Composite Pegboard
Final Design Review

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Statement of Disclaimer

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Abstract

Many of those with mobility limitations who are told they will need a wheelchair for the rest of their lives can actually begin to stand and walk again given the proper tools and support. The current design for a wheelchair seeking to support this process is overly complex, heavy, and exhibits some features that could potentially pose a serious health hazard to those using it. The scope of this project is to aid in the design of an adaptable composite wheelchair frame that can be both lightweight and strong, while still allowing for physical diversity of potential users. Through research and the preliminary design process, this team has determined that the best way to accomplish these goals is by incorporating a composite pegboard system to fix different attachments to, such that the design can adapt to multiple users with varying physical abilities. This document will highlight important aspects of background research, the strategies that the team used to decide the most important qualities that led to the preliminary designs, the final concept selection, and the overall plan to move forward with this project.

The main challenges involved with a design like this have to do with cost, manufacturability, and weight. Most lightweight yet strong materials are expensive considering the application at hand. However, the goal of this project is to design a wheelchair not only for one particular user, but for many users who cannot currently afford the solutions available on the market. In addition to the cost considerations, the overarching design initiative is to create a safe and effective way for many users to regain the ability to stand and possibly walk if given the right set of tools.

The particular design challenge of this team’s project scope focuses on the analysis of the specific strengths of various composite materials and the possibility of delamination in a composite pegboard application. In order to combat these challenges, the team has further discussed a wide range of composite fibers, geometries of cores and layups, and core material selections. To ensure the highest quality result, the team has emphasized a focus on solely designing and testing the best possible material and geometry combination of a single rear framing panel, according to the sponsor’s specifications, rather than attempting to complete the design of a full composite wheelchair.

Utilizing strain gage data and deflection measurements for multiple test panels, the team successfully analyzed the effects of varied geometry and core materials on composite panel bending stiffness. The team formed a recommendation for further research and testing before instituting a design solution for the sponsor to use in improving the current prototype of the assistive wheelchair device.
1 Introduction

The project team is composed of four mechanical engineering students from the California Polytechnic University, in San Luis Obispo, who have been chosen to work on an accessible product for people who are in need of a wheelchair: Luis Corrales, Asa Cusick, Joelle Hylton, and Wyatt Pauley. All team members are in their fourth year of studying mechanical engineering at the California Polytechnic University, in San Luis Obispo. Asa, Luis, and Wyatt are all focused on a general concentration for their major, while Joelle is focusing on the manufacturing aspect. Members of the team have varying experience with composite material manufacturing and engineering towards accessibility. The team believes that their contributions can make a real change to many who cannot attain the resources needed to recover from a life altering experience.

The sponsor, Charlie Gutierrez of Ideomotion LLC, has provided a fully functional prototype of a wheelchair that can transition the user between a sitting and standing position to promote a walking posture within the user. The design currently poses many challenges relating to cost, weight, manufacturability, and accessibility, all of which reflect criteria the team took into consideration when brainstorming improvements for the prototype. Although there are similar designs currently on the market, none are as inventive as the design the sponsor has provided. Many wheelchairs only allow the user to stand or be suspended in an upright position off the ground. Few competing products, if any, actually allow the user to walk and stand on their own feet. The team’s objective is to create the main rear support panel of a frame for a similar walking wheelchair that can adapt to different users and various disabilities while still offering support in various ways. The team has concluded that a composite material with a core would yield the desired results, but further testing is needed to determine the best materials for this project. Included in this document is a breakdown of all the background research, initial design ideas, and the scope of work, as well as the reasoning for all decisions.

![Figure 1-1 Charlie's Current Wheelchair Frame](image-url)
2 Background
The first step of the design process is an understanding of the current market, user needs, and the implied technical challenges. As such, the team began by understanding the needs of the customer, the current market, as well as specific information on composite manufacturing and testing.

2.1 Customer Research
To develop an understanding of the project, the team conducted an interview with the sponsor and main customer, Charlie Gutierrez. Since the team was tasked with redesigning the structural framing component of a device Charlie had already prototyped, the team deemed him the main user. The team will focus the design towards Charlie’s needs and his desire to improve the prototype for the end user. This is achievable by manufacturing the frame out of a system of composite pegboards, as per Charlie’s request.

During this interview, the team asked for the information that the sponsor had already discovered through his own interactive prototyping as well as the improvements he had in mind for the future of his walking wheelchair. Through this process it was concluded that Charlie’s desired outcome would be a second iteration of his prototype. These goals can be categorized as:

- Lighter than the current prototype which is constructed with chromoly steel
- Strong enough to bear the load of a fully developed adult
- Durable enough to withstand the stresses of daily use
- Aesthetically pleasing enough to be desired to use and promote self-confidence in the user
- Cost effective enough to allow the product to be marketable to the general public
- Modular in nature, allowing for attachments to be interchanged for different user’s needs
- Customizable by the user to develop a sense of proud ownership

The team conducted further customer research by reaching out to individuals with personal experience and expertise in the field of physical mobility loss and rehabilitation. Under Charlie’s recommendations, the team reached out for an interview to several individuals who were familiar with both the concept and prototype of Charlie’s walking wheelchair.

The first interview was with a fellow fourth-year Cal Poly Engineering student named Jake Javier on October 9th, 2020. Jake is a biomedical engineering student who experienced an injury to his spinal cord towards the end of his high school education and has used a wheelchair ever since. Our team was able to ask him about his personal experience with wheelchairs as a user and collect his opinions on the initial walking wheelchair prototype that Charlie has developed. Jake’s feedback can be summarized as follows:

- Convenience for the user is critical to the overall experience
- The current chair design is too clunky for real-world everyday use
- The most important attributes of a wheelchair are durability, low vibration, small overall size, sleek (in terms of both size and aesthetics), light/fast, and general aesthetics
- Adjustability to different user form factors is a useful feature to have
- The angle of the seat’s back rest and the seat’s tightness around the lower body are important ergonomic factors to consider
• The rigidity of the device should be prioritized in the design considerations

A second interview was conducted on October 10th, 2020, with a Physical Therapist based in San Francisco, California, named Vincent Leddy. Vincent has assisted patients with brain injuries for the last 30 years, mainly working with children who have experienced a stroke or developed cerebral palsy. It was very enlightening to receive information and professional insight directly from a person that works with a wide variety of rehabilitation equipment and guides his patients through that rehabilitation process on a frequent basis. A distillation of that insight is as follows:

• There are no common treatments in physical therapy, every treatment is tailored to the unique wants and needs of each patient
• It is critical for the rehabilitation process to find the proper balance of physical support in therapy and only provide enough support to allow the user to recover without dependency
• Current products on the market are missing the point of the assistive technology by designing large and bulky fully motorized devices
• Charlie’s prototype has the functionality that could be useful for some his patients but would benefit from an aesthetic remodel since aesthetics are important in such a device
• Colors are one of the most effective ways to drastically increase the aesthetic appeal of such a device
• Mobility in the device is one of the most important features as the purpose is to aid the user rather than hinder them
• Overall, the goal should be to minimize the redundancy in material and create a sleek design that maintains the functionality

2.2 Existing Product Research
This project is a unique one, in that the only product close to what is to be designed and built is a prototype patented by the sponsor. This made finding similar products somewhat of a challenge unless specific aspects were focused on.

The "Able Chair,"[1] Figure 2-1, is an interesting design that closely follows the sponsor’s design ideas; the prototype is currently being funded on Kickstarter and has numerous backers. One of the interesting features is an actuator, similar to what the sponsor has already provided in his prototype design. The actuator on the Able Chair provides a similar mechanism that links two plates that control the height of the wheelchair. The only real differences between the current prototype and the Able Chair are price and electronics; the Able Chair is fully electric, from the wheels to the controls, whereas the current design prototype still uses manual wheels.
A couple other designs for standing wheelchairs focused more on the affordability aspect, which meant completely manual design. Instead of using the electric actuator, The Arise Standing Wheelchair[^2], Figure 2-2, uses a gas spring to allow the user to lift themselves to stand. The Laddroller[^3], Figure 2-3, has a similar design, but a much faster lifting mechanism. Another product focused on this same issue and used what could only be described as a ratcheting system to solve this issue. The user would use their strength to lift themselves and when they stopped lifting, the ratchet would catch them and lock in place. This product however was only a single prototype.

Other products like the TechRMD Robotic Mobilization Device[^4], Figure 2-4, simply allowed the user to stand, but not walk or exercise; the user's feet were still suspended by the wheelchair and the user would only be set upright, rather than standing on their own. These products still had some benefits to their design, including how they suspended the users and how the user could still move around while in an upright position.
An interesting takeaway from the designs that only allow the user to be suspended is the mechanism that the design uses to suspend them. One of the biggest issues that Charlie faced when designing the prototype is figuring out a way to allow users to still be supported while also using their legs naturally to stand. Many of these designs use a harness that goes around the user's chest and under the arms for support rather than between the legs.

Dr. Todd Kuiken from the Shirley Ryan Ability Lab for Bionic Medicine has designed a built-in belt drive on the armrests\(^5\), shown in Figure 2-5, that allows users to move by interacting with the belts rather the wheels. When set upright, users could still use this belt to move the wheelchair around and exercise muscles they normally wouldn’t use while in a conventional wheelchair.
intent of managing the person’s disabilities and allowing them to maintain a normal life, whereas the goal for this project is rehabilitation, in addition to normalcy.

The final similar product aspect that was researched was composites manufacturing. There is a broad number of companies that manufacture carbon fiber bars, rods, angle brackets and most importantly, sandwich boards. For the project, combining carbon fiber composites with filler to make a sandwich board is a great option. One company of note is DragonPlate, as they manufacture numerous composite products with a large variety of fillers – wood, foams, and honeycomb patterned materials – all of which are useful considerations for the project.

2.3 Patent Research
To further understand which similar products and design components or methods exist in the market already, a search of relevant patents was conducted. The first area of interest was how the team would create holes in composite panels. The team found the patents shown in Figure 2-6 and Figure 2-7, which both provide dedicated composite layup techniques for improved hole strength. These solutions are mechanically advantageous to simply drilling holes in the composites.

US10315461B2 - Advanced composite rim having molded in spoke holes

This patent shows a bicycle rim that has molded holes for the spokes. This means the holes were creating during the composite layup phase. The patent claims the rim with molded holes has superior strength to previous versions with drilled holes. This could prove useful as there will be a pattern of holes in the composite board.

US20150314553A1 - Reinforced structural component made of composite material

This patent details what seems to be half of a composite clevis, and it includes a method of laying up the composite to reinforce the hole in the structure. This may be another useful method when creating holes in the composite panels, to ensure that the modules will be properly supported by the panel without damaging the panel.

With the information about holes in mind, the team sought to find attachment methods for future wheelchair modules. The team found multiple composite-specific attachments methods, shown in Figure 2-8 through Figure 2-11, that can be used as a reference when attaching panels to each other or developing a way to attach modules to the panels.
US10342332B2 - Modular shelving systems and methods

This modular shelving patent shows some fixturing options for load bearing shelves. There are various types of connections shown between shelves and the frame. This variety of mounting types might prove useful as the team designs the best fixturing for the modular wheelchair components to the composite panel.

US6824341B2 - Integrated anchoring system and composite plate for a trailer side wall joint

US7069702B2 - Composite joint configuration

Both of these patents are different parts of the same design. They detail the attachment on either side of a support beam to load-bearing composite panels for use as the structure of a truck trailer. The chosen design will more likely be supported on one side, but similar fixturing principles may be applicable.

US10690159B2 - Fastening system with a washer having an enlarged bore facing a composite panel

This patent shows a way of fixing two composite panels with a fastener going normal to the panel surface, much like two sheets of aluminum being attached with a rivet. This patent is an aerospace application of attaching composite aircraft panels together. This may be useful as a reference for how to attach panels together or how to attach the future modules to the panels created.
US6663314B2 - Device for joining a panel and a structure, able to transmit significant forces

This patent shows a method and type of fixturing to allow through-holes in a panel to support the high loads of an attached system. This could be useful in the design process as the team figures out the best way to attach future modules to composite panels.

![Figure 2-11 High-load panel fixture](image1)

Lastly, the team researched existing methods of improving composite panel rigidity, as the team anticipates that the large panel suggested by Charlie may be encounter issues with flexure. The team found two possible solutions, shown in Figure 2-12 and Figure 2-13, to the rigidity problem. These patents may be referenced if rigidity becomes an issue.

US20090202785A1 - Reinforcement strip for a composite panel

This patent details a method of strengthening the edges of a composite -- composed of at least two cover layers with at least one core between the cover layers -- by using another composite sheet attached to the edge. Depending on the shape of the composite panel created, this could prove as a useful technique in how to attach the composite panel to other parts of the structure.

![Figure 2-12 Composite panel edge reinforcement strip](image2)

US4786343A - Method of making delamination resistant composites

This patent specifically addresses the problem of delamination and gives some layup and geometric ideas to reduce the chance of delamination. Combining some of the methods shown in the patent will help combat bending in the composite panels, if that issue is encountered during the design process.

![Figure 2-13 Delamination-resistant composite panel shapes](image3)
2.4 Technical Literature Research

Most of the technical research was focused on how the team could accomplish creating a pegboard using composites. Composites are usually woven fibers, and creating holes in the fibers could damage the integrity of the composite, potentially leading to premature failure at what should be considered a safe load.

A collection of papers published in the "FRC 2000: Composites for the Millennium"[6] provided numerous topics of interest for the design. Some of the papers focused on core selection, fiber selection, the effects of honeycomb cores, and steel strip hybrid composite composition. When dealing with the selection of a composite pegboard, it is important to take topics like these into account.

One of the main areas of research that was investigated was the analysis of both the manufacturing process and stress analysis of holes in composites. While there was plenty of material on this, some notable results were as follows. A doctoral thesis published in 1999 by Tomas Ireman[7] goes into detail on the analysis of the integrity of composites with drilled holes for both 2D and 3D analysis. This will come in handy later when calculating the stresses and strains that the composite panels will be experiencing. The other paper is “Behavior of Composite Plates with drilled and molded holes under tensile load”[8] which discusses, much as the title indicates, the difference in stress concentrations and failure modes of two different ways of putting holes in composites. Also, this was of interest since some patents were found for technologies to manufacture molded holes.

The other main area of research was mixing different composites, delamination, and other failure modes of composites. The possibility of laying up carbon fiber with some sandwich material is immediately apparent. However, another way to improve the qualities of a composite board is to mix the fabrics themselves (e.g. carbon and Kevlar, carbon and fiberglass, etc.). These combinations of composites can increase favorable properties as noted in the article “Fatigue Behavior of Hybrid Composites”[9] in the Journal of Materials Science.

Finally, but most certainly not least, is the issue of delamination of composites with the surfaces between the fabric and what it is attaching to. The paper on “Delamination Analysis of Carbon Fiber/Epoxy Composite Laminates Under Different Loading Rates Using Acoustic Emission”[10] goes into the way different loadings can affect this mode of failure. This is important to consider since the wheelchair frame will go through static, dynamic, and impact loading.

2.5 Applicable Standards

After conducting research on numerous industry codes and regulations, three particular standards were deemed most relevant and are listed below in Table 2-1. All three of the included standards involve testing methods used in the construction of sandwiched composite materials. These will be valuable resources as the team develops ideas that need to be tested with composites. Following these standards will allow the team to collect accurate data to inform the design process.
<table>
<thead>
<tr>
<th>Standard Number</th>
<th>Standard Name</th>
<th>Standard Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM C480/C480M</td>
<td>Standard Test Method for Flexure Creep of Sandwich Constructions</td>
<td>This standard details how to test a composite sandwich structure for the effects of creep due to flexure. Considering that these panels will be supporting a cantilever load for a long duration, they might experience creep, so it may be important to analyze that properly.</td>
</tr>
<tr>
<td>ASTM D7249/D7249M</td>
<td>Standard Test Method for Facesheet Properties of Sandwich Constructions by Long Beam Flexure</td>
<td>This standard details how to test a composite sandwich structure for the effects of repeated flexure. Considering that these panels will be supporting a cantilever load, they might experience small flexures over time that will induce flexure effect, so this is an area the team may need to test.</td>
</tr>
<tr>
<td>ASTM C364/C364M</td>
<td>Standard Test Method for Edgewise Compressive Strength of Sandwich Constructions</td>
<td>This standard gives a method for characterizing the compressive strength of sandwich composite when loaded edgewise (on the side where the lamination is visible). Depending on how the holes are made in the composite laminate, the weight of the attached modules will be applied to the edges of the composite sandwich. As such, it is important to analyze the edgewise strength of the panels, especially at those points.</td>
</tr>
</tbody>
</table>
3 Objectives
As a compilation of research and an indicator of this project scope, the objectives detail the team’s understanding of the problem, boundaries of the solution, needs of all stakeholders, and specifications generated to meet those needs.

3.1 Problem Statement
The sponsor of this project, Charlie Gutierrez, has worked with many individuals who are told they will need a wheelchair for the rest of their lives because of mobility limitations. Through his interactive prototyping, he has found that many of them can begin to stand and walk again given the right tools and support. Wheelchairs need to rehabilitate people and provide a custom way of recovering that specifically addresses the user's needs, allows them to return to baseline, and helps them discover new possibilities. This design will focus on helping those with limitations regain or develop the strength to stand, exercise, and possibly walk. The current market does not offer a solution that is adaptable, strong, durable, aesthetically pleasing, and cost effective. The team’s task is to create a wheelchair that can adapt to a variety of users and mobility limitations as well as encourage self-confidence in the recovery process.

At the time of CDR, after further discussing the project’s direction with the sponsor and the project advisor, the team’s updated task is to determine a geometrical design and material combination solely for the rear panel of an adaptable wheelchair that best meets the sponsor’s specifications.

3.2 Boundary Diagram
The scope of this project is to design a wheelchair frame that is compatible with a modular attachment system. This frame is referred to as a “composite pegboard” that will meet the dimensional and functional requirements set by the sponsor. The team will only be responsible for items shown below within the dotted line of Figure 3-1, which is the frame of the wheelchair. The team will not be designing a new type of wheelchair or creating any modular attachments. Rather, the project team will be making modifications and substitutions to an existing design.

At the time of CDR, with the updated understanding of the team’s task, the design responsibilities have been reduced to focus only on the rear panel replacement of the existing design. The updated boundaries for the team are reflected below in Figure 3-1.

3.3 Summary of Customer Wants and Needs
After compiling what the team has learned through the conducted interviews and customer research, the team developed a concise Table 3-1 to summarize what was believed to be the different stakeholders involved in the project and what they want and need from the design.
Figure 3-1 Initial boundary sketch outlined in grey on the left, updated boundary sketch outlined in red on the right.

Table 3-1 Listing of the Stakeholders’ Wants and Needs

<table>
<thead>
<tr>
<th>Customer</th>
<th>Needs</th>
<th>Wants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Users with Mobility Limitations</td>
<td>• A wheelchair that is comfortable</td>
<td>• Aesthetic wheelchair that they feel good about being in</td>
</tr>
<tr>
<td></td>
<td>• A wheelchair that is mod-able to unique sizes</td>
<td>• A light enough wheelchair that they can manage it themselves if needed</td>
</tr>
<tr>
<td></td>
<td>• Something that can adapt to their specific recovery process</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• An affordable wheelchair</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• A design that is sturdy</td>
<td></td>
</tr>
<tr>
<td>Individuals Helping those with Mobility Limitations</td>
<td>• A way to easily transport their loved ones</td>
<td>• A lightweight alternative</td>
</tr>
<tr>
<td></td>
<td>• A device that is easy to use and help the person use</td>
<td>• A wheelchair that allows for access to the person in it (for self-care and other daily needs)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• A portable wheelchair that can be put in the car</td>
</tr>
<tr>
<td>Charlie</td>
<td>• A modular design that can attach his support systems</td>
<td>• A pegboard made from composites</td>
</tr>
<tr>
<td></td>
<td>• A design that is sturdy</td>
<td>• Ease of manufacturing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Cheap</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Fast design process</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Aesthetic design</td>
</tr>
</tbody>
</table>
3.4 Engineering Specifications

The team used a Quality Function Deployment (QFD) design tool to collectively decide what specifications would contribute to the design of the project. With the QFD, the team first listed the significance of each design requirement to the top stakeholders of the project to see which requirements are the most important in the design process. Upon doing so, it was agreed that the four main customers would be Charlie, the sponsor, recently injured patients trying to get back to baseline, family members of said patients, and manufacturing companies that could be interested in making this product. Then, the team analyzed the correlations between the list of stakeholder requirements and a list of engineering specifications that could measurably quantify each of the stakeholder requirements. In total, there were about 16 different specifications that the team agreed upon as well as 12 engineering specifications to quantify the customer specifications. Ultimately, the established correlations between both categories helped determine whether there were too many, not enough, or the proper amount of specifications to satisfy the stakeholder requirements. The team’s decision for which specifications to design for was made after conducting background research and analyzing the four main stakeholders’ wants and needs with the QFD, as shown in Appendix A. The resulting specifications are listed in Table 3-2 below.
Table 3-2 Engineering Specifications Table

<table>
<thead>
<tr>
<th>Spec #</th>
<th>Specification Description</th>
<th>Requirement or Target [units]</th>
<th>Tolerance</th>
<th>Risk</th>
<th>Compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Attachment Point Stresses</td>
<td>50 [lbs] Per Point</td>
<td>Min</td>
<td>High</td>
<td>Analysis, Test</td>
</tr>
<tr>
<td>2</td>
<td>Attachment Point Location</td>
<td>1” x 1” Grid</td>
<td>Min</td>
<td>Med</td>
<td>Inspection</td>
</tr>
<tr>
<td>3</td>
<td>Weight of the Device</td>
<td>45 [lbs]</td>
<td>Max</td>
<td>High</td>
<td>Inspection</td>
</tr>
<tr>
<td>4</td>
<td>Weight Capacity (User)</td>
<td>250 [lbs]</td>
<td>Max</td>
<td>High</td>
<td>Analysis, Test</td>
</tr>
<tr>
<td>5</td>
<td>Weight Capacity (Attachments)</td>
<td>27.5 [lbs] ± 2.5 [lbs]</td>
<td>High</td>
<td>Analysis, Test</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Number of Attachment Points</td>
<td>90 Points ± 10 Points</td>
<td>Med</td>
<td>Inspection</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Rigidity</td>
<td>1/8” Maximum Deflection</td>
<td>Max</td>
<td>High</td>
<td>Analysis, Test</td>
</tr>
<tr>
<td>8</td>
<td>Height Range of Device</td>
<td>22” - 72” ± 0.5”</td>
<td>Low</td>
<td>Inspection</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Width of Frame</td>
<td>32”</td>
<td>Max</td>
<td>Low</td>
<td>Inspection</td>
</tr>
<tr>
<td>10</td>
<td>Thickness of Panels</td>
<td>1”</td>
<td>Max</td>
<td>Med</td>
<td>Inspection</td>
</tr>
<tr>
<td>11</td>
<td>Production Cost</td>
<td>$300</td>
<td>Max</td>
<td>High</td>
<td>Analysis</td>
</tr>
<tr>
<td>12</td>
<td>Material Selection</td>
<td>Composite</td>
<td>N/A</td>
<td>Low</td>
<td>Inspection</td>
</tr>
<tr>
<td>13</td>
<td>Ergonomics</td>
<td>PMA (Premarket Approval)</td>
<td>N/A</td>
<td>High</td>
<td>Analysis</td>
</tr>
</tbody>
</table>

- **Spec #1, Attachment Point**: This specification describes the loading stresses applied to each attachment point on the frame of the device before considering factors of safety; the team will analyze this spec by using FEA modeling and test it by conducting stress application tests in the laboratory.
- **Spec #2, Attachment Point Location**: This specification describes the spacing throughout the panel on which there will be attachment points located; the team will inspect this spec by using measurement devices to confirm the placement of each point.
- **Spec #3, Weight of the Device**: This specification describes the weight of the entire device after assembly; the team will inspect this spec by weighing the device once complete.
- **Spec #4, Weight Capacity (User)**: This specification describes the maximum allowable weight of the user the device can hold before reaching a point of failure; the team will analyze this spec by using FEA modeling and test it by conducting stress application tests in the laboratory.
• **Spec #5, Weight Capacity (User):** This specification describes the maximum allowable total weight of the user’s external attachments the device can carry before reaching a point of failure; the team will analyze this spec by using FEA modeling and test it by conducting stress application tests in the laboratory.

• **Spec #6, Number of Attachment Points:** This specification describes the quantity of attachment points present in the framing of the device; the team will inspect this spec by counting each attachment point present on the frame.

• **Spec #7, Rigidity:** This specification describes the stiffness of the device’s frame; the team will analyze this spec by using FEA modeling and test it by conducting stress application tests in the laboratory.

• **Spec #8, Height Range of the Device:** This specification describes the minimum and maximum heights the device will reach; the team will inspect this spec by using measurement devices to confirm the target values have been met.

• **Spec #9, Width of the Frame:** This specification describes how wide the frame needs to be; the team will inspect this spec by using measurement devices to confirm the target value have been met.

• **Spec #10, Thickness of Panels:** This specification describes how thick the framing panel needs to be; the team will inspect this spec by using measurement devices to confirm the target value have been met.

• **Spec #11, Production Cost:** This specification describes the expenses required to manufacture the frame of the device; the team will analyze this spec by listing and summing the expenses made during the project to determine the overall cost.

• **Spec #12, Material Selection:** This specification describes the type of composite materials used in the framing of the device; the team will inspect this spec by visually confirming that the framing material selected during the design is the material used during building.

• **Spec #13, Ergonomics:** This specification describes the shaping of the device overall as well as the component accessibility on the device; the team will analyze this spec by determining how it would perform in an FDA Premarket Approval process.
4 Concept Design
The team went through the following process for concept design: functional decomposition, initial ideation, and design convergence. Design convergence methods helped refine the ideas using Pugh, morphological, and weighted decision matrices. The resulting final concept design shows the intended solution method but is not a fully developed design plan. This is due to the need for further structural analysis, prototyping, and consideration of manufacturing restrictions, all of which will be addressed in the next quarter. Figure 4-1 shows a sketch of the final concept design as well as the conceptual CAD of the same design.

Figure 4-1 Rough Sketch and Concept CAD of Final Concept Design

4.1 Initial Ideation and Functional Decomposition
After reviewing the information from collected research and the developed specifications, the team began the ideation process by utilizing functional decomposition to identify the main functions of the intended solution. Afterwards, the team maximized the possibility of idea generation by brainstorming solutions to the intended functions individually and as a group.

A functional decomposition was used to highlight the most important functions that the final design must be able to achieve as well as classifying the importance of each function and how it would relate to the design. Appendix D shows the functional decomposition the group produced. The team determined the main function of the solution was “Helps Rehabilitate Users with Limited Mobility”. From there, the team defined the five most important subfunctions – supports modules, allows for sitting and standing, provides safety, moves easily, and interfaces with user – as well as a multitude of support functions for each subfunction. Each support function outlines a more specific way that each subfunction is defined and can be achieved.
Following the creation of the Functional Decomposition the team set the goal for each team member to individually come up with ten ideas for each subfunction. The team met up several times for collaborative ideation, building ideas off each other, and using a method called “worst possible idea”. The compiled ideas thought of by each team member is compiled in Appendix C. The team soon discovered that the functional decomposition identified requirements of the entire wheelchair not just the frame the team was tasked to build. Consequently, some of the functions were very hard to ideate for and the team fell short of its initial goal of two hundred ideas. Regardless, the team generated a large volume of ideas to move forward with.

4.2 Function Prototyping
The next step the team performed was function prototyping. Using the team’s generated ideas, each team member built five rough prototypes addressing the subfunctions of the functional decomposition. This process helped narrow down what kind of ideas were feasible and applicable to the scope of the project. Figure 4-2 shows two different prototyped functions, the rest are included in Appendix C.

![Figure 4-2 Two examples of the team’s functional prototyping](image)

Pictured on the left of Figure 4-2 is a functional prototype that demonstrates the attachment method of modules onto a panel with ribs for added rigidity. Pictured on the right of Figure 4-2 is a functional prototype that demonstrates a frame design for increased modularity which is made of only rods instead of panels.

4.3 Controlled Convergence - Pugh & Morphological Matrices
The team used Pugh matrices as the first design selection tool. A Pugh matrix takes ideas for a subfunction and compares them to a set datum idea. An example of one of the team’s Pugh matrices is as follows in Table 4-1, the rest are included in Appendix D. Each idea is given a +, -, or S – for better, worse, or same – in comparison with the datum. The pluses and minuses are then totaled to show the best ideas relative to the datum. If the numbers are all close, criteria can be redefined to better differentiate the ideas. It is also possible to use the results to combine ideas, so the strengths and weaknesses offset each other, creating an even stronger option.
### Table 4-1 Pugh Matrix for "Supports Modules"

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Current Prototype</th>
<th>Holes with Pegs</th>
<th>Quick Release Plates</th>
<th>Rods Instead of Panels</th>
<th>Threaded Holes</th>
<th>Industrial Velcro on a Panel</th>
<th>Embedded Magnets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sturdy (Strength)</td>
<td>S</td>
<td>-</td>
<td>S</td>
<td>S</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Rigid (Stiffness)</td>
<td>S</td>
<td>-</td>
<td>S</td>
<td>S</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Durable (Longevity/Life/Cycles)</td>
<td>S</td>
<td>-</td>
<td>S</td>
<td>S</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Aesthetically Pleasing &amp; Customizable</td>
<td>S</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Inexpensive (Consumer Cost)</td>
<td>S</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>S</td>
<td>-</td>
</tr>
<tr>
<td>Physically Easy to Use</td>
<td>S</td>
<td>+</td>
<td>+</td>
<td>S</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Intuitive Component Placement</td>
<td>S</td>
<td>+</td>
<td>+</td>
<td>S</td>
<td>+</td>
<td>+</td>
<td>S</td>
</tr>
<tr>
<td>Sense of Independence</td>
<td>S</td>
<td>+</td>
<td>+</td>
<td>S</td>
<td>+</td>
<td>+</td>
<td>S</td>
</tr>
<tr>
<td>Ease of Transportation</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Functionally Adjustable</td>
<td>S</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Total

|                       | 1 | 2 | 1 | 1 | 7 | 0 |

### Table 4-2 Morphological Matrix

<table>
<thead>
<tr>
<th>Function</th>
<th>Option 1</th>
<th>Option 2</th>
<th>Option 3</th>
<th>Option 4</th>
<th>Option 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supports Modules</td>
<td>Holes with Pegs</td>
<td>Quick Release Plates</td>
<td>Clamp to Rods Instead of using Panels</td>
<td>Threaded Holes</td>
<td>Industrial Velcro on a Panel</td>
</tr>
<tr>
<td>Allows for Sitting and Standing</td>
<td>Linear actuating rails to switch positions</td>
<td>Telescoping frame, EZ-UP locking buttons</td>
<td>Manual lifting mechanism with gas shocks</td>
<td>Swing arm system between the two plates</td>
<td>Bicycle hand crank system to raise and lower manually</td>
</tr>
<tr>
<td>Provides Safety</td>
<td>Ribs on Panels</td>
<td>Hidden Truss work</td>
<td>Rounded edges</td>
<td>Multiple panel sections for easy replacement of damaged parts</td>
<td></td>
</tr>
<tr>
<td>Moves Easily</td>
<td>Folds like a sun chair</td>
<td>Deconstructs into several parts</td>
<td>Integrated Handles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interfaces with User</td>
<td>U-Shaped Panels</td>
<td>Flat Panels</td>
<td>Rods</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

19
The team incorporated the refined ideas from the Pugh matrices into a morphological matrix. The morphological matrix aids in forming multiple full design ideas by listing the best options for all the critical subfunctions. When the team originally did the morphological matrix it quickly became evident that while the ideas were good, many of the ideas were ancillary to the team’s project scope. The team the backtracked, vetted some new ideas, and morphed the morphological matrix into one that produced full design ideas that were within the scope of the project. The resulting morphological matrix is shown in Table 4-2.

4.4 Weighted Matrix
The team used the morphological matrix to agree upon and sketch ten design concepts to compare in a weighted decision matrix, shown in Table 4-3. For the decision matrix, the team determined the relative importance of the eight most critical criteria from the QFD and assigned respective weights to the criteria. Then, on a scale of one to ten, the team rated each design for the criteria. The rating was multiplied against the weighting of that criteria and was then summed for the design. The total scores were very close, so the team decided to make concept design prototypes for the top four ideas and see what could be learned from them.

4.5 Final Concept Design and Prototype
Each team member prototyped one of the top four designs. The team discussed the feasibility of designs and decided that the weighted decision matrix was correct in assigning the *Flat Linear Truss* as the best design option. Therefore, the team created concept CAD of that design and performed some preliminary analysis.

4.5.1 Idea 1: Flat Linear Truss
This concept design is the simplest solution in the scope of the project. It replaces the network of steel tubes in the sponsor’s prototype with composite panels that can slide separate of each other on linear rails. It uses some trussing to connect the panels to the part of the frame that supports the wheels. The initial concept was to have that trussing hidden by the panels, but the concept prototype shows that may not be feasible because of limited space between the panels. The attachment points for modules would take the form of threaded holes in the paneling.

![Figure 4-3 Concept Design Idea 1: Flat Linear Truss](image)
Table 4-3 Weighted Decision Matrix

<table>
<thead>
<tr>
<th>Criteria</th>
<th>F45 Composite Pegboard Walking Wheelchair</th>
<th>Options</th>
<th>F45 Composite Pegboard Walking Wheelchair</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>U-Shaped Linear Truss</td>
<td>Telescoping Sectional Quick Release</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AC</td>
<td>AC</td>
</tr>
<tr>
<td>Weight</td>
<td>0.11</td>
<td>0.09</td>
<td>0.16</td>
</tr>
<tr>
<td>Score</td>
<td>8</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td>0.88</td>
<td>0.63</td>
<td>1.12</td>
</tr>
<tr>
<td>Score</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Total</td>
<td>0.66</td>
<td>0.54</td>
<td>0.80</td>
</tr>
<tr>
<td>Score</td>
<td>7</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td>0.77</td>
<td>0.64</td>
<td>1.12</td>
</tr>
<tr>
<td>Score</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Total</td>
<td>0.66</td>
<td>0.63</td>
<td>1.26</td>
</tr>
<tr>
<td>Score</td>
<td>6</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Total</td>
<td>0.66</td>
<td>0.63</td>
<td>1.26</td>
</tr>
<tr>
<td>Total</td>
<td>6.38</td>
<td>6.15</td>
<td>7.55</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Criteria</th>
<th>F45 Composite Pegboard Walking Wheelchair</th>
<th>Options</th>
<th>F45 Composite Pegboard Walking Wheelchair</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Quick Release Peacock Chair</td>
<td>Deconstructing Quick Release</td>
</tr>
<tr>
<td>Weight</td>
<td>0.11</td>
<td>0.09</td>
<td>0.16</td>
</tr>
<tr>
<td>Score</td>
<td>8</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Total</td>
<td>0.88</td>
<td>0.54</td>
<td>1.28</td>
</tr>
<tr>
<td>Score</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>0.66</td>
<td>0.45</td>
<td>0.80</td>
</tr>
<tr>
<td>Score</td>
<td>5</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>0.77</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>Score</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Total</td>
<td>0.77</td>
<td>0.63</td>
<td>0.64</td>
</tr>
<tr>
<td>Score</td>
<td>7</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Total</td>
<td>0.85</td>
<td>0.63</td>
<td>0.64</td>
</tr>
<tr>
<td>Total</td>
<td>6.68</td>
<td>6.68</td>
<td>6.68</td>
</tr>
</tbody>
</table>
4.5.2 Idea 2: Linear Folder

This uses all panel systems instead of a trusswork support system. Additionally, it has a latching mechanism between the side panels and the back panels that allows the bottom wheel part of the chair to fold up. This would make the chair take up much less space in transport. The other chair functions are identical to Idea 1 – linear rails and threaded bolt holes for module attachments.

![Figure 4-4 Concept Design Idea 2: Linear Folder](image)

4.5.3 Idea 3: Threaded Deconstructing

In this design, the panels that make up the back of the frame are deconstructable segmented panels that further enable the side struts and wheels to be separated. Additionally, the mechanism allowing the wheelchair to stand can be disassembled. The system would function with a linear actuator, and the modules would attach via threaded bolt holes in the segmented panels.

![Figure 4-5 Concept Design Idea 3: Threaded Deconstructing](image)
4.5.4 Idea 4: Actuated Telescoping Rods

This design uses telescoping rods to allow for the wheelchair to go into the standing position. It can be adapted so that it can be operated manually instead of requiring a linear actuator. This increases the marketability to different regions of the world as well as being more cost effective. Otherwise, this design still uses composite panels on the back with threaded bolt holes for module attachment.

The team decided to continue with the Flat Linear Truss design concept. This design ranked first in the weighted decision matrix, and the concept prototype comparison showed that it best met the sponsor’s requirements.

The design of the Flat Linear Truss stood out in manufacturability because the design called for simple flat composite panels and a combination of smaller flat panels or tubed trussing for the remainder of the frame. All these components are either easy to manufacture or can be bought from a company pre-made. Also, this design uses fewer overall parts, which reduces manufacturing and assembly time.

Because of this design’s simplicity, it is the strongest and most rigid. Other designs incorporated telescoping rod structures and detachable or movable joints, which introduce stackable tolerances that require additional structure to maintain strength and rigidity. The Flat Linear Truss design has no features that require consideration of complex joint stresses or additional reinforcement. Additionally,

The team performed preliminary analysis to determine the feasibility of different frame attachment methods. Calculations for a bracket attached to the back panel with glue or a bolt are included in Appendix E and show that both methods have acceptable factors of safety for use in the design.

A CAD model was created to further illustrate the final design concept of the Flat Linear Truss. The model, as shown in Figure 4-7, shows the bare framework of the prototype as described by the design concept. Although the inner trusswork requires further analysis and is subject to change, this preliminary CAD model demonstrates where trussing may be needed to attach the components.
of the current prototype to the composite panels. It also details the team’s current plan for incorporating holes for module attachment.

4.6 Design Risks
The team has identified and listed in Appendix F the potential hazards of the selected design as well as the team’s corrective plan to reduce the risk to the user. Many of these concerns have to do with the potential for users to injure themselves because of the moving parts associated with the design. There will be many points on the design that could possibly pinch the user or trap their body parts during the linear actuation between the sitting and standing position. Additionally, linear actuators are driven by large electric motors which need to be powered by a battery. Proper battery protection is necessary to prevent harm to the user. Lastly, the team is concerned with the selection of a fiber composite. Composite fibers can create splinters around the edges of the panels, which are very painful, so the team is adamant about choosing a composite or manufacturing method to reduce the likelihood of injury from splintering.
5 Design Direction Changes

At the time of CDR, after many discussions with the project’s sponsor and the team’s senior project advisor, the team has decided to narrow the anticipated scope of the project. After the initial phase of research and brainstorming was complete and the team progressed into the design and prototyping phase, it quickly became evident that taking on the task of designing an entire structural frame for a sitting to standing wheelchair resulted in too large of a project to complete within the projected time frame. The team underestimated the amount of analysis and testing that would be required for a single component of the frame, let alone every component; with that in mind, along with the team’s desire to produce a high-quality project in the end, the team has decided to shift the scope of the project to focus solely on the design and manufacturing of the rear structural panel of the wheelchair frame.

All of the previously stated research and brainstorming conclusions remain valid and equally useful to the shifted scope of the project. The consideration of the previous information will be especially relevant when analyzing how the panel could potentially interact with other components of the frame and when subsequently testing the response of the panel to load applications resulting from those interactions. Additionally, the specifications for the project remain the same, and the single panel will be designed to best meet all previously mentioned criterion.
6 Design Verification Plan

One of the most important aspects of the design is the loading on the drilled holes. Charlie has made it clear that the top priority is the pegboard design of the composite to allow for end user customization. However, this design requires more than just drilling holes into the composite. To test the holes and the integrity of the design, the team will use the new cantilever loading test to find the limit torque that the pegboard design could handle with the various geometries.

Further, the panel must withstand the loading of the other wheelchair components and the weight of the user. Meeting these specifications requires a separate set of tests for each panel including bending, tension, and compression. The loading requirements for these aspects are detailed in Appendix G and will be further updated as designs are iterated, and composite materials are better understood.

To test the panel for bending fracture and fatigue, the team will use the 3-point bend test to gauge how the composite will handle bending at higher loads. The machine is simple, as it only requires the use of a different fixture to accommodate this test. There is already a fixture available to use, and it is available in Dr. Elghandour’s lab.

The 3-point bend test will allow the team to determine the material’s Young’s Modulus. This value is used to analyze the material properties in a beam to determine the yield stress, or failure point. The team’s goal is to design the composite with enough of a safety buffer so that the material should never reach the point of fracture even under abuse cases.

The team also aspires to create a seamless design that is aesthetically pleasing to the end user. It seems the only way to verify this design criteria are met is to get a general consensus from people who are not actively involved in the project. This would ensure that not only end users would find the design pleasing, but that the general public would as well.

In addition to these two design criteria, the team also recognizes that the main goal is to create the lightest panel that is also the strongest. After observing the test results, the team will rank each of the composite designs in order from strongest to weakest and then compare that to the weight of each of the combinations. This will create another decision matrix based on testing data which will yield the best overall design combination.
7 Iterative Design

Through conversations with the team’s senior project advisor, Dr. Eltahry Elghandour, the team decided that an iterative design approach was best for this project. This is in opposition to the team’s original interpretation of the design process: finishing the design before manufacturing and finishing manufacturing before testing.

Composite materials have highly geometrically- and directionally-dependent properties that are difficult to predict the response of. Furthermore, the use case for the team’s composite panel falls outside typical empirical data, as the team’s panel will be subject to high bending loads while most composites are used in tension applications. As such, the team designed and tested individual aspects of the panel throughout the design process to ensure that the panel will meet the team’s specifications.

7.1 Material Selection

The team originally planned to test a plethora of material combinations before manufacturing a panel. While the project sponsor requested the use of the cheapest materials possible, Dr. Elghandour made clear that the material can be changed after the proper geometric reinforcement for key components has been determined. Under the recommendation of Dr. Elghandour, the team decided to move forward with carbon fiber for all panel manufacturing and testing.

Dr. Elghandour emphasized that testing different panel geometries is more important than testing materials, as the part geometry has far more influence on the composite strength than the materials alone. Dr. Elghandour’s lab at Cal Poly has a large supply of carbon fiber and core materials that the team was authorized to use during the design process. As such, the team performed all prototyping and iterative design with carbon fiber. This increased the amount of design iteration the team could do because test redundancy with multiple materials was avoided.

7.2 Prototyping Costs

This project was done using the materials available in Dr. Elghandour’s lab at no cost to the team. However, the team applied for and was awarded two grants running upwards of $6700 in funding. With this money the team replaced some of the materials used and purchased necessary components to complete the iterative testing. Portions of the budget are left over for Eltahry to use to replenish other materials in his laboratory as needed. In applying for all the grant money, the team wanted to ensure that they could repay Eltahry for all materials used on the project (e.g. carbon fiber, resin, vacuum bag, gum tape, strain gages, etc.).

After completion of all panels, the team performed a basic cost analysis and determined the approximate cost for each manufactured panel. These values are shown in Table 7-1. Since all panels are approximately one square foot, these panel costs can reasonably be assumed to correlate to one square foot of final panel. Manufacturing and testing of these panels is more thoroughly explained in the following sections.
Table 7-1 Estimated cost of manufactured panels based on amount of material used. Estimated amount of carbon fiber and resin is specified, total cost estimate factors in all additional manufacturing materials.

<table>
<thead>
<tr>
<th>Panel</th>
<th>Amount of Carbon Fiber [ft^2]</th>
<th>Amount of Resin [g]</th>
<th>Panel Cost [$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper Honeycomb</td>
<td>21</td>
<td>440</td>
<td>94.17</td>
</tr>
<tr>
<td>Fiberglass Honeycomb</td>
<td>21</td>
<td>440</td>
<td>94.17</td>
</tr>
<tr>
<td>Corrugated Carbon</td>
<td>22</td>
<td>447</td>
<td>102</td>
</tr>
<tr>
<td>Carbon Fiber-Wrapped Plywood</td>
<td>7</td>
<td>140</td>
<td>34.74</td>
</tr>
<tr>
<td>Double Thin Foam</td>
<td>13.3</td>
<td>288</td>
<td>72.19</td>
</tr>
<tr>
<td>Thick Foam</td>
<td>12.5</td>
<td>280</td>
<td>77.82</td>
</tr>
</tbody>
</table>

7.3 Iteration 0 – Composite Experience
The goal of the project was to find the most reliable composite design in the most affordable manner. First, the team manufactured a few basic composite panels to become more familiar with composite manufacturing techniques, as there was a varying amount of composite manufacturing experience within the team. Additionally, this initial experience allowed the team to become familiar with the specificities of composite material testing.

7.3.1 Panel Design
The initial panel designs were more in tune with getting the senior project team up to speed on manufacturing composite panels. Under the direction of Dr. Elghandour, the team constructed two panels of different cores with 9 layers of carbon on each side, and a single nine-layer thick sheet of carbon by itself. The two different cores were a PVC coated paper honeycomb core and a fiberglass honeycomb core. Cores in composite panels serve to add stiffness to the composite, as well as strength in the directions that the fiber resin matrix would be weak. This is not a fix all solution, and bending loads can still be an issue and will need to be accounted for with testing. Figure 7-1 shows the layup sequence for the composite panels of this iteration, and Figure 7-2 shows the composition of a honeycomb core panel.

![Figure 7-1 Layup sequence for a composite panel.](image-url)
7.3.2 Panel Manufacturing

The panels described above were manufactured using basic hand layup techniques in order to introduce team members on basic principles of layups and to ensure that when the time came to recommend a panel to the sponsor, the methods of manufacturing would be within the sponsor’s capabilities. The full manufacturing process is described in Appendix H. The resulting panels are shown in Figure 7-3 and Figure 7-4. The specifics of the layups are given in Table 7-2.

Table 7-2 Iteration 0 composite panel specifications. Fiber volume fractions calculated using known weight of fibers and epoxy resin used. Values in parentheses are approximated from final panel values or other information known from the manufacturing process.

<table>
<thead>
<tr>
<th>Core Type</th>
<th>Total Panel Weight [g]</th>
<th>Bottom Carbon Fiber Weight, Layers, and Volume Fraction [#], [%]</th>
<th>Core Weight [g]</th>
<th>Top Carbon Fiber Weight, Layers, and Volume Fraction [#], [%]</th>
<th>Approximate dimensions (length, width, thickness) [in]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper Honeycomb</td>
<td>692</td>
<td>(315), 9, (50)</td>
<td>61</td>
<td>(315), 9, (50)</td>
<td>12.25, 11.875, 0.5</td>
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<tr>
<td>Fiberglass Honeycomb</td>
<td>675</td>
<td>(315), 9, (50)</td>
<td>(45)</td>
<td>(315), 9, (50)</td>
<td>12.5, 10.5, 0.5</td>
</tr>
</tbody>
</table>
7.3.3 Panel Testing

Panels were tested with a custom cantilever bending test near the Aero Hangar on Cal Poly campus. In order to complete these tests, the team attached strain gages to the panels with the specific procedure listed in Appendix H . Full descriptions of the individual testing procedures can also be found in Appendix H . The procedure involved fixing the panel in a cantilever loading position and incrementally adding weights while recording strain gage and deflection data, as shown in Figure 7-5.
Using the data gathered from multiple runs of this test, the team compiled an average modulus for each panel (Figure 7-6) and deflection data for each panel (Figure 7-7).

**Figure 7-6** Applied Moment vs. Bending strain for the Iteration 0 panels. Data shown is a single average of all data for each panel. Slopes represent the bending stiffness calculated for each run, calculated with linear curve fit. Legend is arranged from top to bottom with best to worst performing panel.
Figure 7-7 Applied Moment vs. Deflection for the Iteration 0 panels. Data shown is a single average of all data for each panel. Note: the unquantifiable effects of rigid body rotation were not factored into the data, and therefore the displayed data is not fully accurate. Legend is arranged from top to bottom with best to worst performing panel.

7.4 Iteration 1 – Panel Bending

One of the major benefits of working with composites is their strength-to-weight ratio. With this loading comes challenges: delamination, cracking, and fracturing, to name a few. Like all materials, it is important to test these aspects to ensure proper design. To do this, the team needs to analyze the best geometry of the composite panel in multiple aspects. These cannot all be tested simultaneously, so the first iteration of the design pursues the best solution to resisting the moment-induced bending and side effects – primarily delamination. In this iteration, the team analyzed a recommended geometry from Dr. Elghandour and two sponsor-requested geometries.

7.4.1 Panel Design

Dr. Elghandour suggested that the best design would be one with a corrugated carbon fiber core, as shown in Figure 7-8. This allows for a material with high bending resistance to be bonded to the rigid, strong carbon fiber face sheets. To do this, the team was allowed to use an aluminum mold from one of Dr. Elghandour’s previous projects, shown in Figure 7-9.
The team also planned to manufacture the foam panel concept shown in Figure 7-10, but the design was pushed to the next iteration due to manufacturing difficulties.

Further, the project sponsor requested the team perform a comparison of a sheet of plywood and a sheet of plywood wrapped in carbon fiber.

**7.4.2 Panel Manufacturing**

The panels were constructed with the same wet layup technique as the previous iteration. A detailed procedure of how the panels were manufactured is shown in Appendix I. The resulting panels are shown in Figure 7-11. The specifics of the layups are given in Table 7-3. The corrugated
core panel required a very detailed layup process to manufacture and assemble the three separate carbon fiber sheets into a full panel. The corrugated core panel is the only panel to utilize a structural adhesive in the panel construction.

Figure 7-11 Final photos of Iteration 1 panels. Panels are shown with strain gages from testing. (top row) corrugated core panel, (middle row) carbon fiber-wrapped plywood panel, (bottom row) plywood panel.
Table 7-3 Iteration 1 composite panel specifications. Fiber volume fractions calculated using known weight of fibers and epoxy resin used. Values in parentheses are approximated from final panel values or other information known from the manufacturing process.

<table>
<thead>
<tr>
<th>Core Type</th>
<th>Total Panel Weight</th>
<th>Bottom Carbon Fiber Weight, Layers, and Volume Fraction</th>
<th>Core Weight, Layers, and Volume Fraction</th>
<th>Top Carbon Fiber Weight, Layers, and Volume Fraction</th>
<th>Approximate dimensions (length, width, thickness)</th>
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<tr>
<td>Corrugated Carbon Fiber</td>
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<td>275, 9, (50)</td>
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<td>265, 9, 44</td>
<td>12.75, 11.5, 0.6875</td>
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<td>Carbon Fiber-Wrapped Plywood</td>
<td>1029</td>
<td>(113), 3, (50)</td>
<td>(803), --, --</td>
<td>(113), 3, (50)</td>
<td>12, 12, 0.5</td>
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<tr>
<td>Plywood (no Carbon Fiber)</td>
<td>803</td>
<td>--</td>
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<td>12, 12, 0.5</td>
</tr>
</tbody>
</table>

7.4.3 Panel Testing
Panels were tested with the same custom cantilever bending test as the Iteration 0 panels. In order to complete these tests, the team attached strain gages to the panels with the specific procedure listed in Appendix I. Full descriptions of the individual testing procedures can also be found in Appendix I. Using the data gathered from multiple runs of this test, the team compiled an average modulus for each panel (Figure 7-12) and deflection data for each panel (Figure 7-13).
Figure 7-12 Applied Moment vs. Bending strain for the Iteration 1 panels. Data shown is a single average of all data for each panel. Slopes represent the bending stiffness calculated for each run, calculated with linear curve fit. Legend is arranged from top to bottom with best to worst performing panel.
Figure 7-13 Applied Moment vs. Deflection for the Iteration 1 panels. Data shown is a single average of all data for each panel. Note: the unquantifiable effects of rigid body rotation were not factored into the data, and therefore the displayed data is not fully accurate. Legend is arranged from top to bottom with best to worst performing panel.

7.5 Iteration 2 – Panel Bending Continued
After discussion with Dr. Elghandour, the team decided to manufacture panels with the goal of reducing weight. To do this, the team looked to foam core panels. In this iteration, two foam core panels were considered. Additionally, the team planned to construct a balsa wood core panel, but procurement of balsa wood of the necessary dimensions (12”x12” or larger) proved to be too difficult.

7.5.1 Panel Design
Originally, the team planned to continue with the previous foam core design, shown below in Figure 7-14. In this design, there would have been a thin pre-drilled sheet of aluminum placed into the recessed portion, allowing for more stability where the loading will be, as shown in Figure 7-15. This would have alleviated the need for specialized fasteners for composites and will allow the team to simply add a threaded tube instead. The channels and foam core would have been completely wrapped in carbon fiber. The aluminum channels are put in place to reduce the torque loading applied to the panel, as the goal of the experiment is to isolate bending. Aluminum can accommodate torque loads better than the fiber-core interface alone.
However, after discussion with Dr. Elghandour about the resources and manufacturability of the resources in the lab, the team concluded that making channels in the thin foam was not easy. This is seen in the latter portion of Appendix J. The modified designs, therefore, are shown in Figure 7-16 and Figure 7-17. Here, a softer, thick foam was used for the channeled panel, and the thin foam was used in a double-layer technique with a layer of carbon fiber between the layers for better adhesion.
7.5.2 Panel Manufacturing
The panels were constructed with the same wet layup technique as the previous iterations. A detailed procedure of how the panels were manufactured is shown in Appendix J. The resulting panels are shown in Figure 7-18. The specifics of the layups are given in Table 7-4.
Figure 7-18 Final photos of Iteration 1 panels. Panels are shown with strain gages from testing. (top row) corrugated core panel, (middle row) carbon fiber-wrapped plywood panel, (bottom row) plywood panel.

Table 7-4 Iteration 2 composite panel specifications. Fiber volume fractions calculated using known weight of fibers and epoxy resin used. Values in parentheses are approximated from final panel values or other information known from the manufacturing process.

<table>
<thead>
<tr>
<th>Core Type</th>
<th>Total Panel Weight</th>
<th>Bottom Carbon Fiber Weight, Layers, and Volume Fraction</th>
<th>Core Weight, Layers, and Volume Fraction</th>
<th>Top Carbon Fiber Weight, Layers, and Volume Fraction</th>
<th>Approximate dimensions (length, width, thickness)</th>
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<tr>
<td>Thick foam</td>
<td>486 [g]</td>
<td>(191), 4, (40)</td>
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<tr>
<td>Double, thin foam</td>
<td>606 [g]</td>
<td>(144), 4, (50)</td>
<td>2 Foam Sheets 175, --, --</td>
<td>(144), 4, (50)</td>
<td>11.875, 12.125, 1</td>
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7.5.3 Panel Testing

Panels were tested with the same custom cantilever bending test as the Iteration 0 panels. In order to complete these tests, the team attached strain gages to the panels with the specific procedure listed in Appendix J. Full descriptions of the individual testing procedures can also be found in Appendix J. Using the data gathered from multiple runs of this test, the team compiled an average modulus for each panel (Figure 7-19) and deflection data for each panel (Figure 7-20).

![Cantilever Bending Test: Strain Results](image)

Figure 7-19 Applied Moment vs. Bending strain for the Iteration 2 panels. Data shown is a single average of all data for each panel. Slopes represent the bending stiffness calculated for each run, calculated with liner curve fit. Legend is arranged from top to bottom with best to worst performing panel.
Figure 7-20 Applied Moment vs. Deflection for the Iteration 2 panels. Data shown is a single average of all data for each panel. Note: the unquantifiable effects of rigid body rotation were not factored into the data, and therefore the displayed data is not fully accurate. Legend is arranged from top to bottom with best to worst performing panel.

7.6 Final Carbon Fiber Design

The team planned to utilize criteria from the FMEA, Risk Assessment, and Hazard Checklist to evaluate the safety of the final design. However, as documented, the project strayed from a product-based to research-based approach. As such, the final deliverable for the project was not a product that will be used by a consumer. The team was simply tasked with identifying the optimum geometric combination of materials to resist bending loads, as specified by the sponsor. Therefore, the only remaining requirements for the panel itself are the following: high bending resistance-to-weight ratio and easy to manufacture. The results of the testing are shown below in Figure 7-21 through Figure 7-24.

The most relevant data is the bending strain data. For a given applied cantilever load, the average bending strain from each panel is shown in Figure 7-21. The legend is organized from top to bottom with the highest to lowest performing panel. This plot shows that the corrugated core panel is marginally the stiffest overall. However, the sponsor was also concerned with weight. When the data is normalized by dividing by panel weight, as shown in Figure 7-22, it is clear that the double thin foam panel is the highest performing panel. Additionally, the double thin foam panel is significantly easier to manufacture than the second (corrugated core) and third (thick foam) place panels shown in Figure 7-22.
Figure 7-21 Applied Moment vs. Bending Strain for all tested panels. Data shown is an average of data from five separate bending tests. Legend is arranged from top to bottom with best to worst performing panel.
Figure 7-22 Normalized Applied Moment vs. Bending Strain for all tested panels. Moment values are normalized by dividing by panel weight. Data shown is an average of data from five separate bending tests. Legend is arranged from top to bottom with best to worst performing panel.

The sponsor also mentioned a concern for panel deflection. To address this concern, the team has collected and presented the total deflection (Figure 7-23) and normalized deflection (Figure 7-24) data. Both representations of the data shown the double thin foam panel as the top performer in this category. An important consideration in analyzing the deflection data is that the panels experienced some rigid body rotation in the testing apparatus. As such, the deflection values shown in Figure 7-23 and Figure 7-24 are likely higher than the real deflection values the panels would experience under identical loading. This phenomenon is more thoroughly explained in Appendix H, Appendix I, and Appendix J for each of the panels.
Figure 7-23: Applied Moment vs. Deflection for all tested panels. Data shown is an average of data from five separate bending tests. Deflection is measured from horizontal. Note: the unquantifiable effects of rigid body rotation were not factored into the data, and therefore the displayed data is not fully accurate. Legend is arranged from top to bottom with best to worst performing panel.
Figure 7-24 Normalized Applied Moment vs. Deflection for all tested panels. Moment values are normalized by dividing by panel weight. Data shown is an average of data from five separate bending tests. Deflection is measured from horizontal. Note: the unquantifiable effects of rigid body rotation were not factored into the data, and therefore the displayed data is not fully accurate. Legend is arranged from top to bottom with best to worst performing panel.

7.7 Future Iteration and Testing
When all the data was analyzed together, the team noticed the double thin foam panel and the thick foam panel were regularly top performers in all categories. The team hypothesizes the high performance in the normalized category is because the panels were among the lightest of all the panels. For the overall results however, the team is certain the increased thickness of the double thin foam and thick foam panels had a significant contribution to the increased performance. Because these panels were about two to three times thicker than the other panels, they inherently have a higher area moment of inertia, which contributes to a lower amount of bending. In future tests, the team recommends that all panels be manufactured with as close to identical dimensions as possible. In this way, the geometries can be more easily evaluated directly.
8 Project Management
Detailed within this section is the design process of senior project, major deliverable deadlines set by Cal Poly and how this team intends to meet them, and additional processes that will be undertaken for the project.

8.1 Design Process
This design process followed a design, build, test model – specifically, research, problem definition, idea generation and selection, prototyping, then testing. This process was iterative, and the design was expected to continually change as research was done, solutions are selected, and areas for improvement to prototypes were identified.

8.2 Project Deadlines
The team met the deadlines, Table 8-1, set for the senior project design process by adhering to the Gantt Chart shown in Appendix B. The deadlines are set by Cal Poly, but the Gantt Chart was a living document that the project team updated regularly.

Table 8-1 Key Project Deliverables and Deadlines

<table>
<thead>
<tr>
<th>Deliverable</th>
<th>Due Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conceptual Prototype</td>
<td>3 November 2020</td>
</tr>
<tr>
<td>Preliminary Design Review</td>
<td>12 November 2020</td>
</tr>
<tr>
<td>Interim Design Review Presentation</td>
<td>14 January 2021</td>
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<tr>
<td>Critical Design Review</td>
<td>12 February 2021</td>
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<tr>
<td>Manufacturing and Test Review</td>
<td>11 March 2021</td>
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<tr>
<td>Verification Prototype Sign-off</td>
<td>27 April 2021</td>
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<tr>
<td>Senior Project Expo</td>
<td>28 May 2021</td>
</tr>
<tr>
<td>Final Design Review</td>
<td>8 June 2021</td>
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</table>

8.3 Special Processes
Because this project utilized an iterative design process, the team did not provide specific deliverables for the Verification Prototype Sign-off and Design Verification Presentation and Report (DVPR). Both of these documents were intended to be milestone markers for completion of the manufacturing and testing phasing, respectively. However, due to the iterative design process of the project, the team was manufacturing and testing simultaneously all throughout the project timeline.
9 Conclusion and Recommendations

There is a safer and less expensive way to manufacture a wheelchair that can help numerous people return to the life they once knew. By conducting this preliminary analysis of composite panels for cantilever bending applications, the team helped their sponsor move towards a more custom, lightweight, durable design for his current prototype. The team determined the optimum panel from the panel geometries tested and concluded that foams and corrugated cores show the most promise. Additionally, the team discovered a possible positive correlation between panel thickness and bending stiffness. The team recommends that future project groups analyze more test panels while ensuring all panels have the same dimensions. In this way, a more accurate qualification of the geometries can be established. After the adjusted geometry study, the team recommends that the best panels be made to scale and tested under real loading conditions.
10 References


## Appendix A  QFD House of Quality

### QFD House of Quality

**Project:** F45 Composite Pegboard  
**Revision Date:** 10/11/2000

### Correlations

- **Positive**
- **Negative**
- **No Correlation**

### Relationships

- **Strong**
- **Moderate**
- **Weak**

### Direction of Improvement

- **Stakeholder**
- **Voice**
- **Target**
- **Metric**

### QFD House of Quality Matrix

<table>
<thead>
<tr>
<th>Row #</th>
<th>Correlation</th>
<th>Voice</th>
<th>Customer Requirements</th>
<th>Weight</th>
<th>Technical Importance Rating</th>
<th>Max Relationship</th>
<th>Relative Weight</th>
<th>Component Placement</th>
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<tr>
<td>15</td>
<td>Negative</td>
<td></td>
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<td>4</td>
<td></td>
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<td>0.4</td>
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</tbody>
</table>

### How Much Target Values

- **50 lbs**
- **500 lbs**
- **1000 lbs**
- **2500 lbs**
- **5000 lbs**
- **10,000 lbs**
- **25,000 lbs**
- **50,000 lbs**
- **100,000 lbs**
- **250,000 lbs**
- **500,000 lbs**

###.realm
Appendix B  Initial Gantt Chart

Project Gantt Chart
Winter Quarter Gantt Chart

<table>
<thead>
<tr>
<th>ID</th>
<th>Task No.</th>
<th>Task Name</th>
<th>Duration</th>
<th>Start</th>
<th>Finish</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td></td>
<td>Interim Design Review (IDR)</td>
<td>9 days</td>
<td>1/4</td>
<td>1/14</td>
</tr>
<tr>
<td>28</td>
<td></td>
<td>Material Testing</td>
<td>0 days</td>
<td>1/4</td>
<td>1/14</td>
</tr>
<tr>
<td>29</td>
<td></td>
<td>Identify Major Components</td>
<td>4 days</td>
<td>1/4</td>
<td>1/7</td>
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<tr>
<td>30</td>
<td></td>
<td>Analyze Component Functions</td>
<td>2 days</td>
<td>1/8</td>
<td>1/11</td>
</tr>
<tr>
<td>31</td>
<td></td>
<td>IDR Presentation</td>
<td>3 days</td>
<td>1/12</td>
<td>1/14</td>
</tr>
<tr>
<td>32</td>
<td></td>
<td>IDR Due Date</td>
<td>0 days</td>
<td>1/14</td>
<td>1/14</td>
</tr>
<tr>
<td>33</td>
<td></td>
<td>Critical Design Review (CDR)</td>
<td>21 days</td>
<td>1/14</td>
<td>2/12</td>
</tr>
<tr>
<td>34</td>
<td></td>
<td>CAD</td>
<td>10 days</td>
<td>1/15</td>
<td>1/28</td>
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<tr>
<td>35</td>
<td></td>
<td>FEA</td>
<td>10 days</td>
<td>1/15</td>
<td>1/28</td>
</tr>
<tr>
<td>36</td>
<td></td>
<td>Hand Cols</td>
<td>10 days</td>
<td>1/15</td>
<td>1/28</td>
</tr>
<tr>
<td>37</td>
<td></td>
<td>Manufacturing Plan</td>
<td>5 days</td>
<td>1/29</td>
<td>2/2</td>
</tr>
<tr>
<td>38</td>
<td></td>
<td>CDR Presentation</td>
<td>5 days</td>
<td>2/3</td>
<td>2/9</td>
</tr>
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<td>39</td>
<td></td>
<td>CDR Presentation Due Date</td>
<td>0 days</td>
<td>2/9</td>
<td>2/9</td>
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<tr>
<td>40</td>
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<td>CDR Report</td>
<td>7 days</td>
<td>2/3</td>
<td>2/11</td>
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<td>41</td>
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<td>CDR Report Due Date</td>
<td>0 days</td>
<td>2/12</td>
<td>2/12</td>
</tr>
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<td>42</td>
<td></td>
<td>Verification Prototype</td>
<td>52 days</td>
<td>2/15</td>
<td>4/27</td>
</tr>
<tr>
<td>43</td>
<td></td>
<td>Risk Assessment/Safety Review</td>
<td>2 days</td>
<td>2/15</td>
<td>2/16</td>
</tr>
<tr>
<td>44</td>
<td></td>
<td>Manufacturing</td>
<td>30 days</td>
<td>2/15</td>
<td>4/23</td>
</tr>
<tr>
<td>45</td>
<td></td>
<td>Manufacturing and Test Review</td>
<td>2 days</td>
<td>3/10</td>
<td>3/11</td>
</tr>
<tr>
<td>46</td>
<td></td>
<td>Manufacturing and Test Review Due Date</td>
<td>0 days</td>
<td>3/11</td>
<td>3/11</td>
</tr>
<tr>
<td>47</td>
<td></td>
<td>Testing Procedures</td>
<td>3 days</td>
<td>4/1</td>
<td>4/5</td>
</tr>
<tr>
<td>48</td>
<td></td>
<td>Verification Prototype Sign-off</td>
<td>0 days</td>
<td>4/27</td>
<td>4/27</td>
</tr>
</tbody>
</table>

Diagram showing project timeline with key dates: 1/14, 2/9, 2/12, 3/11.
Appendix C  Prototypes of Concepts

Asa’s Solo Ideation

Supports Modules

- Rectangular slots like department store shelves
- Electromagnetic attachments to metal panels
- Bolt through holes
- Quick release plates
- Ribbing that acts as shelving
- Surface with very small bumps so attachments can connect like gecko pads
- Straight-up industrial velcro
- Keep attachments floating by suspending them in a jet of air
- Put rods on surfaces to allow for rod-clamping of attachments
- Magnets nested in the panels
- Modules themselves are structural components
- Modules attach to the person instead
- Threaded inserts for holes
- Structure is rods instead of panels
- Module attachment points are only in the places that the user can reach while operating the chair
- Surfaces are sticky like a mouse glue trap

Allows for Sitting and Standing

- Chair seat attaches to legs to assist position change and walking
- Seat folds down to sides to allow standing
- Manual lift mechanism with gearing to make it easy
- Linear activating rails to switch positions
- Suspend person with air
- Mini jetpack
- Exoskeleton where wheels are attached to suit and lock into a wheelchair form when they sit
- Belt system rotates to pull them up and down
- Extra long range to accommodate short and tall people
- Kicking motion while sitting helps move wheelchair through mechanical linkages

Provides Safety

- Center person’s weight and have stabilizing wheels on front and back
- Install gyroscopic stabilizer under seat or at bottom of chair to counteract tipping
- Chest strap to avoid falling out
- Five-point harness
- Shock absorbers for bumps
- Panel rings to combat bending
- Thigh straps attach to frame in case back of chair breaks
- Mattress with walking holes for feet in case they fall
- Some sort of catch system if the wheel fails so they don’t fall over
• Multiple panel attachment points in case one fails

Moves Easily
• Collapsible chair
• Remove extra material between holes
• Really good bearings allow easy wheel rotation
• Fold out legs like ambulance stretchers allow easy move into car
• Transmit lifting mechanism power into rotating the wheels
• Easily splits into multiple parts to make a heavy wheelchair easy to transport and reassemble
• Exterior motor attachment for those that need it
• Clearance for legs to go back a little while in the walking position. Legs should be free to move forward and back as much as needed
• Wheels, seat, standing plate, and any other critical moving components are adjustable for the person to reach them easily or accommodate their dimensions
• Treads for all-terrain navigation
• Exoskeleton
• Whatever helps the person walk keeps them vertical when going up slopes, not perpendicular to the ground
• Assistive straps allow arms to help lift legs
• Just straight up use adrenaline

Interfaces with User
• Curved design for aesthetics
• Spokeless wheels like “The Reevo” bike
• Exterior layer is a white composite that can be dyed so the user can customize the color
• Multiple panel sizes for different users
• Cushions on contact surfaces
• Custom molded surfaces so no cushioning needed
• No sharp edges to avoid poking
• No bumps that focus pressure on body
• Gesture controls like the Mercedes AVTR
• Soft material surfaces elastically shape to user’s body

This concept shows a module attachment method onto a ribbed panel. Panel ribbing aids in rigidity. From left to right, the images show the panel and faux module, the module on the panel, and the module on the panel from the back.
This is a concept of a seat and leg strap system that can support the user in the sitting and walking positions of the wheelchair. The brown straps secure the user’s thighs and pivot on the bottom of the seat when the chair is raised up.

This concept shows a frame system that allows for easier inclined walking when using the wheelchair. By allowing the vertical support members and chair to rotate about the base, the user will not be forced to lean backwards when going up an incline in the walking position. This could also resist the danger of the chair tipping in the walking position.
This concept does not use panels at all and instead consists of only a rod system. Modules would be attached via commercial or custom clamps.

This bold concept forgoes the idea of wheelchair entirely. Bordering on the line of an exoskeleton, the wheels would be attached to a locking leg structure so that the wheels would not be used during the walking position. In the image above, the green straws represent the user’s legs and whatever system would be necessary around them.
## Joelle's Solo Ideation:

<table>
<thead>
<tr>
<th>Supports Modules</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4 - Leaf clover shape</td>
<td>The attachment for each module will instead have 5 points of contact</td>
</tr>
<tr>
<td>1&quot;x1&quot; diagonal grid</td>
<td>Changing the square grid to a diagonal one</td>
</tr>
<tr>
<td>Tethered truss support</td>
<td>Same as 4-leaf clover, but more of a truss system instead</td>
</tr>
<tr>
<td>Wheel supports on pegboard</td>
<td>Use the back of the pegboard to add a support system for wheels</td>
</tr>
<tr>
<td>Coat hanger lift harness</td>
<td>Pictured below, a module that attaches and uses a harness to support user</td>
</tr>
<tr>
<td>Pegboard hooks</td>
<td>Like all regular pegboard hooks, something similar in design</td>
</tr>
<tr>
<td>Necessary holes only</td>
<td>Only having holes for the pegboard around the outside edge and middle</td>
</tr>
<tr>
<td>Triangle panels</td>
<td>User might enjoy aesthetics of triangle shaped panels instead of rectangles</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sitting &amp; Standing</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Shocks</td>
<td>Replace linear actuator with gas shocks instead</td>
</tr>
<tr>
<td>Pulley system</td>
<td>Replace actuators with a counterweight pulley system</td>
</tr>
<tr>
<td>Accessible buttons</td>
<td>Variety of buttons for users to use to lift themselves up and down</td>
</tr>
<tr>
<td>2 actuators</td>
<td>Replacing the singular actuator with two on each side of the armrests</td>
</tr>
<tr>
<td>Leg straps</td>
<td>Users' legs strapped into seat using Charlie's attachment system</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Safety</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Harness</td>
<td>Body harness sewed into back of seat</td>
</tr>
<tr>
<td>Foam solution</td>
<td>Every exposed piece of composite is covered in foam</td>
</tr>
<tr>
<td>Handrail</td>
<td>Provide a handrail attachment for armrests that gives the users a bar to hold on to</td>
</tr>
<tr>
<td>Bungee straps</td>
<td>Leg straps with bungees to promote healthy muscle development</td>
</tr>
<tr>
<td>Netting</td>
<td>Netting system that slides under the chair for fall prevention</td>
</tr>
<tr>
<td>Scissors jack</td>
<td>Using a scissors jack operation to lift rather than a single actuator</td>
</tr>
<tr>
<td>Built in head restraints</td>
<td>Built in head rest for users with physical ailments that could benefit from head, neck and spine stabilization</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Moves Easily</th>
<th></th>
</tr>
</thead>
</table>

C-5
<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collapsible pins</td>
<td>Push to unlock pins like EZ-Ups have</td>
</tr>
<tr>
<td>Tank drive</td>
<td>Tank drive to move chair</td>
</tr>
<tr>
<td>Telescoping frame</td>
<td>Frame can telescope in and out to collapse easily for transportation</td>
</tr>
<tr>
<td>Sand paddles</td>
<td>Sand paddle tires for off-roading</td>
</tr>
<tr>
<td>Bamboo frame</td>
<td>Making the frame out of bamboo (renewable resource, lightweight, strong)</td>
</tr>
<tr>
<td>Self-parking</td>
<td>Programming the wheelchair to park and load itself into cars/tight spaces</td>
</tr>
<tr>
<td>Assistive motor</td>
<td>Motor that gently pushes wheels along as user is trying to walk</td>
</tr>
<tr>
<td>Slotted expansion joints</td>
<td>Slot the composites to allow for them to slide in and out while expanding for sitting/standing positions</td>
</tr>
</tbody>
</table>

**Interfaces with User**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Memory Foam</td>
<td>Memory foam seat, backrest, and armrests</td>
</tr>
<tr>
<td>Pillow insert</td>
<td>An attachment that allows the user to place a pillow to rest their head and nap</td>
</tr>
<tr>
<td>Integrated seat</td>
<td>Panel that is flat with a seat made out of composites built right into it</td>
</tr>
<tr>
<td>U-shaped composite panel</td>
<td>Custom contours to body, u-shaped panel</td>
</tr>
<tr>
<td>Pressure molded surfaces</td>
<td>Similar to above, design such that no pressure points are pressed</td>
</tr>
<tr>
<td>Alternating pressure point</td>
<td>Seat moves around to prevent user from getting pressure sores</td>
</tr>
<tr>
<td>Foam ball vacuum bag</td>
<td>Foam ball + vacuum seal to contour exactly to user's body</td>
</tr>
</tbody>
</table>
A simple ideation for how modules could be attached to a panel pegboard system. In theory, the attachments could hook through the pegboard and be held in by gravity and loading on the cantilever.

A solution to the current issue of safety for the user; the current design allows the user to support their weight on a unicycle seat which could be deadly. This module attachment system allows the user to be supported from above by an attachment to the wheelchair, or an additional module.

Another helpful solution to the issue of the unicycle seat; using the leg wraps Charlie has already created and integrating them into the seat and allowing the seat to split down the middle and hinge in the back so that it supports the user without impeding motion.
Wyatt’s Solo Ideation:
Supports Modules
- Imbedded clips in the composite
- Metal lined through holes for bolt/nut attachment
- Seated threaded holes in the composite
- Velcro
- Molded insertion points for module base (cupholder kind of thing)
- Suction cups
- Command strips
- Breadboards mounted to frame
- Peg-hole slots (gorilla rack style)
- Indented locations with rare earth magnets in the composite

Allows for sitting and standing
- Belt drive like a tank track that attaches to the back of the seat
- Pulley system
- Hydraulic pistons
- Rack and pinion gears
- Electromagnetic rails
- Chest strap is integrated into the back rest so it can be easily put on and pull the person up into a standing position with the chair back
- Arms for the wheelchair are attached to the back of the seat so when the seat raises, the arms raise with it. This allows the user to hold on to the arms to lift themselves, or at least use them to support/guide the wheelchair when in the standing position
- Seat has ability to have different "0" heights programed into it for different users
- The height the seat raises to is adjustable
- When the seat drops away it reveals more attachment points for modules that help secure/support the user in standing and/or in walking

Provides safety
- Roll cage
- Intercrossing trusswork behind panels out of sight
- Spring suspension system to dampen impacts
- Tempur-Pedic cushion
- Metal honeycomb for increased rigidity and less fail probability
- Layers of carbon with Kevlar for increased abrasion resistance
- Weak points for abuse cases are strategically placed so if frame fails it protects the user from injury and the part is replaceable
- Disk brakes (essentially a very reliable braking system)
- Large enough wheels (both front and back) so that cracks/impacts do not hurt or dislodge user or beach the frame
- Frame is sufficiently piecewise that replacement of worn out pieces is possible

Moves easily
- Chair back can go down farther than seat position to make it fit in cars more easily
- Racing bike high performance bearings
• Large/light wheels (carbon fiber rims)
• Handles built into the frame to make lifting it easier
• Roller bearings on a linear rail track that constrains the seat backs movement in non-wanted direction but introduces minimal friction to raise and lower it
• Narrow enough to fit through standard doors
• Small electric power assist wheels (works like electric bike to amplify user input)

**Interfaces with user**

• Uses special carbon fiber weaves and patterns (aesthetics)
• Colored resins
• Has a tray underneath the seat that pivots to stay upright when the seat is put into standing position
• Has flat places on the side of the frame to put stickers
• The seat bottom is made of carbon fiber and formed to be shaped like a butt imprint and then cushion material is added on top
• Handlebars can adjust their width in connection to the frame
• The seat back can tilt in reference to the bracket that attaches to the raising/lowering mechanism

**Function Prototypes:**

Insertable magnetic hook panels (could be something other than a hook too)

Rack and Pinion gear system for raising and lowering the chair
Hooks /hook system that are permanently included into the composite structure through the fact that they are included in the curing process

Tank track like belt drive for raising and lowering the chair

Hydraulic pistons as the method of raising and lowering the chair
<table>
<thead>
<tr>
<th><strong>Luis’ Solo Ideation</strong></th>
<th><strong>Supports Modules</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Press in form fitters</td>
</tr>
<tr>
<td></td>
<td>Side grid of slots</td>
</tr>
<tr>
<td></td>
<td>Reverse pegboard</td>
</tr>
<tr>
<td></td>
<td>Variable plate attachments</td>
</tr>
<tr>
<td></td>
<td>Embedded threaded inserts</td>
</tr>
<tr>
<td></td>
<td>Command hook mounting</td>
</tr>
<tr>
<td></td>
<td>Sectional plates</td>
</tr>
<tr>
<td></td>
<td>Variable attachment sizes</td>
</tr>
<tr>
<td></td>
<td>Magnetic guides</td>
</tr>
<tr>
<td></td>
<td>Velcro guides</td>
</tr>
<tr>
<td><strong>Allows for sitting and standing</strong></td>
<td>Telescoping quick release frame</td>
</tr>
<tr>
<td></td>
<td>Adjustable end stop</td>
</tr>
<tr>
<td></td>
<td>Car jack lifting crank</td>
</tr>
<tr>
<td></td>
<td>Roller coaster tracks</td>
</tr>
<tr>
<td></td>
<td>Parachute harness</td>
</tr>
<tr>
<td><strong>Provides safety</strong></td>
<td>Trapezoidal frame</td>
</tr>
<tr>
<td></td>
<td>Retractable armrest bumpers</td>
</tr>
<tr>
<td></td>
<td>Tipping dampers</td>
</tr>
<tr>
<td></td>
<td>Upper body breaking</td>
</tr>
<tr>
<td></td>
<td>Add headlights, tail lights, and reflectors</td>
</tr>
<tr>
<td></td>
<td>Include a manual horn or whistle for an emergency</td>
</tr>
<tr>
<td></td>
<td>Secondary arm support</td>
</tr>
<tr>
<td></td>
<td>Gait clearance bracket</td>
</tr>
<tr>
<td></td>
<td>Suspension air bags</td>
</tr>
<tr>
<td></td>
<td>Secondary frame</td>
</tr>
<tr>
<td><strong>Moves easily</strong></td>
<td>Lawn chair foldstyle of the frame</td>
</tr>
<tr>
<td></td>
<td>Quick release pins at the junctions</td>
</tr>
<tr>
<td></td>
<td>Include steering in the front axle</td>
</tr>
<tr>
<td></td>
<td>Adapt steering to be torso driven with pulleys</td>
</tr>
<tr>
<td></td>
<td>Use special wheel bearings with sealed lubrication</td>
</tr>
<tr>
<td></td>
<td>Omniwheel bidirectional wheels</td>
</tr>
<tr>
<td></td>
<td>Reduce friction with magnetic levitation</td>
</tr>
<tr>
<td></td>
<td>Sectional panels to increase portability</td>
</tr>
<tr>
<td></td>
<td>Parking pawl to prevent rolling during walking breaks</td>
</tr>
<tr>
<td></td>
<td>Armrest conveyor belt powered device</td>
</tr>
<tr>
<td><strong>Interfaces with user</strong></td>
<td>Expandable air cushions</td>
</tr>
<tr>
<td></td>
<td>Seat swivel</td>
</tr>
<tr>
<td></td>
<td>Expandable framing</td>
</tr>
<tr>
<td></td>
<td>Pivoting frame</td>
</tr>
</tbody>
</table>
This concept replaces the idea of a 1 x 1 grid with a slotted grid that runs along the sides where they will be needed most.

This concept incorporates a swivel in the middle of the seat to allow the user to stretch and practice developing their muscles with the slight increase in the range of motion.
This concept showcases the idea of a sectional frame with detachable panels. The benefit of many smaller panels over a singular large panel would be the added flexibility in modularity and ease of transportation as well as accessible repair in the case of a structural failure.

This concept is a sling that is integrated into the seating component that would allow the user to remained in a seated position without the pressure of a seat on their body. This would be a periodic use feature used to avoid pressure sores.
This concept aims to solve the challenge of decreased comfortability over prolonged sitting by adding an inner air chamber to an exterior foam cushion that would allow the user to set the amount of variable pressure within the seating.
Appendix D  Functional Decomposition and Decision Matrices

Functional Decomposition

- Helps Rehabilitate Users with Limited Mobility

  - Supports Modules
    - Allows Customizable Module Placement
    - Allows Attachment of Medical Devices
    - Provides Various Attachment Points
    - Prevents Deformation at Attachment Points
    - Interfaces with Current Prototype System

  - Allows for Sitting and Standing
    - Switches Positions Easily
    - Adjusts to User Heights
    - Switches Modes While Under Load
    - Interfaces with User

  - Provides Safety
    - Maintains Rigidity
    - Resists Tipping
    - Tolerates Abuse Cases
    - Secures User

  - Protects User Health
    - Maintains Integrity
    - Sustains Impact Loading
    - Device Fails Safely
    - Does not Cause Pain
    - Does not Further Impair User

  - Transports Easily
    - Easily Carried by One Person
    - Fits Within a Car
    - Fits Different Body Types
    - Provides Comfort
    - Provides Access to Critical Components
    - Adapts to Different User Control Methods
    - Adapts to User Size/Shape
    - Doesn’t Squeak
    - Avoids Stress Points on Body

  - Operates Under User Input
    - Requires Very Little Force
    - Has Ergonomic Control

  - Interfaces with User
    - Allows Aesthetic Customization

Team F45 - Composite Pegboard
15 October 2020
Luis Corrales
Asa Cusick
Joelle Hylton
Wyatt Pauley
<table>
<thead>
<tr>
<th>Function: Supports Modules</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criteria</td>
<td>Current Prototype</td>
</tr>
<tr>
<td>Sturdy (Strength)</td>
<td>S</td>
</tr>
<tr>
<td>Rigid (Stiffness)</td>
<td>S</td>
</tr>
<tr>
<td>Durable (Longevity/Life/Cycles)</td>
<td>S</td>
</tr>
<tr>
<td>Aesthetically Pleasing &amp; Customizable</td>
<td>S</td>
</tr>
<tr>
<td>Inexpensive (Consumer Cost)</td>
<td>S</td>
</tr>
<tr>
<td>Physically Easy to Use Intuitive Component Placement</td>
<td>S</td>
</tr>
<tr>
<td>Sense of Independence</td>
<td>S</td>
</tr>
<tr>
<td>Ease of Transportation</td>
<td>S</td>
</tr>
<tr>
<td>Functionally Adjustable</td>
<td>S</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>--</td>
</tr>
</tbody>
</table>

This analysis shows Velcro is the best, but it doesn’t take into account the fact that aesthetics is highly weighted as well as the fact that there is a large need for weight support, and Velcro can support less than other options.
## Function: Provides Safety

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current Prototype</td>
</tr>
<tr>
<td>Sturdy (Strength)</td>
<td>S</td>
</tr>
<tr>
<td>Rigid (Stiffness)</td>
<td>S</td>
</tr>
<tr>
<td>Durable (Longevity/Life/Cycles)</td>
<td>S</td>
</tr>
<tr>
<td>Medically Effective</td>
<td>S</td>
</tr>
<tr>
<td>Physically Easy to Use</td>
<td>S</td>
</tr>
<tr>
<td>Intuitive Component Placement</td>
<td>S</td>
</tr>
<tr>
<td>Comfortable</td>
<td>S</td>
</tr>
<tr>
<td>Functionally Adjustable</td>
<td>S</td>
</tr>
<tr>
<td>Safety</td>
<td>S</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>--</td>
</tr>
</tbody>
</table>

This type of analysis isn't really suited for choosing safety features. These are all valid things we can incorporate, and I don't think we should just choose "the best."
This analysis provides two viable solutions, but neither of which related to the design of the frame. In the end, the team reworked this specific matrix to only include flat panels, or U-shaped channels for the composite portion of the frame.
### Function: Ease of Transportation

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lightweight</td>
<td>S</td>
</tr>
<tr>
<td>Compact Folds to Fit</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>S</td>
</tr>
<tr>
<td>Maintains Rigidity</td>
<td>S</td>
</tr>
<tr>
<td>Easy to Grab</td>
<td>S</td>
</tr>
<tr>
<td>Ease of Repair</td>
<td>S</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>--</td>
</tr>
</tbody>
</table>

This analysis provided satisfactory results that were pertinent to the frame design.
### Function: Allows for Sitting and Standing

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Linear Actuating Rails to Switch Positions</th>
<th>Extra-long Range to Accommodate Short and Tall People</th>
<th>Seat Folds Down to Sides to Allow for Standing</th>
<th>User’s Legs are Strapped Directly to the Seat Using Charlie’s Adaptive Restraints</th>
<th>Telescoping Quick Release Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sturdy</td>
<td>S</td>
<td>S</td>
<td>-</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Rigid</td>
<td>S</td>
<td>S</td>
<td>-</td>
<td>S</td>
<td>-</td>
</tr>
<tr>
<td>Durable</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>-</td>
</tr>
<tr>
<td>Medically Effective</td>
<td>S</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Physically Easy to Use</td>
<td>S</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Intuitive Component Placement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sense of Independence</td>
<td>S</td>
<td>+</td>
<td>S</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Comfortable</td>
<td>S</td>
<td>+</td>
<td>S</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Functionally Adjustable</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safety</td>
<td>S</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>--</td>
<td>4</td>
<td>0</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

According to the matrix, a variation of the current prototype with a greater allowable vertical travel and an implementation of seat straps would be the best improvements to satisfy the function. While these may be good ideas, they are not related to the frame.
Appendix E  Preliminary Analysis of Frame Attachment

**TEAM F45**  **ME 428**  **ROUGH ANALYSIS**

![Diagram of frame attachment]

- **Carbon Fiber Panel**
- **Bracket connecting to lower frame**
- **Flat Bracket attached with Resin**

Using 105 Epoxy Resin w/ 206 Slow Hardener made by West System

* Company rated Tensile strength of 7320 Psi

* Assuming 2 in² area of interface for bracket

* Force is split between the two brackets

Panel is 1 inch thick

Metal bracket is 1/8 inch thick

Adhesive is 1/16 inch thick

Max shear from load \( \tau = \frac{F}{A} \)

\( \tau = \frac{200 \text{ lb}}{2 \text{ in}^2} = 100 \text{ psi} \)

Max \( \tau \approx 0.577 \sigma_{max} \)

\( \sigma_{max} \approx 0.577 (7320 \text{ psi}) \)

\( \sigma_{max} \approx 4223.64 \text{ psi} \)

Factor of safety = \( \frac{4223.64}{100} \)

\( F_s = 42 \)
Assume stainless steel bolt

\[ \tau_{\text{bolt}} = \frac{4P}{\pi d^2} \]

\[ \tau_{\text{bolt}} = \frac{4(200 \text{ lb})}{\pi (0.25 \text{ in})^2} \]

\[ \tau_{\text{bolt}} = 4071.37 \text{ psi} \]

\[ \sigma_y = 31200 \text{ psi} \]

\[ \tau_{\max} \approx 0.577 \sigma_y \] (we don't want bolt to yield at all)

\[ \tau_{\max} = 18002.4 \text{ psi} \]

\[ F_3 = 4.42 \]
## Appendix F  Design Hazards Checklist

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Y</strong></td>
<td>1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and shear points?</td>
</tr>
<tr>
<td><strong>N</strong></td>
<td>2. Can any part of the design undergo high accelerations/decelerations?</td>
</tr>
<tr>
<td><strong>Y</strong></td>
<td>3. Will the system have any large moving masses or large forces?</td>
</tr>
<tr>
<td><strong>N</strong></td>
<td>4. Will the system produce a projectile?</td>
</tr>
<tr>
<td><strong>Y</strong></td>
<td>5. Would it be possible for the system to fall under gravity creating injury?</td>
</tr>
<tr>
<td><strong>N</strong></td>
<td>6. Will a user be exposed to overhanging weights as part of the design?</td>
</tr>
<tr>
<td><strong>N</strong></td>
<td>7. Will the system have any sharp edges?</td>
</tr>
<tr>
<td><strong>N</strong></td>
<td>8. Will any part of the electrical systems not be grounded?</td>
</tr>
<tr>
<td><strong>N</strong></td>
<td>9. Will there be any large batteries or electrical voltage in the system above 40 V?</td>
</tr>
<tr>
<td><strong>Y</strong></td>
<td>10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?</td>
</tr>
<tr>
<td><strong>N</strong></td>
<td>11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?</td>
</tr>
<tr>
<td><strong>N</strong></td>
<td>12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?</td>
</tr>
<tr>
<td><strong>N</strong></td>
<td>13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?</td>
</tr>
<tr>
<td><strong>N</strong></td>
<td>14. Can the system generate high levels of noise?</td>
</tr>
<tr>
<td><strong>Y</strong></td>
<td>15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc.?</td>
</tr>
<tr>
<td><strong>Y</strong></td>
<td>16. Is it possible for the system to be used in an unsafe manner?</td>
</tr>
<tr>
<td><strong>Y</strong></td>
<td>17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.</td>
</tr>
<tr>
<td>Description of Hazard</td>
<td>Planned Corrective Action</td>
</tr>
<tr>
<td>--------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1) Linear actuator and linear rails pose the risk of pinching and shearing</td>
<td>Ensure that rails and actuator are not easily exposed to fingers when actuating</td>
</tr>
<tr>
<td>3) The user themselves will be a large moving mass within the system</td>
<td>Building a stable base and frame with possible harness attachment to secure the user in a safe position</td>
</tr>
<tr>
<td>5) The system itself is not conducive to falling, but there exists the possibility of the system tipping while in use</td>
<td>Design the frame to have a center of mass closer to the ground and include the current prototype’s implementation of additional supporting wheels for stability</td>
</tr>
<tr>
<td>10) Batteries are required to operate the linear actuating mechanism</td>
<td>The battery system will be enclosed, but detachable to allow for charging but kept away from user’s reach</td>
</tr>
<tr>
<td>15) Possible exposure to environmental conditions that can degrade or change the shape of the materials for the panels and support structure</td>
<td>Proper selection of composite and other materials to resist degradation in predicted use cases</td>
</tr>
<tr>
<td>16) There are a few abuse cases that come to mind, potentially overloading</td>
<td>We will design the wheelchair with a factor of safety of 2 on all parts (taking material selection into consideration)</td>
</tr>
<tr>
<td>17) Composite fibers can cause harm to the respiratory system when drilling, cutting, etc.</td>
<td>When manufacturing composites, the team will use all safety precautions previously put in place by the school to ensure the safety of the team</td>
</tr>
</tbody>
</table>
## TEST PLAN

<table>
<thead>
<tr>
<th>Test #</th>
<th>Specification</th>
<th>Test Description</th>
<th>Measurements</th>
<th>Acceptance Criteria</th>
<th>Required Facilities/Equipment</th>
<th>Parts Needed</th>
<th>Responsibility</th>
<th>TIMING</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Panel Hole - In-plane tension/compression</td>
<td>Test the loading capability of the holes to support a load in tension or compression. Perform this using tensile test machine or hanging weights from the hole as close to the panel as possible.</td>
<td>Total weight carried before failure. Original and final hole shape and size. Deflected shape.</td>
<td>Still being analyzed. Dependent on safety factors, and wheelchair geometry.</td>
<td>Tensile test machine, weights</td>
<td>Long bolt</td>
<td>Asa</td>
<td>Tested with each iteration</td>
</tr>
<tr>
<td>2</td>
<td>Panel Hole - Vertical Bending</td>
<td>Test the loading capability of the holes to support a moment that is induced vertically. Perform this using a cantilever bolt securely fastened in the hole. Hang weights or use a tensile machine to load the panel with a moment until failure.</td>
<td>Total weight carried before failure. Original and final hole shape and size. Deflected shape.</td>
<td>Still being analyzed. Dependent on safety factors, and wheelchair geometry.</td>
<td>Tensile test machine, weights</td>
<td>Long bolt</td>
<td>Joelle</td>
<td>Tested with each iteration</td>
</tr>
<tr>
<td>3</td>
<td>Panel Hole - Horizontal Bending</td>
<td>Test the loading capability of the holes to support a moment that is induced horizontally. Perform this using a cantilever bolt securely fastened in the hole. With panel oriented sideways, hang weights or use a tensile machine to load the panel with a moment until failure.</td>
<td>Total weight carried before failure. Original and final hole shape and size. Deflected shape.</td>
<td>Still being analyzed. Dependent on safety factors, and wheelchair geometry.</td>
<td>Tensile test machine, weights</td>
<td>Long bolt</td>
<td>Wyatt</td>
<td>Tested with each iteration</td>
</tr>
</tbody>
</table>
Appendix H  Iteration 0 Manufacturing and Testing

Construction of the first test panels began with cutting the fiber and cores for the panel layups. Figure H-1 shows the weight of the carbon fiber sheets and core for the paper honeycomb core panel. The honeycomb core was cut to approximately a 12”x12” square, and the carbon fiber sheets were cut to approximately 13”x13” to allow for overlap of the sheets after draping the composite. The overlap of the sheets aids in resisting delamination of the carbon fiber sheets from the core during bending – this delamination is likely due to the small contact area between the sheets and core.

A similar process was performed for the fiberglass honeycomb panel. Both panels followed the same layup procedure, as shown in Figure H-2. Both sides of carbon fiber were wet with resin and laid up separately. The first side of carbon fiber was placed on a protective layer of film on the metal plate surface, the core was placed on top, and the top side of carbon fiber was draped over the top to create a lip all around the part. This lip is better seen in the debagging process photos. Breather material or a perforated film was placed on top of the panel, followed by another release film, a metal plate (for even pressure distribution), a cotton breather, and the final vacuum bag to pull vacuum on the part.

Figure H-1 Weighing carbon fiber and paper honeycomb core. Weighing carbon fiber and paper honeycomb core. (top right) 9 sheets of carbon fiber (228g) for one side of the composite, (top left) 9 sheets of carbon fiber (207g) for the other side of the composite, (bottom) paper honeycomb core (61g).
After all the layups were complete, the parts were left to cure for two days, then they were removed from their curing setups. Figure H-3 shows the result of the flat panel. As expected, there are multiple dry spots from the lack of epoxy in the layup process. This panel was planned to be tested alone but was later used by the team as part of a panel in Iteration 1.

Figure H-4 shows the paper honeycomb panel being removed from the vacuum bag. Inspection of the surface shows that the bottom side (the side in contact with the metal plate) had a mirror finish, and the top side had small dots from the perforated breather film. Further inspection of the panel in Figure H-5 shows that there are small areas around the perimeter of the part where the top and bottom sheets of carbon fiber did not create a bond around the edge of the part because there was not enough material.
Figure H-4 Removing paper honeycomb core panel from vacuum bag. (top row from left to right) Removing layup materials – vacuum bag, cotton breather, and perforated breather – top view of panel, bottom view of panel, (bottom row from left to right) close-up of top surface with surface imperfections from perforated breather, close-up of smooth bottom surface from being in contact with the smooth plate.

Figure H-6 shows the debagging and inspection of the fiberglass honeycomb core panel. The shape seen in the panel is the imprint of the vacuum pump attachment because the piece was put directly on the part without a metal plate in between, so the pump sucked directly on the carbon fiber. The bottom of the panel is again smooth because of the plate, but the top side of this panel is textured due to the use of a cotton breather and no perforated film or other breather material. This panel is culprit to similar edge imperfections as the paper honeycomb panel because it was manufactured in the same sitting.
Figure H-5 Paper honeycomb panel. (top row) Top surface of panel, bottom surface of panel, (bottom row) examples of imperfections in skin bonding at corner of panel and on the side of the panel.
Figure H-6 Fiberglass honeycomb core panel. (top row from left to right) Removing cotton breather, top view of panel with vacuum port imprint, bottom view of panel, full untrimmed panel, (bottom row from left to right) alternate view of bottom surface, detail shot of corner to show how the two skins overlap.

The final panels for this iteration are shown together in Figure H-7, and their individual weights and sizes are shown in Figure H-8.

Figure H-7 Composite panels manufactured for Iteration 0.
The next step in the process is to prepare the parts for testing. This involves applying strain gages in the proper location and orientation to ensure accurate measurement with the strain gage reader.

To ensure all the panels were testing uniformly, a repeatable procedure was developed for applying strain gages to the panels. First, the team scribed a horizontal line 4.25” from the bottom edge of the panel that was most perpendicular to the fiber direction (i.e. the direction of testing). After that, the team scribed a vertical line in the center of the panel. These steps are shown in Figure H-9.
H-7

The process was repeated on the other side, as shown in Figure H-10, with one change. Instead of drawing the vertical line in the center of the panel, the team made sure to draw the line in the same location as the line on the front side of the panel. In some instances, the panel was not perfectly square or of equal shape on both sides. This sometimes resulting from layup or cutting inaccuracies. The team needed the strain gage to be in the exact same location on both sides of the panel in order to properly complete the testing, so this vertical line precaution was introduced.

After the location lines were established, the team sanded and prepared the surface where the strain gage would be applied, as seen in Figure H-11. The team sanded from dry 320 grit to wet 320 grit to wet 400 grit. Then, the team cleaned the surface with a cotton swab and the strain gage kit neutralizing liquid to ensure no sanding residue would interfere with the strain gage adhesion to the surface. After this was completed, the team redrew the alignment guides over the sanded area.
Figure H-11 Panel surface during sanding process. (top row left to right) 320 grit paper, 320 gort paper with sanding liquid, 400 grit paper with sanding liquid, cotton swab and neutralizing liquid; (bottom row left to right) surface after dry 320 grit sanding, wet 320 grit sanding, wet 400 grit sanding, and neutralizing surface and redrawing guide lines.

Next, the team assembled the strain gage for mounting. Using the alignment sheet in the packaging, the team put the terminal 1.5 millimeters above the strain gage. The team made sure that the “I” part of the terminal was on the left and “Y” part of the terminal was on the right for all panels. The team covered the terminal and strain gage with transfer tape, which created a unified assembly that could be transferred and adhered to the panel. The team left excess tape at the top and bottom of the assembly in order to ease the adhesion process.

With the strain gage assembly properly prepared, the team adhered the strain gage in the correct position on the panel, as seen in Figure H-12. The team aligned the bottom of the strain gage with the horizontal line and the strain gage alignment arrows with the vertical line. Then the bottom of the tape was firmly pressed against the panel. This created a hinge that allowed the strain gage assembly on the transfer tape to be peeled back so the superglue could be placed on the surface of the panel. The tape was then re-pressed down, and the team let the glue dry.
With the strain gage assembly applied on the correct position on the panel, the team removed the transfer tape and soldered all necessary components onto the strain gage, as shown in Figure H-13. First, the team used a single strand of solder to attach each terminal to the strain gage. Then, the team attached a red wire to the “I” terminal and a white wire to the “Y” terminal. All wires were 24” long to ensure the most uniformity between testing.

Lastly, the team soldered a bit of extra solder on the exposed end of the wires. This end of the wire interfaces with the strain gage reader, so the team wanted to reduce the risk of fraying, bending, or any other damage to the wire at that end. With the strain gage properly applied, the team tested that the strain gage worked by using the strain gage read for a qualitative test. If the strain gage output values when the team stressed the panel with their hands, the application was a success. The team then repeated the same strain gage application process for the other side of the panel.

In order to test the panels under cantilever loading, the team created a custom testing fixture because there is no lab equipment that can perform that kind of testing. Eltahry recommended that we create the fixturing pieces shown in Figure H-14. The team used some scrap L-brackets that
Eltahry had access to. Eltahry recommended that the cantilever testing be performed on a sturdy metal table outside the Aero Hangar, so the team went there and took measurements of the necessary holes to be drilled in the L-brackets. The team drilled corresponding clearance (+0.25” diameter) holes in the brackets and bought appropriate bolts (3/8”) to and washers to attach brackets to the testing table.

Figure H-14 Weighing cantilever test components. (top row from left to right) Rod for hanging weights, clamping fixture for hanging weights, clamping fixture for holding panel, (bottom row from left to right) corresponding weights for each component directly above.

Knowing that post of the panels to be manufactured would be approximately 12” by 12”, the measured holes centered on the brackets and 14” apart. Drilling holes at these locations, the team created a clamping fixture with ¾” bolts. Additionally, the team drilled a hole as close as possible to the center of the cantilever side of the bracket. This hole would allow the team to hang weights from the cantilever end. To hang weights from that end, the team purchased a 316 stainless steel U-bolt and a reduction coupler to attach it to a threaded rod that Eltahry provided to the team. The rod was cut down from its original length to that it would not hit the ground during testing.
The final manufacturing fixturing is shown in Figure H-14. Here, the weights of the components are shown, as they will affect the cantilever testing performed on the panels and therefore must be factored in to the calculations.

After the completion of the panels, application of the strain gages, and manufacturing of the cantilever testing fixtures, the cantilever testing can be performed on the panels. The team began with the paper honeycomb panel. Figure H-15 shows the testing process. The panel was setup in the cantilever fixturing with the strain gage perpendicular to the fixturing clamp pieces. The fixturing clamp pieces were measured parallel to ensure the weight was being applied in the direction of the strain gage. Note that the weight hook fixturing clamp is placed such that the weight hook is as far away from the fixed end of the panel as possible. A cotton breather was placed over panel to limit the amount of direct sunlight hitting the strain gage and hopefully minimize thermal strain in the readings. For this initial test, a quarter bridge was used with the strain gage. The team eventually switched to a half bridge, so this test data was not used, but it is included for the purpose of documentation. An initial measurement of the deflection was taken with a tape measure to allow for the future deflection measurements to be properly adjusted.

Figure H-15 Setup for cantilever test. (top row from left to right) Setting up paper honeycomb panel in fixturing device, measuring the initial deflection value, attaching the weight rod and covering the strain gage to limit thermal affects, (bottom row) ensuring the clamping fixture are parallel.
Figure H-16 shows the loading process of the panel. Calibrated ten pound weights were added to the panel and strain measurements were taken after each weight was added. Additionally, deflection values were manually measured with a tape measure, in the same manner as the initial deflection measurement. Measurements were taken up to 130 pounds, as that was the maximum amount of weight the team had and the maximum amount of weights that would fit on the weight hook rod.

![Figure H-16 Paper honeycomb cantilever test with quarter bridge setup. (left) Eight ten-pound weights on panel, (right) 13 ten-pound weights on panel.](image)

Figure H-17 details that a small gap developed between the fixturing piece and the panel during testing, which is indicative of some rigid body rotation of the panel. This means that the manually recorded deflection measurements are not simply panel deformation from cantilever bending but also include some movement of the panel in the testing fixture itself. This rigid body rotation is difficult to quantify but is still documented here.

![Figure H-17 Cantilever test fixturing before and after loading. (left) Base of panel before loading, (middle) base of panel after loading, (right) alternate view of base after loading.](image)

With the testing procedure established, the same procedure was followed for all subsequent tests. Each panel was tested five times. Figure H-18 shows the setup of test one for the paper honeycomb panel. Figure H-19 shows the attempted half-bridge setup for measurement of strain. The team
attempted to use a “dummy panel” to offset the thermal effects of testing outside. This would be accomplished by subtracting the “dummy panel” strains from the testing panel strains. However, the team incorrectly set up the system. As seen, instead of subtracting the top and bottom of the “dummy panel” from the top and bottom of the testing panel, respectively, the team accidentally subtracted the bottom of each panel from the top of the same panel. As such, the team accidentally measured two times the bending strain for each panel instead of negating the effects of thermal strain. Therefore, the data from channel 4 is useless, and the “dummy panel” was improperly used. Figure H-20 shows the panel before testing, at maximum load, and after testing.

Figure H-18 Setup of the first paper honeycomb panel test fixturing. (from left to right) leveling the fixed end of the test fixture, measuring the distance of the strain gage from the testing fixture (~2.125”), setting up the loading end of the testing fixture parallel to the fixed end, ensuring the weight hook sits in the center of the panel.

Figure H-19 Setup of the first paper honeycomb panel test strain measurement. Here, the half bridge was incorrectly set up. Instead of negating thermal effects, the team accidentally subtracted the bottom from the top of each respective panel. As such, the team measured double the bending strain of each panel instead.
Figure H-20 Progress photos of the first paper honeycomb panel test. From left to right, pictures are before the testing, at the maximum loading (130 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

Figure H-21 shows the setup of test two for the paper honeycomb panel. Figure H-22 shows the attempted half-bridge setup for measurement of strain. The team made the same mistake as test one. Therefore, the data from channel 4 is useless, and the “dummy panel” was improperly used. Figure H-23 shows the panel before testing, at maximum load, and after testing.
Figure H-21 Setup of the second paper honeycomb panel test fixturing. (top row) leveling the fixed end of the test fixture, number of washers used on testing fixture, ensuring strain gage is perpendicular to testing fixture, (bottom row) ensuring the two side of the testing fixture are parallel (~9” separation), noting that the load end fixture was accidentally placed backwards for this test, and ensuring the weight hook sits in the center of the panel.

Figure H-22 Setup of the second paper honeycomb panel test strain measurement. Here, the half bridge was incorrectly set up. Instead of negating thermal effects, the team accidentally subtracted the bottom from the top of each respective panel. As such, the team measured double the bending strain of each panel instead.
Test three was performed on the same day, directly after test two, so all of the setup did not change. The team made the same mistake as test one. Therefore, the data from channel 4 is useless, and the “dummy panel” was improperly used. Figure H-24 shows the panel before testing, at maximum load, and after testing.
Test four was performed on the same day, directly after test three, so all of the setup did not change. The team made the same mistake as test one. Therefore, the data from channel 4 is useless, and the “dummy panel” was improperly used. Figure H-25 shows the panel before testing, at maximum load, and after testing.
Figure H-25 Progress photos of the fourth paper honeycomb panel test. From left to right, pictures are before the testing, at the maximum loading (130 pounds), and after all weights were removed. (first row) profile view of deflection where an initial photo was not taken, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

Test five was performed on the same day, directly after test four, so all of the setup did not change. The team made the same mistake as test one. Therefore, the data from channel 4 is useless, and the “dummy panel” was improperly used. Figure H-26 shows the panel before testing, at maximum load, and after testing.
After all five runs of testing, the team had the following data: manually-measured deflection values at each weight increment, and strain values for the entire duration of testing. Due to the improper setup of the testing apparatus, the measured strain data from Channel 3 is the only useful data. Each side of the panel develops a strain value that is the sum of three components: axial strain, bending strain, and thermal strain. Axial strain should be equal on both sides, bending strain should be equal and opposite on both sides, and thermal strain is dependent of the temperature of each side of the panel. Because the team accidentally configured the half bridge with both sides of the same panel, the resulting strain measured on Channel 3 is the difference of the strains on the top
and bottom sides of the panel. In this case, that results in a value that is the sum of a small amount of thermal strain two times the bending moment. The thermal effects in this case cannot be negated.

In order to do the analysis for this panel, the team needed to assume the thermal strain was negligible, which is incorrect. After this, the team divided the strain values from Channel 3 by two in order to get the bending strain for the whole panel. The resulting paper honeycomb panel strain data is shown in Figure H-27, and the resulting deflection data is shown in Figure H-28. Applied moment values were generated by multiplying the weight added by the distance of the weights from the fixed end of the panel.

Figure H-27 Applied Moment vs. Bending strain for the Paper Honeycomb Panel. Data shown for four runs of the testing and an average of all data. Only four runs are shown, as data from some runs was corrupted, incorrectly measured, or lost and had to be discarded from the set of analyzed data. Data was collected while putting weights on (upwards triangle symbols) and taking weights off (downwards triangle symbols). Slopes represent the bending stiffness calculated for each run, calculated with liner curve fit.
After testing the paper honeycomb panel, the team wanted to test the fiberglass honeycomb panel. However, at the time, the team was unable to place strain gages on the panel, so the team tested the corrugated core panel first. Testing of that panel is recorded in Appendix I. Then the team tested the fiberglass honeycomb panel. The testing procedure for the fiberglass honeycomb panel was identical to the paper honeycomb panel. All five tests were performed on the same day, so the testing setup was identical for all five tests and is only shown once.

Figure H-29 shows the setup of test one for the fiberglass honeycomb panel. Figure H-30 shows the half-bridge setup for measurement of strain. For this test, the half bridge was correctly utilized. As such, Channel 3 of the strain gage reader provided the sum of axial and bending strain for the top of the panel, and Channel 4 provided the sum of axial and bending strain for the bottom of the panel. Thermal effects were negated through the use of the “dummy panel.” Figure H-31 shows the panel before testing, at maximum load, and after testing.
Figure H-29 Setup of the first fiberglass honeycomb panel test fixturing. (top row) ensuring strain gage is perpendicular to testing fixture, ensuring the two side of the testing fixture are parallel (~8.75” separation), ensuring the weight hook sits in the center of the panel, (bottom row) number of washers used on testing fixture, distance of strain gage from the testing fixture (~1.9375”). The team leveled the fixture, but there are not photos to show it.

Figure H-30 Setup of the first fiberglass honeycomb panel test strain measurement. Here, the half bridge was correctly set up. Thermal effects were negated through the use of a “dummy panel.” As such, the team measured the sum of axial and bending strain for the top and bottom of the testing panel on Channels 3 and 4, respectively.
Test two was performed on the same day, directly after test one, so all of the setup did not change. The half-bridge setup negated the thermal strain effects through the use of a “dummy panel.” Figure H-32 shows the panel before testing, at maximum load, and after testing.
Figure H-32 Progress photos of the second fiberglass honeycomb panel test. From left to right, pictures are before the testing, at the maximum loading (90 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

Test three was performed on the same day, directly after test two, so all of the setup did not change. The half-bridge setup negated the thermal strain effects through the use of a “dummy panel.” Figure H-33 shows the panel before testing, at maximum load, and after testing.
Figure H-33 Progress photos of the third fiberglass honeycomb panel test. From left to right, pictures are before the testing, at the maximum loading (90 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

Test four was performed on the same day, directly after test three, so all of the setup did not change. The half-bridge setup negated the thermal strain effects through the use of a “dummy panel.” Figure H-34 shows the panel before testing, at maximum load, and after testing.
Test five was performed on the same day, directly after test four, so all of the setup did not change. The half-bridge setup negated the thermal strain effects through the use of a “dummy panel.” Figure H-35 shows the panel before testing, at maximum load, and after testing.
Figure H-35 Progress photos of the fifth fiberglass honeycomb panel test. From left to right, pictures are before the testing, at the maximum loading (90 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

After all five runs of testing, the team had the following data: manually-measured deflection values at each weight increment, and strain values for the entire duration of testing. Each side of the panel develops a strain value that is the sum of three components: axial strain, bending strain, and thermal strain. Axial strain should be equal on both sides, bending strain should be equal and opposite on both sides, and thermal strain is dependent of the temperature of each side of the panel. Through the use of the half-bridge testing setup with a dummy panel, the team successfully negated the thermal strain effects from the recorded data. As such, Channel 3 recorded the sum of the axial
and bending strain on the top side of the panel, and Channel 4 recorded the difference of the axial and bending strain on the bottom side of the panel.

For the analysis of this panel, the team summed the data from the two channels, which resulted in a value that is two times the total bending strain in the panel. Then, the team divided the strain values by two in order to get the bending strain for the whole panel. The resulting fiberglass honeycomb panel strain data is shown in Figure H-36, and the resulting deflection data is shown in Figure H-37. Applied moment values were generated by multiplying the weight added by the distance of the weights from the fixed end of the panel.

![Cumulative Cantilever Bending Strain Results for Fiberglass Honeycomb Panel](image)

Figure H-36 Applied Moment vs. Bending strain for the Fiberglass Honeycomb Panel. Data shown for five runs of the testing and an average of all data. Data was collected while putting weights on (upwards triangle symbols) and taking weights off (downwards triangle symbols). Slopes represent the bending stiffness calculated for each run, calculated with liner curve fit.
Figure H-37 Applied Moment vs. Deflection for the Fiberglass Honeycomb Panel. Data shown for five runs of the testing and an average of all data. Data was collected while putting weights on (upwards triangle symbols) and taking weights off (downwards triangle symbols). Note: the unquantifiable effects of rigid body rotation were not factored into the data, and therefore the displayed data is not fully accurate.
Appendix I  Iteration 1 Manufacturing and Testing

Eltahry allowed the team to utilize some of his corrugated composite core molds from previous projects he had performed. Figure I-1 shows the molds that were available for the fabrication of the team’s panel. Under Eltahry’s guidance, the team selected the rounded mold, as this one would be easiest to mold and demold with carbon fiber.

![Figure I-1 Selection of a corrugated mold. (left) Aerial view of trapezoidal mold, (middle) side view of trapezoidal mold, (right) side view of rounded mold.](image)

Next, the team used a spare piece of breather to get the dimensions of a carbon fiber sheet needed to make an approximately 12”x12” corrugated core. This process is shown in Figure I-2, and the cutting of the sheets is shown in Figure I-3. Eltahry recommended that the team use three carbon fiber sheets for the core.

![Figure I-2 Using a scrap piece of breather to get the required carbon fiber sheet size. (left) breather loosely laid on mold, (middle) simulating final composite shape by pressing into mold, (right) piece with ruler for size reference.](image)

As the sheets were being cut, the mold surface was prepared for the wet layup. Figure I-4 shows the application of sealer, nano release film, and wax to the aluminum mold. The three coats of sealer and three coats of nano release film were applied to the surface with a ten-minute drying time between applications. Wax was applied twice over the surface of the mold until no visible clumps of wax remained. The team applied all the coatings to the area of interest for the layup, so parts of the mold surface far from the layup were not covered.
Figure I-3 Cutting carbon fiber plies. (left) measuring the 12.5”x16” plies, (middle) plies cut from roll, (right) three plies weighing 45g.

Figure I-4 Preparation of mold surface. (top row from left to right) sealer and release film used, wax used, applying three coats of the sealer then release film, (bottom row from left to right) applying the wax, the final mold ready for layup.

To streamline the curing process, the vacuum bag for the part was prepared before the layup was performed. Figure I-5 shows the team taking a large section of vacuum bag and turning it into a rectangular prism by making corners in the bag with gum tape. This allows for the bag to be far enough off the work surface to properly compress the mold on all sides and ensure enough extra bag to reach into the channels of the mold.
After that, the team created pleats in the edges of the vacuum bag to allow for extra material to hug the surface of the mold when a vacuum is pulled. There are no photos of creating this, but it is more easily seen later in the process. The team also used Acetone to clean the surface and prepare for setting up the vacuum bag procedure.

After all the vacuum materials and the work surface were prepared, the team began the layup. First, the team measured out the proper ratio of resin and hardener, as seen in Figure I-6. The amount of epoxy used is useful in the eventual calculation of the fiber-weight fraction of the final composite part. Then the team performed the wet layup on a separate piece of vacuum bag and transferred the fully-wetted sheet to the corrugated mold, as seen in Figure I-7.

With the carbon fiber in the mold, Figure I-8 shows the team carefully placing a breather onto the carbon and pressing the carbon fiber into the channels of the mold. After this, the team placed the prepared vacuum bag over the work surface and pulled vacuum. The team made sure that the vacuum bag hugged the interior corners of the channels as closely as possible, but the team realized
they did not give enough extra space on the work surface to provide themselves enough extra vacuum bag. As a result, the section on the interior radii of the channels was less than desired.

Figure I-7 Preparing the corrugated core layup for molding. (from left to right) the first layer of carbon fiber on a vacuum bag sheet, the wetted stack of all three plies, trimming the vacuum bag sheet to fit on the mold, laying the wetted sheet on the mold.

Figure I-8 Molding and vacuum bagging the corrugated carbon fiber core. (top row) transferring and pressing the carbon fiber into the mold, placing a breather on top, adhering the vacuum bag to the plate, (bottom row) adjusting the pleats in the vacuum bag and securing them down, profile view of vacuum bag before pulling vacuum.
The part was then left to sit for two days to cure under vacuum. The part was removed from the mold by another senior team without the knowledge of this senior project team. The final corrugated core is shown in Figure I-9. As seen, the part is far from perfect. There are multiple dry spots where resin did not fully saturate through the layers during curing. However, there is still excess epoxy forming a border around the core. As will be shown in future images as well, not all of the channels are a uniform shape due to the inadequacy of the vacuum setup in pressing the core into the mold during the curing process.

![Figure I-9 Corrugated composite core with multiple view to show imperfections. (top row) views of core side that touched the breather and have few imperfections because they were in contact with the breather, (bottom row) views of core side in contact with the mold that have many imperfections and dry areas due to lack of vacuum pressure against interior corners of mold.](image)

Even with the surface preparation for the layup, resin still adhered to the mold during the curing process. Figure I-10 shows some spots of resin on the mold after demolding and the process of cleaning the mold to ensure it is ready for the next user.
Using the corrugated core manufactured in this iteration and the flat panel from Iteration 0 – shown in Figure I-11 – the team used a structural adhesive – shown in Figure I-12 – to begin the corrugated panel construction. The team measured out the proper ratio of the structural adhesive using a manual scale to ensure enough resolution to get the correct mixture ratio. The image also shows the amount of structural adhesive remaining after the process, which is useful information when analyzing the final composite panel weight.

Figure I-11 Composite skin used for one side of corrugated panel. This is repurposed from the previous iteration. Instead of testing this 9-layer panel, the team used it for the corrugated panel.
Figure I-12 Measuring out structural adhesive for skin bonding to corrugated core. (top row) structural adhesive with 77:100 B:A mixture ratio used to bond skin to corrugated core, (middle row from left to right) balancing scale with cup at 5 grams, adding approximately 31g of Part B, adding approximately 23 grams of Part A, (bottom row) mixing adhesive, and approximately 16.5 grams of leftover adhesive after bonding process.

To ensure the core did not flex during the adhesion of the top surface, the team placed the corrugated core in the mold and attached the top surface as shown in Figure I-13. The team cleaned all mating surfaces with Acetone, applied the structural adhesive to the raised parts of the channels, and weighed the part down for the curing time.
On the same day, the team performed the layup for the second side of the panel. This would allow for the team to do structural adhesive on the other side during the next lab period. Figure I-14 shows the preparation of the carbon fiber sheets in a similar fashion as done for the flat panel of Iteration 0. The sheets were this time 14”x14” to ensure enough extra for full panel coverage. The mixing of the epoxy is shown in Figure I-15, and the layup is shown in Figure I-16. There was no extra epoxy during the layup of the second skin for the corrugated panel.
Figure I-14 Layup preparation for second skin of corrugated core panel. (left) nine carbon fiber sheets for layup, (middle) total weight of sheets is 117 grams, (right) placing first ply on a vacuum bag surface in preparation for a layup.

Figure I-15 Mixing epoxy for layup of second skin of corrugated core panel. This resin amount was used six times during the layup. The total amount of epoxy used was 148 grams. (left) 20 grams of West Systems 105 Epoxy Resin, (right) added four grams of West Systems 205 Hardener to meet the 5:1 ratio.

Figure I-16 Wet layup of second skin of corrugated core panel. (from left to right) nine layers of carbon fiber, adding breathers, adding a protective vacuum bag layer, adding a metal plate to distribute weight across entire part, adding 140 pounds of weight for curing process.
After two days, the team returned and removed the partially-complete panel from the mold once more, as seen in Figure I-17. Due to shifting of the panel while applying the weight, there was some misalignment in the skin and core. This would alter be trimmed from the panel.

![Figure I-17 First half of corrugated core panel. (left) panel after weights removed after curing, (middle) lifting panel out of mold, (right) close-up view of slight misalignment of skin with core due to sliding while weights were applied.](image)

Additionally, the team removed the second skin from the weights and weighed that panel, as seen in Figure I-18. The panel suffered from some sever dry areas near the edges of the sheet due to a focus on proper wetting and adhesion of the central areas during the layup process. The team was later able to remove most of these dry spots by trimming the edges of the panel. This carbon fiber skin could immediately be used for the other side of the corrugated core panel.

![Figure I-18 Finalized second skin for corrugated core panel with skin weight. (top row from left to right) panel cured under weights, weights removed, metal plate removed, vacuum bag layer removed, breathers removed, (bottom row) close ups of dry portions of panel, and photo showing panel weight of 265 grams.](image)
In addition to the process used for the first skin adhesion, the team sanded the raised channels of the core on this side of the panel in an attempt to get an even stronger bond. Figure I-19 shows the sanded channels. Then, the team mixed the structural adhesive, Figure I-20, and bonded the skin to the corrugated core, Figure I-21, in the same manner as was done for the previous side. The team bonded to the rougher side of the flat panel for the same reasons as they sanded the channels.

Figure I-19 Preparing corrugated core surface for skin bonding. (left) side of panel skin will bond to, (middle) roughing the bonding surface with 220 grit sandpaper, (right) final roughed surface that is ready for bonding.

Figure I-20 Measuring structural adhesive for bonding. Using the same structural adhesive, (top row) weighing out the proper ratios to total approximately 67 grams of adhesive, (bottom row) mixing adhesive, and approximately 30.5 grams of leftover adhesive after adhesive application.
Figure I-21 Bonding second skin to corrugated core panel. (from left to right) cleaning core surface with acetone, cleaning the skin, applying structural adhesive to the core, placing the skin on with the same technique as last time and placing a protective vacuum bag layer down, placing down a metal plate and 80 pounds of weight to apply pressure while curing.

After two days, the team removed the final panel from the weights, as seen in Figure I-22. The overall bonding between the skins and corrugated core was inconsistent, as detailed in Figure I-23. This is more easily identified after the trimming of the panel.

Figure I-22 Corrugated panel after final skin adhesion. (left) weights still on part, (middle) weights removed, (right) protective vacuum bag layer removed.
Figure I-23 Analysis of skin bonding. Close-ups of bonding regions along the panel show more adhesive on some ridges than others. This problem is more thoroughly examined after the panel has been trimmed.

The team weighed the final panel, Figure I-24, and prepared it for trimming the edges. Figure I-25 shows the team preparing and trimming the panel to 12.75”x11”. The was not perfectly square, which caused some later trouble during strain gage application. The panel was then reweighed and the bonding between the skins and core could be more easily analyzed. Figure I-26 shows examples of good and bad bonding fillet radii with the structural adhesive. The team desired a structural adhesive fillet radius similar to a weld because of the mechanical advantages of that shape.
Figure I-24 Corrugated core panel weight and dimensions before trimming. (left) panel weighs 781 grams, (middle and right) panel is approximately 14x13 inches.

Figure I-25 Corrugated core panel dimensions and weight after trimming. (top row) panel trimmed to approximately 12.75x11.5 inches to remove all dry and frayed edges, (bottom row) side view of cut panel and final panel weight of 664 grams.

Figure I-26 Analysis of skin structural bonding on trimmed corrugated core panel. Images show that the bottom skin has a more desirable fillet at the skin-core interface when compared to the relatively flat and incomplete bond of the top skin. The top skin will likely have more issue with delamination.
After completion of the corrugated panel, the team began construction of the channel foam panel. This channel foam panel was eventually scrapped due to a poor layup, but a brief description of the manufacturing process the team used is included for posterity. This process involved cutting a 12”x12” piece of structural foam and marking the locations for the channels, as shown in Figure I-27. Additionally, three strips of foam were cut to be structurally adhered to the panel.

![Figure I-27 Structural foam preparation for channeled foam core panel.](image)

As shown in Figure I-28, the team used the same structural adhesive as the corrugated core panel to create the channeled foam panel. Figure I-29 shows the carbon fiber used to create the panel and the final product. Because the team did not use the vacuum method, the resulting surface finish was very poor. Additionally, some areas of the surface were still dry fibers, which means those areas would not properly hold any loading. The team deemed the panel not suitable for testing and did not complete the other side.
At this point, the team began to test the corrugated core panel. Utilizing the testing procedure from the previous iteration, the team tested the corrugated core panel five times. Note: this test was performed before the fiberglass honeycomb panel. As such, this test has the same half-bridge error as the paper honeycomb panel because the team had not yet caught that error. Therefore, the data from channel 4 is useless because the “dummy panel” was improperly used, and the team accidentally measured two times the bending strain for each panel instead of negating the effects of thermal strain. The testing procedure for the corrugated core panel was identical to the other panels.

Figure I-30 shows the setup of test one for the corrugated core panel. Figure I-31 shows the attempted half-bridge setup for measurement of strain. The team made the same mistake as the paper honeycomb tests. Therefore, the data from channel 4 is useless, and the “dummy panel” was improperly used. Figure I-32 shows the panel before testing, at maximum load, and after testing. For the testing of this panel, maximum weight was drastically reduced, as the unwrapped edges of the panel left the panel more prone to delamination. The team heard a “pop” sound during the first
test and subsequently limited the maximum load on the panel. Consequently, the team did not use the data from the first test, so it is referred to as “test zero.” The loading data was still sufficient to characterize the linear elastic region of the panel stiffness.

Figure I-30 Setup of the zeroth corrugated core panel test fixturing. (top row) ensuring strain gage is perpendicular to testing fixture, ensuring the two side of the testing fixture are parallel (~7.5” separation), ensuring the weight hook sits in the center of the panel, (bottom row) distance of strain gage from the testing fixture (~2.09375”). The team leveled the fixture, but there are not photos to show it. Note: the load end fixture was accidentally placed backwards for this test.

Figure I-31 Setup of the zeroth corrugated core panel test strain measurement. Here, the half bridge was incorrectly set up. Instead of negating thermal effects, the team accidentally subtracted the bottom from the top of each respective panel. As such, the team measured double the bending strain of each panel instead.
Figure I-32 Progress photos of the zeroth corrugated core panel test. From left to right, pictures are before the testing, at the maximum loading (70 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

Test one was performed on the same day, directly after test zero, so all of the setup did not change. The team made the same mistake as test one. Therefore, the data from channel 4 is useless, and the “dummy panel” was improperly used. Figure I-33 shows the panel before testing, at maximum load, and after testing.
Figure I-33 Progress photos of the first corrugated core panel test. From left to right, pictures are before the testing, at the maximum loading (50 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

Test two was performed on the same day, directly after test one, so all of the setup did not change. The team made the same mistake as test one. Therefore, the data from channel 4 is useless, and the “dummy panel” was improperly used. Figure I-34 shows the panel before testing, at maximum load, and after testing.
Figure I-34 Progress photos of the two corrugated core panel test. From left to right, pictures are before the testing, at the maximum loading (50 pounds), and after all weights were removed. Note: the team forgot to take picture of the weights and gap for the max loading. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

Figure I-35 shows the setup of test three for the corrugated core panel. Figure I-36 shows the attempted half-bridge setup for measurement of strain. The team made the same mistake as the paper honeycomb tests. Therefore, the data from channel 4 is useless, and the “dummy panel” was improperly used. Figure I-37 shows the panel before testing, at maximum load, and after testing.
Figure I-35 Setup of the third corrugated core panel test fixturing. (top row) the number of washers used on the fixed end, leveling the fixed end, ensuring strain gage is perpendicular to testing fixture, ensuring the weight hook sits in the center of the panel, (bottom row) ensuring the two side of the testing fixture are parallel (~7.5” separation), distance of strain gage from the testing fixture (~2.125”). Note: the load end fixture was accidentally placed backwards for this test.

Figure I-36 Setup of the third corrugated core panel test strain measurement. Here, the half bridge was incorrectly set up. Instead of negating thermal effects, the team accidentally subtracted the bottom from the top of each respective panel. As such, the team measured double the bending strain of each panel instead.
Figure I-37 Progress photos of the third corrugated core panel test. From left to right, pictures are before the testing, at the maximum loading (50 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

Test four was performed on the same day, directly after test three, so all of the setup did not change. The team made the same mistake as test one. Therefore, the data from channel 4 is useless, and the “dummy panel” was improperly used. Figure I-38 shows the panel before testing, at maximum load, and after testing.
Figure I-38 Progress photos of the fourth corrugated core panel test. From left to right, pictures are before the testing, at the maximum loading (50 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

Test five was performed on the same day, directly after test four, so all of the setup did not change. The team made the same mistake as test one. Therefore, the data from channel 4 is useless, and the “dummy panel” was improperly used. Figure I-39 shows the panel before testing, at maximum load, and after testing.
After all five runs of testing, the team had the following data: manually-measured deflection values at each weight increment, and strain values for the entire duration of testing. Due to the improper setup of the testing apparatus, the measured strain data from Channel 3 is the only useful data. Each side of the panel develops a strain value that is the sum of three components: axial strain, bending strain, and thermal strain. Axial strain should be equal on both sides, bending strain should be equal and opposite on both sides, and thermal strain is dependent of the temperature of each side of the panel. Because the team accidentally configured the half bridge with both sides of the same panel, the resulting strain measured on Channel 3 is the difference of the strains on the top
and bottom sides of the panel. In this case, that results in a value that is the sum of a small amount of thermal strain two times the bending moment. The thermal effects in this case cannot be negated.

In order to do the analysis for this panel, the team needed to assume the thermal strain was negligible, which is incorrect. After this, the team divided the strain values from Channel 3 by two in order to get the bending strain for the whole panel. The resulting corrugated core panel strain data is shown in Figure I-40, and the resulting deflection data is shown in Figure I-41. Applied moment values were generated by multiplying the weight added by the distance of the weights from the fixed end of the panel.

![Cumulative Cantilever Bending Strain Results for Corrugated Core Panel](image)

Figure I-40 Applied Moment vs. Bending strain for the Corrugated Core Panel. Data shown for four runs of the testing and an average of all data. Only four runs are shown, as data from some runs was corrupted, incorrectly measured, or lost and had to be discarded from the set of analyzed data. Data was collected while putting weights on (upwards triangle symbols) and taking weights off (downwards triangle symbols). Slopes represent the bending stiffness calculated for each run, calculated with liner curve fit.

After testing the corrugated core panel, the project sponsor requested that the team perform a comparison between regular plywood and plywood wrapped in carbon fiber. The sponsor provided the team with two 12”x12” sheets of Baltic birch plywood. The team kept one panel as the sponsor provided and called it the plywood panel. Additionally, the team used the same layup method as the honeycomb panels to wrap the other sheet of plywood with three layers of carbon fiber on each side. This number of plies was recommended by Eltahry. The team called this panel the carbon
fiber-wrapped plywood panel. The team then applied strain gages to both of these panels to prepare them for testing.

![Cumulative Cantilever Bending Deflection Results for Corrugated Core Panel](image)

Figure I-41 Applied Moment vs. Deflection for the Corrugated Core Panel. Data shown for four runs of the testing and an average of all data. Only four runs are shown, as data from some runs was corrupted, incorrectly measured, or lost and had to be discarded from the set of analyzed data. Data was collected while putting weights on (upwards triangle symbols) and taking weights off (downwards triangle symbols). Note: the unquantifiable effects of rigid body rotation were not factored into the data, and therefore the displayed data is not fully accurate.

Utilizing the testing procedure from the previous iteration, the team tested the carbon fiber-wrapped plywood panel five times. This test was performed after the fiberglass honeycomb panel. As such, this test has the correct half-setup. The testing procedure for the carbon-fiber-wrapped plywood panel was identical to the other panels. All five tests were performed on the same day, so the testing setup was identical for all five tests and is only shown once.

Figure I-42 shows the setup of test one for the carbon fiber-wrapped plywood panel. Figure I-43 shows the half-bridge setup for measurement of strain. For this test, the half bridge was correctly utilized. As such, Channel 3 of the strain gage reader provided the sum of axial and bending strain for the top of the panel, and Channel 4 provided the sum of axial and bending strain for the bottom
of the panel. Thermal effects were negated through the use of the “dummy panel.” Figure I-44 shows the panel before testing, at maximum load, and after testing.

Figure I-42 Setup of the first carbon-fiber-wrapped plywood panel test fixturing. (top row) ensuring strain gage is perpendicular to testing fixture, ensuring the two side of the testing fixture are parallel (~8.75” separation), ensuring the weight hook sits in the center of the panel, (bottom row) distance of strain gage from the testing fixture (~2.0625”). The team leveled the fixture, but there are not photos to show it.

Figure I-43 Setup of the first carbon-fiber-wrapped plywood panel test strain measurement. Here, the half bridge was correctly set up. Thermal effects were negated through the use of a “dummy panel.” As such, the team measured the sum of axial and bending strain for the top and bottom of the testing panel on Channels 3 and 4, respectively.
Figure I-44 Progress photos of the first carbon-fiber-wrapped plywood panel test. From left to right, pictures are before the testing, at the maximum loading (90 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

Test two was performed on the same day, directly after test one, so all of the setup did not change. The half-bridge setup negated the thermal strain effects through the use of a “dummy panel.” Figure I-45 shows the panel before testing, at maximum load, and after testing.
Figure I-45 Progress photos of the second carbon-fiber-wrapped plywood panel test. From left to right, pictures are before the testing, at the maximum loading (90 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

Test three was performed on the same day, directly after test two, so all of the setup did not change. The half-bridge setup negated the thermal strain effects through the use of a “dummy panel.” Figure I-46 shows the panel before testing, at maximum load, and after testing.
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Figure I-46 Progress photos of the third carbon-fiber-wrapped plywood panel test. From left to right, pictures are before the testing, at the maximum loading (90 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

Test four was performed on the same day, directly after test three, so all of the setup did not change. The half-bridge setup negated the thermal strain effects through the use of a “dummy panel.” Figure I-47 shows the panel before testing, at maximum load, and after testing.
Figure I-47 Progress photos of the fourth carbon-fiber-wrapped plywood panel test. From left to right, pictures are before the testing, at the maximum loading (90 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

Test five was performed on the same day, directly after test four, so all of the setup did not change. The half-bridge setup negated the thermal strain effects through the use of a “dummy panel.” Figure I-48 shows the panel before testing, at maximum load, and after testing.
After all five runs of testing, the team had the following data: manually-measured deflection values at each weight increment, and strain values for the entire duration of testing. Each side of the panel develops a strain value that is the sum of three components: axial strain, bending strain, and thermal strain. Axial strain should be equal on both sides, bending strain should be equal and opposite on both sides, and thermal strain is dependent of the temperature of each side of the panel. Through the use of the half-bridge testing setup with a dummy panel, the team successfully negated the thermal strain effects from the recorded data. As such, Channel 3 recorded the sum of the axial
and bending strain on the top side of the panel, and Channel 4 recorded the difference of the axial and bending strain on the bottom side of the panel.

For the analysis of this panel, the team summed the data from the two channels, which resulted in a value that is two times the total bending strain in the panel. Then, the team divided the strain values by two in order to get the bending strain for the whole panel. The resulting carbon fiber-wrapped plywood panel strain data is shown in Figure I-49, and the resulting deflection data is shown in Figure I-50. Applied moment values were generated by multiplying the weight added by the distance of the weights from the fixed end of the panel.

![Cumulative Cantilever Bending Strain Results for Carbon Fiber Wrapped Plywood Panel](image)

Figure I-49 Applied Moment vs. Bending strain for the Carbon Fiber-Wrapped Plywood Panel. Data shown for five runs of the testing and an average of all data. Data was collected while putting weights on (upwards triangle symbols) and taking weights off (downwards triangle symbols). Slopes represent the bending stiffness calculated for each run, calculated with linear curve fit.
Next, the team tested the plywood panel. The testing procedure for the plywood panel was identical to the other panels. Figure I-51 shows the setup of test one for the plywood panel. Figure I-52 shows the half-bridge setup for measurement of strain. For this test, the half bridge was correctly utilized. As such, Channel 3 of the strain gage reader provided the sum of axial and bending strain for the top of the panel, and Channel 4 provided the sum of axial and bending strain for the bottom of the panel. Thermal effects were negated through the use of the “dummy panel.” Figure I-53 shows the panel before testing, at maximum load, and after testing.
Figure I-51 Setup of the first plywood panel test fixturing. (top row) ensuring the two side of the testing fixture are parallel (~7.75” separation), ensuring the weight hook sits in the center of the panel, (bottom row) distance of strain gage from the testing fixture (~1.9375”). The team leveled the fixture and ensured the strain gage was perpendicular to the fixture, but there are not photos to show it.

Figure I-52 Setup of the first plywood panel test strain measurement. Here, the half bridge was correctly set up. Thermal effects were negated through the use of a “dummy panel.” As such, the team measured the sum of axial and bending strain for the top and bottom of the testing panel on Channels 3 and 4, respectively.
Figure I-53 Progress photos of the first plywood panel test. From left to right, pictures are before the testing, at the maximum loading (130 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

The final four tests were performed on another day. Figure I-54 shows the setup of test two for the plywood panel. Figure I-55 shows the half-bridge setup for measurement of strain. For this test, the half bridge was correctly utilized. As such, Channel 3 of the strain gage reader provided the sum of axial and bending strain for the top of the panel, and Channel 4 provided the sum of axial and bending strain for the bottom of the panel. Thermal effects were negated through the use of the “dummy panel.” Figure I-56 shows the panel before testing, at maximum load, and after testing.
Figure I-54 Setup of the second plywood panel test fixturing. (top row) the number of washers used on the fixed end, ensuring the strain gage was perpendicular to the fixture, ensuring the two side of the testing fixture are parallel (~7.5” separation), (bottom row) distance of strain gage from the testing fixture (~2”). The team leveled the fixture and ensured the weight hook sat in the center of the panel, but there are not photos to show it.

Figure I-55 Setup of the first plywood panel test strain measurement. Here, the half bridge was correctly set up. Thermal effects were negated through the use of a “dummy panel.” As such, the team measured the sum of axial and bending strain for the top and bottom of the testing panel on Channels 3 and 4, respectively.
Figure I-56 Progress photos of the second plywood panel test. From left to right, pictures are before the testing, at the maximum loading (130 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading. Note: the team forgot to take pictures of the gap during and after testing.

Test three was performed on the same day, directly after test two, so all of the setup did not change. The half-bridge setup negated the thermal strain effects through the use of a “dummy panel.” Figure I-57 shows the panel before testing, at maximum load, and after testing.
Figure I-57 Progress photos of the third plywood panel test. From left to right, pictures are before the testing, at the maximum loading (90 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading. Note: the team forgot to take pictures of the weights during testing and the gap before testing.

Test four was performed on the same day, directly after test three, so all of the setup did not change. The half-bridge setup negated the thermal strain effects through the use of a “dummy panel.” Figure I-58 shows the panel before testing, at maximum load, and after testing.
Test five was performed on the same day, directly after test four, so all of the setup did not change. The half-bridge setup negated the thermal strain effects through the use of a “dummy panel.” Figure I-59 shows the panel before testing, at maximum load, and after testing.
After all five runs of testing, the team had the following data: manually-measured deflection values at each weight increment, and strain values for the entire duration of testing. Each side of the panel develops a strain value that is the sum of three components: axial strain, bending strain, and thermal strain. Axial strain should be equal on both sides, bending strain should be equal and opposite on both sides, and thermal strain is dependent of the temperature of each side of the panel. Through the use of the half-bridge testing setup with a dummy panel, the team successfully negated the thermal strain effects from the recorded data. As such, Channel 3 recorded the sum of the axial
and bending strain on the top side of the panel, and Channel 4 recorded the difference of the axial and bending strain on the bottom side of the panel.

For the analysis of this panel, the team summed the data from the two channels, which resulted in a value that is two times the total bending strain in the panel. Them, the team divided the strain values by two in order to get the bending strain for the whole panel. The resulting plywood panel strain data is shown in Figure I-60, and the resulting deflection data is shown in Figure I-61. Applied moment values were generated by multiplying the weight added by the distance of the weights from the fixed end of the panel.

Figure I-60 Applied Moment vs. Bending strain for the Plywood Panel. Data shown for five runs of the testing and an average of all data. Data was collected while putting weights on (upwards triangle symbols) and taking weights off (downwards triangle symbols). Slopes represent the bending stiffness calculated for each run, calculated with liner curve fit.
Figure I-61 Applied Moment vs. Deflection for the Plywood Panel. Data shown for five runs of the testing and an average of all data. Data was collected while putting weights on (upwards triangle symbols) and taking weights off (downwards triangle symbols). Note: the unquantifiable effects of rigid body rotation were not factored into the data, and therefore the displayed data is not fully accurate.
Appendix J  Iteration 2 Manufacturing and Testing

In this iteration, the goal was to utilize lightweight foams to try and maximize the stiffness-to-weight ratio of the panels. The first panel the team created was based on the designs shown in Figure J-1. The goal of this panel (called the thick foam panel) was to get the geometrical benefits of channels without the manufacturing complexity of the corrugated core panel from Iteration 1.

First, the team prepared the foam core, as shown in Figure J-2. First, the appropriate size panel of foam was cut from a larger sheet. Then, the team used a hand router to cut the channels into the surface of the foam on both sides. The team decided to have the channels equally spaced from the middle.

First, the team prepared the foam core, as shown in Figure J-2. First, the appropriate size panel of foam was cut from a larger sheet. Then, the team used a hand router to cut the channels into the surface of the foam on both sides. The team decided to have the channels equally spaced from the middle.
Next, the team did a carbon fiber layup on the core in a similar manner to previous iterations. The only difference for this iteration is the drastically lower number of layers and the layer distribution shown in Figure J-1. After wetting the layer of carbon fiber, the team draped them on the thick foam core and cut away the necessary material to properly drape the carbon fiber over the edges and hug the channels, as seen in Figure J-3. For each side, the team used the vacuum method to ensure the carbon fiber had small radii on the interior corners of the channels.

As the thick foam panel was being manufactured, the team also made the double thin foam panel. For this panel, the team aimed to create a panel like the one seen in Figure J-4. Thick foam was a redesign of the failed channeled foam design of Iteration 1, and the double thin foam panel was a second attempt at a design with the thin foam. This panel would hopefully have more rigidity than a single layer of foam, and incorporating a layer of carbon fiber between the foams would hopefully aid in adhesion without needing to mix a structural adhesive. At this point, there was no more structural adhesive to use.
With the design ready, the team created the entire double thin foam panel in one layup, as seen in Figure J-5. All the layers were cut and wetted before assembly on the final surface. The team used the vacuum method for this panel as well in order to have a uniform process with most of the panels.

![Figure J-5 Manufacturing the double thin foam panel. (left) cores with carbon fiber between and under, (right) draping top layer over the whole assembly.](image)

Specific details of both of these panels are found in the Iterative Design Chapter of the report. After the panels were completed, the team applied strain gages to both of the with the process outlined in Iteration 0.

The team encountered an issue with the thick foam panel and the strain gages. The team applied the strain gages in the center channels on the thick foam panel. When testing, the data was random and not representative of the type of data recorded from other panels. The team had to reapply strain gages to the exterior-most surfaces of the thick foam panel. After doing this, the team recorded regular, expected data from the strain gage reader.

Due to the thick foam panel manufacturing taking a long time and difficulties applying strain gages to the thick foam panel, the team tested the double thin foam panel first. The testing procedure for the double thin foam panel was identical to the other panels. Figure J-6 shows the setup of test one for the double thin foam panel. Figure J-7 shows the half-bridge setup for measurement of strain. For this test, the half bridge was correctly utilized. As such, Channel 3 of the strain gage reader provided the sum of axial and bending strain for the top of the panel, and Channel 4 provided the sum of axial and bending strain for the bottom of the panel. Thermal effects were negated through the use of the “dummy panel.” Figure J-8 shows the panel before testing, at maximum load, and after testing. All tests were performed on the same day, so the setup applies to all five tests.
Figure J-6 Setup of the first double thin foam panel test fixturing. (top row) ensuring the strain gage was perpendicular to the fixture, ensuring the two side of the testing fixture are parallel (~8” separation), (bottom row) ensuring the weight hook sits in the center of the panel, the number of washers used on the fixed end. Note: the team leveled the fixture and measured the distance of strain gage from the testing fixture (~1.9375”), but there are not photos to show it.

Figure J-7 Setup of the first double thin foam panel test strain measurement. Here, the half bridge was correctly set up. Thermal effects were negated through the use of a “dummy panel.” As such, the team measured the sum of axial and bending strain for the top and bottom of the testing panel on Channels 3 and 4, respectively.
Figure J-8 Progress photos of the first double thin foam panel test. From left to right, pictures are before the testing, at the maximum loading (90 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

Test two was performed on the same day, directly after test one, so all of the setup did not change. The half-bridge setup negated the thermal strain effects through the use of a “dummy panel.” Figure J-9 shows the panel before testing, at maximum load, and after testing.
Test three was performed on the same day, directly after test two, so all of the setup did not change. The half-bridge setup negated the thermal strain effects through the use of a “dummy panel.” Figure J-10 shows the panel before testing, at maximum load, and after testing.
Test four was performed on the same day, directly after test three, so all of the setup did not change. The half-bridge setup negated the thermal strain effects through the use of a “dummy panel.” Figure J-11 shows the panel before testing, at maximum load, and after testing.
Figure J-11 Progress photos of the fourth double thin foam panel test. From left to right, pictures are before the testing, at the maximum loading (90 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

Test five was performed on the same day, directly after test four, so all of the setup did not change. The half-bridge setup negated the thermal strain effects through the use of a “dummy panel.” Figure J-12 shows the panel before testing, at maximum load, and after testing.
Figure J-12 Progress photos of the fifth double thin foam panel test. From left to right, pictures are before the testing, at the maximum loading (90 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

After all five runs of testing, the team had the following data: manually-measured deflection values at each weight increment, and strain values for the entire duration of testing. Each side of the panel develops a strain value that is the sum of three components: axial strain, bending strain, and thermal strain. Axial strain should be equal on both sides, bending strain should be equal and opposite on both sides, and thermal strain is dependent of the temperature of each side of the panel. Through the use of the half-bridge testing setup with a dummy panel, the team successfully negated the thermal strain effects from the recorded data. As such, Channel 3 recorded the sum of the axial
and bending strain on the top side of the panel, and Channel 4 recorded the difference of the axial and bending strain on the bottom side of the panel.

For the analysis of this panel, the team summed the data from the two channels, which resulted in a value that is two times the total bending strain in the panel. Then, the team divided the strain values by two in order to get the bending strain for the whole panel. The resulting double thin foam panel strain data is shown in Figure J-13, and the resulting deflection data is shown in Figure J-14. Applied moment values were generated by multiplying the weight added by the distance of the weights from the fixed end of the panel.

![Figure J-13](image)

**Figure J-13** Applied Moment vs. Bending strain for the Double Thin Foam Panel. Data shown for five runs of the testing and an average of all data. Data was collected while putting weights on (upwards triangle symbols) and taking weights off (downwards triangle symbols). Slopes represent the bending stiffness calculated for each run, calculated with liner curve fit.
After applying strain gages in the center of the thick foam panel, the team tested the panel with the normal procedure. However, all the results were meaningless noise. The team hypothesizes that the data differed from other panels because the strain gages were not on the outmost surfaces of the panel. As such, the distance of the strain gages from the neutral axis of the complex geometry was likely a contributing factor to the randomness of the data. Because of this, the team applied new strain gages on the outermost surfaces of the panel and retested. The data from those tests was meaningful and consistent with the types of data seen on other panels. For reference, the procedure of the meaningless data is provided as test zero.

The testing procedure for the thick foam panel was identical to the other panels. Figure J-15 shows the setup of test zero for the thick foam panel. Figure J-16 shows the half-bridge setup for measurement of strain. For this test, the half bridge was correctly utilized. As such, Channel 3 of the strain gage reader provided the sum of axial and bending strain for the top of the panel, and Channel 4 provided the sum of axial and bending strain for the bottom of the panel. Thermal effects were negated through the use of the “dummy panel.” Figure J-17 shows the panel before testing, at maximum load, and after testing.
Figure J-15 Setup of the zeroth thick foam panel test fixturing. (top row) ensuring the strain gage was perpendicular to the fixture, ensuring the two side of the testing fixture are parallel (~7.75” separation), ensuring the weight hook sits in the center of the panel, (bottom row) the distance of strain gage from the testing fixture (~1.96875”). Note: the team leveled the fixture, but there are not photos to show it.

Figure J-16 Setup of the zeroth thick foam panel test strain measurement. Here, the half bridge was correctly set up. Thermal effects were negated through the use of a “dummy panel.” As such, the team measured the sum of axial and bending strain for the top and bottom of the testing panel on Channels 3 and 4, respectively.
On another day, after applying strain gages to the outer surfaces of the panel, the team performed all five tests of the thick foam panel, so the following setup applies to all five tests. Figure J-18 shows the setup of test one for the double thin foam panel. Figure J-19 shows the half-bridge setup for measurement of strain. For this test, the half bridge was correctly utilized. As such, Channel 3 of the strain gage reader provided the sum of axial and bending strain for the top of the panel, and Channel 4 provided the sum of axial and bending strain for the bottom of the panel. Thermal effects were negated through the use of the “dummy panel.” Figure J-20 shows the panel before testing, at maximum load, and after testing.
Figure J-18 Setup of the first thick foam panel test fixturing. (top row) ensuring the strain gage was perpendicular to the fixture, ensuring the two side of the testing fixture are parallel (~8” separation), ensuring the weight hook sits in the center of the panel, (bottom row) the number of washers on the fixed end, the distance of strain gage from the testing fixture (~2.03125”). Note: the team leveled the fixture, but there are not photos to show it.

Figure J-19 Setup of the first thick foam panel test strain measurement. Here, the half bridge was correctly set up. Thermal effects were negated through the use of a “dummy panel.” As such, the team measured the sum of axial and bending strain for the top and bottom of the testing panel on Channels 3 and 4, respectively.
Figure J-20 Progress photos of the first thick foam panel test. From left to right, pictures are before the testing, at the maximum loading (90 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

Test two was performed on the same day, directly after test one, so all of the setup did not change. The half-bridge setup negated the thermal strain effects through the use of a “dummy panel.” Figure J-21 shows the panel before testing, at maximum load, and after testing.
Figure J-21 Progress photos of the second thick foam panel test. From left to right, pictures are before the testing, at the maximum loading (90 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

Test three was performed on the same day, directly after test two, so all of the setup did not change. The half-bridge setup negated the thermal strain effects through the use of a “dummy panel.” Figure J-22 shows the panel before testing, at maximum load, and after testing.
Figure J-22 Progress photos of the third thick foam panel test. From left to right, pictures are before the testing, at the maximum loading (90 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

Test four was performed on the same day, directly after test three, so all of the setup did not change. The half-bridge setup negated the thermal strain effects through the use of a “dummy panel.” Figure J-23 shows the panel before testing, at maximum load, and after testing.
Figure J-23 Progress photos of the fourth thick foam panel test. From left to right, pictures are before the testing, at the maximum loading (90 pounds), and after all weights were removed. (first row) profile view of deflection, (middle row) closer look at fixed end of testing setup that shows some rigid body rotation of the panel within the testing fixture, (bottom row) further evidence of rigid body rotation evidenced by the gap developed between fixture and panel at maximum loading.

Test five was performed on the same day, directly after test four, so all of the setup did not change. The half-bridge setup negated the thermal strain effects through the use of a “dummy panel.” Figure J-24 shows the panel before testing, at maximum load, and after testing.
After all five runs of testing, the team had the following data: manually-measured deflection values at each weight increment, and strain values for the entire duration of testing. Each side of the panel develops a strain value that is the sum of three components: axial strain, bending strain, and thermal strain. Axial strain should be equal on both sides, bending strain should be equal and opposite on both sides, and thermal strain is dependent of the temperature of each side of the panel. Through the use of the half-bridge testing setup with a dummy panel, the team successfully negated the thermal strain effects from the recorded data. As such, Channel 3 recorded the sum of the axial
and bending strain on the top side of the panel, and Channel 4 recorded the difference of the axial and bending strain on the bottom side of the panel.

For the analysis of this panel, the team summed the data from the two channels, which resulted in a value that is two times the total bending strain in the panel. Then, the team divided the strain values by two in order to get the bending strain for the whole panel. The resulting thick foam panel strain data is shown in Figure J-25, and the resulting deflection data is shown in Figure J-26. Applied moment values were generated by multiplying the weight added by the distance of the weights from the fixed end of the panel.

![Cumulative Cantilever Bending Strain Results for Thick Foam Panel](image)

Figure J-25 Applied Moment vs. Bending strain for the Thick Foam Panel. Data shown for five runs of the testing and an average of all data. Data was collected while putting weights on (upwards triangle symbols) and taking weights off (downwards triangle symbols). Slopes represent the bending stiffness calculated for each run, calculated with liner curve fit.
Figure J-26 Applied Moment vs. Deflection for the Thick Foam Panel. Data shown for five runs of the testing and an average of all data. Data was collected while putting weights on (upwards triangle symbols) and taking weights off (downwards triangle symbols). Note: the unquantifiable effects of rigid body rotation were not factored into the data, and therefore the displayed data is not fully accurate.