University of Massachusetts Amherst

College of Engineering
Mechanical and Industrial Engineering

MIE 415 Final Report

#1513
Building Integrated Photovoltaics

Sponsored by Manhattan 2

5/2/21

Ben Tan - Team Lead

Hector Espinal - Analysis Lead

Joseph Soucy - Evaluation Lead

Alex Wurst - Fabrication Lead

George Lastowka - Design Lead

Executive Summary:

This project is a proof of concept design, intending to design a joint that will mount flexible solar material to a roof or wall. Our sponsor's end goal of reducing carbon emissions will be met by providing a lightweight and flexible alternative to today's 40 pound, rigid solar panels. The design will have some typical features of a standard framed solar panel. However, our design will uniquely have the Photovoltaic material fixed directly to the plywood of a roof and act as the primary water barrier in place of shingles. After the creation of our final design, we performed thorough wind load and thermal expansion analysis on CAD drawings and tests with parts similar to our design for the load tests. For the waterproofing test, we ran water over the system's surface for several hours with a piece of paper underneath the connecting joint to detect if any water leaks through to the plywood surface. An image of our prototype is seen in figure 1 below. The results yielded protection of the plywood, but not complete waterproofing for the rails.

Figure 1: Full assembly of the prototype demonstrating the interface of two solar panels

For the future of this project we recommend that the design is prototyped with aluminum using metal extrusion or CNC machining yielding results more accurate to the design. We also recommend further investigation of berm geometry to fight water creep to the wood screws and to assist assembly. More elaborate and controlled testing can be done with a larger assembly and in a lab setting to get more accurate results. The design should be altered to allow for smaller segments of rail to make transportation simpler. A design for sealing the sides of the whole assembly should also be generated and implemented in testing.

Summary of Impact:

This project is a part of a larger intelligent house project sponsored by Manhattan 2 to reduce carbon emissions emitted by the average residential home. The flexible materials to be used would allow for a much lighter design. With direct surface mounting, the supporting roof's strength could supplement regular mounted panels' specific strength.

This resilience has been demonstrated in other flexible panels that experienced typhoons, such as the case with MiaSolé, panels withstanding one in Shanghai Lingang Sonjian. Our client's hope is that our design will eventually be integrated into roll-to-roll manufacturing, allowing for cheaper production in larger quantities. Our sponsor's wish is that this project will provide incentives for companies to adopt this kind of solar integration. There is a more significant amount of green energy powering the world, assisting in decarbonization. Our project is the first step in proving the waterproof capabilities for this PV material deployment method. We will provide a prototype for a more lightweight mounting system that is permanent for flexible photovoltaics, which can also substitute for current conventional roofing methods like asphalt shingles.

Introduction and Objectives:

Our sponsor, Manhattan 2, has an overarching goal to decarbonize the world through different engineering projects. Bi (Building Integration) and Li (Land Integration) PV are some of the projects being worked on by Manhattan 2 to achieve this. By making more solar material cheaper to produce and install while maintaining industry standards, our sponsor hopes to incentivize more companies to transition to solar as a means of energy production by designing an implementation method. Last semester, we designed a material stack up and overall geometry for the custom PV material. This semester, this project aims to provide a proof of concept for the mounting method of the PV material that is waterproof.

Developing a lightweight and rollable solar material could lead to an automated installment system being shown in figure 10 that reduces installment costs. When carrying out large-scale solar projects, there is almost always a need for higher skilled labor to install because the job is so complex. Automation is beyond our project's scope, but our sponsor hopes that this is what the project will progress to after developing the actual solar material and mounting methods. The ease of installation will add incentives for people to invest in solar energy for their buildings, homes, and solar farms due to the reduced labor cost. Our sponsor's primary goals are to ensure that the joints fastening the PV material are a secure water barrier for the roof and that there is proper drainage in case of failure in the screws fastening the joints. To meet this, we must consider some of the necessary building codes.

Team Member Contributions:

Benjamin Tan [Team Lead]

- Communicated with sponsor on how to achieve acceptable design
- Coordinated with shop team to obtain materials for manufacturing
    - prepared materials for assembly
- Designed and drafted many iterations of mounting system in CAD
- Performed stress simulations on the rails using Ansys
- Collaborated with analysis lead on practical testing methods
- Manufactured final prototype with design lead

  Impact:

  Communicative contributions lead to organized meeting and collaboration among team members, faculty, and the shop. Design and drafting efforts progressed towards a final design acceptable to the sponsor. Assistance in analysis clarified analysis parameters and methods.

Hector Espinal [Analysis Lead]

- Assisted on the analysis of the innovative mounting rail design

- Generated thermal analysis calculations
- Generated wind uplift calculations
- Assisted on the engineering standard research
- Analyzed wind load and its effect on the design
- Contributed analysis for material's selection

  Impact: Contributed to the system analysis that led to the final design—analyzed and resolved the potential issue affecting our design. Make mathematical approaches to validate a successful final performance of the design.

Joseph Soucy [Evaluation Lead]

- Assist in development of the design concepts of two-rail mounting system.
- Validate concepts at each phase to ensure that they are in the scope of the project and they are effective to project completion.

  Impact:

  Facilitated in the development of design concepts that lead to the final roof mourning system. Determined if approaches for the prototype were feasible, ex: minimum thread length. Participated in team meetings in order to bring the project to completion.

Alex Wurst [Fabrication Lead]

- Coordinate with Analysis Lead and Team Lead to help meet design needs.
- Determine and execute prototyping methods.
- Coordinate with Design Lead to develop the most efficient and effective rail mounting system.
- Assisted in several iterations of rail mounting design.
- Verify ability to fabricate conceptual designs.

  Impact:

  Brainstormed and presented several mounting designs which have been workshopped and altered to lead to final design decision. Validated the ability of parts to be fabricated and assembled in these concepts.

George Lastowka [Design Lead]

- Assisted in brainstorming different design orientations
- Aided in the modeling of the mounting rails in CAD software

- Produced visuals demonstrating the implementation of new designs
- Determined material requirements for development of physical prototype within the allowed budget
- Assembly of the prototype

  Impact:

  Validated and aided the procuration of several designs for the mounting system. Analysis of design capability pushed the design process along the correct path. Assisted with communication throughout the team and other faculty resources to keep the project on track. Transported materials and provided a location for the prototype to be built and stored. Assembled the prototype.

Functional Decomposition:

The flow chart in figure 2 shows the functional decomposition of this project. Major concepts are broken down into their specific subcategories, which are afterward described in more detail. Our team's objective is to develop a waterproof mounting system that secures the roof's solar material. In order to achieve this, there must be an overlapping connection between adjacent layers of solar material. Water must be able to flow over the joint and the geometry of the design should also not leak in the event that a screw comes loose or is missing. This joint will also be the point where the panels are secured to the plywood of the roof, so the design must have a way to protect the wood screws that will be used to secure the whole assembly to the roof.

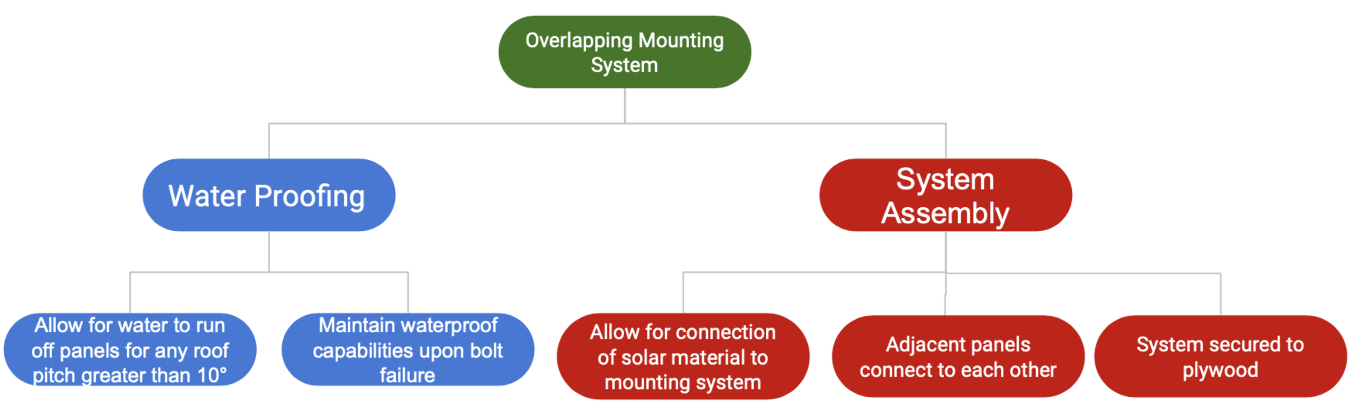


Figure 2: Functional decomposition

Mounting method: The method for mounting our solar material to the plywood, attaching each subsequent layer to each other, and sealing the roof so that the PV material can act as the water barrier in place of shingles.

Analysis: The mounting system will have met the objectives when it can be feasibly fabricated, provides continuous overlap for water and debris flow, and can be securely fastened to the plywood. As a proof of concept, we will only consider a simple rectangular house with one long apex, no valleys, a standard 4/12 roof pitch, and no obstructions. The pitch of 4/12 was decided on as that is the minimum standard in areas with snow, such as Massachusetts. It is important to note that with our final design, a roof of 10° or less will not run off.

1. Rail Design
   - **Fabrication Methods** - The design of the rails must be made to be feasibly fabricated using existing manufacturing processes and materials.
2. Joint Design
   - **Water and Debris Flow -** The joints must allow for continuous overlap from each joint and roll of PV material to allow for water and debris to flow without being trapped in channels which would cause damage due to corrosion or freezing.
   - **Attachment to Plywood -** The joint design must allow for secure fastening to the plywood underneath.
   - **Water tight sealing** - There must be no exposed opening or seams that will allow water to enter into or underneath the solar material that might compromise the entire roof.

Engineering Standards:

Massachusetts State Building Codes 9th edition (Roof Top - Water Barrier Photovoltaic)

Section 15 - General Code Roof Assemblies and Rooftop Structures

- Section 1503.1-3 - Weather Protection

Specification of materials and its dimensions needed for roof covering. Flashing must be installed to prevent moisture entering the roof and wall through joints and others penetrations through the roof plane. The locations of flashing installation are but not limited to wherever is a change in roof slope and around roof opening. The material used for flashing must be corrosion resistant metal with a minimum thickness of 0.019 inch (No. 26 galvanized sheet).

- Section 1505 - Fire Classification (ASTM E108 or UL 790)

Engineering standard ASTM E108 or UL 790 do not directly apply to our design. The standards ASTM E108 or UL 790 apply to the following roof covering materials, including but not limited to: asphalt shingles, sheet roofing, fire-retardant-treated wood shingles and shakes. Our photovoltaic design diverge from those materials. Our design must consider fire safety, so these standards will serve as a guide.

- Section 1507.2.6 - Fastener (ASCE 7)

General information of materials, spacing and dimensions of fasteners. Fasteners must be galvanized(anti-corrosion). Fastener spacing and dimensions will depend on the length of the photovoltaic product. The length of the photovoltaic product will depend on the roof dimensions of the desired house of installation. Fastener must withstand a wind load of approximately 180 mph. The ultimate design wind speed is based on the regional climate data provided by the MA State Building Code.

IBC 2018 Chapter 15 - Provides various standards and requirements for roofing systems.

Section 1504.3.1- Built up, modified bitumen, fully adhered or mechanically attached single-ply roof systems, metal panel roof systems applied to a solid or closely fitted deck and other types of membrane roof coverings shall be tested in accordance with FM 4474, UL 580 or UL 1897.

- FM 4474, UL 580 and UL 1897 - Test requirements for simulated wind uplift, applies to all components in the roof system.

Section 1507.10 Provides compliance requirements of built-up roofs

- 1507.10.1 Slope - Slope must be at least one-fourth unit vertical in 12 units horizontal (2-percent slope)

Engineering Patents

The sponsor of our product has an open patent according to set goals. The sponsor works in partnership with multiple universities to improve the product. As a result, the companies and agencies have access to all the information collected. The open patent allows sponsors, companies, and agencies to manufacture, implement and modify our design.

Specifications:

These specifications were derived from the house of quality in Appendix D.

Table 1: Target Specifications

Specification	Marginally Acceptable	Ideal
Waterproofability	Minimal water leakage (eyedropper sized marks on paper)	No leakage (no water marks on the paper)
Thickness for thread engagement	>0.14998 inches	0.14998 inches
Walking test	no deflection	minimal deflection
Height for electrical components	>13.5 mm	13.5 mm

Our team arrived at each value for specification of the design based on how we intend the system to perform and what capabilities it will hold. Our group aimed to create a continuous surface that works on a wide range of roof pitches. Our current design is capable of a continuous surface with proper water drainage for roof pitches above 10°. A height of 13.5" will allow the mounting system to insulate the solar panel's electronic components properly. The 0.14998-inch minimum thickness for thread engagement will allow for the minimum allowable amount of thread engagement to ensure a strong mate between parts.

Design Selection and Solution:

The first design, shown in Figure 3, was a T-shaped cross-section, with larger holes in the center for wood screws to secure the rail to the plywood and smaller holes along the sides to bolt the rail to the panels.

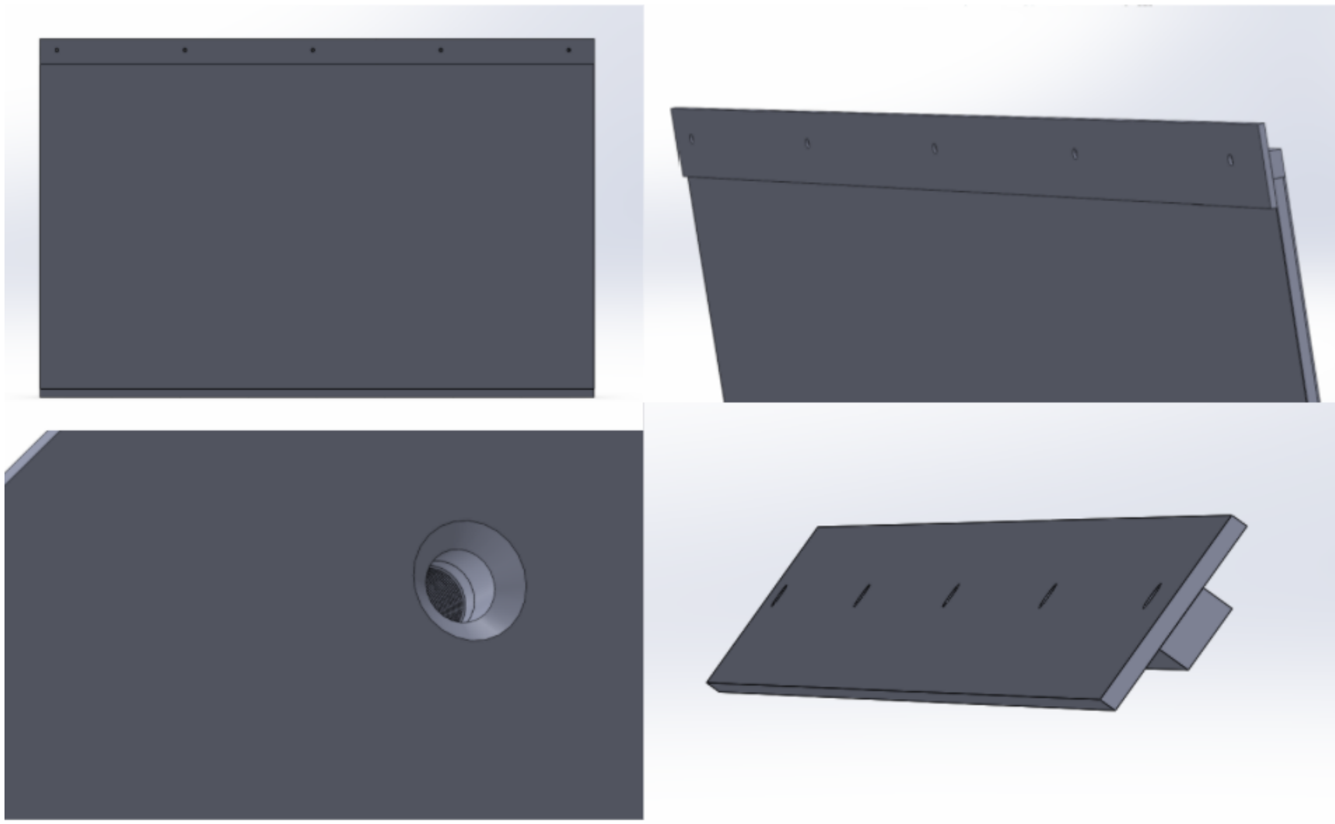


Figure 3: T-shaped mounting design

This would simplify the rail into one part and provide some overlap between the rail and the panels. The main problem with this design was that the overlap between the panel that would be higher on the roof and the rail meant that there would be an edge causing water and debris to build up as they tried to flow down over the joint. The new design in figure 4 would feature fins that extend under the photovoltaic material and into the supporting layers attached via adhesive. The joint then meets the surface of the solar material creating a flush continuous surface. The bottom rail would provide material for the wood screws to secure the assembly to the plywood underneath and would also have threaded holes for additional screws to fasten the top rail to the bottom rail.

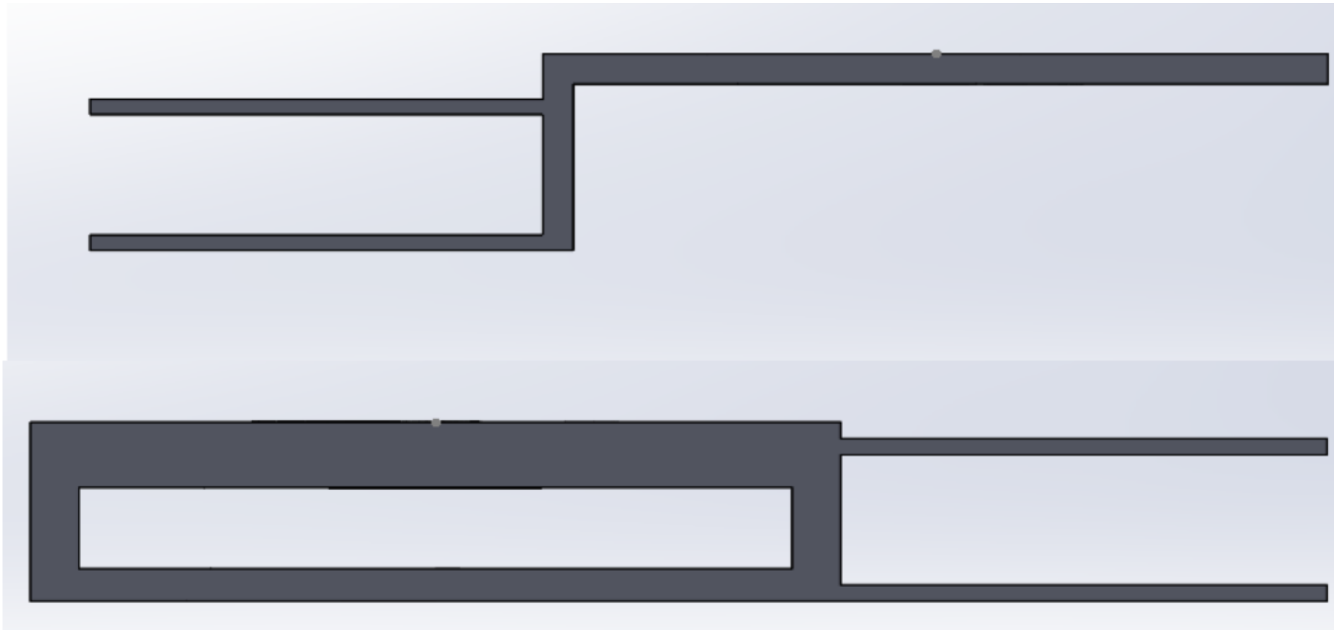


Figure 4: Second mounting design, top rail side view (top), bottom rail side view (bottom)

The next issue faced was the need for drainage in case water was able to seep into the holes that the screws were located in or if they failed and somehow became damaged. In order to overcome this obstacle, channels were created that protruded from the screw holes leading to the surface of the joint. A subtle incline meant that this drainage channel would not work on flat roofs. An image of the drainage channels can be found below in figure 5

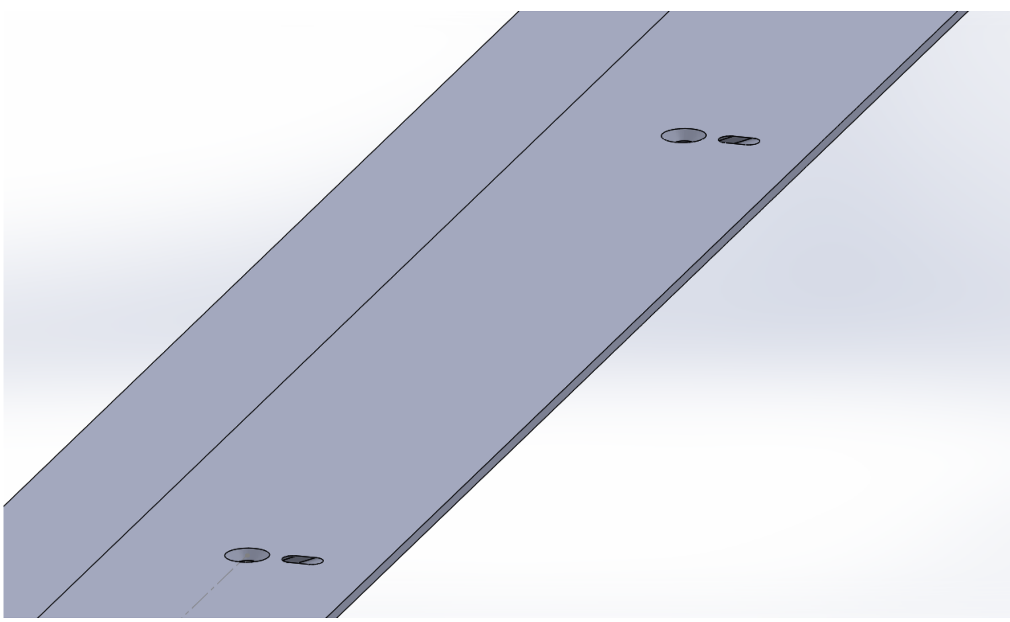


Figure 5: Second mounting design, drainage method 1

A significant drawback to this design is the extra cost of adding these drainage features. If this design was to be mass produced through extrusion, additional machining operations would be needed for the drainage. After talking with our sponsor, it was clear that this design would not meet the requirements and so we moved on to the design, which was edited into our final design, shown in Figure 7.

Detailed Design:

Our design process was most significantly influenced by the geometrical needs of the rails to meet the required goals. As we were designing, we evaluated the effectiveness of the overlap for the joint, and how much it would rely on sealant. After considering installation issues, our sponsor directed us to focus on waterproofing the joint only. We then iterated and redesigned our geometry to solve these problems we had noticed. We discussed design with our sponsor who would give feedback and suggestions which we implemented in the design. There was always communication with the sponsor before any major design decision and testing. We performed detailed analysis to determine the expected performance of the design. Thermal expansion calculations, wind uplift calculations, and ANSYS FEA simulations were performed to validate the design for the walking test and confirm that the system would not fail. We selected the material to be used based on its corrosion resistance, strength, and cost. After determining how we were going to fabricate our prototype and what tests we would run, we were able to generate a bill of materials. due to the limitations in machinery and time available to us, we used ABS from a 3D printer to prototype

The design needed to have overlapping sections and be able to permit run off at any angle greater than 10°. In case of screw failure, slots for water to drain onto the lower panel surface were implemented. Our design was generated with the following guiding principles: The rails were designed to have geometry with the most waterproof capability without relying too much on sealant when possible. They were also required to be designed to have room for PCB and its components at the bottom of the panels. The design needed to ensure that it would survive a technicians weight, and wind uplift at a certain wind speed, in accordance with building standards. Throughout the design process we attempted to minimize material and number of parts needed in order to reduce the overall cost of the design.

Detailed Engineering Analysis (Selected Design):

Our sponsor requested consistent thickness throughout the system. The thickness of the system was limited by the requirement for minimum thread engagement for the bolt. This would then in turn determine how little mass we could use, as the minimum thread engagement determined the amount of material needed for our selected screw. The minimum value for the bolt's threaded length within the system was determined with the following formula, found in the engineering toolbox [4], and influenced the thickness of the system.

$$L = \frac{2 \cdot A}{0.5\pi(D - 0.64952p)}$$

Where:

L = Minimal Thread Engagement Length

A = Tensile Stress Area

D = Major Diameter of Bolt

p = 1/Number of threads per inch

The design was optimized by satisfying the minimum thread engagement requirement while obtaining the smallest thickness. Another sponsor requirement was for the mounting system to work for any roof pitch greater than 10°. To meet this criteria a slope was included on the upper rail at the minimum angle desired as seen in figure 17.

Bolts and screws will often fail over time in outdoor systems. A fail-safe concept was included at the request of the sponsor to address this in our design. The screw that secures that system to the plywood was closed to the top rail's outside environment. A unique approach was made to the upper rail to ensure no water damage upon bolt failure. The screw connection between the two rails has been modified to avoid water pooling upon screw failure. A channel was added to the lower rail ensuring water to continue its downward path regardless of screw presence. Our method of optimization for this criteria was an iterative approach in which the design changed several times.

The analysis of thermal expansion of the materials is approximated using theoretical calculations (Appendix G). The theoretical calculations identify whether or not thermal expansion is a cause of failure. This would identify any potential areas where expansion could damage the screws, or plywood by pulling them out of place.

Wind uplift theoretical calculation analyzed the strength of the mounting system in a multi-pressure environment. Uplift force is due to differences in pressure caused by the speed of the wind flowing over the roof. The theoretical calculation approaches the strength of a single screw over a specific area of pressure concentration(Appendix E and F). The results of the theoretical calculations are compared with the withdrawal test results to identify if the system fails under the maximum wind speed according to the International Building Code.

In order to ensure that the rails would not fail during maintenance or application from a roofer or technician, a simple static structural analysis was performed in Ansys as seen in figures 31-33. This finite element analysis proves that our design meets a specific building standard required of roofing systems.

Waterproofing the joint was the primary requirement for the design. In order to test the waterproofing capabilities of the design, we set up the assembly as seen in figure 1. Water was run over the center assembly at 45°, 36.9°, 18.4° each for an hour. These angles are determined as extreme to shallow by OSHA. Eventually we deliberately exposed the screw hole on the top rail to test if our safety drainage feature was functioning properly. This was tested at the lowest angle. As the angle became shallower, water managed to work its way towards the woodscrews. Initially, there was an issue with the evacuation of success, as the paper seen in figure 27 drew water up to the plywood instead of simply showing if the water reached it. An augmentation of this set up, figure 28, showed that water was not creeping that far. The primary issue was the stripping of the screw threads and the warping of the assembly as it was disassembled and reassembled multiple times during testing. Some additional designs were looked into to see how greater success could have been achieved, and the addition of a press-fit berm between the fastening screw and the wood screw on the bottom rail allowed the rail to succeed at angles well below 18.4°.

The screw removal test was performed to determine how much force the wood screws we had selected for our design could withstand while embedded in the plywood. The goal of this test was to simulate the result of our wind uplift calculations to ensure that the force caused by 180 miles per hour wind, the maximum wind speed outlined in building codes, would not cause our system to fail.

Final Design:

The design process started with the geometry of the rails which would be used to secure the photovoltaic material to the plywood and also to connect consecutive layers of photovoltaics. The first design geometry was a simple T-shaped joint that would secure consecutive layers at the same level to achieve a continuous surface for water to flow across.

The issue with this design was that the joint would create a raised edge that would lead to debris build-up and possible ice if the weather was cold enough. To address this, a new design was required that would establish a continuous surface that is flush to the surface of the photovoltaics.

After discussing with the sponsor, another detail was brought up regarding the requirements for the internal electronics. In order for the assembly to properly house the PCBs and other components the height of the upper rail would need to be increased. This way there would be enough room underneath the solar material so the electronics are protected. From here there needed to be a drastic re-design that would include all of the requirements from before and also have the capability of securing a surface with a small gradual slope that would allow the electronics to be implemented. The resulting design can be found below in figure 6

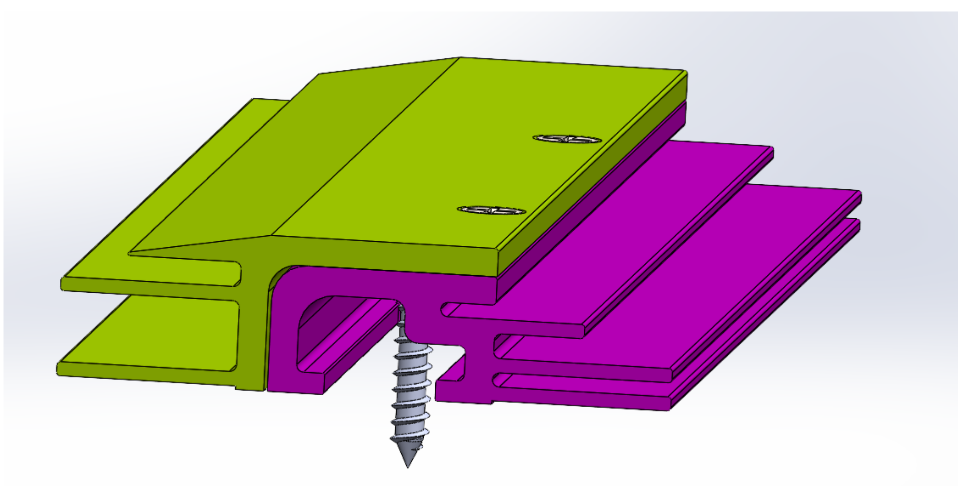


Figure 6: First design approved for assembly

This design featured the bottom rail in purple which will secure the assembly to the plywood much like the designs before it. The main feature that sets it apart from the others is a channel runs beneath the screw fastening the two rails, creating an opening at the bottom of the screw hole. This provides an avenue for drainage onto the surface of the next photovoltaic layer if the screw were to fail at the top surface due to over tightening, under tightening, or complete removal. The top rail, in green, an inclined ramp of 10° to discourage the build-up of water and debris. More visuals of each component of this design can be found in appendix B.

This design was approved by the sponsor and was used to create a physical prototype. After testing the prototype at multiple angles to simulate heavy rains on a variety of steepnesses, the results showed that although the drainage channel did work to deal with a majority of the water that would flow through the mounting hole if a screw was removed, the surface between the top and bottom rails did not control the water creep due to adhesion. To address this issue, a berm was added in the joining surface between the rails to stop the water from making its way to the wood screws. This modification can be seen in figure 7

Figure 7: Additional design with added berm

Design Evaluation:

For the durability analysis of the joint system that has been developed, the individual aluminum stock was purchased, which roughly resembles the shape of the design with the same wall thicknesses. Since the prototype joint would be 3D printed, it does not make sense to complete a strength test because it does not have the same material properties. A 1-foot section of 90° stock will be placed on top of a 1 foot long U-channel stock which will then have a load applied to the top surface to simulate a roofer standing on the structure. This test will prove the strength of the rails that will be installed on a roof.

To test the success of the waterproofing of the joint, the prototype will be placed at an incline of 10°, and a hose will dispense water down the surface of two panels that have been joined using the existing design. The water will continue to flow over the surface for an extended period at a comparable rate to heavy rains. Paper will be placed in between the plywood and the seam that is located at the joint intersection. The paper will act as an indicator of whether or not the joint successfully prevents the water from getting under the joint.

Another area where we will be collecting data is the withdrawal strength of the wood screws into the plywood roof. This design will be done using an Instron Test Machine, which will apply an upward force on the head of the wood screw until the screw is pulled from the plywood. That force will tell us the maximum load that can be withstood before the system is pulled off the roof.

Discussion:

Our testing yielded mixed results and did not meet our expected performance. Success was only seen at the most extreme angle with decreasing success as the angle became more shallow. When further testing was performed, it was found there was an issue with the manner in which we were placing the paper for our indicators. In figure 27 their vertical alignment across the interface of the two rails drew water to the plywood. In figure 28 when oriented horizontally along the plywood, water only came up onto the top of the wood screws. This was still considered a failure. Our team was not aware of the porosity that ABS had. This factor likely contributed to water creep. Additionally, the fragility of the material yielded in damaged threads upon disassembly and reassembly for testing. Damage to the threads accrued during this process is shown in figure 29 with each repetition worsening the condition. The design relied on a strong clamping force from the fastener screws, and the fragility and flexibility of ABS hindered this function especially when testing for drainage without a screw. Despite the nature of the material, a third round of testing was done implementing two design augmentations that yielded successful results at angles close to parallel; far more shallow than the lowest angle of the first round of testing. While the results showed that we were unable to completely keep water out of our design, our designed drainage methods were successful in protecting the plywood and proved satisfactory to our sponsor.

Conclusions and Recommendations:

This project succeeded as a proof of concept for a water proof rail mounting system for building integrated photovoltaics, displaying that with further development this concept can be an effective method of large scale installation to make solar power more widespread and accessible. The design holds a uniform cross section, which will allow for mass production through metal extrusion. Roll-to-roll manufacturing of solar material could in turn be able to match the metal extrusion in mass production. Our analysis of the thermal expansion of the rails and the uplift force created by wind load predict that these will not be modes of failure for the design. The uplift force was simulated with a withdrawal test which showed that the fasteners in our design will withhold significantly more force than would be generated by 180 miles per hour wind. For the waterproof testing, the prototype needed to be made out of 3D printed ABS plastic, which is more porous and less durable than the aluminum we expected the design to be fabricated with. This meant that our results for waterproofing are promising as it performs decently in plastic and the aluminum is expected to improve performance. Furthermore, additional testing on the final design shows promise with the inclusion of an extra barrier between the wood screw and the fastener screws as seen in figure 7.

For the future of this project, we recommend that aluminum prototypes are fabricated through metal extrusion or CNC machining to gain performance data more accurate to the design. We also recommend that a design for sealing the sides of the assembly is generated. This portion of the design was not in the scope of our project, however it is potentially a large failure point for the wind load. Currently, our design is using long aluminum rails across the length of the house. This design would yield long and unwieldy parts for shipping and installation. Modification of the design to be more compartmental or segmented would solve this issue. Another area to examine is the economic feasibility of gaskets in the fasteners. Our team also began preliminary designs using berms on the rail interfaces between the wood screws and fastener screws to prevent water creep that we observed in our prototype. Several different shapes were tested showing greater success than our chosen final design. One of these was a dovetail shape with one side rounded by sanding. This yielded a simple “snap fit” installation.

These design ideas should be further analyzed and tested as they will likely provide significant performance benefits.

Integrative Experience:

Team 1513 has had the opportunity to be exposed to a real world problem and solution scenario. The purpose of designing the application of photovoltaics is to address global warming issues. How the innovative mounting design will incorporate the photovoltaics can contribute positively to climate change if implemented properly. The innovative photovoltaic system will reduce natural resources consumption and reduce carbon dioxide emissions; something our professors have been speaking on for the duration of our university education. We were able to utilize much of our engineering acumen, including thermodynamics, fluid dynamics, 3D CAD Design and FEA simulation. Perhaps the most important challenge that our team faced was clear and concise communication. The scope of our work ended up changing after the first semester, emphasizing the importance of proper communication with our sponsor. Because of this, we accrued setbacks reducing the window of time we had to output new designs and meet our deadlines. Despite this, we were able to iterate and improve several designs and implement testing. While we were not able to use the material we originally wanted due to the limitations of the resources we had available to us, we were able to draft and test more rapidly using the 3D printed ABS. All team members were able to exercise their knowledge gained over their undergraduate education towards a final product.

References:

Cavallo, Christian. "All About 6061 Aluminum (Properties, Strength and Uses)." *Thomasnet® - Product Sourcing and Supplier Discovery Platform - Find North American Manufacturers, Suppliers and Industrial Companies*, Thomas www.thomasnet.com/articles/metals-metal-products/6061-aluminum/.

Engineering toolbox, Factors of Safety. (n.d.). Retrieved from https://www.engineeringtoolbox.com/factors-safety-fos-d_1624.html

Engineering toolbox, Thread Stress area calculator. (n.d.) Retrieved rom https://www.engineersedge.com/calculators/thrd_strss_100a_pop.htm

Engineering toolbox, Minimum Thread engagement equation and calculator ISO. (n.d.). Retrieved from https://www.engineersedge.com/thread_strength/thread_minimum_length_engagement.htm

(ICC), International Code Council. “2018 International Building Code.” *2018 INTERNATIONAL BUILDING CODE - CHAPTER 15*, codes.iccsafe.org/content/IBC2018/chapter-15-roof-assemblies-and-rooftop-structures**.**

Kaminski, Deborah A. *Introduction to Thermal and Fluids Engineering.* S.L., John Wiley, 2017.

“Technical Pages B, Fastening Technical Guide.” *Triangle Fastener - Triangle Fastener Corporation*, Triangle Fastener Corporation, www.trianglefastener.com/.

Appendices:

Appendix A - Bill of Materials

Amazon		
Item	Quantity	Price
TP-Solar Semi-Flexible Solar Panel	1	$139.99
Foam Insulation (2'x2' 6-Pack)	1	$35.20
GE Silicone Adhesive (2-Pack)	1	$22.99
	TOTAL:	$198.18

Home Depot		
Item	Quantity	Price
OSB Plywood (4'x8')	1	$51.57
Zinc Plated Phillips Head Flathead Wood screws (50-Pack)	1	$6.57
Stainles Steel Phillips Head Machine Screws (4-Pack)	5	$6.27
	TOTAL:	$64.41

McMaster-Carr		
Item	Quantity	Price
6061 Aluminum U-Channel. 0.13" thick	1 ft	$7.18
6061 Aluminum 90 degree Angle, 3/16" thick	1 ft	$6.12
	TOTAL:	$13.30

Appendix B - Design Images

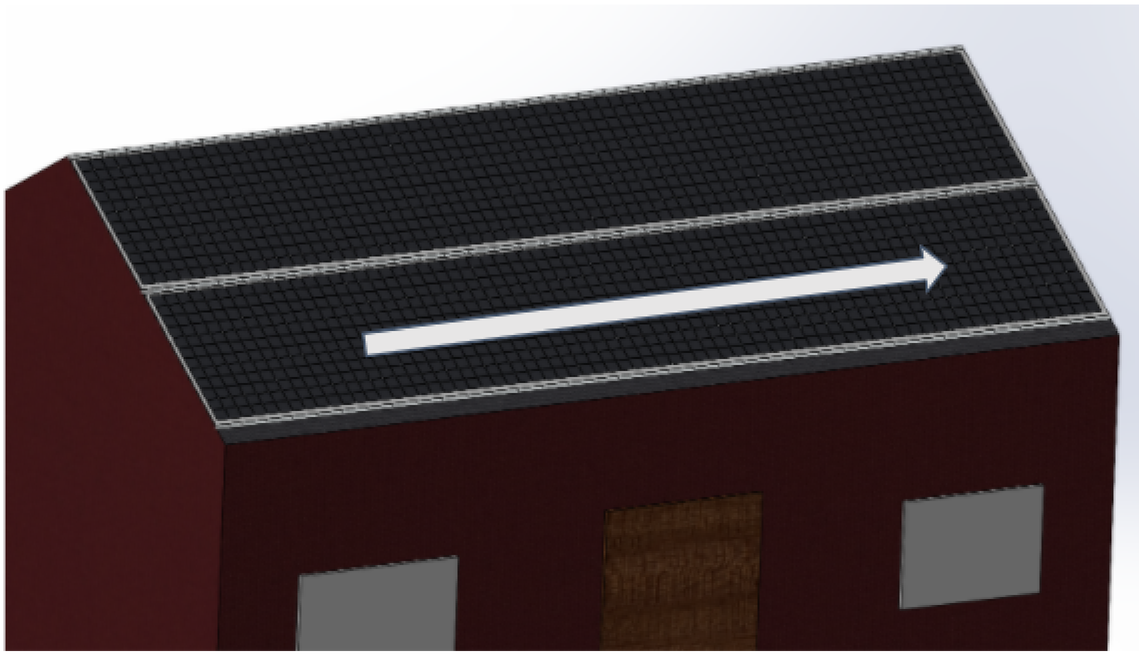


Figure 8: Direction of application on a roof

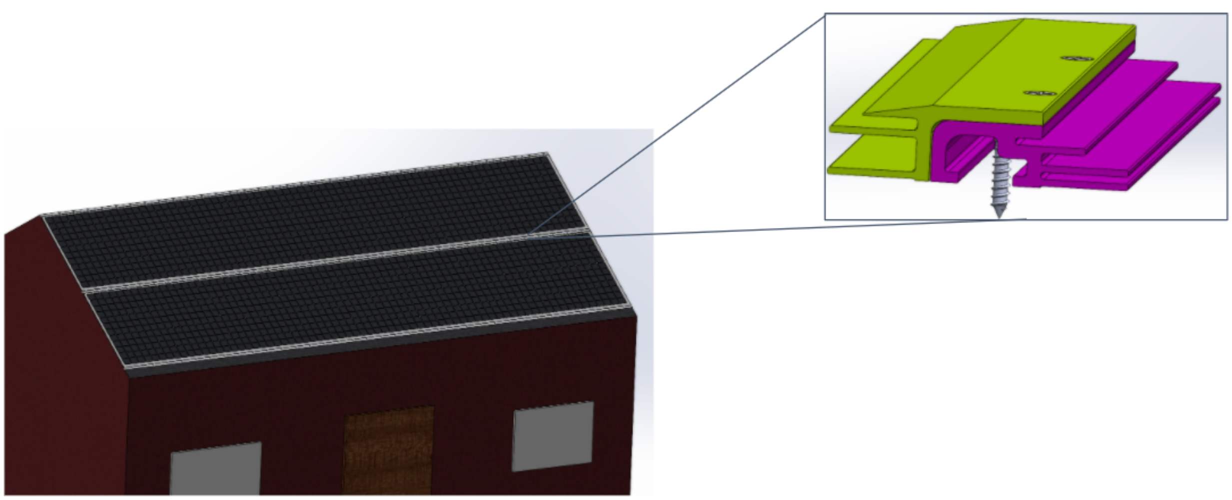


Figure 9: Application of rail design

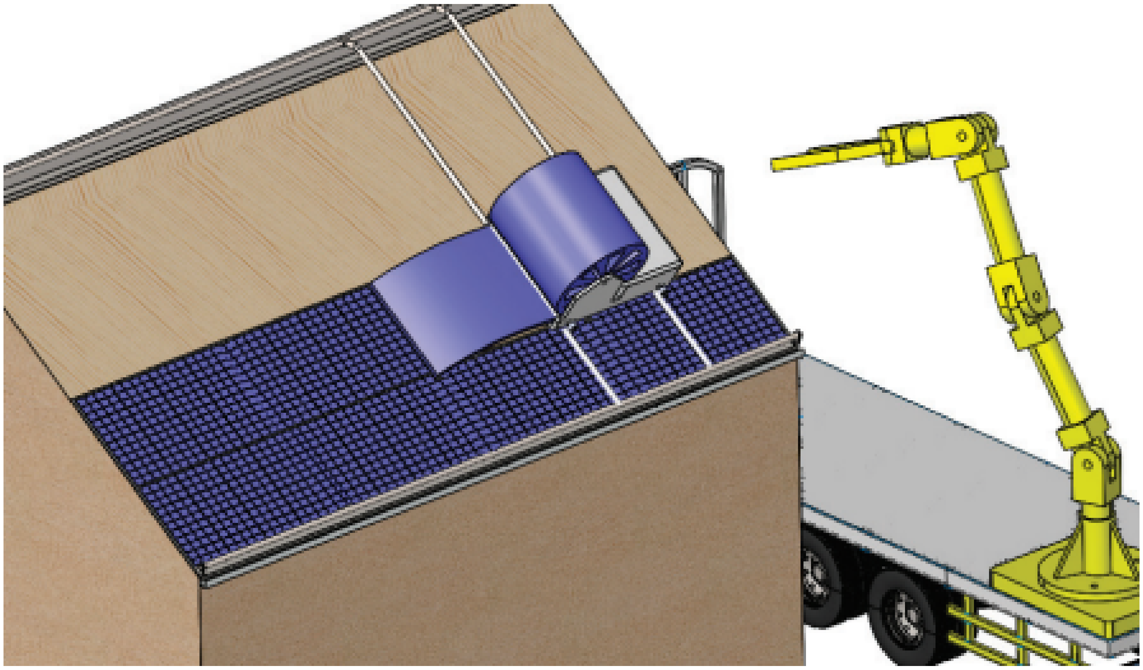


Figure 10: Future Installation methods

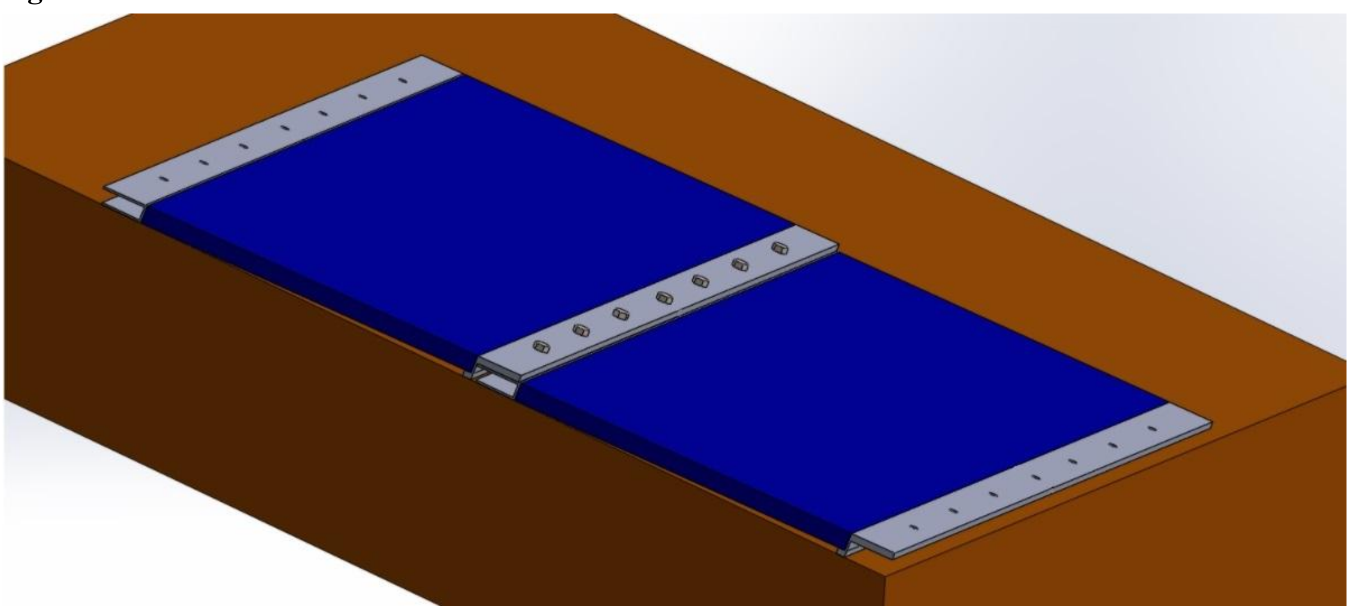


Figure 11: Initial Design Concept

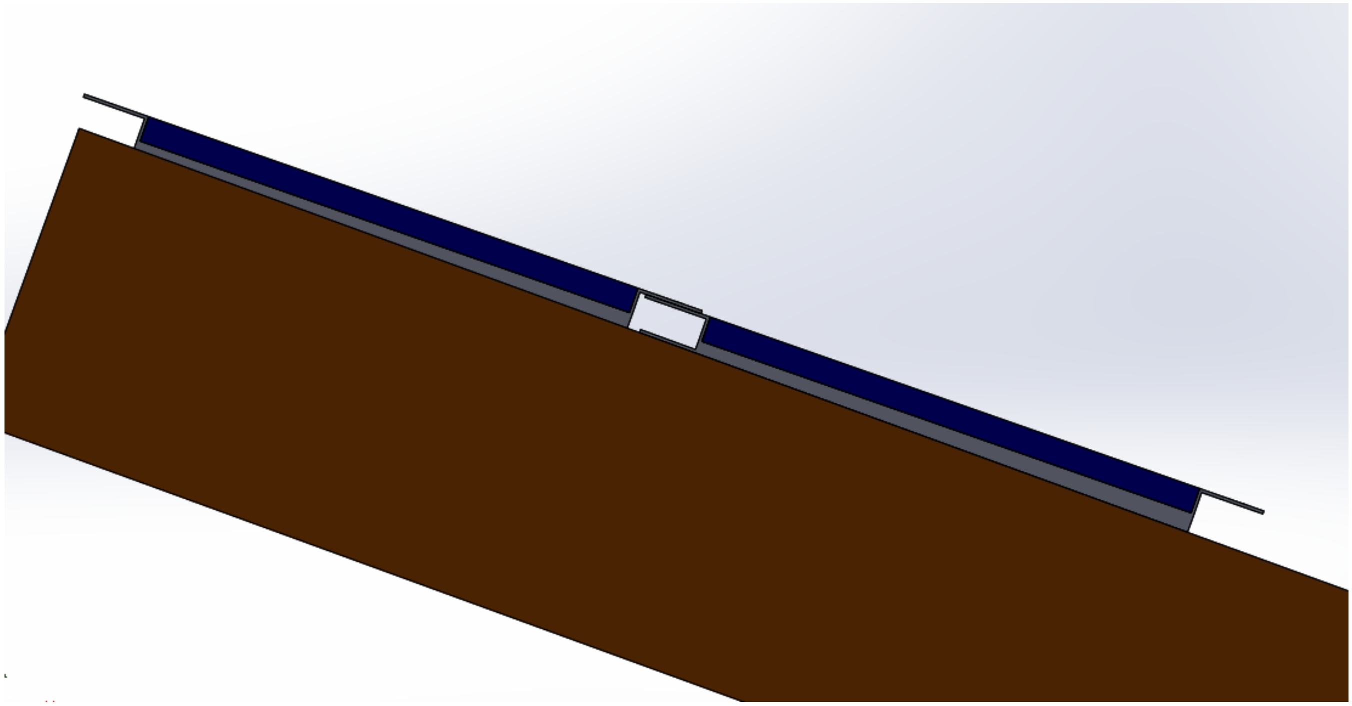


Figure 12: Initial Design Concept- Side View

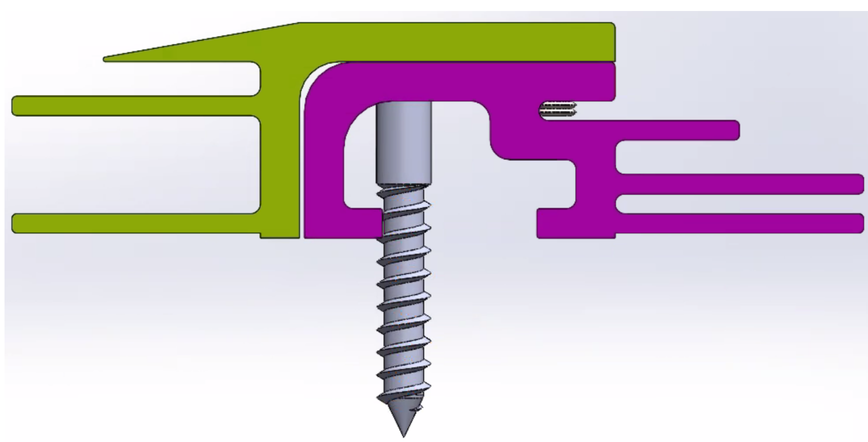


Figure 13: First design approved for assembly sid

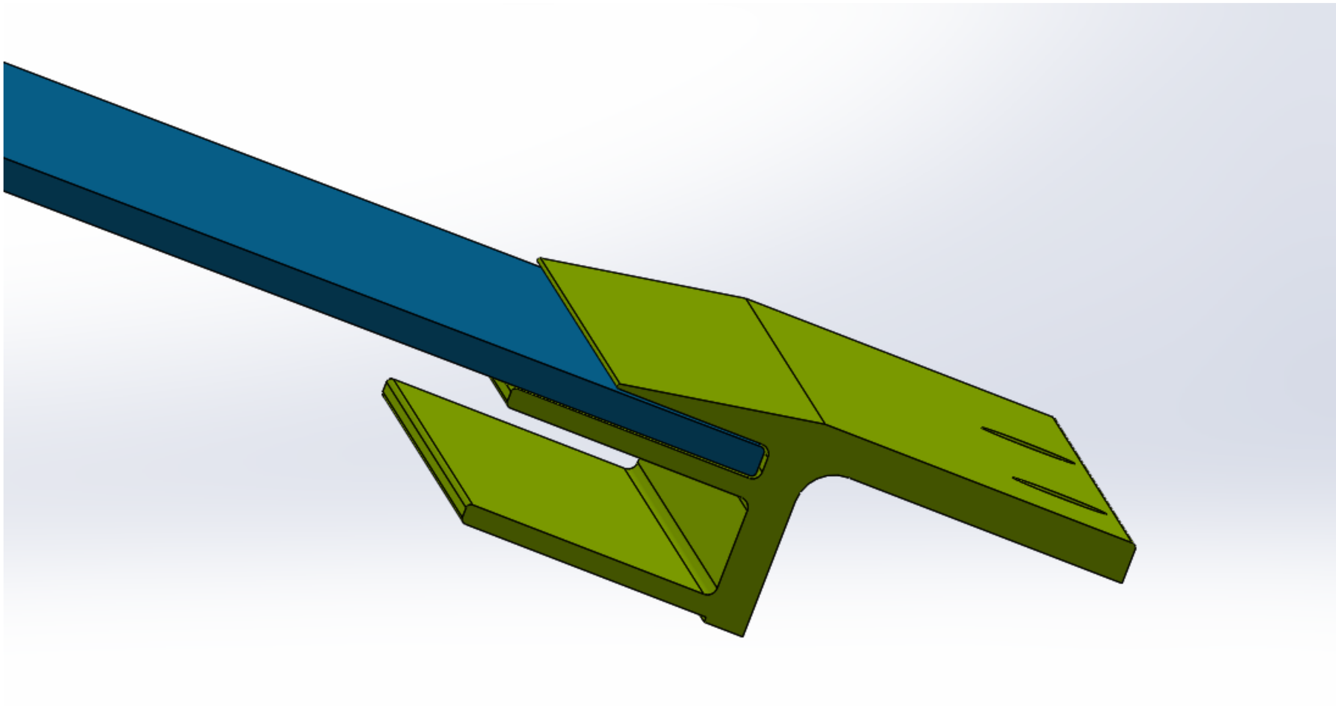


Figure 14: Top rail with PV material

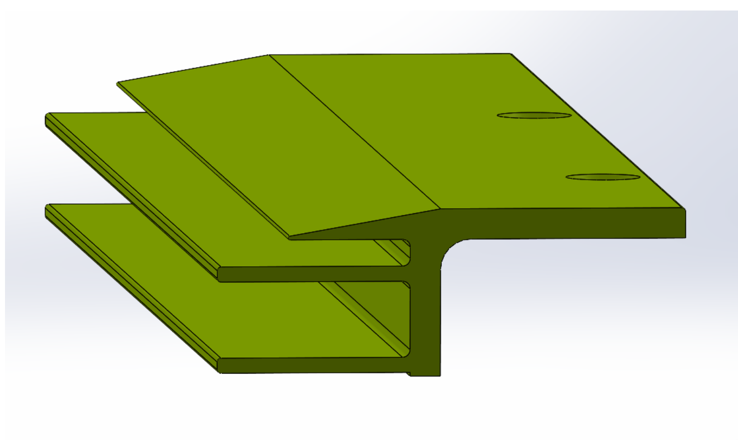


Figure 15: Top rail

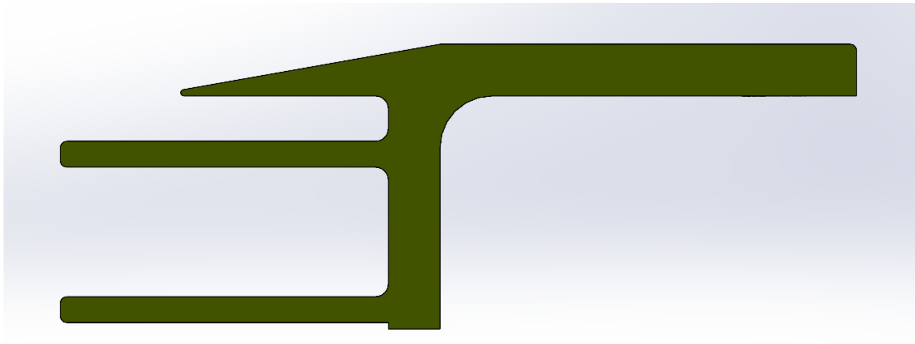


Figure 16: Top rail side view

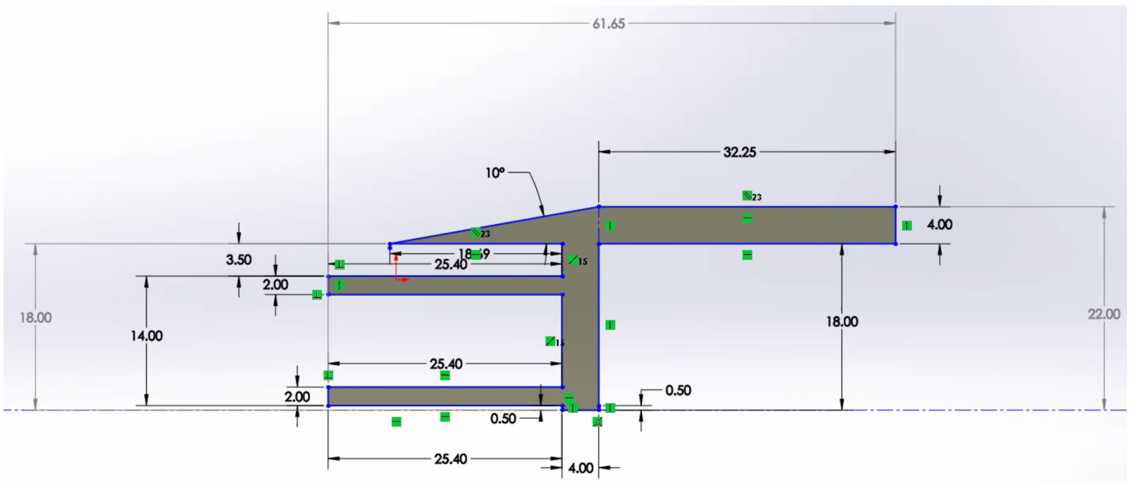


Figure 17: Top rail dimensions (mm)

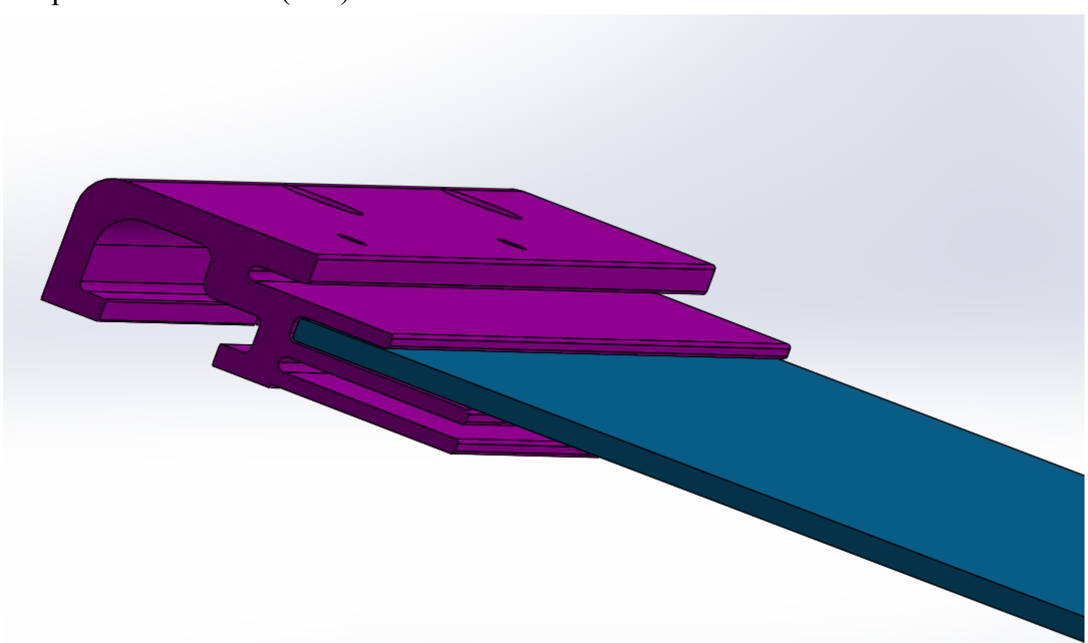


Figure 18: Bottom Rail with PV material

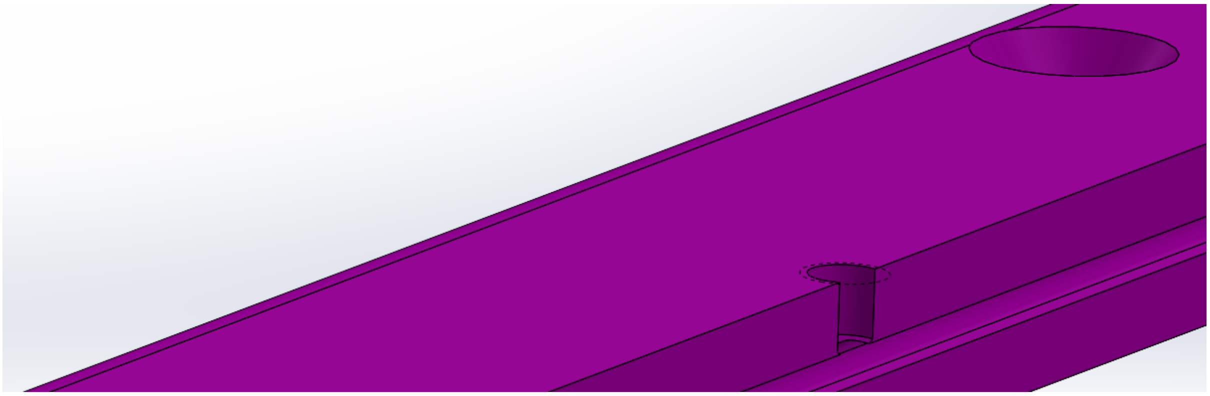


Figure 19: cross section view of drainage channels

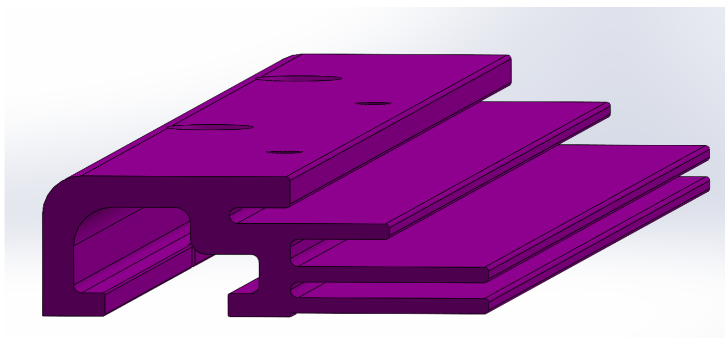


Figure 20: Bottom rail

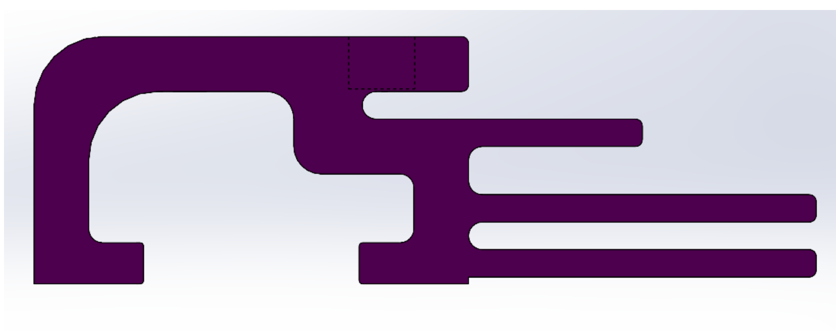


Figure 21: Bottom rail side view

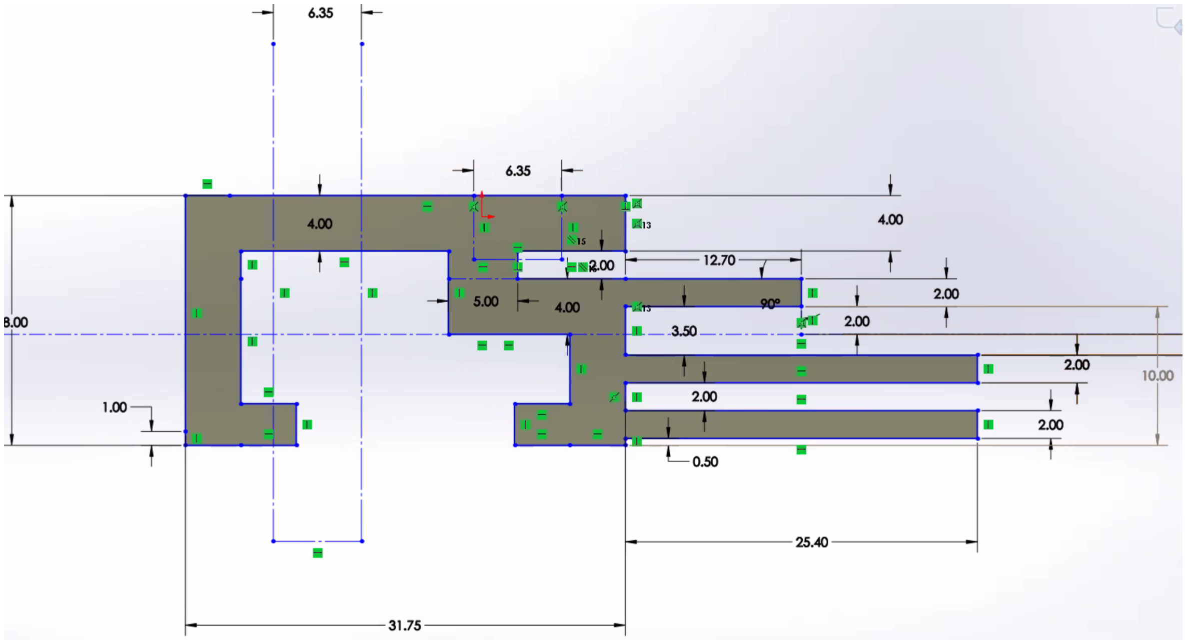


Figure 22: Dimensions of Bottom rail (mm)

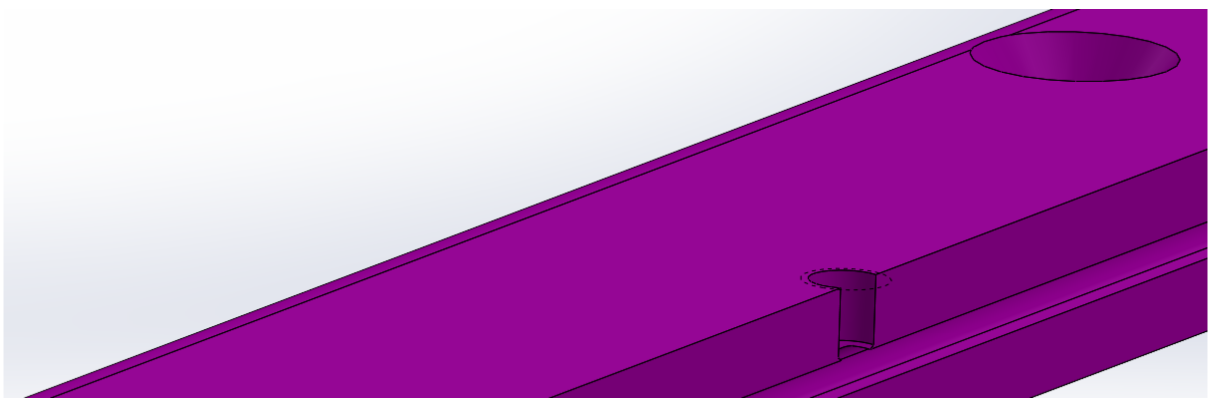


Figure 23: Final design, drainage method 2

Appendix C - Testing images

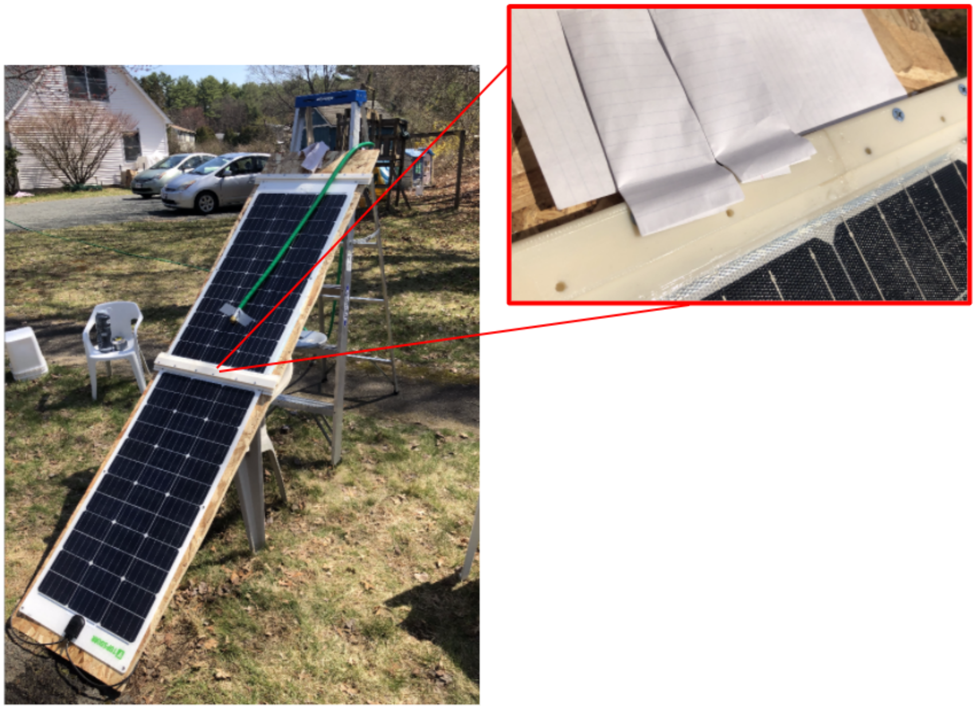


Figure 24: 1st round of testing, set up at 45°

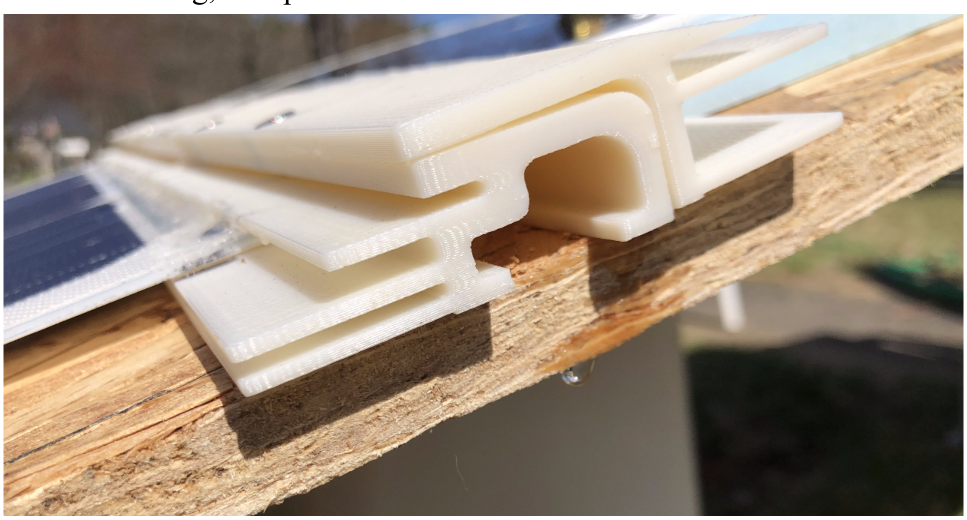


Figure 25: 2nd round of testing, leakage observed at the side at 18.4°

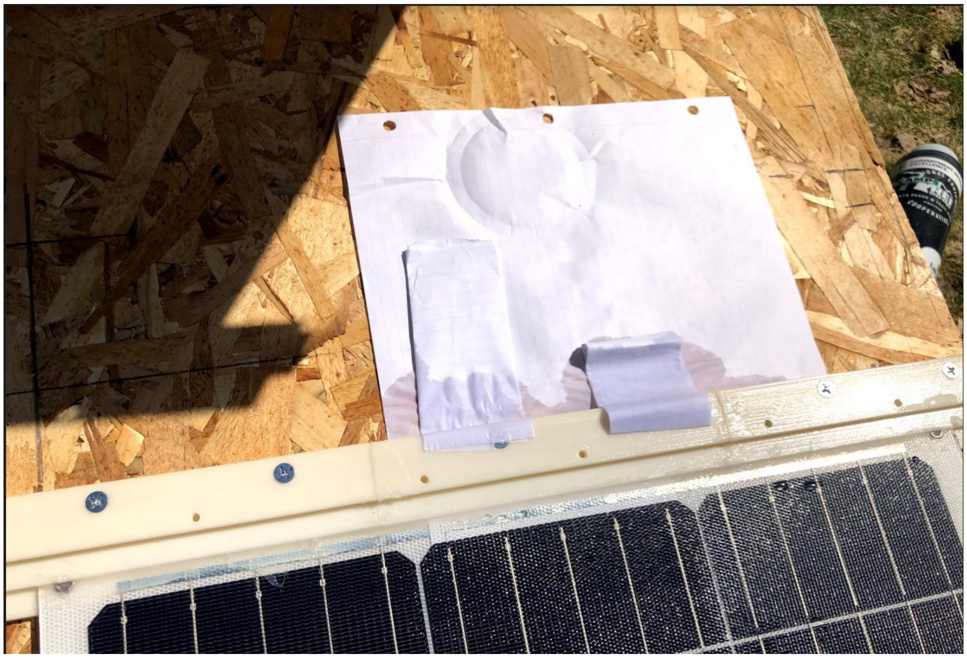


Figure 26: 2nd round of testing, wet paper on plywood

Figure 27: 3rd round of testing, 45° test with a removed fastener and paper on bottom rail

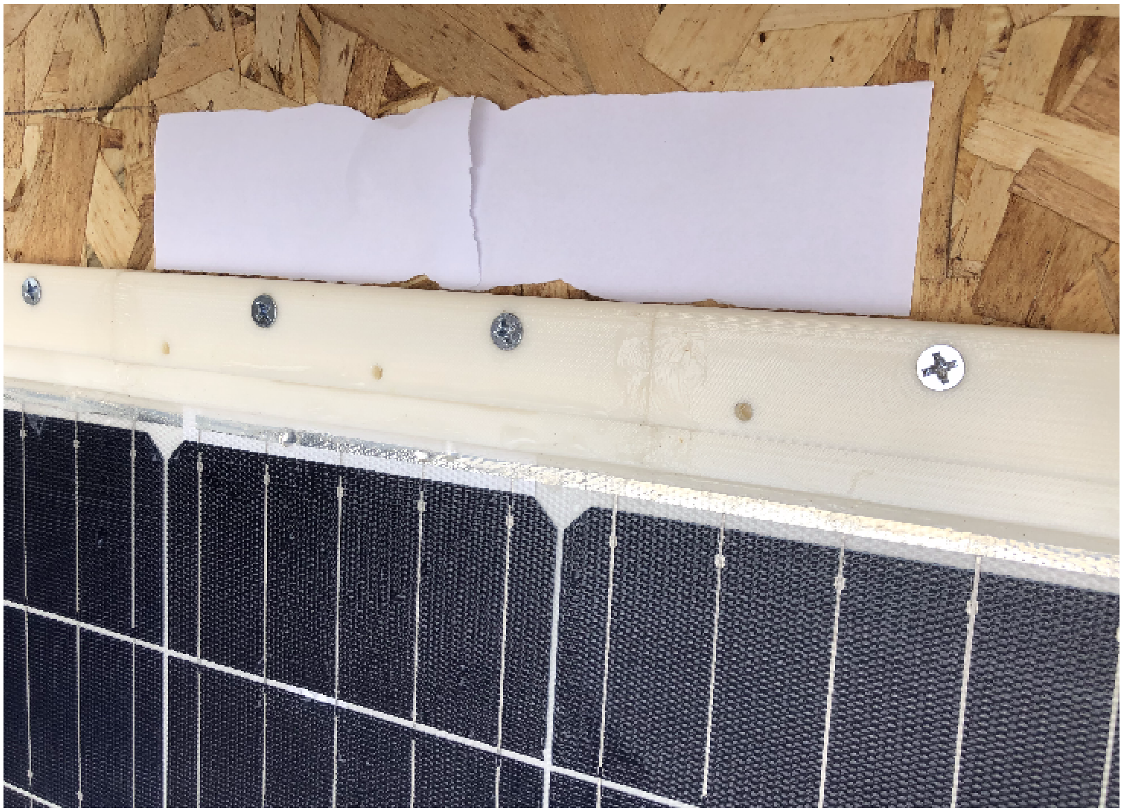


Figure 28: 3rd round of testing, 45°, top fastener removed, paper on plywood only

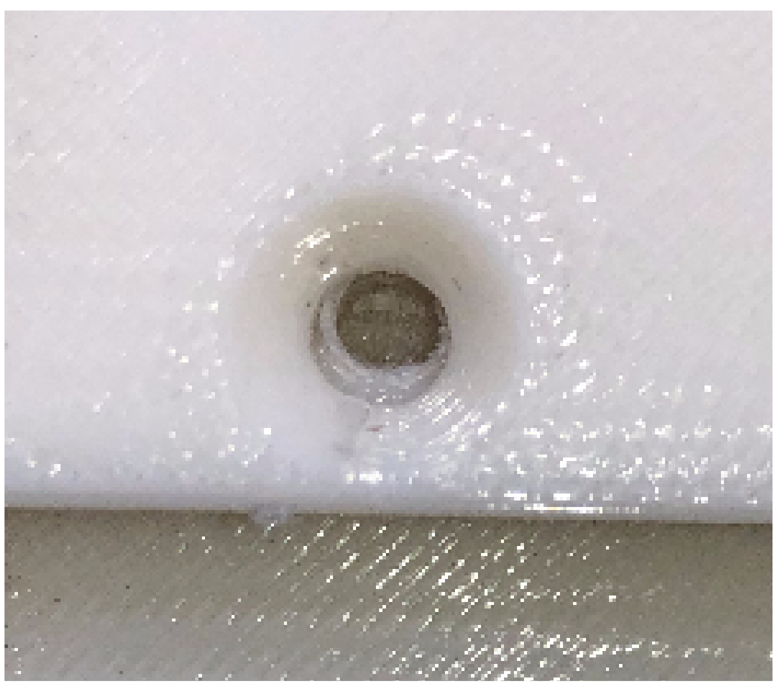
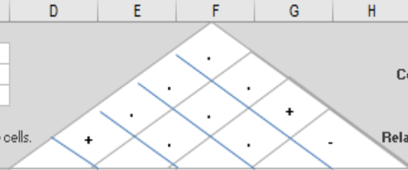


Figure 29: 3rd round of testing, screw is visibly stripped of plastic threads

Appendix D - House of Quality

Project Title: Bi PV
Project Leader: Ben Tan
Date: 4/6/2021

You need only to fill the white and blue cells.



Correlation: + Positive; . No correlation; - Negative

Relationships: 9 Strong; 3 Moderate; 1 Weak; None

	Customer importance rating (1: low, 5: high)	Functional Requirements (How) → / Customer Requirements - (What) ↓	Yield Strength of Mounting	Material selection	Screw selection	Continuous Overlap	PV material Surface Height	Weighted Score	Satisfaction rating	Competitor rating 1	Competitor rating 2	Competitor rating 3
		Desired direction of improvement (↑,0,↓)										
1	1	Water Proofing	0	3	9	9	0	21				
2	2	Corrosion resistance	3	9	9	1	0	44				
3	3	Durability	9	9	9	0	0	81				
4	4	Space for Electronics (PCBs)	0	0	0	1	9	40				
5	5	Cost	3	9	3	0	1	80				
6								0				
7								0				
8								0				
9								0				
		Technical importance score	48	93	69	15	41	266				
		Importance %	18%	35%	26%	6%	15%	100%				
		Priorities rank	**3**	**1**	**2**	**5**	**4**					
		Current performance										
		Target or limit	<=276MPa		<= 1.85"	<=10"	0.53"					
		Benchmark										
		Difficulty	1	1	1	4	4	1: very easy, 5: very difficult				
		Cost and time	1	1	2	5	5	1: low, 5: high				

Competitive evaluation (1: low, 5: high)

Appendix E- Wind Uplift Analysis

Wind Uplift Force Analysis

Assunptions:
- Steady-State Condition
- Density of air is calculated based on atmospheric pressure
- Wind speed is based on International Building Code 2015 (IBC 2015)
- Maximum lift coefficient at a angle of attack (Deg) of 17.5° (KAMINSKI, DEBORAH A. INTRODUCTION TO THERMAL AND FLUIDS ENGINEERING. JOHN WILEY, 2017.)

Analysis :

Pressure

$$P := 1\ atm = 101.325\ kPa$$

Area of Photovoltaic

$$A := (3.5\ in) \cdot (1\ m) = 0.089\ m^2$$

Wind Speed

$$V := 180\ mph$$

Lift coefficient

$$C\_L := 1.72$$

For a hot summer the following air properties are going to be considered

Temperature

$$Tsummer := 315\ K = 107.33\ °F$$

Density of Air

$$\rho\_s := 1.134895\ \frac{kg}{m^3}$$

Uplift Force on Summer

$$F\_lift := C\_L \cdot \left(\frac{1}{2} \cdot \rho\_s \cdot V^2 \cdot A\right) = 561.815\ N$$

For a cold winter the following air properties are going to be considered

Critical Temperature

$$Tsummer := 250\ K = -9.67\ °F$$

Density of Air

$$\rho\_w := 1.3947\ \frac{kg}{m^3}$$

Uplift Force on Winter

$$F\_lift := C\_L \cdot \left(\frac{1}{2} \cdot \rho\_w \cdot V^2 \cdot A\right) = 690.429\ N$$

Appendix F - External Flows Plot (Coefficient of Lift)

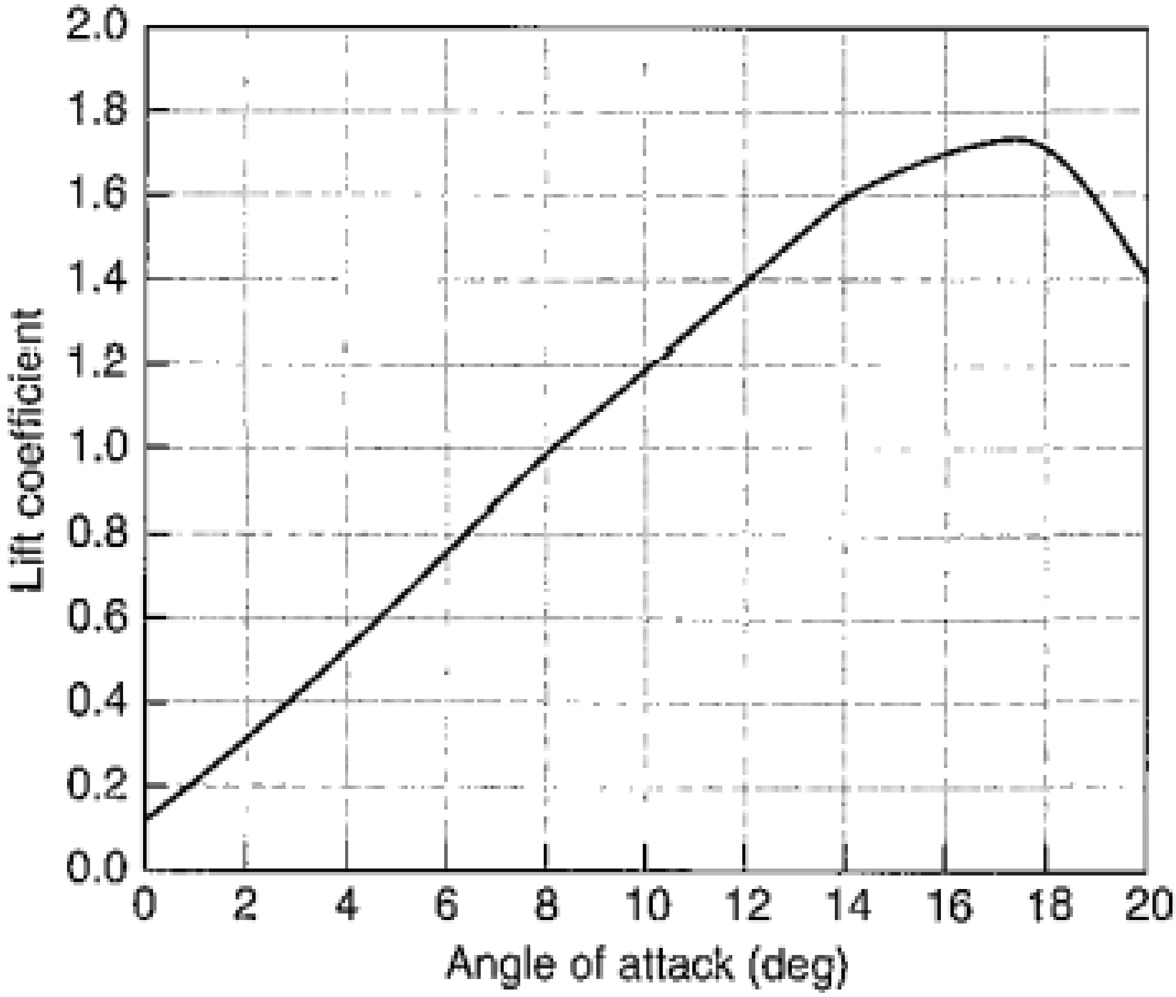
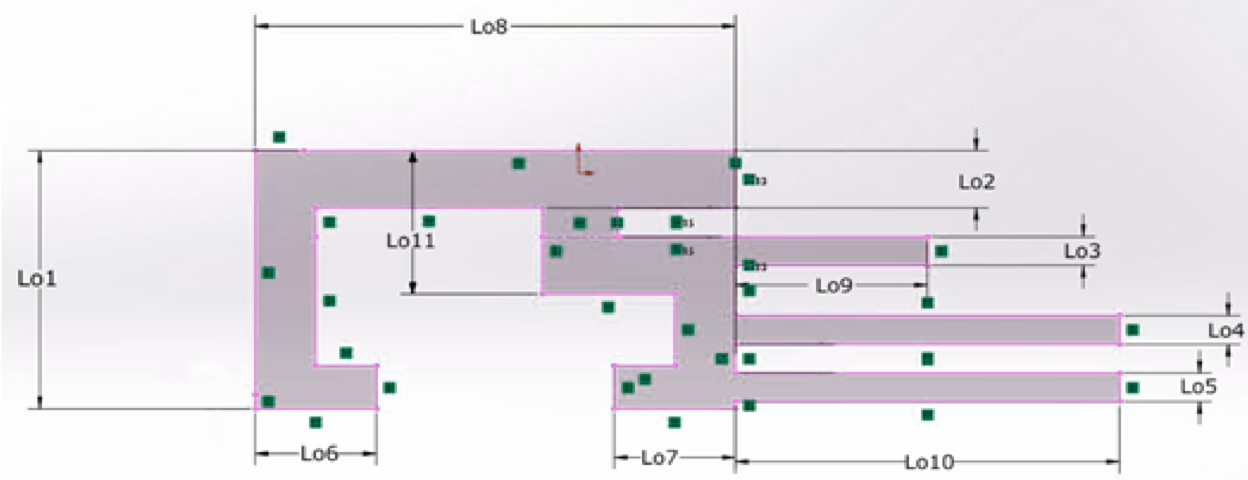


Figure 30: Lift Coefficient versus Angle of attack (deg)

Source: Kaminski, Deborah A. *Introduction to Thermal and Fluids Engineering.* S.L., John Wiley, 2017.

Appendix G - Thermal Analysis

Thermal Expansion of Lower Design



Assumptions :

- Steady-State Condition
- Bean Analysis Approach
- Neglect Convection and Radiation
- Initial temperature will be considered as room temperature (T0 = 70 °C)

The material of the design is Aluminum 6061-T6

- Coefficient of Thermal Expansion (@ 20 to 100) °C

$$\alpha := 23.6 \cdot 10^{-6} \frac{m}{m \cdot \Delta°C}$$

$To := 70\ °C$ $\qquad Tf := 100\ °C$ $\qquad \delta T := Tf - To = 30\ \Delta°C$

From the above figure, the referred initial Lengths are the following :

$Lo1 := 0.018\ m$ $\quad Lo2 := 0.004\ m$ $\quad Lo3 := 0.002\ m$ $\quad Lo4 := 0.002\ m$

$Lo5 := 0.002\ m$ $\quad Lo5 := 0.002\ m$ $\quad Lo6 := 0.008\ m$ $\quad Lo7 := 0.008\ m$

$Lo8 := 0.03175\ m$ $\quad Lo9 := 0.0127\ m$ $\quad Lo10 := 0.0254\ m$ $\quad Lo11 := 0.01\ m$

The change in length corresponding to the thermal expansion is the followings :

$\delta L1 := \alpha \cdot \delta T \cdot Lo1 = 0.013\ mm$

$\delta L2 := \alpha \cdot \delta T \cdot Lo2 = 0.003\ mm$

$\delta L3 := \alpha \cdot \delta T \cdot Lo3 = 0.001\ mm$

$\delta L4 := \alpha \cdot \delta T \cdot Lo4 = 0.001\ mm$

$\delta L5 := \alpha \cdot \delta T \cdot Lo5 = 0.001\ mm$

$\delta L6 := \alpha \cdot \delta T \cdot Lo6 = 0.006\ mm$

$\delta L7 := \alpha \cdot \delta T \cdot Lo7 = 0.006\ mm$

$\delta L8 := \alpha \cdot \delta T \cdot Lo8 = 0.022\ mm$

$\delta L9 := \alpha \cdot \delta T \cdot Lo9 = 0.009\ mm$

$\delta L10 := \alpha \cdot \delta T \cdot Lo10 = 0.018\ mm$

$\delta L11 := \alpha \cdot \delta T \cdot Lo11 = 0.007\ mm$

Table 1: Thermal Expansion Analysis

Lo (m)	Lo_n (m)	δT $(\Delta °C)$	α $\left(\frac{m}{m \cdot \Delta °C}\right)$	δL (mm)
$Lo1$	0.018	30	$23.6 \cdot 10^{-6}$	0.013
$Lo2$	0.004	30	$23.6 \cdot 10^{-6}$	0.003
$Lo3$	0.002	30	$23.6 \cdot 10^{-6}$	0.001
$Lo4$	0.002	30	$23.6 \cdot 10^{-6}$	0.001
$Lo5$	0.002	30	$23.6 \cdot 10^{-6}$	0.001
$Lo6$	0.008	30	$23.6 \cdot 10^{-6}$	0.006
$Lo7$	0.008	30	$23.6 \cdot 10^{-6}$	0.006
$Lo8$	0.03175	30	$23.6 \cdot 10^{-6}$	0.022
$Lo9$	0.0127	30	$23.6 \cdot 10^{-6}$	0.009
$Lo10$	0.0254	30	$23.6 \cdot 10^{-6}$	0.018
$Lo11$	0.01	30	$23.6 \cdot 10^{-6}$	0.007

Appendix H - Structural analysis

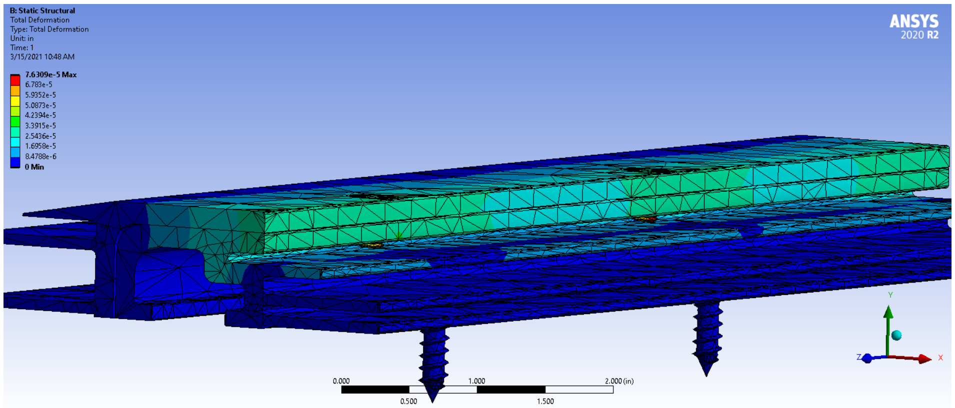


Figure 31: Total deformation of assembly

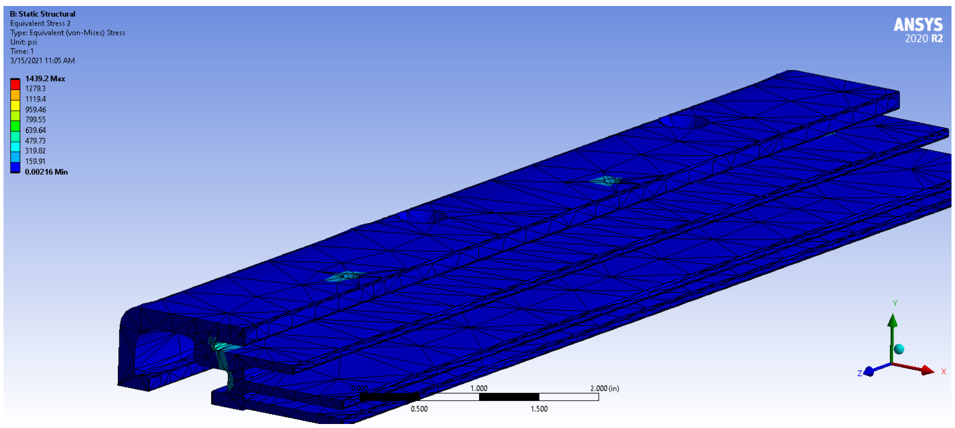


Figure 32: Equivalent stress bottom rail

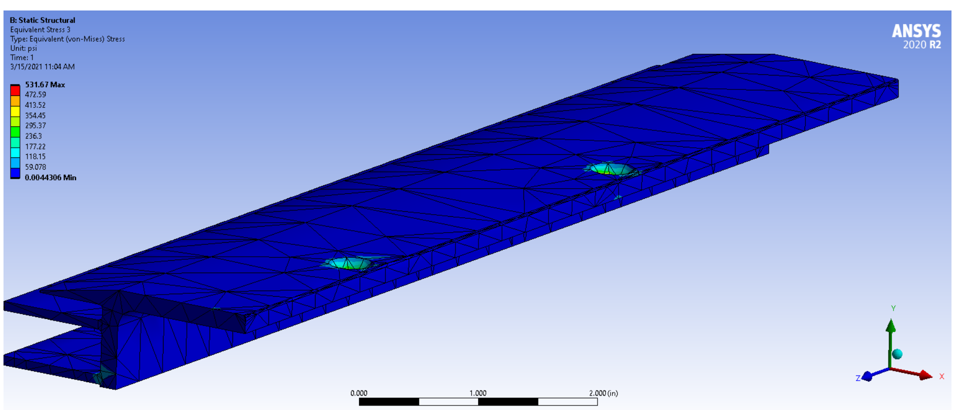


Figure 33: Equivalent stress Top rail