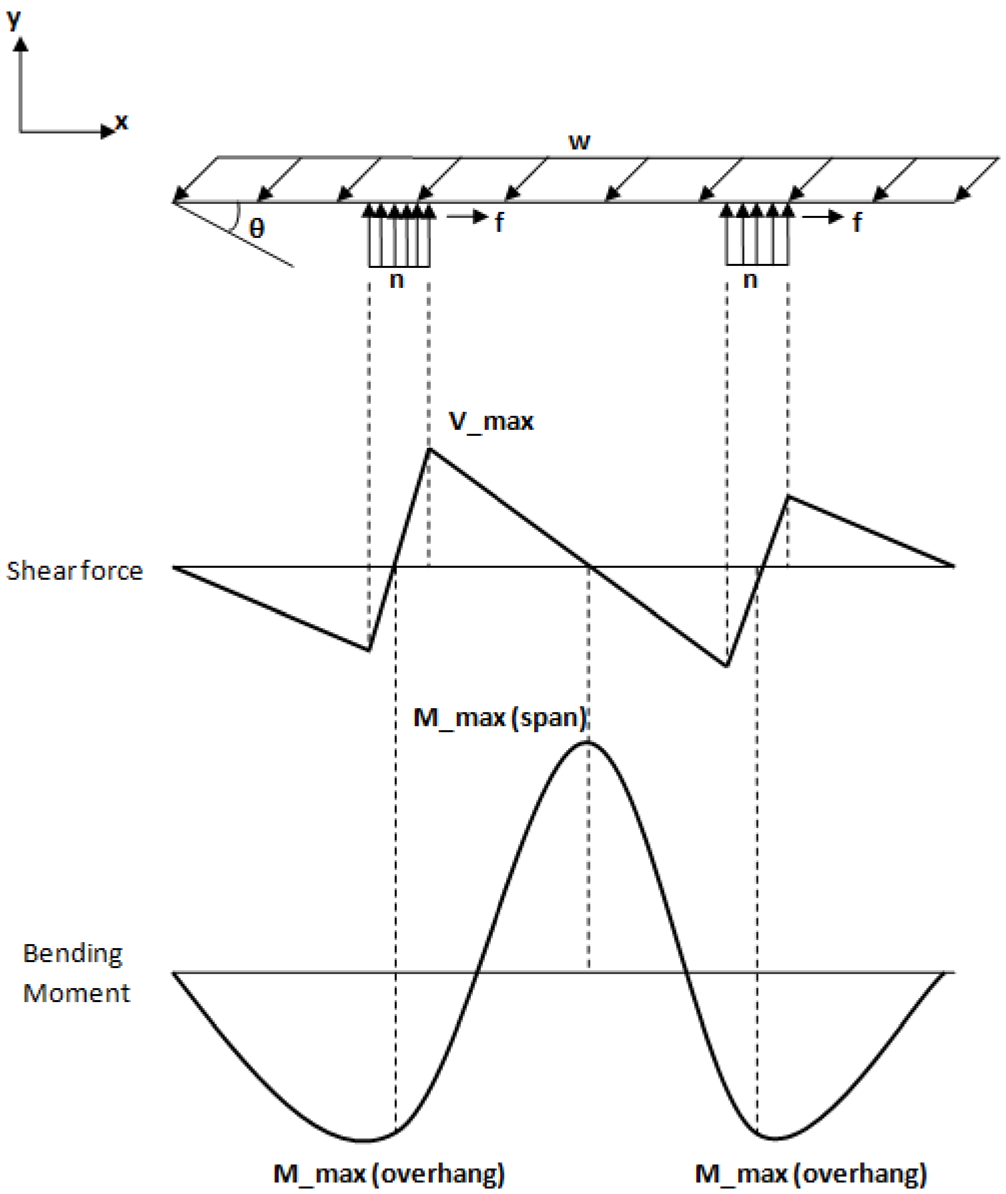


Figure F- 2: Shear force and bending moment diagram of the shed roof in horizontal coordinate system.

Equations:

$$\sum F_x = 0 = -(P + L_r w l)\sin\theta + B\cos\theta \tag{F-1}$$

$$\sum F_y = 0 = -(P + L_r w l)\cos\theta - B\sin\theta + n t_w \tag{F-2}$$

$$n = \frac{(P + L_r w l)\cos\theta + (P + L_r w l)\tan\theta\sin\theta}{t_w} \tag{F-3}$$

$$B = (P + L_r w l)\tan\theta \tag{F-4}$$

$$M_{max} = \frac{h(h + a)\left(\frac{P}{l} + L_r w\right)\cos\theta}{2} \tag{F-5}$$

$$\sigma_{total} = \sigma_{bending} + \sigma_{tension} = \frac{M_{max} t}{2I} + \frac{\left(\frac{P}{w} + L_r l\right)\sin\theta}{t} \tag{F-6}$$

Table F- 2: Overhang/Span Stress Analysis (4 in. thick roof panel)

Set Values:			**Results (gable):**		
Specific Weight (gamma)	0.004825	lbs/in^3	Total roof panel length(l_tot)	292	in
Roof panel width (w)	24	in	Cross-Sectional Area (A_c)	1.687398	in^2
Wedge (t_w)	4	in	Inertia (I)	22.44415	in^4
Panels per 24 in.	1		Weight of roof panel(P)	0.6948	lb_f/in
			Distance from outer wall to maximum moment (a)	0.131319	in
Codes			Distance from inner wall to max. moment in span (b)	115.8347	in
Live load (L_r)	30.525	psf	Normal force from wedge (n)	211.89	lb_f/in
	0.211979	psi	Anchor force (B)	1004.687	lb_f
			Maximum moment (overhang) (M_{max})	5557.625	lb_f-in
Input Variables:			***Max stress (overhang) (σ_{max})***	***749.3645***	***psi***
Panel thickness (t)	**6**	**in**	Maximum moment (span) (M_{max})	24638.93	lb_f-in
Length of overang (h)	48	in	***Max stress (span) (σ_{max})***	***3299.87***	***psi***
Roof pitch (theta)	8	12			
	0.588003	rads	**Results (shed):**		
Steel gauge (g)	0.1084	in	Total roof panel length(l_tot)	292	in
Indoor span of roof panel (l_i)	240	in	Cross-Sectional Area (A_c)	1.687398	in^2
			Inertia (I)	22.44415	in^4
			Weight of roof panel(P)	0.6948	lb_f/in
			Distance from outer wall to maximum moment (a)	0.15854	in
			Distance from inner wall to max. moment in span (b)	120	in
			Normal force from wedge (n)	175.6075	lb_f/in
			Fastener force (f)	468.2867	lb_f
			Maximum moment (overhang) (M_{max})	5560.768	lb_f-in
			Max stress (overhang) (σ_{max})	***749.7846***	***psi***
			Maximum moment (span) (M_{max})	33564.38	lb_f-in
			Max stress (span) (σ_{max})	***4492.891***	***Psi***

Table F- 3: Overhang/Span Stress Analysis (6 in. thick roof panel)

Set Values:			**Results (gable):**		
Specific Weight (gamma)	0.004825	lbs/in^3	Total roof panel length(l_tot)	292	in
Roof panel width (w)	24	in	Cross-Sectional Area (A_c)	1.253798	in^2
Wedge (t_w)	4	in	Inertia (I)	7.635549	in^4
Panels per 24 in.	1		Weight of roof panel(P)	0.4632	lb_f/in
			Distance from outer wall to maximum moment (a)	0.091122	in
Codes			Distance from inner wall to max. moment in span (b)	115.8347	in
Live load (L_r)	30.525	psf	Normal force from wedge (n)	203.4032	lb_f/in
	0.211979	psi	Anchor force (B)	964.4456	lb_f
			Maximum moment (overhang) (M_{max})	5330.568	lb_f-in
Input Variables:			***Max stress (overhang) (σ_{max})***	***1405.615***	***psi***
Panel thickness (t)	**4**	**in**	Maximum moment (span) (M_{max})	23672.5	lb_f-in
Length of overang (h)	48	in	***Max stress (span) (σ_{max})***	***6209.968***	***psi***
Roof pitch (theta)	8	12			
	0.588003	rads	**Results (shed):**		
Steel gauge (g)	0.1084	in	Total roof panel length(l_tot)	292	in
Indoor span of roof panel (l_i)	240	in	Cross-Sectional Area (A_c)	1.253798	in^2
			Inertia (I)	7.635549	in^4
			Weight of roof panel(P)	0.4632	lb_f/in
			Distance from outer wall to maximum moment (a)	0.109993	in
			Distance from inner wall to max. moment in span (b)	120	in
			Normal force from wedge (n)	168.5738	lb_f/in
			Fastener force (f)	449.5303	lb_f
			Maximum moment (overhang) (M_{max})	5332.66	lb_f-in
			Max stress (overhang) (σ_{max})	***1406.163***	***psi***
			Maximum moment (span) (M_{max})	32225.18	lb_f-in
			Max stress (span) (σ_{max})	***8450.194***	***psi***

Assumptions:

1) By=0, i.e. the moment at the peak of the roof is negligible
2) All friction components are negligible. This conservative assumption contributes to the safety factor of the system.

Given Values: Density of material

Variable	Value	Units
Density	0.004825	lbs/in^3

Note: Density based on sample measurements and calculations

Input Variables: Dimensions of Panel and Components

Panel thickness (t)	6	in
Panel width (w)	2	ft
Roof Pitch (Θ)	0.167448	rads
Overhang (h)	2	ft
Roof Span (s)	20	ft
Wall panel width (tw)	4	in
Wall panel Length (l)	22.33806	ft

Note: Panel length calculated from other values in table of inputs

Calculations: Panel Weight and Supporting Forces

$$\boxed{l = h + s + \frac{t_w}{\cos\theta}}$$

$$\boxed{n = \frac{N}{t_w/\cos\theta}}$$

$$\boxed{W = \rho \times l \times w \times t}$$

$$\boxed{\sum F_y = 0 = W - \frac{N}{\cos\theta}}$$

Results:

Weight/Force on Joint		
Panel weight (W)	186.23	lbs
Normal Wall Force (N)	188.87	lbs
Distributed Normal (n)	46.55722	lbs/in

G Thermal Calculations

This section includes calculations on the thermal conductivity of the roof panel and total roof system.

R-Value Calculations for Roof Panel

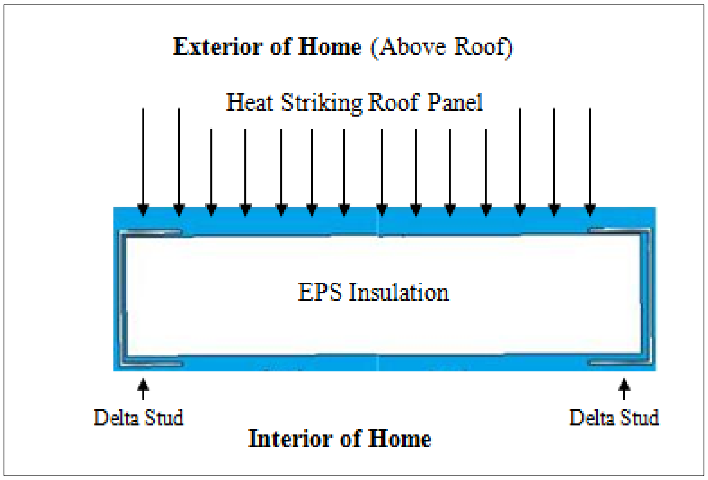


Figure G- 1: Heat Transfer into interior of Home used for Transcon Panel R-Value Calculation

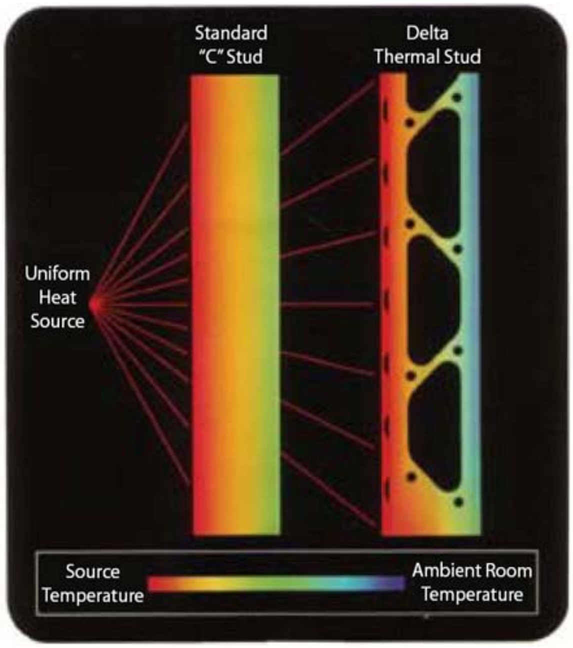


Figure G-2: Difference in Thermal Resistance of two Stud Types (Transcon Steel)

Assumptions:

1) Lip of Delta Stud (portion above EPS) has minimal affect on thermal resistance of panel
2) Used typical 12 gauge Cold-Rolled Steel for R-value and increased by 75% for R-value of Delta stud
Transcon calculations show that delta stud is 75% less thermal transference than standard C-stud [2]
3) Only used main components of panel in calculations EPS insulation and delta stud excluding fasteners

Input Variables: Area of Panel and Components

	Values	Units
EPS (Expanded Polysterine)	4.5	R - Value/ in
Width of Stud	0.1046	in
Width of EPS	23.79	in
Panel Size	4"x24"x24'	in x in x ft
Area of EPS (Cross-Sect.)	6851.75	in^2
Area of Stud (Cross Sect.)	30.12	in^2

Calculations: % Area of Each Material and Total R-Value of Panel

Material	%Area of Panel
EPS (Expanded Polystyrene)	99.56
Transcon Delta Stud	0.44

Note: Used Percent Area of Panel in R-Total equation

$$\boxed{C = \frac{k}{\text{Thickness In Inches}}} \qquad \boxed{C = \frac{1}{R}}$$

	Value	Units
Thermal Conductivity, k	360	BTU-in/hr-ft^2-F°
Thermal Conductance, C	90	BTU/hr-ft^2-F°
R-Value Delta Stud	0.0194	hr-ft^2-F°/BTU
R-Value C Stud	0.0111	hr-ft^2-F°/BTU

$$\boxed{\frac{1}{Rtotal} = \frac{1}{Reps} \cdot Aeps + \frac{1}{Rstud} \cdot Astud}$$

Note: Calculation of Thermal Value into the House through Roof Panel (See Above Figure)

Results:

Total R-Value of Panel		
Trancon Delta Stud	2.24	per inch depth
Typical C-Stud	1.63	per inch depth

R-Value Calculations for Composite Roof System

Figures:

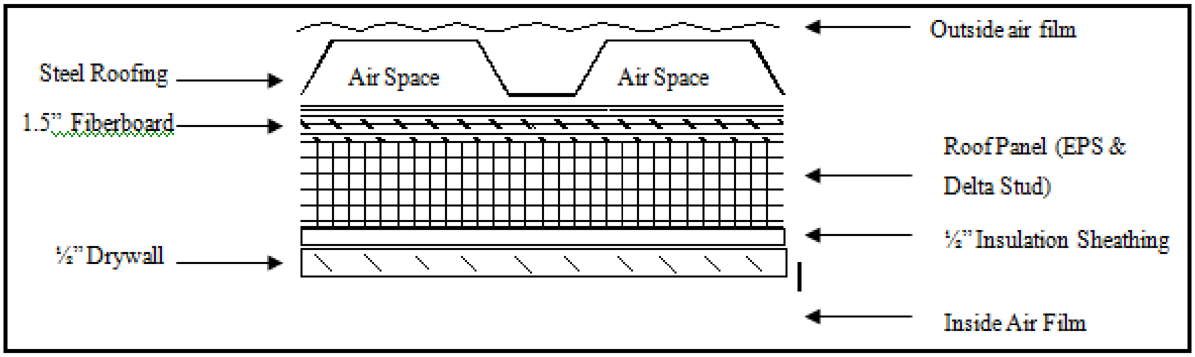


Figure G-3: Composite Roof System

Given Values:

Component	R-Value	Depth	R-Value * Depth
Outside Air Film	0.17	N/A	0.17
Steel Roof	0	2"	0
Fiberboard	2.78	1.5"	4.17
Roof Panel	2.24	4"	8.96
1/2" Insulation Sheathing	3.2	1/2"	3.2
1/2" Drywall	0.45	N/A	0.45
Inside Air Film	0.92	N/A	0.92

**Note: Depth N/A becaused R-value given for a specific thickness*

TOTAL	17.87

H Roof-to-Wall Joint Buckling Calculations

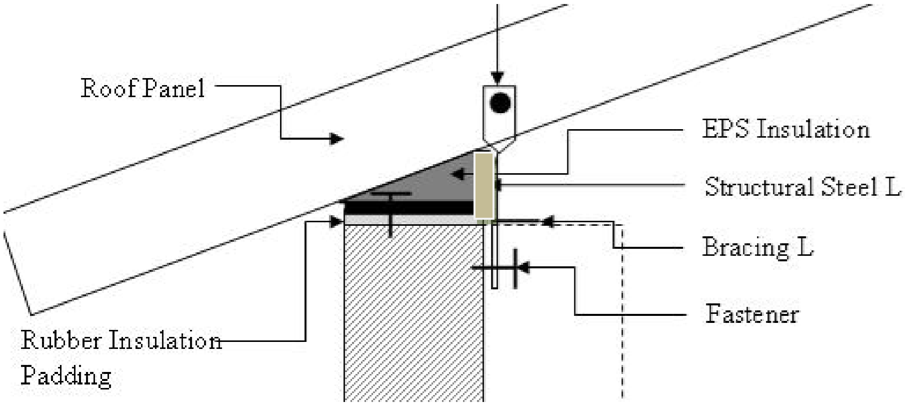


Figure H- 1: Roof System Vertical Portion of L-Joint

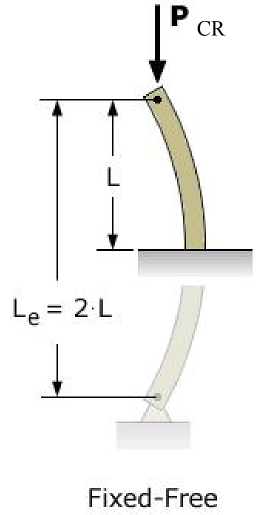


Figure H- 2: Vertical Portion Model – Critical Load

(ENGRASP: Worldwide Engineering Solutions)

Input Variables:

	Value	Units
Modulus of Elasticity (E)	29 x 10^6	lb/in^2
Area Moment of Inertia (I)	.78 x 10^4	in^4
Length (L)	0.5 to 4	in

Calculations:

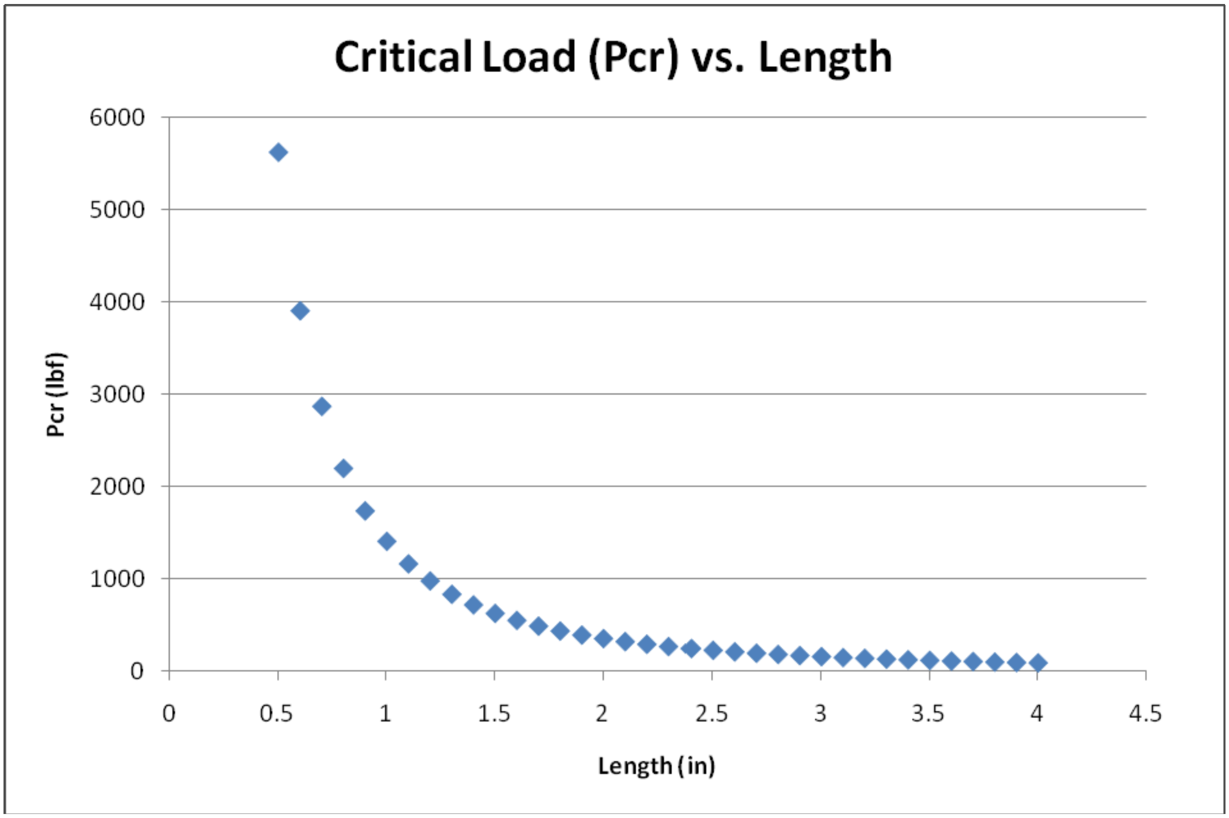
Moment of Inertia

$$\boxed{I = \frac{b \cdot h^3}{12}}$$

Critical Load (Pcr)

$$\boxed{Pcr = \frac{\pi^2 \cdot E \cdot I}{4 \cdot Le^2}}$$

*Note: For Free Fixed Column (Le = 2*L)*



Note: Length refers to height of the vertical section of the wedge from the top of the wall to the roof panel

I Total Hours Spent

Table I-1: Total Man hours

Group Member	Total Hours	Weekly Average Hours
Andrew Freeland	171	7.1
James Brown	162	6.8
Julia Zangirolami	215	9.0
Kelechi Ogba	200	8.3
Kristin Golmon	234	9.8