Project Title: Enduro Camper Senior Project

Company Name: Enduro Campers

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Abstract

The Enduro Campers senior project team (Formerly known as Lobo Campers senior project team) was recruited by Mr. Leif Stein to assist in the design, manufacturing, and testing of the materials and components of his company’s expedition box camper. The two main focuses of the project, divided into two sub-teams, were on the testing and manufacturing process of the materials used in the camper, and on the design and analysis of the camper’s access door, step box, and other subsystems.

The focus of the materials analysis and manufacturing team was based around the design parameter to use composite sandwich panels for the majority of the camper structure as set by Mr. Stein. This made the manufacturing and analysis of the camper much more complex than if a homogeneous material such as aluminum was used for the structure’s body. This increase in complexity is because composites are more difficult than homogenous materials to manufacture, test, and analyze. Because of this, the company needed a standardized physical testing procedure as well as an optimized bonding process for the sandwich materials. In order to choose the combination of materials for the sandwich panel construction, the project required a material analysis through physical testing and development of an FEA material model. The program ABAQUS was used to model the sandwich panel and can be applied to future analyses that Mr. Stein will need for larger, specific sections of the camper’s structure under different loading cases.

The sub-component design & analysis team delivered a design for the door and step box of the camper that allows for maximum accessibility while maintaining the camper’s structural integrity while sealing the cabin from the elements. This design is also aesthetically pleasing, as these are the main visible components on the expedition box product. The design derived by our team was based on input from Mr. Stein, as well as the findings from the materials research team through analysis and physical testing. The manufacturing process of the step box was started and plans were handed to Mr. Stein for completion.

This final design report goes over the project’s scope of work, concept design development, final design choices, manufacturing, design verification, project management, and the conclusions and recommendations the team has for Mr. Stein and his developing company. The report also includes recommendations for future analysis that can be helpful to better understanding the sandwich material used in the construction of the camper.
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1. Introduction

Expedition box campers allow outdoor enthusiasts to save time and money by transforming their daily pick-up truck as a versatile, off road camper. These camping systems convert a pick-up truck into a configurable indoor-outdoor living area without sacrificing the mobility and 4x4 capability of the truck. An expedition box is a customizable RV-style camping solution that replaces the bed of a truck and maintains the balance between off road capability and convenient, comfortable camping. The box has a pop-top wedge assembly on the roof of the unit with a built in tent. The storage space lost in removing the truck bed is gained in other areas of the box such as internal storage space, roof, and rear mounting. A basic, barebones model of the Enduro Camper’s expedition box is shown in Figure 1.

By designing and building these pop up campers in a lightweight and compact fashion, off road driving capabilities can be maintained, which is something that traditional RVs have not been able to accomplish. This is however not a new idea. In recent years, companies have been constructing campers similar to the Enduro Camper in nature, however they have primarily used aluminum as their construction material. The main design goal for this project is to minimize the final weight of the product. To accomplish this, mainly composite materials are to be used in the construction of this product. Other camper shapes were considered, but ultimately the sponsor decided on the expedition box. Similar style campers are currently only manufactured in Germany, Spain, & Australia, but have recently been on the rise in popularity in U.S. markets. These systems are in high demand since they are obviously much more luxurious than a tent but much less cumbersome than a full RV. This balance in function is what truly makes the Enduro Camper expedition box unique.
This document begins with the presentation of the sub teams responsible for the development of each of the design processes for the Enduro Camper. The document outlines relevant background research on the direct competitors to the Enduro Camper business and emphasizes the weak design areas of other companies where Enduro Campers proves superior. A quality function design chart is included in the appendices section to highlight the differences between all of the market competitors. Relevant patents that exist were considered during the design process to ensure legality. A technical research section is included to highlight the many details that were considered for this project and outlines how the team navigated to make technical design choices. A boundary diagram is included to show the breakdown of responsibilities based on the developed engineering specifications for the Enduro Camper. A management plan is provided along with a timeline for future work. This report also goes into detail about the manufacturing of panels and testing fixtures, the detailed ASTM testing procedures, and the ABAQUS model made to simulate the sandwich panels. Finally, in the appendices section, key technical data sheets are provided for reference to show for the basis of the team’s technical product selection decisions.

After talking with Mr. Stein, the senior project group is more focused on the fabrication of individual composite panels than the construction of the camper itself. The group decided that testing different materials for the composite panels and the corresponding manufacturing processes involved is a good focal point for this project. The second group agreed to focus on the structural design and analysis of various subsystems of the camper including the camper door and a fold down step under the door that doubles as a storage box.

The Enduro Campers senior project team was divided into two sub-teams that undertook the following sub-projects listed below. Due to the changing business model of Mr. Stein, both teams initially focused their attention to the materials and manufacturing side of the camper. Later in the project, the structural team split off to work on the step box while the materials team continued on to create the ABAQUS model. The complete structural design of the assembled Enduro camper will most likely become the main focus for the next Enduro Campers senior project team.

- Sub-team/project #1: Material analysis & manufacturing
  - Members: Alexander Horst, Kevin Pickering, Ryan Shomsky

- Sub-team/project #2: Sub-assembly structural design & analysis
  - Members: Jackson Aplanalp, Luke Arana, Will Firestone
2. Background

The senior project team worked for a local company, Enduro Campers, formerly known as Lobo Campers, to help design and manufacture a pop up expedition box truck camper. Initially, producing a pop up style camper was the primary focus of Enduro Campers, however the business scope shifted more towards creating expedition box style campers that will be customizable and built to order. As a result, the scope of the project shifted more towards emphasising material selection and characterization of the composite panels rather than focusing on the overall structural design of the camper. The team also considered the design of the door and step box of the expedition box camper, which includes sealing for dust proofing. Figure 2 shows the initial SketchUp model for the Lobo Camper wedge camper. This concept model shows the camper body constructed of composite panels and also showcases the super-wide barn doors in the back. While this design was ultimately scrapped, it is still important that the team captures the same aesthetic and function while designing the new expedition box. The box should have the same essence of spaciousness, utility, and simplicity.

![Figure 2. Lobo Camper wedge-camper concept model](image)

Figure 3 illustrates a concept sketch for the original door design. Enduro Campers instead chose to build an expedition box and consequently the door’s location changed to be positioned on the side and does not require the same large width. Originally, the doors were designed to be very wide in order to preserve the storage functionality of a truck’s bed. Since the expedition box installation requires full removal of a truck’s bed, this design consideration was ultimately eliminated.
Figure 3. Barn door concept on Ford F-150

Through testing and analysis of the composite panels, the team characterized the mechanical properties, thus allowing future engineers of Enduro Campers to perform structural analysis and validation of camper designs. Similar expedition box style campers exist, but at this time, the market for such campers is still in its infancy and rapidly growing. The Enduro Camper is unique when compared to other competing companies due to its high customizability. In addition to the unique design features of the Enduro Camper, the fiber-reinforced plastic (FRP) composite panels used to construct it will be an industry first as well. Similar expedition box campers on the market rely heavily on aluminum as their primary structural material. The FRP panels employed in the Enduro Camper design produce comparable mechanical properties to these campers while reducing their weight. Due to the limited number of suppliers available in the United States, this project required custom FRP composite panel construction for the proposed design. This required extensive material research and testing to produce a panel that is suitable for the project’s design requirements.

2.1 Competing Products:

Previously, there were five existing products that the team considered as direct competitors to the Enduro Camper since they all incorporate the wedge top design. However, now that the project scope has shifted to focus on expedition box campers, the primary competitors consist of five companies that produce similar expedition box campers. The market research conducted by Leif Stein has shown that there is a high demand for the expedition box style camper, and none that are currently manufactured in the United States. This makes obtaining an expedition box style camper exceedingly expensive and time consuming for American customers due to shipping, customs, and other associated costs. For this reason, creating such a camper became the new focus for Mr. Stein’s business. Some of the main features and specifications of the direct competitors are listed in the following sections.
**Wedgetail Campers (AUS)**

Wedgetail Campers is an australian pop-top camper manufacturer. They have several different camper models in production, all of which require a complete removal of the truck bed. Most of the models are designed to expand in all directions as much as possible, creating a very large and comfortable space in the camper. [1]

![Figure 4. Wedgetail Camper](image)

**Supertramp Campers (US)**

Supertramp Campers is located in Colorado and is currently in the late stages of prototyping their campers. One note is that their campers have an expedition box design, but do not require the removal of the truck bed. This allows for easier removal of the camper, but comes at a cost of convenience and accessibility. Without a full-sized door, the Supertramp could be difficult to enter and exit. [2]

![Figure 5. Supertramp Camper](image)
**Tommy Campers (AUS)**

The Tommy Camper S-Range model is a custom camping box built on a custom truck bed. These products are built by a father son duo in Australia. They are made to order and are sold for anywhere between 25 and 40 thousand dollars. Specifications on the product’s weight and specific material are not available, but it is assumed that this product is quite heavy due to its boat-like construction. [3]

![Tommy Camper](image)

**Figure 6. Tommy Camper**

**Maltec (DEU)**

German company Maltec builds custom box campers on a catalogue of SUV style vehicles not available in the United States. These campers are extremely high quality, and should be seen as a benchmark product. Maltec vehicles are customizable, with lots of added options for solar power systems, water systems, and luxury cabin upgrades. [4]
2.2 Patent Research:

*Patent No. US7942464B2* is The Tonneau Pop-up Camper. It is a pickup truck pop-up camper used to convert a pickup truck into a hospitable camping living and sleeping space. The camper claims to not affect the truck's safety, visibility, aerodynamics, or economics. The camper is claimed to be able to be set up in less than a couple of minutes. The sleeping area is located on top of the truck bed. The living area is at ground level in an attached tent. This patented design shares many similar components to the Enduro Camper.

*Patent No. US9834374B2* is for a composite panel for air cargo containers. The panel is composed of a closed cell foam core, a surface skin, and fire-resistant fibers in a matrix resin. These composite panels are very similar to those used by the company Styromax which the founder of Enduro Campers, Leif Stein, plans to do business with and use similarly built panels.

*Patent No. US6013586A* is assigned to Dimension Polyant Sailcloth Inc. The patent describes a tent material with a resin coating with titanium dioxide for UV resistance. The tent material can be assigned many different colors with the applied coating. The material is claimed to retain its color and will not peel or flake over a long period of time. This tent material is similar to what may be used on the pop-up tent of the Enduro Camper due to the fact that the Enduro Camper will spend lots of time in harsh sunlight environments with UV exposure.

*Patent No. CN206749169U* is for insulating tent material. The patent describes a three-layer material made of oxford layers, graphene electric heating film, glass layers, heat insulation foam layers, and thermal insulation air bag. Tear resistance of the material is claimed to be good, and it is claimed to be suitable for extreme cold weather camping. This is of interest to the Enduro
Campers team because of the requirement for multiple camping environments that the camper must operate in. From hot desert climates to cold, snowy mountain climates, insulating the tent is extremely important for the user.

_Patent No. US20030015879A1_ is an interesting door latch design for use on trucks and certain sliding doors. The latch claims to prevent bursting open with vibrational or impact loads. The latch is a single rotary latch bar with ratchet steps and a locking arm that engages a strike and captures it as the door is moved into a latched position. The locking arm restrains the rotary latch bar so as to prevent it from releasing the strike.

2.3 Technical Research:

The material analysis and manufacturing team conducted material research to use for the overall structure which is mainly composed of sandwich panels of varying thicknesses in the core and skin material. There are many different cores and panel combinations that were considered for their strength and/or insulating properties. During production, the sandwich panels are constructed in house by Mr. Stein and a team of fabricators so it was important to choose a manufacturing method that does not incorporate the use of overly expensive specialty equipment. Table 1 lays out foams that were chosen mostly for their weight, strength, and insulating properties. The list of composite materials researched for the outermost portion of the sandwich panels can also be seen in Table 1. The composite skin chosen was based on its strength, impact resistance, and ability to withstand a harsh outdoor environment.

A critical component of the sandwich panel is the adhesion of the core to the outer composite skin. Delamination could occur in the panels if the wrong adhesive is used for the core and skin combination and also from the environment they are used in. The adhesive chosen has the ability to retain the bond between the skin to the core, and mitigates noise and vibration. A quality and repeatable manufacturing method was established for the application of the adhesive that joins the core to the skins and joins the panels together making up the overall structure of the camper.
### Table 1. Structural Composite Materials Data

<table>
<thead>
<tr>
<th>Core Materials</th>
<th>Brand Name</th>
<th>Standard Thickness</th>
<th>Standard Size</th>
<th>TDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>DOW Styrofoam XPS</td>
<td>1.0”</td>
<td>4’ x 8’ sheet</td>
<td>Appx. C</td>
</tr>
<tr>
<td>High Performance</td>
<td>DOW Styrofoam HIGHLOAD</td>
<td>2.0”</td>
<td>4’ x 8’ sheet</td>
<td>Appx. C</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Skin Materials</th>
<th>Brand Name</th>
<th>Standard Thickness</th>
<th>Standard Size</th>
<th>TDS</th>
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<tbody>
<tr>
<td>Standard 1</td>
<td>Vetroresina LD series</td>
<td>2.0 mm</td>
<td>8’ x 200’ roll</td>
<td>Appx. C</td>
</tr>
<tr>
<td>Standard 2</td>
<td>Vetroresina G series</td>
<td>2.0 mm</td>
<td>8’ x 200’ roll</td>
<td>Appx. C</td>
</tr>
<tr>
<td>High Performance</td>
<td>Optiplan Polydet HG</td>
<td>1.5/2.0 mm</td>
<td>8’ x 200’ roll</td>
<td>Appx. C</td>
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<table>
<thead>
<tr>
<th>Adhesives</th>
<th>Brand Name</th>
<th>Standard Thickness</th>
<th>Standard Size</th>
<th>TDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Adhesive</td>
<td>Teroson (Loctite) MS 939</td>
<td>-</td>
<td>570 ml tube</td>
<td>Appx. C</td>
</tr>
<tr>
<td>Activator</td>
<td>Teroson MS 9371 B</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Other components of the camper use the same or very similar composite sandwich panels such as compartments and doors. These sub-components fasten securely to the structure as well as seal off the inside from the elements. A solid method of fastening in combination with a good seal is critical in keeping the elements out. Various products for the purpose of sealing, fastening, latching, and hinging can be seen in Table 2 as well as few products that can be used to seal compartments, doors, and anything else exposing the interior to the elements.
### Table 2. Door Hardware, Sealing, and Component Data

<table>
<thead>
<tr>
<th></th>
<th>Brand Name</th>
<th>Type</th>
<th>Features</th>
<th>Material</th>
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</thead>
<tbody>
<tr>
<td><strong>Latches</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doors</td>
<td>Polar Hardware</td>
<td>Cam action lockable door latch</td>
<td>Locks both doors and top/bottom</td>
<td>Steel</td>
</tr>
<tr>
<td>Components/ wedge top</td>
<td>JW Winco</td>
<td>Heavy Duty Toggle Latch</td>
<td>Latches one component to another</td>
<td>Steel</td>
</tr>
<tr>
<td><strong>Sealing</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Around door</td>
<td>McMaster Carr</td>
<td>Push on seal with bulb on side</td>
<td>Positive locking around door edge</td>
<td>EPDM Foam</td>
</tr>
<tr>
<td>Door edge</td>
<td>McMaster Carr</td>
<td>Hollow surface mount</td>
<td>Seals where doors come together</td>
<td>EPDM Rubber</td>
</tr>
<tr>
<td>Threshold</td>
<td>McMaster Carr</td>
<td>Push on rubber wiper</td>
<td>Seals threshold with wiper. Strong mounting</td>
<td>EPDM Rubber</td>
</tr>
<tr>
<td>Windows</td>
<td>Henkel Teroson RB 477</td>
<td>Extruded</td>
<td>Adheres and seals.</td>
<td>Multipolymer</td>
</tr>
<tr>
<td><strong>Hinges</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Door</td>
<td>McMaster Carr</td>
<td>Full surface mount</td>
<td>Lift off hinge</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Door</td>
<td>McMaster Carr</td>
<td>Mortice mount</td>
<td>Lift off hinge</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Door</td>
<td>McMaster Carr</td>
<td>Full surface mount</td>
<td>Full length Piano style</td>
<td>Stainless Steel</td>
</tr>
</tbody>
</table>

### 3. Objectives

#### 3.1 Problem Statement:

Enduro Campers is a wedge camper manufacturer for pick-up trucks. At the time of this project, the company was in the early prototyping phase and needed engineering support in the material selection and structural analysis of the camper. The camper and its components need to be lightweight but sturdy enough to withstand the high demands of an off-road driving environment. Current truck mounted campers do not provide enough accessibility by having a rear crossbar blocking the top of the entrance and do not allow the user to enter the camper without crouching and discomfort.
The problem statement changed as the company shifted from wedge-top campers to expedition boxes. The sub-team projects below however stayed accurate.

**Sub-team/project #1**: Material analysis & manufacturing  
This team focused on the composite sandwich material manufacturing, testing, and analysis in ABAQUS. The sub-team determined the best process for bonding FRP to the closed cell foam to create the sandwich panels used in the construction of the expedition box. The sub-team also investigated methods to analyze the material with both physical tests as well as Finite Element Analysis (FEA).

**Sub-team/project #2**: Sub-assembly structural design & analysis  
This team focused on the design and selection of a variety of components for the side door and step box of the expedition box camper. This team centered around the door and step box structures as well as the latching, hinging, and sealing componentry. The door needs to be lightweight yet strong and also must match the overall build quality and strength of the camper itself.

3.2 Boundary Diagram:

Figure 8 shows the boundary diagram illustrating the responsibilities of Mr. Stein’s Enduro Campers team, the senior project team and the overlap between these responsibilities.

*Note that since the inception of this boundary diagram some changes have been made. The doors are no longer “rear doors” but rather a single side door, and sub-team #2 is also responsible for the step box sub-system as well. Sub-team #2 planned to also focus on the locking mechanisms and positive pressurization of the camper, but these projects were later determined not to be an immediate priority by the sponsor. The focus of this team was primarily on the step box and door structures of the camper.*
3.3 Customer Wants:

The Enduro Camper needs to be lightweight, able to withstand off-road driving conditions, and needs to support static loads both on top and on the rear of the structure. The door needs to fit and seal snugly to the structure, as to minimize rattling and vibration damage when driving. A tight seal will also prevent any dirt or outside particle debris from entering the cabin space. Mr. Stein wants the door to open vertically, with stairs that deploy from the bottom door for ease of entering and exiting. The weight of the top door should be held by hatch struts when in use. The door should lock electronically. The final product should have a remote locking system integrated into the electronic power locking system of the vehicle. There should only be one locking mechanism that locks the entirety of the vehicle.

Changes to the door design were made due to the complexity of the sealing and latching of a vertical split door. A simpler off-the-shelf product was decided upon. The stair/step under the door remains a similar concept.

3.4 QFD Process:

Creating the QFD in Appendix A involved listing the needs and wants of Mr. Stein for this wedge camper, and then thinking of specific engineering specifications that would be needed to attain the customer requirements. The customer wants were weighted on the basis of the desires.
of the actual user/camper, the desires of the installation technician, and the marketing potential of each want. Then a list of the six top competitors was made, and as a team it was discussed how well each competitor met both the wants of Mr. Stein, and the engineering specifications that the team created. The house of quality was then used to generate specific objectives for the project. This QFD process was completed for the wedge-camper design, and all of the specific information found in Appendix A may not apply to the expedition box design.

3.5 Engineering Specifications:

Given that the camper is to be attached to a vehicle for on and off-road use there were important, high risk specifications that needed to be addressed. These high-risk specifications included weight, cost, and safety of the user and others on the road. The safety of the user and others cannot be defined directly so the team analyzed the specifications laid out in Table 3 that allowed the team to design a safe product.

Since the teams focused on smaller scale projects and not a completed camper, the engineering specifications listed below became mostly irrelevant and therefore were not progressed. The specifications however are still important for the overall completion of the camper and could be used in the future.

Engineering specifications measurement and analysis:

- Weight: The structure and its components were weighed as the project progressed. Components on hand were simply weighed on a scale and data was collected from manufacturers for components we had not yet had access to.
- Production cost: A spreadsheet was made and revised continually as the project moved forward, tallying all purchases made. (Mr. Stein handled the expenses for the project)
- Driving speed: No visual stress in the structure, doors, top etc. is to be seen at 80 MPH under normal weather conditions (i.e. less than 30 MPH crosswinds). Cameras can be placed under the structure to monitor vehicle movement during high speed, on-road use.
- Rear door static load: With the door(s) fully opened, a static load is placed on the furthest point of the door and vertical displacement measured at the furthest point. Horizontal displacement is measured at the top and bottom of the door where it connects to the rear of the structure.
- Camper top static load: Static load is placed on the top of the camper in various locations and the vertical displacement measured in various places around the camper, mainly inside near the middle and the cantilevered portion over the cab.
- Tent wind load: With the wedge camper up and in a windy environment, cameras and other various measurement devices observe the wind speed and displacement of the tent and pop-up portion. A visual inspection is made to ensure no ripping or separation of the tent material and its components from the camper itself.
Table 3. Engineering Specifications

<table>
<thead>
<tr>
<th>Spec. #</th>
<th>Specification Description</th>
<th>Requirements or Target</th>
<th>Tolerance</th>
<th>Risk</th>
<th>Compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Weight</td>
<td>350 lb</td>
<td>Max</td>
<td>High</td>
<td>I</td>
</tr>
<tr>
<td>2</td>
<td>Production Cost</td>
<td>$10,000</td>
<td>Max</td>
<td>High</td>
<td>A</td>
</tr>
<tr>
<td>3</td>
<td>Driving speed</td>
<td>80 mph</td>
<td>Max</td>
<td>Low</td>
<td>T</td>
</tr>
<tr>
<td>4</td>
<td>Rear door static load</td>
<td>100 lb</td>
<td>Min</td>
<td>Medium</td>
<td>T, A</td>
</tr>
<tr>
<td>5</td>
<td>Camper top static load</td>
<td>500 lb</td>
<td>Min</td>
<td>Medium</td>
<td>T, A</td>
</tr>
<tr>
<td>6</td>
<td>Tent wind load</td>
<td>50 mph</td>
<td>Min</td>
<td>Medium</td>
<td>T, I</td>
</tr>
</tbody>
</table>

It should be noted that in Table 3 the information listed for “requirements or target” is no longer accurate. These were idyllic values chosen by Leif Stein for his original wedge-camper design. The expedition box is much larger and will require more material, meaning that even with mostly composite construction, the box is likely to be heavier and more expensive than the original target value. However, the nature of the specifications has stayed the same. While exact target values are currently unknown, the design of the Enduro Campers expedition box is desired to be as light as possible and thus minimizing the application of any metal materials in the construction of this box.

The door for the expedition box is no larger than 52” in height, 26” in width, and 1” thick. These dimensions are constrained by the dimensions of the box wall itself where the door is located. This door opens vertically, with the top part opening first and bottom opening second. This opening design will be referred to as a “clam-shell” door. The top door is held up in place, while the bottom folds out into a step or stair to increase the ease of entry. Values for the size ratio between the top and bottom door are calculated based on ergonomics and vehicle clearance measurements. The distance from the bottom of the expedition box and therefore the bottom of the door is 31” based on the size of a 2017 Ford F150 with larger than stock tires. The distance from the first step of the bottom door stair to the ground is roughly 10”. It is assumed that the top and bottom sections of the door are roughly the same size. The area of the floor near the door has a rectangular section cut out of it in order for the bottom door to swing properly. The door structure is manufactured by panels cut out from the expedition box wall. Given this plan, the walls of the box are built, a section cut out for the door, and the material cut out in this process used as the base for the door construction. This cut out panel is edged with aluminum extrusions and customized with hardware, sealing, and finishing features.
4. Concept Design Development

In order to manufacture and test the FRP panels used in constructing the camper body, the team first considered what combination of panel, foam, and adhesive would result in the optimum panel for the construction of the project. To do this, the team considered the options and created decision matrices for the adhesive and foam components as shown in Tables 4 and 5. Leif Stein selected the material of the panels to be Vetroresina LD series woven fiberglass.

Table 4. Decision Matrix for Adhesive

<table>
<thead>
<tr>
<th>CRITERIA</th>
<th>ADHESIVE ALTERNATIVES</th>
<th>Weight</th>
<th>Teroson MS 939</th>
<th>Teroson MS 5510</th>
<th>Teroson MS 935</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength</td>
<td>0.30</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>0.25</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Temperature Range</td>
<td>0.10</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Manufacturability</td>
<td>0.20</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Curing Time</td>
<td>0.05</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Elasticity</td>
<td>0.10</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1.00</td>
<td>22</td>
<td>21</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Weighted total</td>
<td></td>
<td>3.8</td>
<td>3.5</td>
<td>3.4</td>
<td></td>
</tr>
</tbody>
</table>

None of the adhesive products listed in Table 4 ended up being used in the manufacturing of the panels. Mr. Stein was having issues with the adhesive supplier and took his business from Henkel to 3M. Because of this change, the 3M adhesive equivalent to the Teroson MS 939 called Scotch-Weld Toughened Epoxy Adhesive LSB60NS was used in its place. After discussion with a 3M representative, it was determined that their alternative product is essentially identical to the Henkel Teroson product. The 3M supplier recommended another 3M contact adhesive called Fastbond Contact Adhesive 30NF that was also used in the manufacturing and testing of the panels.

Table 5. Decision Matrix for Foam

<table>
<thead>
<tr>
<th>CRITERIA</th>
<th>FOAM ALTERNATIVES</th>
<th>Dow XPS Foams</th>
<th>15psi</th>
<th>25psi</th>
<th>40psi</th>
<th>60psi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weight</td>
<td>15psi</td>
<td>25psi</td>
<td>40psi</td>
<td>60psi</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>0.4</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Strength</td>
<td>0.4</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Manufacturability</td>
<td>0.2</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1</td>
<td>11</td>
<td>13</td>
<td>10</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Weighted total</td>
<td>3.4</td>
<td>4.2</td>
<td>3.6</td>
<td>3.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
After analyzing the importance of the criteria for both the foam and adhesive selection, the team completed the decision matrices and obtained a general idea of how the panels will be constructed. As shown in the above tables, the team approximated that the Teroson MS 939 is the most effective adhesive, and that 25 psi Dow XPS Foam is the best foam for manufacturing the sandwich panels for the Enduro Camper. Once manufactured, the priority of the materials team shifted to characterizing the sandwich panel in ABAQUS.

For panel testing procedures, the team decided to follow ASTM standardized tests. ASTM has been producing tests for many years which are widely used in industry. The specific test designations followed were the C393 and D7249 standardized tests. The C393 is a test for core material properties and the D7249 is a test designed for face sheet properties. These two tests gave the team insight in determining the most suitable sandwich panel construction for the loading cases. In order to not produce extra variables in these tests, coupons were prepared uniformly and test conditions remained unchanged. Each coupon was cut from manufactured panels using a track saw supplied by the sponsor and a minimum of 5 specimens per test condition were tested as recommended by ASTM. The team utilized the composites lab and the Ametek LD50 to conduct the tests.

The C393 test method determines core shear properties of sandwich panels. Bending moments are applied normal to the plane of the sandwich panel to produce force versus deflection measurements. Since only core properties are analyzed with the C393 test, failure modes due to the sandwich panel facings are not acceptable; the only failure modes allowed are core shear or core to face sheet bonds (delamination). To conduct the tests, the team used a standard 3-point, mid span bend test as shown in Figure 10. To ensure proper failure modes, equations for the core shear strength and core compression strength are given by ASTM (shown in Figure 10) and are ideally satisfied. After completing an analysis of these equations with the material properties obtained (shown in Appendix G), the equations did not converge on a single span length. It was calculated that a coupon of span less than 32 inches was needed to satisfy the $F_s$ equation and greater than 101 inches to satisfy the $F_c$ equation. This was not ideal since some trial and error had to be used and the tested coupons had to be analyzed carefully for the correct failure mode. Ultimately, the team decided to first test a slender beam profile of coupon size 1.0” x 10.0” and a span length of 9 inches, which had successfully produced the proper failure modes on similar sandwich panel constructions by other students. This long and slender coupon enabled the team to determine the bending stiffness.

With regards to collecting data, ASTM recommends taking about two to three recordings per second with a target minimum of 100 data points. The team recorded force versus crosshead displacement at this recording rate. The team also recorded initial (non-catastrophic) failures including facesheet delamination, core-to-facesheet disbond, partial core fracture, and local core crushing. The team recorded the mode, area and location of each initial failure (if applicable). Shear failures of the sandwich core or failures of the core-to-facing bond are the only acceptable
failure modes for this test. Failure of one or both of the facings preceding failure of the core or core-to-facing bond is not an acceptable failure mode. To examine the data, the materials team plotted force vs. displacement data to discover trends and material properties. These plots gave the team the data necessary to create an ABAQUS model to simulate the physical tests. After the first round of ASTM C393 tests, the team worked with Mr. Stein to determine the right test specimen combination (glue, foam thickness), and proceeded with more tests of the chosen specimen.

To evaluate the tests, the team used the ASTM identification codes in Table 6. Figures 9, 10, 11, and 12 as well as Table 6 are drawn from Appendix E, which provides the complete ASTM testing documents of tests C393 and D7249.

\[
F_s \leq \frac{2k\sigma t}{(S-L)} \quad F_c \geq \frac{2(c+t)\sigma t}{(S-L)l_{pad}}
\]

**Figure 9.** C393 Equations for Determining Geometric Testing Parameters

![Diagram](image)

**Figure 10.** ASTM C393 3-point bend test

<table>
<thead>
<tr>
<th>Table 6. Sandwich panel three part failure identification codes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure Type</td>
</tr>
<tr>
<td>skin to core Delamination</td>
</tr>
<tr>
<td>Filament fracture</td>
</tr>
<tr>
<td>Layer instability</td>
</tr>
<tr>
<td>local Wrinkling</td>
</tr>
<tr>
<td>Multi-mode</td>
</tr>
<tr>
<td>core Crushing</td>
</tr>
<tr>
<td>longitudinal splitting</td>
</tr>
<tr>
<td>tear</td>
</tr>
<tr>
<td>transverse shear</td>
</tr>
<tr>
<td>explosive</td>
</tr>
<tr>
<td>Other</td>
</tr>
</tbody>
</table>

The ASTM D7249 test method was used on the chosen sandwich panel to determine face sheet strength and stiffness properties by applying moments to produce compressive and tensile forces in the face sheets. This test method setup is different from test C393, in that longer coupons and
a 4-point loading fixture is used. For this test, the only acceptable failure modes are internal to the face sheets. Any core failures or delaminations are an inadequate result. The equations to verify the span length are shown below and although this time the material properties converged on a required span length of at least 105 inches, this was way outside the physical limitations of the Ametek LD50. The team decided to analyze a coupon of 3 inches wide and a span of 22 inches, which is the maximum length the team was able to test. The post processing is the same as the C393 tests, with an end result of force vs deflection plots.

\[
F_s \geq \frac{2\sigma t}{k(S-L)} \quad F_c \geq \frac{2(c+i)\sigma t}{(S-L)L_{pad}}
\]

**Figure 11.** D7249 equations for determining geometric testing parameters

![Diagram of 4-point bend test](image)

**Figure 12.** ASTM D7249 4-point bend test

<table>
<thead>
<tr>
<th>Test</th>
<th>Properties to be Found</th>
<th>Standard Setup</th>
<th>Proposed Coupon Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>C393</td>
<td>Core shear strength, core to facing shear strength, stiffness of sandwich beam</td>
<td>3 Point Bend Test</td>
<td>1.0” x 10.0” (bending stiffness)</td>
</tr>
<tr>
<td>D7249</td>
<td>Strength and stiffness of sandwich panel face sheets</td>
<td>4 Point Bend Test</td>
<td>3.0” x 24.0”</td>
</tr>
</tbody>
</table>

The testing variables can be seen in Table 8: foam core thickness, adhesives, and foam preparation methods. Mr. Stein narrowed down the foam core to be Dupont (DOW) XPS foam in either the standard 25 psi compressive strength, which comes in a 1” or 1.5” thickness or possibly the Hi-Load 60 psi version which comes 2” thick but can be cut down utilizing a hot wire cutter. For testing, the team focused on the thickness of the core and the two different adhesive types.
For the facing of the panels, Mr. Stein was interested in using 2 mm Fiberglass Reinforced Plastic. For bonding the FRP and foam the team analyzed two of 3M adhesives, the first being a one-part contact adhesive and the second being a two-part toughened epoxy. The team also tested two different foam preparation methods: the factory finish on the foam panels and the finish after the hot wire cutting process. Foam preparation is important for getting the best adhesion between the face and the core. The foam was tested using both of the previously mentioned methods as well as the factory finish after being sanded with a low grit sandpaper. While the adhesive has a very similar thickness after the panel has been compressed and set, the initial amount of adhesive applied to the panel is a crucial variable. The team tested panels using a thinner initial adhesive coating as well as a thicker one. With the results the team determined a final sandwich panel combination by examining strength, cost, and manufacturability.

<table>
<thead>
<tr>
<th>Table 8. FRP testing variables</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Brand/Type</strong></td>
</tr>
<tr>
<td><strong>Face</strong></td>
</tr>
<tr>
<td><strong>Core</strong></td>
</tr>
<tr>
<td><strong>Core Prep</strong></td>
</tr>
<tr>
<td><strong>Adhesive</strong></td>
</tr>
</tbody>
</table>

**4.1 Concept Prototypes:**

An example of a sandwich panel testing coupon is shown in Figure 13. The testing coupon consists of a 2 mm fiber reinforced plastic face and DOW XPS foam core of varying thickness. The adhesive used to bond the face and core was either the 3M scotch weld toughened epoxy (two part) or the 3M green contact adhesive. The sample coupon sizing was 1”x10” for the 3-point bend test.

![Figure 13. Sample sandwich panel with 1-inch blue XPS foam core and 2mm FRP facings on either side](image-url)
Figure 14 shows the preliminary sketch of the fixture the team considered for the ASTM C393 3-point bend test. The standard sample dimensions for this test are 3”x 8” but were changed to produce the proper failure modes.

Figure 14. ASTM C393 3-point loading fixture (simplified standard configuration) drawing with dimensions shown in inches

Figure 15 is an example of a 4-point bend test that could be utilized as an alternate setup in test C393. The 4-point test is also the standard configuration in test D7249. The dimensions were subject to change depending on the span length calculations for each test.
A final design for the 3-point bend test fixture was decided upon and can be seen in Figure 21 in the manufacturing plan section of this report. This design conformed with the 3-point bend test fixture configuration as determined by ASTM C393 and allowed the team to test a variety of coupon sizes to meet the failure mode criteria.

The preliminary model for clam-shell door design is shown in Figure 16. This model features vertically opening doors on the right rear side of the expedition box camper. This model does not include hardware, aluminum edging, or sealing, but serves to provide a visual for how the door should look in both closed and opened positions and also provide insight on how the mechanical system will work.
After doing preliminary design and analysis of the camper door, the sponsor decided that the door design was premature and that a full frame expedition box prototype was needed before the door was to be fully designed. Also, there was a consensus that the design was too complicated for a camper door and that an off-the-shelf door would be the cheapest and best option for the camper. The expedition box is designed with off-road abuse in mind, and the clam-shell door design has simply too many moving parts for it to be feasible on an off-roading vehicle. This left sub-team #2 to focus primarily on the step box sub-system of the camper.

After a meeting with the sponsor, it was decided that sub-team #2 would be designing a set of steps that could be used to get up into the camper. These steps would be mounted to the bed of the camper and would allow easy access into and out of the camper. Another critical design feature was the ability to quickly pull out and use the steps, as well as putting them away. Several off-the-shelf designs were considered. These designs are shown in Figure 17. They include both sliding and folding mechanisms. After consideration, the sponsor decided that these designs were far too complicated and flimsy. Also, they would be expensive to buy off the shelf or attempt to replicate. He asked us to design something that was extremely simple and robust.

![Figure 17. Folding Step Designs](image-url)
4.2 Conceptual Manufacturing:

Consistent and accurate manufacturing of the panels was required to maintain the strength and integrity of the camper for 10+ years in harsh outdoor environments. Listed below are the conceptual manufacturing techniques and steps in order to produce a quality, long lasting product.

1. Face the panels to the correct thickness using a hot wire and rough it using a low grit sandpaper in order to ensure good adhesion between the FRP faces and the foam core.
2. Cut the foam and the FRP to an approximate size (oversized), then after adhering the faces to the core, cut them to the exact size needed.
3. With a two part epoxy caulking gun, apply the 3M Toughened Epoxy and with a brush and roller, apply the 3M contact adhesive.
4. Cut rough sizes with a track saw or any carbide toothed circular saw blade.
5. Rough sizes of the foam core can be cut using a hot wire and/or serrated knife or the same track saw or circular saw blade as mentioned in step 4.
6. FRP faces were adhered to the core using two different methods. The 2 part epoxy needed to be vacuum bagged for a minimum of 4 hours to ensure a full cure of the adhesive. The contact adhesive was applied to both the foam and the face, allowed to dry for about 10 minutes, and then pressed together via a large rubber roller. A cross section of the vacuum bagging process and layup can be seen in Figure 18.
7. Test fixtures were fabricated from steel to the dimensions specified in ASTM C393 which can be referenced in Appendix E.
8. Test samples were cut using a track saw to ensure accuracy and with square edges for consistent testing.

After a series of testing panel samples with the different manufacturing methods and adhesives used, it was determined that the 1” foam with the 2-part 3M adhesive will be used for the bulk of the panel manufacturing. The materials team then moved on to modeling the sandwich panel in the FEA software ABAQUS.

Figure 18. Cross section of the vacuum bag model
As mentioned before, the door will be constructed using the same material the walls and the majority of the expedition box will be constructed from. This section of the panel will then be resized, cleaned up, and cut into two sections for the top and bottom parts of the door. These panels will then be capped with aluminum extrusions to form the outside edge of the door. The aluminum extrusions will be adhered to the edges of the panels using the adhesive. The aluminum extrusions that frame the door have special seats in them that house a bulb seal that mate with the extrusions that frame the door. The door closes into the frame in such a way that the exterior is flush and has a somewhat seamless look.

_The door is still planned to be created in the same way as outlined above, however, due to the changing nature of the project, the senior project team did not focus on the door during the end of the project and instead focused on the step box as requested by the sponsor._

4.3 Concept Analysis:

The team advised the sponsor regarding the material selection as well as the construction techniques based on proven uses and methods within other industries. The team researched the construction of large RVs that are manufactured with FRP composite panels in order to gain confidence in a successful solution for the Enduro Camper’s construction material choice. The other major driving factor for material selection and general design decisions came from the sponsor, Enduro Campers. The sponsor made many decisions based on the business connections he had established as well as his own financial analysis of his start-up company’s capability.

However, in spite of the proven uses for FRP panels and the sponsor’s guidance, there were many risks that came with selecting these materials for the Enduro Camper because the project explores the groundbreaking territory of FRP composite panels being used for heavy off road usage. There are many unknowns with this kind of abuse on the material. Some aspects of the design that are not within the direct bounds of the test procedure are damages due to vibrations, extreme heat and radiation, freezing conditions, puncture, and humidity effects to name a few. The team planned to be able to test these parameters later in the design phase if they became apparent problems but the team did not see them as substantial problems in the current material solution. _The team did not advance far enough to reach further testing parameters._

The possible safety issues and hazards in the design are outlined in detail in the Design Hazard Checklist in Appendix D. The primary hazards discussed relate to the heavy wedge camper top and the high mass of the product in general. The swinging motion of the camper top as it closes poses itself as a dangerous pinch point if failure of the pop top support system were to occur. In the event of the top closing quickly, there is a risk of the operator’s hand or other appendages

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being pinched between the top and the body of the camper. In addition to this, the side doors could be another potential pinch point if not used properly.

5. Final Design

The final design is focused around the panels that make up the overall expedition camper box structure. The structure consists of panels that make the roof, walls, doors, compartments, and some components of the interior as well. The panels the team manufactured for testing represent small scale models of the panels that will be used in the overall camper construction. The results from testing assisted with choosing one combination of foam thickness and adhesive. The testing results also gave the team confidence in the ability of the sandwich panel to perform well under the load cases.

The project is unique due to the final camper box design being primarily up to the sponsor and the Enduro Campers company. The team’s final design was largely based on the ABAQUS models produced for the sponsor. The ABAQUS models are a base for any future analysis that needs to be done to different parts and iterations of Enduro Campers. The models include the correctly characterized material properties of the sandwich panels that are used for the structure of the camper, so any design updates can be properly analyzed. In the conclusion of the team’s project there are a few different major components of the current design iterations of the Enduro Camper modeled in the program, such as the roof, rear doors, surrounding walls, and different joint sections.

_The materials team hoped to be able to correctly model the material and move onto modeling bigger sections of the camper but due to difficulty in calibrating the ABAQUS model to the physical tests, the team did not achieve this._

Enduro Campers is working on an extruded aluminum cap prototype that will be pressed and glued onto the edges of the panels. These edges act as a “frame” to each individual panel and aid in the joining and sealing of the joints where the panels meet. This design will allow the panels to be modular in a way so that the manufacturing and joining process of the camper will require less manual labor and fewer custom fabricated components for the corners, edges, etc.

These edges were the basis for further designs, specifically the team’s final design of the door. The door is hinged on these edge extrusions and allow for a strong joint between the composite sandwich panel material that makes up the body of the camper and the side door of the camper. Further design choices about the door such as the general dimensioned design of the camper door and weather sealing will be implemented, possibly by a future senior project group.
As stated earlier, sub-team #2 focused their efforts on creating a step box used to get in and out of the camper. The box consists of aluminum sheet metal and a composite panel that is used as the door of the box. The panel also functions as a step when the box is opened. Custom aluminum extrusions, similar to those used to frame the exterior of the camper, are used as edging for the panel door. The hinge and supporting cables are mounted to the aluminum extrusions, providing added structural integrity to the step box. A simple bulb sealing system is used to seal the box. The single step into the camper is functional, but a second step would make getting into the camper more convenient. This design allows the user to store a second step/step stool inside the box to be used for easier access into the camper.

6. Manufacturing

6.1 Sandwich Panel Manufacturing:

The camper will be constructed using sandwich panels and extruded aluminum edges and corners to hold the panels together and form a simple box shape. The main starting point of this project was the manufacturing of the sandwich panels. To start, Enduro Campers had bought a large quantity of Vetroresina FRP, 3M adhesives, and DOW XPS 25 psi blue board foam. The company has also purchased a vacuum generator and several cutting tools necessary for shaping the panels.

The first step in the manufacturing process is cutting both the facing and the core foam to the desired size using a handheld track saw. The second step is preparing the surface of the foam to create a better bond between the face and the core. To do this, a medium grit sandpaper is used to rough the surface on both sides of the foam. This is done in order to remove the glossy surface finish that the foam comes with from the manufacturer. The panel is now ready to be assembled.

There were two main adhesives used to manufacture the panels, the 3M contact adhesive, and the 3M toughened epoxy. Each has a different procedure for application and curing. The procedures for each are outlined in the following paragraphs.

3M contact adhesive application procedure:

This adhesive comes in a 5 gallon bucket, so first, it is to be poured into a paint tray to reduce waste and ease of use. The adhesive is applied in a very thin layer to both the facing and the foam core using a high nap (around ½”) paint roller, as seen in Figure 19. The adhesive is then left to dry for around 20 minutes before the facing is placed on the foam core. With this adhesive, the bond is almost instant, so placing the facing on the core must be done carefully. A force is then applied to the panel using a heavy duty hand roller. The panel is ready for use in only a few hours.
3M toughened epoxy 2-part application procedure:

This adhesive is applied to the facing only, in a relatively thin layer, using a large, coarse paintbrush and/or high nap (about $\frac{1}{2}"$) paint roller. The facing is then placed on the foam core. The adhesive takes about 4 hours to cure, and must be placed in the vacuum bag, as seen in Figure 20, for the duration of the cure time. The vacuum generator is run the entire time, keeping the seal in the bag at around 15 psi. Once removed from the vacuum bag, the panel is fully cured and the edges are cleaned up. The panel is now ready to be cut to its exact size.

Once it has been decided where the panel will go (e.g. the roof, side panel, door, storage compartment etc.), it will be cut to the exact dimensions using the Makita track saw, or any quality and track saw, which is capable of providing an accurate enough cut for the application. Then extruded aluminum caps are pressed and adhered to the edges of the panel. These extruded aluminum caps frame each panel in a way so they can be joined with other panels in the desired configuration to make up the body of the camper box. This same technique is used for any panel that will have an exposed edge such as any doors or compartments etc. These caps aid in the necessary sealing between the panel joints and mitigate delamination on exposed edges. Enduro Campers is currently working on developing a prototype of the caps that incorporate a bulb seal and a slot for retaining the tent fabric with a small, sewn-in plastic pipe. Figure 20 shows an uncured panel being prepared in the vacuum bag.
6.2 Test Fixture Manufacturing:

This section documents the fabrication process and the specifications of the testing fixture for the 3-point bend test on the composite sandwich panels. The existing fixtures for the 3-point bend test in the composites lab at Cal Poly San Luis Obispo all had cylindrical supports rather than free rotating flat bar supports. The rotating flat bar supports can provide more precise test data (no localized crushing). For this reason, the team decided to make this fixture and use it for all of the 3 and 4 point bend testing. Figure 21 shows the fixture design in Solidworks and Figure 22 shows the manufactured fixture final product.
The manufactured fixture includes a C-channel base that is adjustable to account for testing of different sample lengths. The holes drilled in the rectangular base tube are spaced 1 inch apart from each other for adjustments to be made by 1 inch increments. This was done to plan ahead for possible different sample lengths for different test failure modes.

The 2 bearings on each side of the support flat bars are welded to the support rod, allowing for the free rotation of the composite sandwich panel test specimen at the loading points. This free rotation allows for more accurate test results as it properly supports the test specimen as it bends and deforms through the entire loading cycle. The bearings were pressed onto the support rod which has end diameters of 0.32 in. which were turned down on a lathe. The center diameter of this support rod is 0.5 in. and has a 1 x 3 x 0.25 in. flat loading bar welded to the top to support the test specimen and can be seen in Figure 23. A rubber pad with an approximate thickness of 0.125 in. and a shore A hardness of 60A, the same size as the support flat bars, is glued to the top of the flat bars, shown in Figure 24. The rubber sheet provides extra protection against local specimen crushing at the loading points. The loading bar, rod, and bearings subassembly rests in a piece of 1 x 1 in. steel angle to support the fixture by the welded rectangular tube fixture base and still allows for the free rotation of the specimen.
Figure 23. Fixture flat bar supports and support rod with turned ends to fit bearings

Figure 24. Fixture supports, pad, and bearings subassembly resting in steel angle to allow for free loading support rotation
The rest of the fixture was manufactured with rigid rectangular tubing with a welded fixture construction to prevent any deflections within the fixture during bend tests. All parts of the fixture are made of mild steel and were TIG welded with ER70S2 filler rod. The entire fixture was made to fit in the Ametek LD50 materials testing machine, within the shielding glass that surrounds the loading jaws. The upper load bar/pad clamps into the loading jaw-clamp of the LD50 machine and is used to provide the center load of the 3-point bend test on the specimen. The top piece is consistent with the support flat bars in dimensions and includes the same rubber loading pad.

A few manufacturing challenges faced was being able to physically move the large roll of FRP into a position where it can be cut efficiently and reduce waste due to the roll being in a non-ideal position. The FRP rolls come in various sizes but are generally quite large and heavy, making them difficult to easily move around. The FRP roll that Mr. Stein has chosen is 10 feet in width, about 3 feet in diameter and weighs approximately 1000 pounds. A stand needed to be built in a way so the roll can be loaded and rolled around the shop to wherever it is to be cut. The design of the stand must allow the roll to dispense FRP from the top at a level nearly even with the surface it is to be cut. Because of the weight of the roll, the stands needed to be strong enough to withstand not only the static load but a dynamic load from rolling the assembly around a mostly flat and smooth shop floor. Quality casters were needed as well to ensure a smooth rolling operation to reduce injury caused by the possibility of the FRP roll falling on the operator due to a failed caster or an obstacle large enough that the caster cannot overcome. The roll and stands can be seen in Figure 25 and Figure 26. The stands were made primarily of 2” x 1” x .095” rectangular mild steel and the casters are 2.5” in diameter and support a load of 350 pounds each.
Figure 25. FRP roll mounted on the rolling stands. The roll is 10 feet long and weighs approximately 1000 pounds

Figure 26. FRP rolling stands. A 2” x 1” x 10’ steel rectangular tube supports the roll and it is pinned between the stands
A large flat surface, and general working surface, was also necessary for the manufacturing of the panels. This surface needed to be at a standard working height for efficient and safe manufacturing. This is the working surface that the FRP roll will be laid onto for cutting. This work surface needed to be mobile and conform to the same design/safety features as the FRP rolling stand. The table can be seen in Figure 27. The team fabricated the table using a variety of 3”x2”x.120”, 4”x2”x.120”, and 2”x1”x.120” rectangular mild steel tubing. The top is 5’x10’x.250” mild steel plate and the casters are 4” in diameter and can support a load of 700 pounds each.

![Figure 27. Steel table/flat working surface. It measures 5’ x 10’ and the top surface sits 36” from the ground](image)

**6.3 Step Box Manufacturing:**

The Step box that doubles as storage and a step into the camper mounts directly under the entrance door and behind the passenger side rear wheel. The box was designed to be sturdy enough to support the weight of someone stepping down onto the step approximately 12 inches from the bottom of the entrance door. The box is mounted with 4 bolts going through the floor of the camper, two of which pass through a 1” x 1” aluminum tube built into the structure of the floor. The step is mounted to the box with a piano style hinge that is welded to the bottom of the box on one side and to the aluminum frame of the step on the other. The step swings out from the box and is suspended by cables. The cables are connected to the through bolts, fastening the box to the camper on one end, and the other end will go through the step and fasten to the aluminum frame of the step. Manufacturing directions of the box can be seen below.
1. Box:
   Cut aluminum plate (14-gauge) to size using a toothed blade saw, cnc plasma cutter, water jet, etc.
   Brake the aluminum sheet to the specified angles and TIG weld the edges together.
2. Step:
   Lay up a sandwich panel using the same methods described in the panel manufacturing section.
   Cut the panel to the exact dimensions of the opening face of the step box.
   Frame the step panel with ¾” x ¾” x ⅛” aluminum angle.
   Miter cut the angles of the frame to match the angles of the step and fully weld all seams.
   Weld the frame to the hinge and the hinge to the bottom of the step box. Rivets can be used.
   Adhere the FRP panel into the aluminum frame.
3. Fastening/Cables:
   Cut cables to length
   Crimp steel swivel end to one side of each cable
   Drill a cable sized hole through the step on both sides/corners, passing through the aluminum.
   Pass each cable through each hole and crimp the steel cable stop onto each end
4. Latch Install:
   Route out a space for the latch to reside in. Fasten using through bolts
   Cut/drill a hole for the latch to snap into, securing the step/door
5. Sealing the box:
   Add the bulb seal that clips over the exposed edge on both sides of the opening on the box
   Adhere the bulb seal near the top inside of the box to seal the top portion of the door
6. Fastening the box to the camper:
   Drill holes through the top of the box and through the floor of the camper.
   Pass the bolts through the floor and through the top of the step box
   Add the swivel bracket to the through bolts closest to the step/door. Securely fasten.
   Connect the swivelling cable ends to the swivel brackets via ¼” pins

The beginning stages of the step box manufacturing can be seen in Figure 28. A 14-gauge 5000 series aluminum sheet was cut with a carbide toothed circular metal saw, in two separate pieces. The separate pieces were bent using a sheet metal brake to the specified angles. The edges were sanded and cleaned with acetone, then the outside edges were fully TIG welded. The separate pieces that were welded together after braking the sheet metal can be seen in Figure 29. The step panel was laid up oversized, using the same procedure as the main camper body panels, then cut to size. Unfortunately the aluminum extrusions that would frame the step/door were not ready in
time to complete the process, along with various other components. A concept of what the completed step box would look like can be seen in Figure 30 and 31.

![Completed Step box frame without the hardware](image)

**Figure 28.** Completed Step box frame without the hardware

![Backside of the step box showing the two separate pieces that were cut, bent then welded together](image)

**Figure 29.** Backside of the step box showing the two separate pieces that were cut, bent then welded together
Figure 30. Concept of the finished step box

Figure 31. View from underneath the step box displaying the angled aluminum extrusion framing the step panel.
7. Design Verification

Three members of the team were certified to work in the composites lab where the Ametek LD50 testing machine was used. First, different panel constructions were tested by using 1.0” x 10.0” coupons for test C393. The statistical measurements of all the coupons for this test were documented and attached in Appendix K. These measurements were made to ensure the manufacturing consistency within all the samples tested. The plan was to characterize the bending stiffness and interlaminar shear properties of the panels with these coupons. From the results of test C393 a specific panel was chosen to move forward with. The D7249 test was then conducted at the max range of 22 inches for the span length and max width of 3 inches. The testing procedures outlined in section 4 were followed for both tests. These tests consisted of a 3-point and a 4-point bend test respectively. The type of failure mode produced signifies whether the tests could be accepted: core failures for test C393 and facesheet failures for test D7249.

7.1 Sandwich Panel Testing Results:

The physical testing of the sandwich panels produced force-displacement data which was analyzed for transition regions and also the maximum force prior to failure. These plots gave material properties through basic mechanics of materials equations such as the elastic modulus that was attempted to be simulated in ABAQUS. To analyze the results of the tests, the collected (.txt) file data from the LD50 machine was imported into MATLAB as data arrays and load vs deflection was plotted. In total, six sets of tests were conducted, each having at least five samples. Data sets A, B, C and D were ASTM C393 tests where the team analyzed 1” and 1.5” foam thicknesses with epoxy and contact adhesive. Test set E was of a perforated 1” thick, epoxy bonded coupon, however inadequate bonding of the FRP to foam produced poor results. The perforations were made with a spiked roller with spikes of 1mm diameter and 10mm length. The perforation spacing was approximately a 10mm by 10mm grid throughout the entire panel. The panel for test set E was laid up with an aluminum extrusion that was thicker than the foam, which led to air pockets in the epoxy and poor data for 6 of the 8 tests. However, out of the successful tests for set E, the perforations did not improve the strength of the coupon when compared to its non-perforated counterparts of coupon set C. Finally, in data set F, the 4-point bend test of ASTM D7249 was conducted. This 4-point test verified that the material was displaying the same initial load/deflection slope (~300 lbf/in) while in its pseudo-elastic phase as seen in the 3-point test, and as expected, a stronger yield load considering the larger sample.
Figure 32. ASTM C393, 3-point bend test, 1in x 10in samples, 9in span length, 1.5in Dow XPS 25psi foam and 3M toughened epoxy

Figure 33. ASTM C393, 3-point bend test, 1in x 10in samples, 9in span length, 1.5in Dow XPS 25psi foam and 3M contact adhesive
Figure 34. ASTM C393, 3-point bend test, 1in x 10in samples, 9in span length, 1in Dow XPS 25psi foam and 3M toughened epoxy

Figure 35. ASTM C393, 3-point bend test, 1in x 10in samples, 9in span length, 1in Dow XPS 25psi foam and 3M contact adhesive
Figure 36. ASTM C393, 3-point bend test, 1in x 10in samples, 9in span length, 1in Dow XPS 25psi foam (with small perforations in foam before adhesive applied) and 3M toughened epoxy

Figure 37. ASTM D7249, 4-point bend test, 3in x 24in samples, 22in span length, 1in Dow XPS 25psi foam and 3M toughened epoxy

The figures below are some of the pictures from the real world testing of the sandwich panels from both the C393 3-point bend test and the D7249 4-point bend test. The pictures are from the
composites lab on the campus of Cal Poly San Luis Obispo where the LD50 tensile test machine was used to apply the load for the bend tests. The pictures outline the failure modes observed for each test. The failure identification codes listed in the figure captions come from Table 6.

**Figure 38.** ASTM C393, 3-point bend test, initial bending occurring at load in elastic region of sandwich material

**Figure 39.** ASTM C393, 3-point bend test, extreme bending of sandwich material moments before failure
Figure 40. ASTM C393, 3-point bend test, top facesheet failure (failure code FAT), buckling in center of FRP (failed test due to failure mode in topsheet according to ASTM standards)

Figure 41. ASTM C393, 3-point bend test, core shear failure (failure code SOC), foam break then delamination
Figure 42. ASTM D7249, 4-point bend test, initial fixture setup before loading

Figure 43. ASTM D7249, 4-point bend test, bending during loading
7.2 ABAQUS FEA Modeling Introduction:

The next step in analyzing the sandwich panels was to model the 3-point and 4-point tests in ABAQUS. In ABAQUS, the materials team attempted to calibrate the model to the 3-point bend test and then later validate it to the 4-point bend test. The sponsor chose to move forward with a hard decision on the 1” foam and epoxy bonded panel so this specific combination was attempted to be simulated. The force versus displacement plots from testing were the standard that were attempted to be reproduced in ABAQUS. After successful matching of the tests in ABAQUS, the gathered material properties were planned to be applied to different subsystems and loading cases in the camper. However, due to time restraints and difficulty in characterizing the material, the team was unable to conduct further simulations. These simulations would ideally take place as different subsystems are being designed.

For example, characterization of the material gained through testing and analysis would allow for advancements in the design of the camper’s entrance door. Validation of the feasibility of the preliminary door design came in two forms; spatial and mechanical. Starting with spatial, it was necessary to first gain a better understanding of the envelope in which the design will encompass. This includes spatial constraints on the camper, as well as the truck body. Preliminary inspections have determined that components such as the truck’s frame, leaf spring hangers, and exhaust system will serve as spatial constraints in the design of the door. In order to verify the door design it will be necessary to perform analysis in ABAQUS, followed by physical
prototyping and testing. Through these modes of analysis, a test of predetermined boundary conditions can be performed to ensure the mechanical integrity of the door design.

A detailed Design Verification Plan and Report (DVP&R) can be found in Appendix H.

7.3 Material Characterization:

In ABAQUS, a crucial step in accurately modeling the sandwich panel was inputting the proper material properties. The FRP was modeled as an elastic material with \( E_1 = E_2 = E_3 \) as 5.7 GPa, which was given in the material data sheet for the Vetroresina LD 600 material. All three shear moduli were assumed to be a factor of 30 smaller than the elastic moduli which was based on a model of a similar FRP material. The foam properties were much harder to characterize since there was very limited information in the material data sheet. In ABAQUS, the foam was modeled as a hyperfoam with imported uniaxial test data. From the technical data sheet it is known that the vertical compressive strength of 25 psi is measured at 10 percent deformation or yield, whichever occurs first. With this given parameter, a series of potential foam compression test curves were modeled to produce the proper force vs. deflection curve for the 3-point bend test. Compression data that follows the trend in Figure 45 was produced, going through the given stress of 25 psi at 10% strain or yield. Initially, the foam can be approximated as an elastic material since the stress increases pretty linearly with increased strain. Then the foam crushes at a constant stress and is packed down as the cell walls buckle. Finally, stress increases exponentially once the foam has been completely compressed and all the air gaps have been closed.

![Figure 45. Example of typical polystyrene stress strain curve and key zones that occur](image)

Figure 46, shows the iteration process of modeling different foam curves on a spreadsheet data plot to input into the uniaxial compression test data. The solid black line labeled “Yield Point Line for 25 PSI” represents the 25 psi stress ay 0.1 deformation or yield. It is horizontal at 25 psi until 0.1 strain where it increases with a slope of 25psi/0.1. The data set must initially rise
linearly to anywhere on the black line to agree with the information on the technical data sheet. Foam data V4 and V6 fail to go through this point, but they were documented to examine the effects of going outside the parameters since it was difficult to match the numerical data to the physical data. Initially, foam data V1 was tried and then adjusted to produce force vs. deflection data in ABAQUS that matched more closely with the physical testing data. Table 9 documents the general changes made from data set V1 to produce the other data sets.

![25 PSI Dow XPS Experimental Uniaxial Foam Compression Data](image)

**Figure 46.** Experimental polystyrene foam stress strain data curves that were iterated and used in trial ABAQUS simulations, including 25 PSI foam specification foam

<table>
<thead>
<tr>
<th>Foam V1</th>
<th>First attempt at a foam curve similar to research</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foam V2</td>
<td>Slacken elastic slope from foam V1 and put yield point on diagonal of yield point line</td>
</tr>
<tr>
<td>Foam V3</td>
<td>Steepened the elastic slope from foam V1</td>
</tr>
<tr>
<td>Foam V4</td>
<td>Increased yield point of foam, higher than yield point line (outside parameters)</td>
</tr>
<tr>
<td>Foam V5</td>
<td>Extended crushing zone of foam V3</td>
</tr>
<tr>
<td>Foam V6</td>
<td>Decreased yield point of foam from foam V3, lower than yield point line (outside parameters)</td>
</tr>
<tr>
<td>Foam V7</td>
<td>Extended crushing zone to achieve more strain, foam V4 with only stress reduced</td>
</tr>
<tr>
<td>Foam V8</td>
<td>Elastic region similar to foam V3 and V5, but higher densification zone curvature</td>
</tr>
</tbody>
</table>

Table 9. Description of Foam Version Iterations and What was Changed for Each Version
7.4 ABAQUS Modeling Process:

To begin modeling the sandwich panels in ABAQUS, two separate parts, the foam and the FRP, were created and assigned their respective material properties as outlined in the Material Characterization section above. The FRP and foam were modeled as 3D deformable parts. The additional parts that were created were the loading and support interfaces that represent the ASTM C393 and D7249 bending test fixtures that were used on the LD50 tensile testing machine. These fixture parts were modeled as discrete ridged shell elements to represent that there were essentially no deformations within the fixture as the only concern is with the deformations of the sandwich panel during loading.

To create the entire sandwich panel and the fixture in the same assembly, interactions between all of the parts were defined before anything else could be simulated. The epoxy glue connection between the foam and the FRP was modeled as a rigid tie constraint. In reality, there was some slight deformation of the epoxy glue when the sandwich panel was under load, but the effect was determined to be minute in comparison to the foam and FRP deformations that were modeled so it was left as a rigid connection. The interaction between all of the fixture parts and the sandwich panel was determined to be a hard contact interaction where separation is allowed to occur after contact. A friction coefficient of 0.4 was also assigned to represent a similar friction effect that was present in the real world test. This interaction was the best available option to represent the fixture model as closely to how the fixture interacted with the sandwich panels in the real world tests.

A mesh was applied to each part in the model individually with the mesh density biased towards the fixture to sandwich panel interactions as there was the most localized deformation in these areas. An overall dense mesh across all parts was avoided due to its effect in making the simulation run time exponentially longer than it needed to be. A much coarser mesh was applied to the fixture because these parts were modeled as discrete rigid parts which tells the program that none of its finite elements can move at all, so the mesh density became only a factor of maintaining the shape of the object rather than for simulation accuracy.

The next step in the ABAQUS modeling process was to define boundary conditions for the parts. Boundary conditions are only applied to the fixture because this leaves the sandwich panel free to deform under the defined constraints to the fixture and its loading movement. The two support blocks for both the 3 and 4-point tests were modeled the same as an encastre, meaning no movement whatsoever. In the real world test, the two support fixtures were allowed free rotation on the defined z-axis, however when attempting to model this effect in ABAQUS, an error appeared that was caused in the simulation where there were not enough constraints in the model. This is one of the biggest disconnects found between the ABAQUS model and the real
world test, and future investigation on this rotation would definitely be essential moving forwards. For the 3-point bend test, the top loading block, and for the 4-point bend test, the two top loading cylinders were assigned boundary conditions of fully constrained movement other than the y-direction. In both tests, a set displacement of 0.6 inches and 1 inch for the 3 and 4-point tests respectively was assigned. This allowed ABAQUS to apply a steady downwards displacement of the loading fixture relative to time in the same way that the LD 50 test machine displaces steadily with time and records the force throughout.

The figures shown below represent some of the stresses and displacement results from the 3 and 4-point bend tests simulated in ABAQUS. In the upper FRP, S11, the stress in the x-direction, is compressive on the top and is in tension on the bottom as expected. Also, S22, the stress in the y-direction, is propagating from the points of contact at the loading and support fixture pieces. The displacement results are also shown for reference with the 3-point model being displaced -0.6 inches in the y-direction, and the 4-point model being displaced -1 inch in the y-direction.

![Figure 47. ABAQUS model of C393 test showing stress [psi] in x-direction, S11](image)

![Figure 48. ABAQUS model of C393 test showing stress [psi] in x-direction, S11 (X-Y plane view)](image)
Figure 49. ABAQUS model of C393 test showing stress [psi] in y-direction, S22

Figure 50. ABAQUS model of C393 test showing stress [psi] in x-direction, S22 (X-Y plane view)

Figure 51. ABAQUS model of C393 test showing displacement [in] in y-direction, U2
Figure 52. ABAQUS model of D7249 test showing stress [psi] in x-direction, S11

Figure 53. ABAQUS model of D7249 test showing stress [psi] in x-direction, S11(X-Y plane view)

Figure 54. ABAQUS model of D7249 test showing stress [psi] in y-direction, S22
In order to gather the data for the load vs displacement plots from the ABAQUS simulation, field and history outputs were required to be prescribed to the model before running the simulation job. The field output is a variable that is recorded over an entire portion of the model and was assigned to be the U2 displacement of the loading fixture in the model. The history output is a variable that tracks the interaction at a specific node or spot on the model and was chosen to be a contact force interaction between the loading fixture and the top FRP layer of the sandwich panel. These two variable outputs allow for post-simulation data analysis. XY data from each variable can be taken and combined into one singular XY plot that gives the force vs. displacement of the model as it is simulated. This allowed for the direct comparison of the plots produced from testing as seen in the previous section.
7.5 Modeling Results and Challenges:

Modeling of the sandwich panel in ABAQUS proved to be a significant challenge. First, just being able to run a job in ABAQUS without aborting or producing errors was a task in itself. Never having worked with the interaction module in the previous classes involving ABAQUS, nor having worked with hyper-foams made for an extra learning challenge. Many small details in the model also had to be analyzed and worked out, such as increment sizes/time steps, obtaining the contact force field output variable, non-linear effects, partitions, and outputting the X-Y data into a spreadsheet format.

One major challenge and area of ABAQUS that required lots of time messing with and fine tuning was the mesh on the parts for the FEA to simulate. Initially, the parts were modeled using a coarser mesh to run the models due to the significant amount of time for the job to complete. However, after producing desired results with a coarse mesh, the mesh was refined but this led to completely different results so another fresh start was required. Ultimately the mesh was optimized in certain areas to create a balance of accurate results and processing times.

The results of the simulation were highly dependent on how fine the mesh of the parts were, especially near the interactions of the fixture and the sandwich panel. In order to get the most accurate results with the most uniform stress distributions and deformations most similar to the real world samples, the meshes of each part had to be partitioned and biased in density towards the interactions at the fixtures. The big initial issue with the FRP mesh was that it only had one seed layer in the y-direction. This issue was overlooked at first and resulted in the tuning of the foam uniaxial data sets to an ABAQUS model that was producing inaccurate results. Also when a larger fixture displacement boundary condition was prescribed, the job would abort due to the excessive distortion of specific nodes because the mesh was not dense enough in some areas. Applying a 4 layer mesh with the bias in density as described, the stress distribution was smoothed out and accurate results were achieved in the model without incredibly long computational run times as seen with an extremely dense overall model mesh.

Once the model parameters in ABAQUS were up to a satisfactory representation of the physical model, the foam data was iterated to match the ABAQUS force vs deflection curve to the physical data. This was the calibration phase of the model to the 3-point bend test. The results of the iterations of foam data produced force vs. deflection curves shown in Figure 57.
Figure 57. Load vs deflection results of sandwich panel C393 3-point bend test with all foam iterations run through ABAQUS and the real world test data from data set C5

Despite many attempts to change the shape of the force vs. deflection curve to more closely resemble the physical data, a perfectly matching curve was not produced, but close results were obtained. The black data series is representing the average physical testing results of the 1” epoxy bonded coupons for the 3-point bend tests and what the goal was to simulate. Numerous models were run with altered foam data but ultimately did not match up to the physical test data. Foam data V8 initially behaved as the physical model but was unable to prevent the stress from increasing with increased strain. In the end the team decided to not to move forward with any specific foam for recommendation but rather to just recommend that a uniaxial compression test be run on this specific foam to get better and more accurate foam data to input into ABAQUS. It was determined that the foam would need to be refined further before accurate results can be generated for the overall properties of the sandwich material.

In order to make sure the data would stay consistent, a 4-point ASTM D7249 test was also simulated in ABAQUS to match with the 4-point real world test data. Figure 58 verifies that the data from the 4-point test in ABAQUS displays similar errors and is the same approximation as with the 3-point smaller coupon data sets for the load deflection curves. These results are a display of the verification of the earlier calibration with the 3-point bend test ABAQUS model, and proves that the material properties and ABAQUS model set up are sufficient to describe the actual sandwich material in an FEA environment. Even though perfectly matching curves for both tests, from ABAQUS to the real world test, were not achieved, the trends in all the versions of foam iterations stays the same across both models signifying that the only work left to be done is the tuning of the foam data to get a more accurate curve across both test models.
To increase the accuracy of the model, a compression test in the composites lab specific to the foam is recommended. Ideally this would be imported into ABAQUS as the uniaxial test data. The data sets that were formed in, and plotted from, a spreadsheet initially seemed to be adequate but perhaps there was not enough data points included or the foam potentially did not behave quite as expected. If the foam is not the issue in the model, further investigation of the FRP, interactions, tie constraints, or boundary conditions would be needed.

Throughout the modeling phase in ABAQUS, the team discovered how deeply involved of a process it is to accurately run models, even relatively simple ones such as the composite sandwich panel coupons. Even with the model running successfully without aborting, it was also a challenge of optimizing the mesh to produce reasonable run times while maintaining accuracy. Finally, calibrating the ABAQUS model to match desired physical results was very tedious. Many iterations of foam were attempted, but ultimately none could calibrate the model as accurately as hoped for.

8. Project Management

The Enduro Camper team used background research to refer to throughout the project to validate decisions. The originally defined engineering specifications and customer wants guided the team through decisions throughout the project during the engineering and development stages.

Once the material research team had gained enough knowledge on the mechanical properties of the composite materials used, the team hoped to perform a more in-depth analysis of the Enduro
Camper structure through the use of the FEA program ABAQUS, however, the project commenced before there was a chance to develop more in depth models of the camper and its features in ABAQUS. Alongside FEA, the team needed to perform physical tests on the material to verify the results. Through this analysis, the team was able to confirm the sandwich panel design of the camper body that had already been largely determined by Mr. Stein. Any faults or areas of weaknesses, such as inadequate bonding of the FRP and foam, were exposed in this process and possible solutions were determined. Following this design verification, the team was able to develop values for the mechanical characteristics of the sandwich panels. Enduro Campers will have the ability to market the camper with defined loading values (such as for the roof, door, etc.). The testing will also help convince the end user that this composite foam material that is being planned for use, is actually very strong and comparable to the welded aluminum frames already on the market, but at a lighter weight.

For the scope of the project, no purchases were made using the Cal Poly senior project team’s budget. All materials that were tested were purchased and provided by the team sponsor, Mr. Stein. The structural prototype of the expedition camper is planned to be built by Mr. Stein during the summer of 2021. The team obtained most of the materials (foam, glue, FRP panels, vacuum bags) through Mr. Stein and his budget for the Enduro Campers company. The team obtained some materials, like smaller scrap materials, from the composites lab on the campus of Cal Poly when they became available to help offset the costs for Mr. Stein. (There ended up being no need for this scrap material as the sponsor was able to provide all required materials)

Due to the design scope of the project shifting from a pop up wedge camper to an expedition box style camper, there were some resulting delays in the progress of the door design team. Upon the completion of this project, the door design team aimed to have a completed door design and physical prototype. However, it did not end up being possible to achieve this level of development of the door by the completion of the project. The updated goal of the door team was to have a completed CAD design of the steb box leading into the door along with the selection of hardware and locking components. This goal was achieved as outlined in previous sections.

These unexpected delays mentioned previously did not hinder the progress made by the materials research team. Being that both structures, wedge camper and expedition box, use the same sandwich panel, the plan for manufacturing, testing and analysis had not been changed. As a result of this, they were able to proceed according to the plan. As previously mentioned, the materials team was able to determine the necessary test coupon sizes to produce the proper failure modes during testing. The materials team was able to manufacture these coupons, and the test fixtures necessary for testing. During fall quarter, the materials team was able to test these coupons and produce valid data which allowed them to characterize the sandwich panels. With testing completed in fall quarter, the materials team was able to characterize and analyze the sandwich panels via ABAQUS during winter quarter of 2021.
The completion of the goals for both of these teams during fall quarter allowed us to work in unison during the winter quarter. With the implementation of ABAQUS during winter quarter and the completed step box design, both teams were able to work together to validate the design. With the virtual step box design and known loading conditions, the feasibility of the design can be confirmed and revisions can be made as necessary.

After the completion of both subteam projects, the next logical step would be to address another component of the camper structure together. Leif Stein has emphasized the importance of the structural integrity of the roof of the camper and its load bearing capacity. The next step for the materials team would be determining the boundary conditions in ABAQUS and then simulating the door design with the desired loading conditions. Then the door team could use the verification from the materials team and start manufacturing a prototype assembly.

The goal of sub-team 2 was to have the step box completed by the end of winter quarter. Significant progress was made, and the box prototype would have been completed if all of the hardware was able to be sourced. The main issue was the step box design involved using custom aluminum extrusions to edge the door of the box and attach the hinge and cables to the box. The sponsor had not yet ordered the extrusions, as he was planning on one big order for all the extrusions needed in the camper. The team then decided that it was best to build out the aluminum box and composite door for the box, but leave the actual hardware manufacturing process for the sponsor to complete in the future. A recommendation for the manufacturing of the door is included in section 6 of this report.
8.1 Timeline & Deliverables:

The following tables cover the deliverables that the team completed by the due dates listed. These tables cover the academic report, materials testing and analysis, and sub-system design deadlines.

<table>
<thead>
<tr>
<th>Deliverable</th>
<th>Description</th>
<th>Due Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scope of Work</td>
<td>Research, problem definition, deliverables, etc.</td>
<td>05/07/20</td>
</tr>
<tr>
<td>Schedule PDR</td>
<td>Scheduled PDR with Mr. Stein</td>
<td>05/21/20</td>
</tr>
<tr>
<td>PDR Presentation in Lab</td>
<td>Presentation finalized</td>
<td>06/04/20</td>
</tr>
<tr>
<td>PDR Presentation with Leif</td>
<td>Presentation with changes to cater to Leif Stein</td>
<td>06/05/20</td>
</tr>
<tr>
<td>PDR Report</td>
<td>FMEA, concepts, analysis plan, etc.</td>
<td>06/07/20</td>
</tr>
<tr>
<td>Schedule CDR</td>
<td>Scheduled CDR with Mr. Stein</td>
<td>10/15/20</td>
</tr>
<tr>
<td>CDR Report</td>
<td>Final design, DVP, manufacturing plan, etc.</td>
<td>10/23/20</td>
</tr>
<tr>
<td>CDR Presentation</td>
<td>Presentation finalized</td>
<td>10/29/20</td>
</tr>
<tr>
<td>Final Report</td>
<td>Final report completed</td>
<td>3/12/21</td>
</tr>
<tr>
<td>Project Expo Presentation</td>
<td>Posters completed</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 10 gives a project timeline that lists the larger deadlines of the project. Tables 11 and 12 lists the specific deadlines for each of the two sub-teams.
<table>
<thead>
<tr>
<th>Week Starting</th>
<th>Task Completions</th>
</tr>
</thead>
</table>
| 10/13         | ● Completed manufacturing of ASTM testing jig  
                   ● Prepared for CDR presentation |
| 10/19         | ● Completed CDR report |
| 10/26         | ● Tested 1” x 10” coupons for ASTM C393 Test |
| 11/2          | ● Processed testing data, import into MATLAB  
                   ● Went over results with Mr. Stein |
| 11/9          | ● Manufactured perforated sandwich panel  
                   ● Tested coupons in lab |
| 11/16         | ● Compared coupons, decided on which one to move forward with  
                   ● Began ABAQUS phase |
| 1/4           | ● Researched conducting composite analysis in ABAQUS.  
                   ● Followed tutorials on other sandwich panel analysis |
| 2/1           | ● Modeled specific tests in ABAQUS  
                   ● Ran a successful analysis |
| 2/22          | ● Manufactured panel in Mr. Stein’s shop for test ASTM D7249  
                   ● Conducted ASTM D7249 test on 22” (span) x 3” coupons |
| 3/2           | ● Mesh optimized and minor adjustments made to model  
                   ● Completed calibration phase to 3-pt model |
| 3/9           | ● Verification of sandwich panel to 4-pt model |
| 3/11          | ● Finished design verification section in FDR |
Table 12. Project tasking sub-team #2

<table>
<thead>
<tr>
<th>Week Starting</th>
<th>Task Completions</th>
</tr>
</thead>
</table>
| 10/19         | ● Door design ideation  
                 ● Chassis mounting scheme  
                 ● Took bed off of truck & take measurements |
| 10/26         | ● Hardware selection completed  
                 ● Door framing, opening, & stair designed |
| 11/2          | ● Dimensioned door model with hardware |
| 11/9          | ● Locking mechanism & sealing design finalized |
| 11/16         | ● Full assembly model completed |
| 11/23         | ● Sponsor change of plans, began looking for new sub-assembly to work on |
| 1/4/21        | ● Decided on step sub assembly, began ideation for steps |
| 1/11          | ● Finalized step box design concept |
| 1/25          | ● Began Step box detailed design |
| 2/8           | ● Full assembly model completed |
| 2/22          | ● Began hardware selection/manufacturing |
| 3/1           | ● Hardware selection complete  
                 ● Manufacturing of step box underway |
| 3/8           | ● Unable to get all of selected hardware (custom aluminum extrusions)  
                 ● Step box frame completed  
                 ● Updated report to reflect progress and changes in design goals |

In the grand scheme of the project, the timelines were followed roughly, but not with utmost detail. The timeline changed throughout the project much more than the team would have liked, but most of these changes were unavoidable. In hindsight, the scope and timelines should have been tighter from the beginning, and had the team spent more effort with more detailed planning, the project may have ran with less volatility.

9. Conclusion & Recommendations

With the completion of Critical Design Review (CDR), the team entered the material testing phase of the project. As was presented in section 4, the team followed standardized ASTM testing procedures specific to sandwich panels to compare the different panel options. In
conjunction with Mr. Stein, the team then began to manufacture the panel samples, and soon after, conducted tests in the composites lab and analyzed the failure data. The team was then able to determine the highest performing and most economical sandwich panel material combination for the desired loading conditions. At that point the sub-component design & analysis team (sub-team #2) shifted into the mechanical design of the doors and other various subsystems of the expedition box structure, and the materials analysis and manufacturing team (sub-team #1) continued to test and conduct numerical analysis on the manufactured sandwich panels primarily through the FEA software, ABAQUS.

The overarching goal of this project was to provide engineering analysis of the Enduro Camper. At the time of completing the project, the team’s sponsor, Mr. Stein, had an Enduro Camper expedition box prototype completed with most of the primary concepts and features decided upon. This caused some of the design work done in previous quarters by sub-team #2 to become obsolete and thus shifted the focus of this team mainly to the verification of the designs and concepts shown on the final prototype. The panel analysis work conducted by sub-team #1 was not so much affected by the dynamic nature of the expedition box project. The prototype included the camper floor structure, interior layout, some wall construction, but some primary mechanical components were not fully engineered, including the mechanical intricacies of the side-door, the pop-top, and the roof panel. At the completion of this project, this prototype was made primarily out of wood framing around the manufactured sandwich panels. In the end, sub-team #2 was able to design and build an aluminum step box for the camper, but were unable to make significant fabrication progress on the side access door. Due to the consistent changes to the features on the expedition box combined with the nature of the COVID-19 pandemic, a lot of progress that should have been made was slowed and even sometimes halted. The next iteration of the prototype should include systems discussed in this report such as mechanical hardware, custom extruded aluminum framing, and sealing. If this project were to be repeated, the team might have spent more time and attention defining a non-changing scope and a more realistic timeline for sub-team #1.

In the end sub-team #1 successfully created an ABAQUS model of the chosen 1” foam, epoxy bonded, frp faced, sandwich panel. The model does verify the physical tests to a reasonable level, however, it should be further calibrated for more accuracy. The team believes the main source of error in the model occurred from the imported compression test foam data to characterize the DOW 25 psi foam. After many trials of adjusting the foam data, the model was unable to be calibrated to an accuracy standard that was satisfactory. With more time, more composites lab testing and data collection from a compression test of the isolated foam is recommended. This would increase confidence in the data that was imported for the foam properties used in ABAQUS. If this data does not significantly help with calibration of the model, then at least the foam can be eliminated as an error causing factor from the model. The team would suggest then to move on and investigate other parameters of the model.
With the current ABAQUS setup, a single characterization of the foam was not sufficient in modeling the total range of deflections of the coupons. Foam V4 and V8 initially matched the data well but foams V1, V5, and V7 approximated the data better. Due to this variation, progress on increasing model accuracy was halted and a single foam was unable to be chosen to move forward with. Originally the goal was to be able to calibrate the model to the physical 3-point bend test results and then verify it to the physical 4-point bend test results. A successful calibration and verification would allow for the modeling of bigger panels of the camper with confidence, however the team did not progress to this stage within the given time frame.

9.1 Next Steps:

If Mr. Stein decides to sponsor more senior project groups in the future, their projects will likely be to redesign and manufacture the side-access door to fit the new, more simplified design parameters, completely ditching the clam-shell mechanics, and going with something more traditional. A lot of work is left to be done on the specifics of the sealing and hardware of the door, and also the integration into the rest of the expedition box structure. Using the panels that the team designed and manufactured in conjunction with extruded aluminum framing that Mr. Stein will likely have by the start of the next project, the next team should be able to make quick work of designing and manufacturing the door.

The next steps for the material analysis team would be to further improve the model by first conducting a compression test for the foam and importing the data into the uniaxial test data for the characterization of the hyper-foam. Then to fine tune the ABAQUS model, applying a rotation to the support blocks, adding in the rubber pads and its material property, and tweaking the interaction properties is recommended. With improved interaction properties, an attempt to simulate delamination of the FRP from the foam would be possible. At this level of refinement, the model would be able to get through the calibration and verification phase accurately when comparing it to the physical results of the 3-point and 4-point test results. After successful verification of the ABAQUS model, entire panels could be modeled with confidence. Loads subjected on the roof, side, and back panels could be analyzed for their deflections, stresses, and failure points. Various panel joining techniques could also be analyzed in ABAQUS and compared against each other.
References

[1] Wedgetail Campers

[2] Supertramp Campers
*Famtram, models.* Supertramp Campers, 2020

[3] Tommy Campers


*Campers, Product Info.* GoFast Campers, 2020,

[6] AluCab
*Canopy Camper, Products.* Alu-Cab Ultimate Overland Products, 2020,

[7] Snap Treehouse
*Standard Snap! Treehouse.* Snap! Outfitters. 2020,

[8] 50Ten
*Full Size Camping System.* Fifty Ten USA 2020,

[9] Overland Explorer
*Overland Explorer - CAMP Series Pop-Up Campers.* Overland Explorer 2020,

[10] EarthCruiser
*EarthCruiser GZL.* Earth Cruiser 2020,

A. QFD House of Quality

QFD: House of Quality
Project: Lulu Center
Revision: 1
Date: 05/23/02

Coefficients

- Positive
- Negative
- No Correlation

Relationships

- Positive
- Negative
- Regular

Exercise of Improvement

- No
- Yes

Table 1

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No. of Failure

1. 3
2. 2
3. 1
4. 0
5. 0
6. 0
7. 0

Analysis

- Analytic
- Visual

Conclusion

- 1
- 2
- 3
- 4
- 5
- 6
- 7
C. Material Data Sheets

STYROFOAM™ Brand Square Edge Insulation

1. **PRODUCT NAME**
STYROFOAM® Brand Extruded Polystyrene Foam (XPS) Square Edge Insulation

2. **MANUFACTURER**
The Dow Chemical Company
Dow Building Solutions
200 Luckin Center,
Midland, MI 48640
1-866-583-BLUE (2583)
Fax 1-989-822-4465
dowbuildingsolutions.com

3. **PRODUCT DESCRIPTION**
STYROFOAM® Brand Square Edge Insulation is an extruded polystyrene foam insulation board that meets the needs of the commercial foundation and building floor slab market. This insulation can also be used for attics, foundationslabs and crawl spaces in residential applications. STYROFOAM® Brand Square Edge Extruded Polystyrene Foam (XPS) Insulation has more than 50 years of proven performance in wet environments. The closed-cell structure of STYROFOAM® Brand Square Edge Extruded Polystyrene Foam (XPS) Insulation resists water pickup, enabling it to retain a high R-value® over time—a necessary property in wet, below-grade commercial foundation applications.

**Basic Use**
STYROFOAM® Brand Square Edge Extruded Polystyrene Foam (XPS) Insulation helps protect foundation damp-proofing and waterproofing, especially during backfilling. It also provides a secondary barrier against groundwater leakage. With STYROFOAM® Brand Square Edge Insulation, freeze-thaw cycling of the foundation wall is minimized, reducing the potential for cracking. And a weatherization can reduce the potential for condensation.

STYROFOAM® Brand Square Edge Insulation can be used against commercial interior walls and exterior foundation walls in above- and below-grade applications. STYROFOAM® Brand Square Edge Insulation can be used under the slab or over the deck or subfloor. STYROFOAM® Brand Square Edge Insulation is suitable for use in pervious, semi-pervious and practically impermeable soils.

**Sizes**
Square Edge
Width and length: 2’ x 8’ and 4’ x 8’
Thickness: 1”, 1.5”, 2”, 2.5”, 3”, 4”
Not all product sizes are available in all parts of the country. Contact your local Dow representative for details.

4. **TECHNICAL DATA**

**Applicable Standards**
STYROFOAM® Brand Square Edge Insulation meets ASTM C578, Type IV—Standard Specification for Rigid Cellular Polystyrene Thermal Insulation. Applicable standards include:

- D1621—Standard Test Method for Compressive Properties of Rigid Cellular Plastics
- E56—Standard Test Methods for Water Vapor Transmission of Materials
- D696—Standard Test Method for Coefficient of Linear Thermal Expansion of Plastics Between 30°C and 30°C with a Vitreous Silica Dilatometer
- C203—Standard Test Methods for Breaking Load and Flexural Properties of Block-Type Thermal Insulation
- D2240—Standard Test Method for Response of Rigid Cellular Plastics to Thermal and Humid Aging
- C227—Standard Test Method for Water Absorption of Core Materials for Structural Sandwich Constructions

**Code Compliances**
STYROFOAM® Brand Square Edge Insulation complies with the following codes:
- International Residential Code (IRC)
- International Building Code (IBC)
- Underwriters Laboratories, Inc. (UL)

**TABLE 1: Physical Properties of STYROFOAM™ Brand Square Edge Insulation**

<table>
<thead>
<tr>
<th>Property and Test Method</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Resistance* per inch, ASTM C-111, hr°F/ft² Btu, R-value, min.</td>
<td>5.0</td>
</tr>
<tr>
<td>@ 70°F mean temp.</td>
<td>5.0</td>
</tr>
<tr>
<td>@ 50°F mean temp.</td>
<td>5.0</td>
</tr>
<tr>
<td>Compressive Strength* ASTM D1621 psi, min.</td>
<td>25</td>
</tr>
<tr>
<td>Water Absorption, ASTM C297, % by volume, max.</td>
<td>0.0</td>
</tr>
<tr>
<td>Water Vapor Permeance* ASTM E96, perm, max.</td>
<td>1.5</td>
</tr>
<tr>
<td>Maximum Use Temperature, °F</td>
<td>100</td>
</tr>
<tr>
<td>Coefficient of Linear Thermal Expansion, ASTM D696, in/in°F</td>
<td>3.0 × 10⁻⁶</td>
</tr>
<tr>
<td>Flexural Strength, ASTM C203, psi, min.</td>
<td>50</td>
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</table>

*Higher the R-value, the greater the insulating power. R-value determined by ASTM C-578.

(1) Values are consistent with those of ASTM D-696 and the requirements of the IICR standards (ICIC, Part 408).
(2) Vertical compressive strength is measured at 10 percent deformation or yield, whichever occurs first.
(3) Based on 1” thickness.
STYROFOAM™ HIGHLOAD 40, 60 and 100
Extruded Polystyrene Insulation

1. PRODUCT NAME
STYROFOAM™ HIGHLOAD Extruded Polystyrene Foam Insulation

2. MANUFACTURER
The Dow Chemical Company
Dow Building Solutions
200 Larkin Center
Midland, MI 48640
1-866-534-BLUE (2583)
Fax 1-989-632-6463
Dow Chemical Canada ULC
Dow Building Solutions
450 - 1 St. SW, Suite 200
Calgary, AB T2P 5H1
1-866-534-BLUE (2583) (English)
1-800-363-6310 (French)
dowbuildingsolutions.com

3. PRODUCT DESCRIPTION
STYROFOAM™ HIGHLOAD Extruded Polystyrene Foam Insulation is a closed-cell foam insulation available in compressive strengths of 40, 60 and 100 psi (275, 415 and 690 kPa). STYROFOAM™ HIGHLOAD insulation features exceptional moisture resistance and R-value retention. All three STYROFOAM™ HIGHLOAD insulation products resist compressive creep and fatigue, delivering long-term compressive strength. Like all STYROFOAM™ insulation products, STYROFOAM™ HIGHLOAD 40, 60 and 100 are durable, versatile and expandable – making them a preferred choice for a variety of high-load applications.

Basic Use
STYROFOAM™ HIGHLOAD insulation is designed for use in low-temperature (freezer floor) applications, highways, airport runways, bridge abutments, parking decks, utility areas, industrial floors and plate decks. It is the responsibility of the designer to select the proper STYROFOAM™ HIGHLOAD insulation product based on the dead and live loads expected in the application.

4. TECHNICAL DATA

Applicable Standards
STYROFOAM™ HIGHLOAD 40, 60 and 100 insulation meets ASTM C578 – Standard Specification for Rigid Cellular Polystyrene Thermal Insulation. Applicable ASTM standards include:
- D2940 – Standard Test Method for Water Absorption of Rigid Cellular Plastics
- C372 – Standard Test Method for Water Absorption of Core Materials for Structural Sandwich Constructions

Code Compliance
STYROFOAM™ HIGHLOAD 40, 60 and 100 insulation complies with the following codes:
- International Residential Code (IRC) and International Building Code (IBC) see IBC/ES ESR 2042 (excluding STYROFOAM™ HIGHLOAD 100)
- California Std. Reg. 4CA 1-644
- Underwriters Laboratories, see Classification Certificate E396
- Underwriters Laboratories Verifed to ESR 2142
- CMCC – EVALUATION 04880-1

Contact your Dow sales representative or local authorities for state/provincial and local building code requirements and related acceptances.

TABLE 1: U.S. VALUES AND TYPICAL PHYSICAL PROPERTIES OF STYROFOAM™ HIGHLOAD 40, 60 AND 100 INSULATION

<table>
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<tr>
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<th>HIGHLOAD 40</th>
<th>HIGHLOAD 60</th>
<th>HIGHLOAD 100</th>
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<td>Thermal Resistance, psi/inch, ASTM C518/IC 177, at 75°F mean temp., R-value, min.</td>
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<td>5.0</td>
<td>5.0</td>
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<td>Compressive Strength, psi, ASTM D602, psi/lin. in., min.</td>
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<td>Water Absorption, ASTM C170, % by volume, 0.4 hr water immersion</td>
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<td>Water Vapor Permeance, ASTM E96, perms</td>
<td>1.0 (81), ng/(Pa*cm²)</td>
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<td>0.6 (48.5), ng/(Pa*cm²)</td>
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Complies with ASTM/C578, Type VI

(1) Compressive strength is measured at 5% strain deformation or at point, whichever occurs first. Since STYROFOAM™ Insulations are static load materials, underdeformation factors should be used in preventing stress concentrations in structural use. It is suggested, for dynamic loads, a factor of 1.5 be used. (2) Flame spread values are based on the Likens method and they apply to insulation 1" or greater in thickness.
**LOW DENSITY LAMINATES WITH GELCOAT**

**TECHNICAL DATA SHEET**

### LAMINATES WITH MAT GLASS FIBRE

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# LAMINATES WITH MAT GLASS FIBRE

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## MECHANICAL PROPERTIES

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### TECHNICAL SHEET

**GRP LAMINATES WITH MAT + WOVEN ROVING**

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<td>ZOD impact strength</td>
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<td>70</td>
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<td>85</td>
<td>100</td>
<td>92</td>
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<tr>
<td>Glass content</td>
<td>%</td>
<td>30</td>
<td>33.3</td>
<td>30.4</td>
<td>33.3</td>
<td>30.8</td>
<td>33.3</td>
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<td>31.2</td>
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<tr>
<td>Density</td>
<td>g/cm³</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
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<td>1.4</td>
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<tr>
<td>Thermal expansion</td>
<td>10⁻⁶/°C</td>
<td>22-26</td>
<td>20-26</td>
<td>22-26</td>
<td>26-26</td>
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<td>20-26</td>
<td>22-26</td>
</tr>
</tbody>
</table>

The results of mechanical tests on composite materials typically exhibit some scatter; for this reason the data here indicated have to be considered only as a guide.
### GRP LAMINATES WITH MAT + WOVEN ROVING

<table>
<thead>
<tr>
<th>PRODUCT CODE</th>
<th>COMPOSITION</th>
<th>NOMINAL THICKNESS</th>
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</thead>
<tbody>
<tr>
<td>LD 30/30</td>
<td>Mat 300 gr/m² + Woven Roving 300 gr/m²</td>
<td>mm 1.5 inch 0.059</td>
</tr>
<tr>
<td>LD 30/50</td>
<td>Mat 300 gr/m² + Woven Roving 500 gr/m²</td>
<td>mm 1.8 inch 0.071</td>
</tr>
<tr>
<td>LD 40/30</td>
<td>Mat 400 gr/m² + Woven Roving 300 gr/m²</td>
<td>mm 1.8 inch 0.071</td>
</tr>
<tr>
<td>LD 40/50</td>
<td>Mat 400 gr/m² + Woven Roving 500 gr/m²</td>
<td>mm 2.1 inch 0.082</td>
</tr>
<tr>
<td>LD 50/30</td>
<td>Mat 500 gr/m² + Woven Roving 500 gr/m²</td>
<td>mm 2.1 inch 0.082</td>
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<tr>
<td>LD 50/50</td>
<td>Mat 500 gr/m² + Woven Roving 500 gr/m²</td>
<td>mm 2.3 inch 0.090</td>
</tr>
<tr>
<td>LD 60/30</td>
<td>Mat 600 gr/m² + Woven Roving 300 gr/m²</td>
<td>mm 2.4 inch 0.094</td>
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<tr>
<td>LD 60/50</td>
<td>Mat 600 gr/m² + Woven Roving 500 gr/m²</td>
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<tr>
<td>LD 80/30</td>
<td>Mat 800 gr/m² + Woven Roving 300 gr/m²</td>
<td>mm 2.9 inch 0.114</td>
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### MECHANICAL PROPERTIES

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th>Unit of measure</th>
<th>LD 30/30</th>
<th>LD 30/50</th>
<th>LD 40/30</th>
<th>LD 40/50</th>
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<td>Nominal thickness</td>
<td>mm</td>
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<td>2.1</td>
<td>2.1</td>
<td>2.3</td>
<td>2.4</td>
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<tr>
<td></td>
<td>inch</td>
<td>0.059</td>
<td>0.071</td>
<td>0.071</td>
<td>0.082</td>
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<td>0.090</td>
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<tr>
<td>Weight</td>
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<td>3.6</td>
</tr>
<tr>
<td></td>
<td>Lbs/5f</td>
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<td>0.49</td>
<td>0.47</td>
<td>0.55</td>
<td>0.63</td>
<td>0.61</td>
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<td>Barcol hardness</td>
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<td>30-20</td>
<td>30-20</td>
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<tr>
<td>Tensile strength</td>
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<tr>
<td>Elongation at break</td>
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<td>1.5</td>
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<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>ZOD impact strength</td>
<td>KJ/m²</td>
<td>56</td>
<td>62</td>
<td>67</td>
<td>73</td>
<td>69</td>
<td>80</td>
<td>71</td>
<td>81</td>
<td>83</td>
</tr>
<tr>
<td>Glass content</td>
<td>%</td>
<td>30</td>
<td>33.3</td>
<td>30.4</td>
<td>33.3</td>
<td>30.8</td>
<td>33...</td>
<td>30</td>
<td>32.3</td>
<td>30.6</td>
</tr>
<tr>
<td>Density</td>
<td>gr/cm³</td>
<td>1.33</td>
<td>1.33</td>
<td>1.29</td>
<td>1.29</td>
<td>1.24</td>
<td>1.3</td>
<td>1.25</td>
<td>1.28</td>
<td>1.24</td>
</tr>
<tr>
<td>Thermal expansion</td>
<td>10^-6 / °K</td>
<td>22-26</td>
<td>22-26</td>
<td>22-26</td>
<td>22-26</td>
<td>22-26</td>
<td>22-26</td>
<td>22-26</td>
<td>22-26</td>
<td>22-26</td>
</tr>
</tbody>
</table>

The results of mechanical tests on composite materials typically exhibit some scatter; for this reason the data here indicated have to be considered only as a guide.
Terostat MS 939 is a gun-grade, one-component sealant based on silane modified polymers, which cures by reaction with moisture to an elastic product. The skin formation and curing times are dependent on humidity and temperature, and the curing time also depends on joint depth. By increasing the temperature and moisture these times can be reduced; low temperature as well as low moisture retard the process. Terostat MS 939 is particularly sag-resistant leading to a high position tack after matching of the parts to be bonded. Terostat MS 939 is free of solvents, isocyanates, silicones and PVC. It demonstrates good adhesion to many substrates and is compatible with suitable paint systems. The sealant also demonstrates good UV resistance and can therefore be used for interior and exterior applications. Terostat MS 939 demonstrates the strength necessary for elastic bonding. This property of the product also remains at the temperatures in repair ovens (max. 100°C). Terostat MS 939 shows no shrinkage, and therefore dimpling and tension stress are not observed under these conditions. Terostat MS 939 allows accelerated curing as two-component material. See separate data sheets Terostat MS Power & Speed Technology or Terostat MS 2s-Technology.

Application Areas:
Terostat MS 939 is used for the following applications: elastic bonding of metals and plastics, e.g. side paneling and bonding of the roof skin in the vehicle and caravan manufacture, elastic, interior and exterior seams and joint sealing in the following areas: vehicle body, caravan, railway carriage, container and general metal construction; the electrical, plastics, air conditioning and ventilation industries.

TECHNICAL DATA

- Tensile strength (acc. to ISO 37), MPa: approx. 3.0
- Elongation at break (acc. to ISO 37, speed 200 mm/min), %: approx. 250
- Stress at 100 % elongation (acc. to ISO 37), MPa: approx. 1.6
- Volume change (acc. to DIN 52461), %: <2
- Paint compatibility: in principle compatible
- UV resistance: no significant changes
- UV source: Osram Vitalux 300W, dry UV
- Distance to the specimen, cm: 20
- Test period, weeks: 8
- QUV resistance: no significant changes
- QUV source: weatherometer acc. to DIN 53884-A
- Test period, weeks: 0
- Reference IEC 81215/81848 clause 10.13: given
- Test period, hours: 1,000
- Application temperature, °C: 5 to 40
- In service temperature range, °C: -40 to +100
- Short exposure (up to 1 h), °C: -20
- *ISO 2561 standard climate: 23°C, 50% relative air humidity
- **Damp heat conditions: 55°C, 80% relative air humidity

Certificates and Approvals
- approved to UL (Underwriters Laboratories) "Polymeric Adhesive Systems, Electrical Equipment - Component", File: QQW2.MH127655

DIRECTIONS OF USE
Preliminary statement:
Prior to application it is necessary to read the Material Safety Data Sheet for information about precautionary measures and safety recommendations. Also, for chemical products exempt from compulsory labeling, the relevant precautions should always be observed.
D. Design Hazard Checklist

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Team: Lobo Campers Senior Project</td>
<td>Faculty Coach: John Fabijanic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>N</td>
<td></td>
<td></td>
</tr>
<tr>
<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>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Can any part of the design undergo high accelerations/decelerations?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Will the system have any large moving masses or large forces?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Will the system produce a projectile?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Would it be possible for the system to fall under gravity creating injury?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Will a user be exposed to overhanging weights as part of the design?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Will the system have any sharp edges?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Will any part of the electrical systems not be grounded?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Will there be any large batteries or electrical voltage in the system above 40 V?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<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>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<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>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14. Can the system generate high levels of noise?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16. Is it possible for the system to be used in an unsafe manner?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For any “Y” responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the reverse side.
<table>
<thead>
<tr>
<th>Description of Hazard</th>
<th>Planned Corrective Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Pinch points between camper and truck</td>
<td>Minimize pinch points in design model, also use rubber guarding to minimize pinch space in the large hinge on wedge camper</td>
</tr>
<tr>
<td>2. Pinch points between the wedge and the rest of camper when in use</td>
<td>Ensure that camper sits flush on truck to minimize gaps and pitch points between camper and truck bed</td>
</tr>
<tr>
<td>3. Top of wedge can swing down at a high acceleration/force if struts were to fail</td>
<td>Ensure the top is fitted with struts of adequate lifting capacity as well as a strong enough hinge system</td>
</tr>
<tr>
<td>4. Wedge camper component is large and over the head of user</td>
<td>Minimize weight of wedge camper top while still maintaining the roof static loading conditions</td>
</tr>
<tr>
<td>5. Sharp edges on the front wedge assembly and hinges</td>
<td>Chamfer or fillet, then sand all sharp edges to minimize hazard</td>
</tr>
<tr>
<td>6. The adhesives and other materials used in the process of manufacturing the shell panels could be harmful to humans</td>
<td>Wear appropriate protective equipment when working with hazardous materials during manufacturing (i.e. a respirator when working with adhesives)</td>
</tr>
<tr>
<td>7. Product can be unsafe if a car is driven with the wedge camper in the upright position</td>
<td>This harm can only be avoided by a customer choosing to not drive the vehicle when the tent is upright</td>
</tr>
</tbody>
</table>
E. ASTM Testing Guidelines

This international standard was developed in accordance with internationally recognized principles on standardization established by the International Organization for Standardization (ISO). This document is a guide to the development of International Standards, Guidelines, and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

Designation: C393/C393M-16

Standard Test Method for Core Shear Properties of Sandwich Constructions by Beam Flexure

This standard is issued under the fixed designation C393/C393M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the U.S. Department of Defense.

1. Scope

1.1 This test method covers determination of the core shear properties of flat sandwich constructions subjected to flexure in such a manner that the applied moments produce curvature of the sandwich facing plates. Permissible core material forms include those with continuous bonding surfaces (such as balsa wood and foams) as well as those with discontinuous bonding surfaces (such as honeycomb).

1.2 The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

1.2.1 Within the text the inch-pound units are shown in brackets.

1.3 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 ASTM Standards:

- C273 Test Method for Shear Properties of Sandwich Core Materials
- D687 Terminology Relating to Plastics
- D3878 Terminology for Composite Materials
- D3222/D3222M Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials

3. Terminology

3.1 Definitions—Terminology D3878 defines terms relating to high-modulus fibers and their composites, as well as terms relating to sandwich constructions. Terminology D3883 defines terms relating to plastics. Terminology D3883 defines terms relating to mechanical testing. Terminology E456 and Practice E77 define terms relating to statistics. In the event of a conflict between terms, Terminology D3878 shall have precedence over the other terminologies.

3.2 Symbols:

- a = specimen width
- e = core thickness
- CV = coefficient of variation statistic of a sample population for a given property (in percent)
- \( E_{\text{eff}} \) = effective sandwich flexural stiffness
- \( F_{\text{fmax}} \) = maximum load in facing
- \( f_{\text{u},\text{f}} \) = facing ultimate strength (tensile or compressive)
- \( F_{\text{c}} \) = core compression allowable strength
- \( F_{\text{c},\text{a}} \) = core shear allowable strength
- \( F_{\text{c},\text{m}} \) = core shear ultimate strength
- \( F_{\text{c},\text{y}} \) = core shear yield strength
- k = core shear strength factor to ensure core failure
- \( l_{\text{f}} \) = length of facing span
- \( l_{\text{s}} \) = length of support span
- \( l_{\text{m}} \) = length of loading pads
- n = number of specimens
- \( F_{\text{a}} \) = applied force
$f_{\text{max}}$ = maximum force carried by test specimen before failure.

$f_{u} = \text{ultimate failure tensile strength}$

$s_{\bar{x}}$ = standard deviation statistic of a sample population for a given property.

$s$ = facing stress or strength

$x = \text{test result for an individual specimen from the sample population for a given property}$

$x = \text{mean or average (estimate of mean) of a sample population for a given property}$

4. Summary of Test Method

4.1 This test method consists of subjecting a beam of sandwich construction to a bending moment normal to the plane of the sandwich. Force versus deflection measurements are recorded.

4.2 The only acceptable failure modes are core shear or core-to-facings bond. Failure of the sandwich facing preceding failure of the core or core-to-facings bond is not an acceptable failure mode. Use Test Method D7290/D7289M to determine facing strength.

5. Significance and Use

5.1 Flexure tests on flat sandwich construction may be conducted to determine the sandwich flexural stiffness, the core shear strength and shear modulus, or the facings compressive and tensile strengths. Tests to evaluate core shear strength may also be used to evaluate core-to-facings bond.

5.2 This test method is limited to obtaining the core shear strength on core-to-facings shear strength and the stiffness of the sandwich beam, and to obtaining load-deflection data for use in calculating sandwich beam flexural and shear stiffness using Practice D7290/D7289M.

Note 1—Core shear strength and shear modulus are determined in accordance with Test Method D2739 provided that core material is available.

5.3 Facing strength test is determined in accordance with Test Method D7290/D7289M.

5.4 Practice D7290/D7289M covers the determination of sandwich flexural and shear stiffness and core shear modulus using calculations involving measured deflections of sandwich flexure specimens.

5.5 This test method can be used to produce core shear strength and core-to-facings shear strength data for structural design allowing material specifications, and research and development applications; it may also be used as a quality control test for bonded sandwich panels.

5.6 Factors that influence the shear strength and shall therefore be reported include the following: facing material, core material, adhesive material, methods of material fabrication, core geometry (cell size), core density, adhesive thickness, specimen geometry, specimen preparation, specimen conditioning, environment of testing, specimen alignment, loading procedure, speed of testing, and adhesive void content.

Part 2—Core-to-facing strength may be different between precracked/bonded and co-coated facings in sandwich panels with the same core and facing material.

Note 2—Concentrated loads or beams with thin facings and low density cores can produce results that are difficult to interpret, especially close to the failure point. Water-dampened rubber pads may assist in distributing the loads.

6. Interference

6.1 Material and Specimen Preparation—Poor material fabrication practices and damage induced by improper specimen machining are known causes of high data scatter in composposites and sandwich structures in general. A specific material factor that affects sandwich core is variability in core density. Important aspects of sandwich core specimen preparation that contribute to data scatter include the existence of joints, voids or other core discontinuities, transverse curvature, and surface roughness.

6.2 Geometry—Specific geometric factors that affect core shear strength include core orthotropy (i.e., fibrous versus transverse direction for honeycomb core materials) and core cell geometry.

6.3 Environment—Results are affected by the environmental conditions under which specimens are conditioned, as well as the conditions under which the tests are conducted. Specimens tested in various environments can exhibit significant differences in both strength behavior and failure mode. Critical environments must be assessed independently for each specific combination of core material, facing material, and core-to-facings facing/interfacial adhesive (if used) that is tested.

6.4 Core Material—In the core material has insufficient shear or compressive strength, it is possible that the core may locally crack at or near the loading point, thereby resulting in failure due to local stress. In other cases, facing failure can cause local core cracking. When there is both facing and core failure in the vicinity of one of the loading points, it can be difficult to determine the failure sequence in a post-mortem inspection of the specimen as the failed specimens look very similar for both sequences. For some core materials, the shear strength is a function of the direction that the core is oriented relative to the length of the specimen.

7. Apparatus

7.1 Micrometers and Calipers—A micrometer with a 4 to 7 mm (0.16 to 0.28 in.) diameter ball interface or a flat anvil interface shall be used to measure the specimen thickness. A ball interface is recommended for thickness measurements when facings are bonded to the core and at least one surface is irregular (e.g., the back side of a thin facings laminate that is neither smooth nor flat). A micrometer or caliper with a flat anvil interface is recommended for thickness measurements when facings are bonded to the core and both surfaces are smooth (e.g., lapped surfaces). A micrometer or caliper with a flat anvil interface shall be used for measuring length and widths, as well as the specimen thickness when no facings are present. The use of alternative measurement devices is permitted if specified (or agreed to) by the test requestor and approved by the testing laboratory. The accuracy of the instruments shall
be suitable for reading to within 1% of the sample dimensions. For typical specimen geometries, an instrument with an accuracy of ± 0.025 mm [±0.001 in.] is adequate for the length, width, and thickness measurements.

Note 1: The values given above are based on achieving measurements that are within 1% of the sample length, width, and thickness.

7.2 Loading Fixtures—The loading fixture shall consist of either a 3-point or 4-point loading configuration with two support bars that span the specimen width located below the specimen, and one or two loading bars that span the specimen width located on the top of the specimen (Fig. 1). The force shall be applied vertically through the loading bar(s), with the support bars fixed in place in the test machine.

7.2.1 Standard Configuration—The standard loading fixture shall be a 3-point configuration and shall have the centroids of the support bars separated by a distance of 150 mm [6.0 in.].

7.2.2 Non-Standard Configurations—All other loading fixture configurations are considered non-standard, and details of the fixture geometry shall be documented in the test report. Fig. 3 shows a typical 4-point short beam test fixture. Non-standard 4- and 5-point loading configurations have been rejected within this standard (a) for historical continuity with previous versions of Test Method C39, (b) because some sandwich panel designs require the use of non-standard loading configurations to achieve core or bond failure modes, and (c) load-deflection data from non-standard configurations may be used with Practice D7210/D7210M to obtain sandwich beam flexural and shear stiffnesses.

7.2.3 Support and Loading Bars—The bars shall be designed to allow free rotation of the specimen at the loading and support points. The bars shall have sufficient stiffness to avoid significant deflection of the bars under load; any obvious bowing of the bars or any raps occurring between the bars and the test specimen during loading shall be considered significant deflection. The recommended configuration has a 25 mm [1.0 in.] wide flat steel loading block to contact the specimen (through rubber pressure pads) and is loaded via either a cylindrical pivot or a V-shaped tab running in a V-groove in the top of the flat-bottomed steel loading pad. The tips of the V-shaped loading bars shall have a minimum radius of 3 mm [0.12 in.]. The V-groove in the loading pad shall have a radius larger than the loading bar tip and the angular opening of the groove shall be such that the sides of the loading bars do not contact the sides of the V-groove during the test. Loading bars consisting of 25 mm [1.0 in.] diameter steel cylinders may also be used, but there is a greater risk of local specimen crushing with cylindrical bars. Also, the load and support span lengths tend to increase as the specimen deflects when cylindrical loading bars without V-grooved loading pads are used (for example, rolling supports).

7.2.4 Pressure Pads—Rubber pressure pads having a Shore A durometer of approximately 60, a nominal width of 25 mm [1.0 in.], a nominal thickness of 3 mm [0.125 in.] and spanning the full width of the specimen shall be used between the loading bars and specimen to prevent local damage to the facings.

FIG. 1 Loading Configurations

FIG. 2 Sandwich Panel Thickness Dimensions
shall be capable of maintaining the required temperature to within ±3°C and the required relative humidity level to within ±1%. Chamber conditions shall be monitored either on an automated continuous basis or on a manual basis at regular intervals.

7.6 Environmental Test Chamber—An environmental test chamber is required for test environments other than ambient testing laboratory conditions. This chamber shall be capable of maintaining the gage section of the test specimen at the required test environment during the mechanical test.

8. Sampling and Test Specimens

8.1 Sampling—Test at least five specimens per test condition unless valid results can be gained through the use of fewer specimens, as in the case of a designed experiment. For statistically significant data, consult the procedures outlined in Practice E 122. Report the method of sampling.

8.2 Geometry—The standard specimen configuration should be used whenever the specimen design equations in 8.2.3 indicate that the specimen will produce the desired core or core-to-face bond failure mode. In cases where the standard specimen configuration will not produce a desired failure, a non-standard specimen shall be designed to produce a core or bond failure mode.

8.2.1 Standard Configuration—The test specimen shall be rectangular in cross section, with a width of 75 mm [3.0 in.] and a length of 200 mm [8.0 in.]. The depth of the specimen shall be equal to the thickness of the sandwich construction.

8.2.2 Non-Standard Configuration—For non-standard specimen geometries the widths shall be no less than twice the total thickness nor more than six times the total thickness, not less than three times the dimension of a core cell, nor greater than one half the span length. The specimen length shall be equal to the support span plus 30 mm [1.2 in.] or plus one half the sandwich thickness, whichever is the greater. Limitations on the maximum specimen width are intended to allow for the use of simplified sandwich beam calculations; plate flexure effects must be considered for specimens that are wider than the restrictions specified above.

8.2.3 Specimen Design—Practise design of the sandwich flexural test specimen for determining shear strength of the core or core-to-face bond is required to avoid failure modes. Proper design of the test specimen for compatibility of the core and superpan shall be sufficient such that transverse shear forces are produced under applied forces low enough so that the allowable facing stress will not be exceeded. However, if the facings are too thick, the transverse shear force will not be considerable extent by the facings, thus leading to a higher apparent core shear strength compared by the equations given in this standard. The following equations can be used to size the test specimen (these equations assume that both facings have the same thickness and modulus, and that the facing thickness is small relative to the core thickness [l/k < 0.01]):

The support span length shall satisfy:

\[ s = \frac{24k}{f_{y}} - L \]  

(1)

or, the core shear strength shall satisfy:
The core compression strength shall satisfy:

\[ F_c = \frac{2kt}{(2L^2 - L)} \]  
\[ F_{Rc} = \frac{2kt}{(2L^2 - L)} \]  

(1)

where:
- \( S \) = support span length, mm [in.]
- \( L \) = loading span length, mm [in.], \( L = 6 \) for 3-point loading
- \( a \) = expected facing ultimate strength, MPa [psi]
- \( t \) = facing thickness, mm [in.]
- \( c \) = core thickness
- \( F_c \) = measured core shear strength, MPa [psi]
- \( k \) = facing strength factor to ensure core failure (recommended \( k = 0.75 \))
- \( F_{Rc} \) = dimension of loading pad in specimen lengthwise direction, mm [in.]
- \( F_c \) = core compression allowable strength, MPa [psi]

8.3 Facings:
8.3.1 Layup—The apparent flexural stiffness obtained from this method may be dependent upon the facing stacking sequence, albeit to a much lesser degree than is typical for laminate failures. For the standard test configuration, facings consisting of a laminated composite material shall be balanced and symmetric about the sandwich beam midplane.

8.3.2 Thickness—For the standard specimen, the facings shall be the same material, thickness and layup. The calculations assume constant and equal upper and lower facing stiffness properties. This assumption may not be applicable for certain facing materials (such as aramid fiber composite) which have significantly different tensile and compressive moduli or which exhibit significant non-linear stress-strain behavior.

8.3.3 Facing Thickness—Accurate measurement of facing thickness is difficult after bonding or coating of the facings and core. The test supervisor is responsible for specifying the facing thicknesses to be used for the calculations in this test method. For metallic or precured composite facings which are secondary bonded to the core, the facing thickness should be measured prior to bonding. In these cases the test supervisor may specify that either both measured and nominal thicknesses be used in the calculations. For precured composite facings, the thicknesses are generally calculated using nominal ply thickness values.

8.4 Specimen Preparation and Machining—Specimen preparation is important for this test method. Take precautions when cutting specimens from large panels to avoid notches, tears, or uneven surfaces, or delaminations due to inappropriate machining methods. Obtain flat dimensions with water-lubricated precision sawing, milling, or grinding. The use of diamond coated machining tools has been found to be extremely effective for many material systems. Edges should be flat and parallel within the specified tolerances. Record and report the specimen cutting preparation method.

8.5 Labeling—Label the test specimens so that they will be distinct from each other and traceable back to the panel of origin, and will neither influence the test nor be affected by it.
11.5 **Test Environment**—If possible, test the specimen under the same fluid exposure level used for conditioning. However, cases such as elevated temperature testing of a moist specimen place stringent requirements on the capabilities of common testing machine environmental chambers. In such cases, the mechanical test environment may need to be modified, for example, by testing at elevated temperature with no fluid exposure control, but with a specified limit on time to failure from withdrawal from the conditioning chamber. Record any modifications to the test environment.

11.6 **Fixture Installation**—Arrange the loading fixture as shown in Fig. 1 as appropriate and place in the test machine.

11.7 **Specimen Insertion and Alignment**—Place the specimen into the test fixture. Align the fixture and specimen so that the longitudinal axis of the specimen is perpendicular (within 1°) to the longitudinal axes of the loading bars, and the bars are parallel (within 1°) to the plane of the specimen facing.

11.8 **Transducer Installation**—Attach the deflection transducer to the fixture and specimen, and connect to the recording instrumentation. Remove any remaining preload, zero the strain gages and balance the deflection transducers.

11.9 **Loading**—Apply a compressive force to the specimen at the specified rate while recording data. Load the specimen until failure or until a deflection equal to the specimen thickness is reached.

Note: Some core materials do not exhibit a well-defined failure with sudden loss of load-carrying capacity, rather failures are characterized by a gradual yield of the core in shear, resulting in large core shear deformation while continuing to carry load. Tests of such materials should be stopped within the limits of linear beam theory.

11.10 **Data Recording**—Record force versus axial displacement, and force versus deflection data continuously, or at frequent regular intervals (at a rate of 2 to 3 recordings per second, with a target minimum of 100 recorded data points per test). If any initial failures are noted, record the force, displacement, and mode of damage at each point. Potential initial (non-catastrophic) failures should be reported in the text. Recount the load, area and location of each initial failure. Use the failure identification codes shown in Table 1. Record the method used to determine the initial failure (visual, acoustic emission, etc.). Count the maximum force, the failure force, the head displacement and the deflection at, or as near as possible to, the moment of ultimate failure.

11.11 **Ultimate Failure Mode**—Record the mode, area and location of ultimate failure for each specimen. Use the failure identification codes shown in Table 1. Shear failures of the sandwich core or failures of the core-to-facing bond are the only acceptable failure modes. Failure of one or both of the facings preceding failure of the core or core-to-facing bond is not an acceptable failure mode.

12. **Validation**

12.1 Values for ultimate properties shall not be calculated for any specimen that breaks at some obvious flaw, unless such flaw constitutes a variable being studied. Retests shall be performed for any specimen on which values are not calculated.

12.2 A significant fraction of failures in a sample population occurring in one or both of the facings shall be cause to reexamine the loading and specimen geometry.

13. **Calculation**

13.1 **Force-Displacement Behavior**—Plot and examine the force-displacement data to determine if there is any significant compliance change (change in slope of the force-displacement curve, sometimes referred to as a transition region) prior to ultimate failure (significant is defined as a 10% or more change in slope). An example of a transition region is shown in Test Method D 3410. Determine the slope of the force-displacement curve above and below the transition point using chord values over linear regions of the curve. Intersect the linear slopes to find the transition point. Report the force and displacement at such points along with the displacement values used to determine the chord slopes. Report the mode of any damage observed during the test prior to specimen failure.

13.2 **Shear Mid-span Loading**

13.2.1 **5 Point Mid-span Loading**—Calculate the core shear ultimate stress using Eq. 4:

\[ \sigma_{cu} = \frac{P_{cu}}{2bf} \]  

where:
- \( \sigma_{cu} \) = core shear ultimate strength, MPa [psi];
- \( P_{cu} \) = maximum force prior to failure, N [lb];
- \( b \) = nominal facing thickness, mm [in.];
- \( f \) = sandwich thickness, mm [in.];
- \( c = f + 2t \) (see Fig. 2, and
- \( t \) = sandwich width, mm [in.].

Note: Since it is generally not practical to accurately measure the facing thickness of co-cured sandwich panels, the calculations are based on a nominal thickness specified by the test request.

The rate of application to the shear stress distribution through the thickness of a thin facc-core sandwich panel uses a linear
distribution of shear stress in the lap joint is zero at the free surface and increasing to the core shear stress value at the loadline core interface. Therefore, the effective area of noncore shear stress in the core thickness is 1.5d on each base sheet thickness, which is equal to 1.5d + 1.5d = (λ + 1)d.

13.2.2 Core Shear Yield Stress—For core materials that yield more than 2% strain calculate the core shear yield stress using Eq 8:

\[ \sigma_{y} = \frac{P_{y} - P_{s}}{2(\lambda + 1)d} \]  

(8)

where:
- \[ P_{y} \] = core ultimate strength, MPa [psi],
- \[ P_{s} \] = force at 2% offset shear strain, N [lb],
- \[ \lambda \] = span length, mm [in].

Note 10—The shear stress is calculated as a reference value at the maximum applied force. Since this test method is restricted to core or core-to-fascia shear failures, the shear stress does not represent the true shear strength. Use Test Method D7249/D7249M to obtain the true shear strength.

13.3 4-Point (Quarter Point) Loading:

13.3.1 Core Shear Ultimate Stress—Calculate the core shear ultimate stress using Eq 7:

\[ \sigma_{u} = \frac{P_{u}}{2(\lambda + 1)d} \]  

(7)

13.3.2 Core Shear Yield Stress—For core materials that yield more than 2% strain calculate the core shear yield stress using Eq 8:

\[ \sigma_{y} = \frac{P_{y} - P_{s}}{2(\lambda + 1)d} \]  

(8)

13.3.3 Facing Bending Stress—Calculate the facing bending stress using Eq 11:

\[ \sigma = \frac{3P_{s}}{4(\lambda + 1)d^{3}} \]  

(9)

Note 10—The shear stress is calculated as a reference value at the maximum applied force. Since this test method is restricted to core or core-to-fascia shear failures, the shear stress does not represent the field shear strength. Use Test Method D7249/D7249M to obtain the true shear strength.

13.4 4-Point (Third Point) Loading:

13.4.1 Core Shear Ultimate Stress—Calculate the core shear ultimate stress using Eq 10:

\[ \sigma_{u} = \frac{P_{u}}{2(\lambda + 1)d} \]  

(10)

13.4.2 Core Shear Yield Stress—For core materials that yield more than 2% strain calculate the core shear yield stress using Eq 11:

\[ \sigma_{y} = \frac{P_{y} - P_{s}}{2(\lambda + 1)d} \]  

(11)

13.4.3 Facing Bending Stress—Calculate the facing bending stress using Eq 12:

\[ \sigma = \frac{3P_{s}}{4(\lambda + 1)d^{3}} \]  

(12)

Notes 10—The facing stress is calculated as a reference value at the maximum applied force. Since this test method is restricted to core or core-to-fascia shear failures, the facing stress does not represent the field shear strength. Use Test Method D7249/D7249M to obtain the true shear strength.

1.5 StatisticsFor each series of tests calculate the average value, standard deviation, and coefficient of variation (in percent) for ultimate strength:

\[ \bar{x} = \frac{\sum x_{i}}{n} \]  

(13)

\[ s = \sqrt{\frac{\sum (x_{i} - \bar{x})^{2}}{n-1}} \]  

(14)

where:
- \[ x \] = sample mean (average),
- \[ s \] = sample standard deviation,
- \[ CV \] = sample coefficient of variation, %,
- \[ n \] = number of tested specimens, and
- \[ x_{i} \] = measured or derived property.

14. Report

14.1 Report the following information, or references pointing to other documentation containing this information, to the maximum extent applicable (reporting of items beyond the control of a given testing laboratory, such as might occur with material details or panel fabrication parameters, shall be the responsibility of the requestor):

14.1.1 The revision level or date of issue of this test method.

14.1.2 The name(s) of the test operator(s).

14.1.3 Any variations to this test method, anomalies noticed during testing, or equipment problems occurring during testing.

14.1.4 Identification of all the materials constituent to the sandwich panel specimen (including facing, adhesive, or core materials), including for each a material specification, material type, manufacturer's material designation, manufacturer's batch or lot number, source (if not from manufacturer), date of certification, and expiration of certification. Description of the core orientation.

14.1.5 Description of the fabrication steps used to prepare the sandwich panel including fabrication start date, fabrication end date, process specification, and a description of the equipment used.

14.1.6 Method of preparing the test specimen, including specimen labeling scheme and method, specimen geometry, sampling method, and specimen cutting method.

14.1.7 Results of any destructive evaluation tests.

14.1.8 Calibration data and methods for all measurements and test equipment.

14.1.9 Details of loading platens and apparatus, including leading configuration, loading and support span dimensions, leading bar details and materials used.

14.1.10 Type of test machine, alignment results, and data acquisition sampling rate and equipment type.

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14.1.11 Type, range and sensitivity of LVDT, or any other instruments used to measure loading platen deflection.
14.1.12 Measured lengths, widths and thicknesses for each specimen.
14.1.13 Weight of specimen, if requested.
14.1.14 Conditioning parameters and results.
14.1.15 Relative humidity and temperature of the testing laboratory.
14.1.16 Environment of the test machine environmental chamber (if used) and soak time at environment.
14.1.17 Number of specimens tested.
14.1.18 Speed of testing.
14.1.19 Failing thickness used in the calculation.
14.1.20 Individual ultimate shear strength and average value, standard deviation, and coefficient of variation (in percent) for the population.
14.1.21 Individual facing stresses at maximum applied force and average value, standard deviation, and coefficient of variation (in percent) for the population.
14.1.22 Force versus crosshead displacement data for each specimen.
14.1.23 Force versus deflection data for each specimen.
14.1.24 Failure mode and location of failure.

15. Precision and Bias

15.1 Precision—The data required for the development of a precision statement is not available for this test method.
15.2 Bias—Bias cannot be determined for this method as no acceptable reference standards exist.

16. Keywords

16.1 bonding stress; core modulus; core stress; facing stress; sandwich construction; sandwich deflection; shear stress.
Standard Test Method for Facesheet Properties of Sandwich Constructions by Long Beam Flexure

This standard is issued under the fixed designation D7249/D7249M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers determination of facesheet properties of the sandwich constructions subjected to flexure in such a manner that the applied moments produce curvature of the sandwich facesheets planes and result in compressive and tensile forces in the facesheets. Permissible core material forms include those with continuous bonding surfaces (such as beech wood and foam) as well as those with discontinuous bonding surfaces (such as honeycomb).

1.2 Units—The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system are not necessarily exact equivalents; therefore, to ensure conformance with the standard, each system shall be used independently of the other, and values from the two systems shall not be combined.

1.2.1 Within the text, the inch-pound units are shown in brackets.

1.3 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and environmental practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 ASTM Standards:

C237M/C237M-17 Test Method for Shear Properties of Sandwich Core Materials

C956/C956M Test Method for Core Shear Properties of Sandwich Constructions by Beam Flexure

D3419/D3419M Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gauge Section by Beam Loading

D3878 Terminology for Composite Materials

D5229/D5229M Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials

D6673/D6673M Test Method for Compressive Properties of Unidirectional Polymer Matrix Composite Materials Using a Sandwich Beam

D7250/D7250M Practice for Determining Sandwich Beam Flexural and Shear Stiffness

E4 Practices for Force Verification of Testing Machines

E5 Terminology Relating to Methods of Mechanical Testing

E122 Practice for Calculating Sample Size for Estimating, With Specified Precision, the Average for a Characteristic of a Lot or Process

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

E201 Test Methods for Performance Characteristics of Metal Bonded Resistance Strain Gages

E456 Terminology Relating to Quality and Statistics

E1357 Guide for Installing Bonded Resistance Strain Gages

3. Terminology

3.1 Definitions—Terminology D3878 defines terms relating to high-modulus fibers and their composites. Terminology E1357 defines terms relating to mechanical testing. Terminology E456 and Practice E177 define terms relating to statistics. In the event of a conflict between terms, Terminology D3878 shall have precedence over the other terminologies.

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This standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

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3.2 Symbols:

- \( b \) = specimen width
- \( c \) = core thickness
- \( CV \) = coefficient of variation statistic of a sample population for a given property (in percent)
- \( d \) = sandwich total thickness
- \( D_{fore} \) = effective sandwich flexural stiffness
- \( E \) = effective face sheet chord modulus
- \( e \) = measuring strain in face sheet
- \( F^e \) = face sheet ultimate strength (tensile or compressive)
- \( F^c \) = core shear allowable strength
- \( F^p \) = core compression allowable strength
- \( k^c \) = core shear strength factor to ensure face sheet failure
- \( L \) = length of loading span
- \( l_{pad} \) = length of loading pad
- \( n \) = number of specimens
- \( P^a \) = applied force
- \( P_{max} \) = maximum force carried by test specimen before failure
- \( S \) = length of support span
- \( S_{std} \) = standard deviation statistic of a sample population for a given property
- \( \alpha \) = face sheet stress
- \( \tau \) = face sheet thickness
- \( r \) = test result for an individual specimen from the sample population for a given property
- \( \bar{x} \) = mean or average (estimate of mean) of a sample population for a given property

4. Summary of Test Method

4.1 This test method consists of subjecting a long beam of sandwich construction to a bending moment normal to the plane of the sandwich, using a 4-point loading fixture. Deflections and strain values for some measurements are recorded.

4.2 The only acceptable failure modes for sandwich face sheet strength are those which are internal to one of the face sheets. Failure of the sandwich core or the core-to-face sheet bond preceding failure of any one of the face sheets is not an acceptable failure mode. Careful post-test inspection of the specimens is required to determine if face sheet failure occurred in proximity to the loading points can be caused by local through-thickness compression or shear failure of the core that provides failure of the face sheet.

5. Significance and Use

5.1 Flexure tests on flat sandwich construction may be conducted to determine the sandwich flexural stiffness, the core shear strength, shear modulus, or the face sheets' compressive and tensile stiffnesses. Tests to evaluate core shear strength may also be used to evaluate core-to-face sheet bond.

5.2 This test method is limited to obtaining the strength and stiffness of the sandwich panel face sheets, and to obtaining load-deflection data for use in calculating sandwich beam flexural and shear stiffness using Practice D7249/D7249M-20.

5.3 Core shear strength and shear modulus are best determined in accordance with Test Method C273/C273M provided bare core material is available. Test Method C933/C933M may also be used to determine core shear strength. Practice D7249/D7249M may be used to calculate the flexural and shear stiffness of sandwich beams.

5.4 This test method can be used to produce face sheet strength data for structural design allowables, material specifications, and research and development applications. Each may also be used in a quality control test for bonded sandwich panels.

5.5 Factors that influence the face sheet strength and shall therefore be examined include the following: face sheet material, core material, adhesive material, method of material fabrication, face sheet stacking sequence and overall thickness, core geometry (cell size), core density, adhesive thickness, specimen size, specimen preparation, specimen conditioning, environment of testing, specimen alignment, measuring procedure, speed of testing, face sheet void content, adhesive void content, and face sheet volume percent reinforcement. Further, face sheet strength may be different between pressure/bonded and co-cured face sheets of the same material.

Note 2—Concentrated loads on beams with thin face sheets and low density cores can produce results that are difficult to interpret, especially close to the failure point. Wide loading blocks and rubber pressure pads may assist in distributing the forces.

Note 3—To ensure that simple sandwich beam theory is valid, a good rule of thumb for the four-point bending test is the support span length divided by the sandwich thickness should be greater than 20 (l/b > 20) with the ratio of face sheet thickness to core thickness less than 0.1 (t/\( t_c \) < 0.1).

6. Interferences

6.1 Material and Specimen Preparation—Poor material fabrication practices and damage induced by improper specimen machining are known causes of high data scatter in composites and sandwich structures in general. A specific material factor that affects sandwich cores is variability in core density, and important aspects of sandwich core specimen preparation that contribute to data scatter include the existence of joints, voids, or other core discontinuities, out-of-plane curvature, and surface roughness.

6.2 Geometry—Specific geometric factors that affect sandwich face sheet strength include face sheet thickness, core cell geometry, and face sheet surface roughness (incompressible or biphasic surface in compression).

6.3 Environment—Results are affected by the environmental conditions under which specimens are conditioned, as well as the conditions under which the tests are conducted. Specimens tested in various environments can exhibit significant differences in both strength behavior and failure mode. Critical environments must be assessed independently for each specific combination of core material, face sheet material, and core-to-face sheet interfacial adhesives (if used) that is assessed.

6.4 Core Material—If the core material has insufficient shear or compressive strength, it is possible that the core may locally crush at or near the loading points thereby resulting in face sheet failure due to local stresses. In other cases, face sheet...
failure can cause local core crushing. When there is both faceted and core failure in the vicinity of one of the loading points, it can be difficult to determine the failure sequence in a post-process inspection of the specimen as the failed specimens look very similar for both sequences.

7. Apparatus

7.1 Micrometers and Calipers—A micrometer having a flat anvill, interface, or a caliper of suitable size, shall be used. The micrometer shall have an accuracy of ±0.001 in. for thickness measurement, and an accuracy of ±0.003 in. for length and width measurement.

Note—The accuracies given above are based on achieving measurements that are within 1% of the sample length, width, and thickness.

7.2 Loading Fixtures

7.2.1 Standard Configuration—The standard loading fixture shall consist of a 4-point loading configuration with two support bars that span the specimen width located below the specimen, and two loading bars that span the specimen width located on the top of the specimen (Fig. 1). The fixture shall be applied vertically through the loading bars, with the support bars fixed in place in the test machine. The standard loading fixture shall have the centerlines of the support bars separated by a distance of 506 mm [22.0 in.] and the centerlines of the loading bars separated by a distance of 100 mm [4.0 in.].

7.2.2 Non-standard Configurations—All other loading fixture configurations (see Fig. 2) are considered non-standard and details of the fixture geometry shall be documented in the test report. Figs. 3-5 show typical test fixtures. Non-standard 3- and 4-point loading configurations have been retained within this standard (as) for historical continuity with previous versions of Test Method C293/C293M, (b) because some sandwich panel designs require the use of non-standard loading configurations to achieve face sheet failure modes, and (c) load-deflection data from non-standard configurations may be used with practice D7240/D7240M to obtain sandwich beam flexural and shear stiffness.

7.2.3 Support and Loading Bars—The bars shall be designed to allow free rotation of the specimen at the loading and support points. The bars shall have sufficient stiffness to avoid significant deflection of the bars under load, any obvious bowing of the bars or any gaps occurring between the bars and the test specimen during loading shall be considered significant deflection. The recommended configuration has a 25 mm [1.0 in.] wide flat steel loading block to contact the specimen (through rubber pressure pads) and is loaded via either a cylindrical pivot (see Fig. 3) or a V-shaped bar riding in a V-groove in the top of the flat-bottomed steel loading pad. The tip of the V-shaped loading bars shall have a minimum radius of 3 mm [0.12 in.]. The V-grooves in the loading pad shall have a radius larger than the loading bar tip and the angular opening of the groove shall be such that the sides of the loading bars do not contact the sides of the V-groove during the test. Loading bars consisting of 25 mm [1.0 in.] diameter steel cylinders may also be used, but there is a greater risk of local specimen crushing with cylindrical bars. Also, the load and support span lengths tend to increase as the specimen deflects when cylindrical loading bars without Vgrooved loading pads are used (for example, rolling supports).

7.2.4 Pressure Pads—Rubber pressure pads having a Shore A durometer of 60, a width of 25 mm [1.0 in.], a nominal thickness of 3 mm [0.125 in.], and spanning the full width of the specimen shall be used between the loading bars and specimen to prevent local damage to the facesheets.

7.3 Testing Machine—The testing machine shall be in accordance with Practice E4 and shall satisfy the following requirements:

FIG. 1 Test Specimen and Fixture

FIG. 2 Loading Configurations

FIG. 3 Standard 4-point Loading Configuration
7.3.1 Testing Machine Configuration—The testing machine shall have both an essentially stationary head and a movable head.

7.3.2 Drive Mechanism—The testing machine drive mechanism shall be capable of imparting to the movable head a controlled velocity with respect to the stationary head. The velocity of the movable head shall be capable of being regulated in accordance with 11.4.

7.3.3 Force Indicator—The testing machine force-sensing device shall be capable of indicating the total force being carried by the test specimen. This device shall be essentially free from inertia-lag at the specified rate of testing and shall indicate the force with an accuracy over the force range(s) of interest of within ±1% of the indicated value.

7.4 Deflection (L/D)—The deflection of the specimen shall be measured in the center of the support span by a properly calibrated device having an accuracy of ±1% or better.

7.5 Stress-Indicating Device—Stress data, when required, shall be determined by means of bonded resistance strain gages. One axial gage element shall be located on each face at the center of the specimen, with the gage aligned with the specimen length axis. Strain gages cannot be used on the non-standard 3-point loading configuration due to interference with the center loading bar.

7.5.1 Bonded Resistance Strain Gage Selection—Strain gage selection is based on the type of material to be tested. An active gage length of 1.5 mm (0.06 in.) is recommended for composite laminates fabricated from unidirectional layers. Larger strain gage sizes may be more suitable for some textile fabrics. Gage calibration certification shall comply with Test Methods E251. Strain gages with a minimum normal strain range of approximately 3% are recommended. When using textile fabric laminates, gage selection should consider the use of an active gage length that is at least as great as the characteristic repeating unit of the fabric. Some guidelines on the use of strain gages on composite materials follow. A general reference on the subject is Tuttle and Breslin.5

7.5.1.1 Surface preparation of fiber-reinforced composites in accordance with Guide E127 can penetrate the matrix material and cause damage to the reinforcing fibers, resulting in improper coupon failures. Reinforcing fibers should not be exposed or damaged during the surface preparation process. The strain gage manufacturer should be consulted regarding surface preparation guidelines and recommended bonding agents for composites, pending the development of a set of standard practices for strain gage installation surface preparation of fiber-reinforced composite materials.

7.5.1.2 Consideration should be given to the selection of gages having larger resistances to reduce heating effects on low conductivity materials. Resistances of 350 Ω or higher are preferred. Additional consideration should be given to the use of the minimum possible gage excitation voltage consistent with the desired accuracy (1 to 2 V is recommended) to reduce the power consumed by the gage. Heating of the coupon by the gage may affect the performance of the material directly or it may affect the indicated strain as a result of a difference between the gage temperature compensation factor and the coefficient of thermal expansion of the coupon material.

7.5.1.3 Consideration of some form of temperature compensation is recommended, even when testing at standard laboratory atmosphere. Temperature compensation may be required when testing in non-standard temperature environments.

7.5.1.4 Consideration should be given to the transverse sensitivity of the selected strain gage. The strain gage manufacturer should be consulted for recommendations on transverse sensitivity corrections and effects on composites.

7.6 Conditioning Chamber—When conditioning materials at non-laboratory environments, a temperature and humidity-controlled environmental conditioning chamber is required that shall be capable of maintaining the required temperature to within ±0.5°C (±0.5°F) and the required relative humidity level to within ±2%. Chamber conditions shall be monitored either on an automated continuous basis or on a manual basis at regular intervals.

7.7 Environmental Test Chamber—An environmental test chamber is required for test environments other than ambient testing laboratory conditions. This chamber shall be capable of maintaining the gage section of the test specimen at the required test environment during the mechanical test.

8. Sampling and Test Specimen

8.1 Sampling—Test at least five specimens per test condition unless valid results can be gained through the use of fewer specimens, as in the case of a design experiment. For statistically significant data, consult the procedures outlined in Practice E112. Report the method of sampling.

8.2 Geometry—The standard specimen configuration shall be used whenever the specimen design equations in 8.2.3 apply.

---

indicate that the specimen will produce the desired facessheet failure mode, in cases where the standard specimen configuration will not produce a facessheet failure, a non-standard specimen shall be designed to produce a facessheet failure mode.

8.2.1 Standard Configuration—The standard test specimen shall be rectangular in cross section, with a width of 75 mm [3.0 in.] and a length of 600 mm [24.0 in.]. The depth of the specimen shall be equal to the thickness of the sandwich construction.

8.2.2 Non-Standard Configuration—For non-standard specimen geometries, the width shall be less than twice the total thickness for more than six times the total thickness; not less than three times the dimension of a core cell, or greater than one-quarter the span length. The specimen length shall be equal to the support span length plus 50 mm [2 in.], or plus one-half the sandwich thickness, whichever is the greater. Limitations on the maximum specimen width are intended to allow for the use of simplified sandwich beam calculations; plate flexure effects must be considered for specimens that are wider than the restrictions specified above.

8.2.3 Specimen Design—Proper design of the sandwich flexure test specimen for determining compressive or tensile strength of the facessheets is required to avoid core crushing, core shear, or core-to-facessheet failures. The facessheets must be sufficiently thin and the support span sufficiently long so that the allowable core shear stress will not be exceeded. The core must be sufficiently thick to avoid excessive deflection. The following equations can be used to size the test specimen (these equations assume that both facessheets have the same thickness and modulus, and that the facessheet thickness is small relative to the core thickness [ie E \ll 0.10]):

\[ L \geq \frac{2\pi^2 E}{(1 - \nu^2)\sigma_t}\]  

where \( L \) = support span length, mm [in.], \( \sigma_t \) = facessheet ultimate strength, MPa [psi], and \( E \) = core thickness.

8.3 Facessheets

8.3.1 Compression Side Facessheet—Unless otherwise specified by the test requestor, the hinge-side facessheet of a cored composite sandwich panel shall be placed as the upper, compression loaded facessheet during testing, as facessheet compression strength is more sensitive to imperfections typical of hinge-side surfaces (for example, in-cord slitting) than facessheet tension strength.

Note—Tensile failure rarely occurs unless the tensile facessheet is thinner or of different material than the compression facessheet. Failure in the compression facessheet may occur by debonding, yielding, or splitting. In compression, the facessheet tends to debond from the core, or the facessheet splitting into the honeycomb core cells.

8.3.2 Laminated Facessheets—The apparent flexural strength, effective facessheet moduli, and flexural stiffness obtained from this method may be dependent upon the facessheet stacking sequence, albeit to a much lesser degree than is typical for
laminate flexure. For the standard test configuration, facsheets consisting of a laminated composite material shall be balanced and symmetric about the sandwich beams mid-plane.

8.3.3 **Stiffness**—For the standard specimen, the facesheets shall be the same material, thickness, and layup. The calculations assume constant and equal upper and lower facesheet stiffness properties. This assumption may not be applicable for certain facsheet materials (such as anisotropic composites) which have significantly different tensile and compressive modulus or which exhibit significant nonlinear stress-strain behavior.

8.3.4 **Facsheet Thickness**—Accurate measurement of facsheet thickness is difficult after bonding or co-curing of the facsheets and core. The test requester is responsible for specifying the facsheet thicknesses to be used for the calculations in this test method. For metallic or precured composite facsheets which are adhered to the core, the facsheet thickness should be measured prior to bonding. In these cases, the test requester may specify that either or both measured and nominal thicknesses be used in the calculations. For co-cured composite facsheets, the thicknesses are generally calculated using nominal ply thickness values.

8.4 **Core**—For test specimens using a honeycomb core material, the core ribbon direction shall be oriented in the specimen longwise direction to aid in avoiding core shear failures. The core material shall be selected to provide sufficient local compression and shear strength under the loading points to avoid local core crushing or shear failures that precede and cause premature facsheet failure.

8.5 **Specimen Preparation and Machining**—Specimen preparation and machining is extremely important for this test method. Take precautions when cutting specimens from large panels to avoid notches, cracks, or stresses in the specimen. Use sharp tools and avoid tool marks or scratches. Use contrasting materials to machine and avoid chatter. The use of diamond coated machining tools has been found to be extremely effective for many materials systems. Edges should be flat and parallel within the specified tolerances. Record and report the specimen cutting preparation method.

8.6 **Labeling**—Label the test specimens so that they will be distinguishable from each other and traceable back to the panel of origin, and will neither influence the test nor be affected by it.

9. **Calibration**

9.1 The accuracy of all measuring equipment shall have certified calibrations that are current at the time of use of the equipment.

10. **Conditioning**

10.1 The recommended pre-test specimen condition is effective moisture equilibrium at a specific relative humidity per Test Method D5229/D5229M. However, if the test requester does not explicitly specify a pre-test conditioning environment, conditioning is not required and the test specimens may be tested as prepared.}

10.2 The pre-test specimen conditioning process, to include specified environmental exposure levels and resulting moisture content, shall be reported with the test data.

Note: The term moisture, as used in Test Method D5229/D5229M, includes not only the vapor of a liquid and its condensate, but the liquid itself in large quantities, as for immersion.

10.3 If no explicit conditioning process is performed, the specimen conditioning process shall be reported as "unconditioned" and the moisture content as "unknown."

11. **Procedure**

11.1 **Parameters to Be Specified Before Test**

11.1.1 The specimen sampling method, specimen geometry, and conditioning environment (if required).

11.1.2 The properties and data reporting format desired.

11.1.3 The environmental conditioning test parameters.

11.1.4 The nominal thicknesses of the facsheet materials.

Note: Enter specific material property, accuracy, and data reporting requirements prior to testing for proper selection of instrumentation and data recording equipment. Estimate the specimen strength to aid in transverse section, calibration of equipment, and determination of equipment settings.

11.2 **General Instructions**

11.2.1 Report any deviations from this test method, whether intentional or inadvertent.

11.2.2 Condition the specimens as required. Store the specimens in the conditioned environment until test time, if the test environment is different than the conditioning environment.

11.2.3 Before testing, measure and record the specimen length, width, and thickness at three places in the test section. Measure the specimen length and width with an accuracy of ±0.0005 in. Measure the specimen thickness with an accuracy of ±0.002 in. Record the dimensions to two or more significant figures in units of inches.

11.2.4 If strain is to be measured, apply one longitudinal strain gauge to each facsheet at the center of the specimen.

11.3 Measure and record the length of the support and loading spans.

11.4 **Speed of Testing**—Set the speed of testing so as to produce failure within 3 to 5 min. If the ultimate strength of the material cannot be reasonably estimated, initial trials should be conducted using standard speeds until the ultimate strength of the material and the compliance of the system are known, and speed of testing can be adjusted. The suggested standard speeds are:

11.4.1 **Steady-Loaded Test**—A standard strain rate of 0.01 in. per min.

11.4.2 **Constant Load Rate Test**—A standard cross head displacement of 0.25 in. per min.

11.5 Test Environment—If possible, test the specimens under the same fluid exposure level used for conditioning. However, if excessive temperature or pressure testing of a moist specimen is required, the capabilities of the test equipment are limited.

11.6 Test Environment—If the test specimen is under the same fluid exposure level used for conditioning. However, if excessive temperature or pressure testing of a moist specimen is required, the capabilities of the test equipment are limited.

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from withdrawal from the conditioning chamber. Record any modifications to the test environment.

11.6 Fixture Installation—Mount the loading fixture as shown in Fig. 1 and Fig. 2 and place in the test machine.

11.7 Specimen Insertion and Alignment—Place the specimen into the test fixture. Align the fixture and specimen so that the longitudinal axis of the specimen is perpendicular (within 1°) to the longitudinal axes of the loading bars, and the bars are parallel (within 1°) to the plane of the specimen facesheet.

11.8 Transducer Installation—Attach the strain recording instrumentation to the strain gages on the specimen. Attach the deflection transducer (LVDT) to the fixture and specimen, and connect to the recording instrumentation. Remove any remaining preload, zero the strain gages, and balance the LVDT.

11.9 Loading—Apply a compressive force to the specimen at the specified rate while recording data. Load the specimen until failure.

11.10 Data Recording—Record force versus head displacement, force versus strain, and force versus LVDT deflection data continuously, or at frequent regular intervals (in the order of 20 Hz readings per second, with a target minimum of 100 recorded data points per test). If any initial failures are noted, record the force, displacement, and mode of damage at such points. Potential initial (non-catastrophic) failures that should be reported include: facesheet delamination, core-to-facesheet debond, partial core fracture, and local core crushing. Record the mode, area, and location of each initial failure. Use the failure identification codes shown in Table 1. Record the method used to determine the initial failure (visual, acoustic emission, etc.). Record the maximum force, the failure force, measured strain, the head displacement, and the LVDT deflection at, or as near as possible to, the moment of ultimate failure.

11.11 Ultimate Failure Modes—Record the mode, area, and location of ultimate failure for each specimen. Use the failure identification codes shown in Table 1. Tensile or compressive failures of the sandwich facesheets are the only acceptable failure modes. Failure of the sandwich core or the core-to-facesheet bond preceding failure of one of the facesheets is not an acceptable failure mode.

11.11.1 Acceptable Failure Area—The acceptable failure area is between the loading bars for a 4-point loading test, or within 12 mm (0.48 in.) of the loading bar for a 3-point loading test.

12. Validation

12.1 Values for ultimate properties shall not be calculated for any specimens that breaks at some obvious flaw, unless such flaw constitutes a variable being studied. Retests shall be performed for any specimens on which values are not calculated.

12.2 A significant fraction of failures is a sample population occurring in the core or core-to-facesheet bond shall be cause to re-estimate the loading and specimen geometry.

13. Calculation

13.1 Force-Displacement Behavior—Plot and examine the force-displacement data to determine if there is any significant compliance change (change in slope of the force-displacement curve, sometimes referred to as a transition region) prior to ultimate failure (significant is defined as a 10% or more change in slope). An example of a transition region is shown in Test Method D5334/D5334M. Determine the slope of the force-displacement curve above and below the transition point using chord values over linear regions of the curve. Intersect the linear slopes to find the transition point. Report the force and displacement at such points along with the force values used to determine the chord slopes. Report the mode of any damage observed during the test prior to specimen failure.

13.2 Facesheet Ultimate Stress—Calculate the facesheet ultimate stress and report the results to three significant figures.

13.2.1 Specimens with Equal Facesheet Materials and Thickness—Calculate and report the facesheet ultimate stress using Eq. 1.

### Table 1: Sandwich Panel Facesheet Three Part Failure Identification Codes

<table>
<thead>
<tr>
<th>Failure Type</th>
<th>First Character</th>
<th>Second Character</th>
<th>Third Character</th>
<th>Code</th>
<th>Code</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>adhesive delamination</td>
<td>D</td>
<td>A</td>
<td>AD</td>
<td>A</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Filament fracture</td>
<td>E</td>
<td>G</td>
<td>EG</td>
<td>G</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>Forward/Backward</td>
<td>H</td>
<td>M</td>
<td>HM</td>
<td>M</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>Longitudinal</td>
<td>L</td>
<td>D</td>
<td>LD</td>
<td>D</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>local wrinkling</td>
<td>W</td>
<td>V</td>
<td>WV</td>
<td>V</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Multitude</td>
<td>M</td>
<td>U</td>
<td>MU</td>
<td>U</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>Core Crush</td>
<td>C</td>
<td>W</td>
<td>CW</td>
<td>W</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>Others</td>
<td>O</td>
<td>D</td>
<td>OD</td>
<td>D</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

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\[ P = \frac{b}{d} \left( \frac{L - L_f}{2} \right) \left( \frac{1}{c} + \frac{1}{c + 1} \right) \frac{1}{d} \frac{1}{h} \]

\[ P = \frac{b}{d} \left( \frac{L - L_f}{2} \right) \left( \frac{1}{c} + \frac{1}{c + 1} \right) \frac{1}{d} \frac{1}{h} \]

where:
- \( b \) = specimen width, mm [in.]
- \( c \) = calculated core thickness, mm [in.], \( c = d - 2 \) see Fig. 6.
- \( d \) = measured sandwich total thickness, mm [in.].
- \( L \) = loading span length, mm [in.] (L = 0 for 3-point loading).
- \( L_{max} \) = maximum force prior to failure, N [lb].
- \( S \) = support span length, mm [in.], and \( t \) = nominal facesheet thickness, mm [in.].

13.2.2. Specimens with Unusual Facesheets (Non-standard Test Specimens) — Calculate and report a separate facesheet ultimate stress for each facesheet using Eq. 5.

**Note:** These equations are used when the two facesheets are different materials or layups, or both. The facesheet moduli used in the equations are laminate moduli, which account for the facesheet layup. In the case of asymmetric layups, the core provides restraint from bending-extension coupling, so the model should be calculated from the inverse of the [6x6] stiffness matrix rather than the inverse of the [6x6] stiffness matrix. The laminate stress through each facesheet is actually non-uniform, varying linearly through the facesheet thickness. Since the facesheets are assumed to be thin relative to the sandwich panel thickness, the variation of stress in the facesheet is the effect of any variation of ply modulus through the facesheet thickness is assumed to be insignificant.

\[ f = \frac{P_{max}(L - L_f)}{b} \left( 1 + \frac{S}{L} \right) \]

\[ f = \frac{P_{max}(L - L_f)}{b} \left( 1 + \frac{S}{L} \right) \]

\[ f = \frac{P_{max}(L - L_f)}{b} \left( 1 + \frac{S}{L} \right) \]

\[ f = \frac{P_{max}(L - L_f)}{b} \left( 1 + \frac{S}{L} \right) \]

**Fig. 4 Sandwich Panel Thickness Dimensions**

**Fig. 5 Sandwich Panel Thickness Dimensions**

\[ \sigma_{f,\text{new}} = \sigma_{f,\text{old}} \frac{(\epsilon + \tau_f)}{(\epsilon + \tau_f)} \]

\[ \sigma_{f,\text{new}} = \sigma_{f,\text{old}} \frac{(\epsilon + \tau_f)}{(\epsilon + \tau_f)} \]

\[ \sigma_{f,\text{new}} = \sigma_{f,\text{old}} \frac{(\epsilon + \tau_f)}{(\epsilon + \tau_f)} \]

\[ \sigma_{f,\text{new}} = \sigma_{f,\text{old}} \frac{(\epsilon + \tau_f)}{(\epsilon + \tau_f)} \]

\[ \sigma_{f,\text{new}} = \sigma_{f,\text{old}} \frac{(\epsilon + \tau_f)}{(\epsilon + \tau_f)} \]

where:
- \( \sigma_{f,\text{new}} \) = effective facesheet 1 chord modulus, MPa [psi].
- \( \sigma_{f,\text{old}} \) = effective facesheet 2 chord modulus, MPa [psi].
- \( \sigma_{f,\text{new}} \) = facesheet 1 stress calculated using Eq. 4 for applied force corresponding to \( \tau_{f,\text{max}} \), MPa [psi].
- \( \sigma_{f,\text{old}} \) = facesheet 2 stress calculated using Eq. 4 for applied force corresponding to \( \tau_{f,\text{max}} \), MPa [psi].
- \( \sigma_{f,\text{new}} \) = recorded facesheet 1 strain value (magnitude) closest to 1000 micro-strain.
- \( \sigma_{f,\text{old}} \) = recorded facesheet 1 strain value (magnitude) closest to 1000 micro-strain.


13.4 Sandwich Flexural Stiffness—Calculate the effective sandwich flexural stiffness using Eq. (7) and report the results to three significant figures.

\[
P_{eff} = \frac{P_{nom}}{\sqrt{\frac{\ell}{\ell_{nom}}}} \left( \frac{1}{\ell_{nom}} \right)
\]

where:

- \( P_{eff} \) = sandwich flexural stiffness, \( \text{N/m}^2 \) [lb/in^2]
- \( P_{nom} \) = face sheet 2 (top surface) recorded strain value (magnitude) closest to 3000 micro-strain.
- \( \ell_{nom} \) = face sheet 1 (top surface) recorded strain value (magnitude) closest to 1000 micro-strain.
- \( \ell \) = applied force corresponding to face sheet 1 strain.
- \( \ell_{nom} \) = applied force corresponding to face sheet 1 strain.
- \( \ell_{eff} \) = face sheet 2 (bottom surface) recorded strain value (magnitude) corresponding to \( P_{eff} \), and
- \( \ell_{eff} \) = face sheet 2 (bottom surface) recorded strain value (magnitude) corresponding to \( P_{nom} \).

Note 10—Eq. (7) is strictly valid only for cases where the shear flexibility of the sandwich beam is negligible. For procedures and equations for calculating the sandwich flexural and through-thickness shear stiffnesses in cases where the shear flexibility cannot be neglected, see Practice D7259/D7259M.

13.5 Stresses—For each series of tests, calculate the average value, standard deviation, and coefficient of variation (in percent) for ultimate strength and modulus:

\[
S_{\text{eff}} = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} S_{\text{eff}}[i]
\]

\[
S_{\text{eff}} = \sqrt{\left( \frac{1}{N} \sum_{i=1}^{N} S_{\text{eff}}[i] \right)^2 - \left( \frac{1}{N} \sum_{i=1}^{N} S_{\text{eff}}[i] \right)^2}
\]

\[
C_V = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} S_{\text{eff}}[i]
\]

where:

- \( S_{\text{eff}} \) = sample mean (average).
- \( S_{\text{eff}}[i] \) = sample standard deviation, \( i \).
- \( C_V \) = sample coefficient of variation, %.
- \( N \) = number of tested specimens, and
- \( S_{\text{eff}} \) = measured or derived property.

14. Report

14.1 Report the following information, or references pointing to other documentation containing this information, to the maximum extent applicable (reporting of items beyond the control of a given testing laboratory, such as might occur with material details or panel fabrication parameters, shall be the responsibility of the requester):

14.1.1 The revision level or date of issue of this test method.

14.1.2 The name(s) of the test operator(s).

14.1.3 Any variances from this test method, anomalies noticed during testing, or equipment problems occurring during testing.

14.1.4 Identification of all the materials consistent to the sandwich panel specimen tested (including face sheet, adhesive, and core materials), including for each: material specification, material type, manufacturer's material designation, manufacturer's batch or lot number, source (if not from manufacturer), date of certification, and expiration of certification. Description of the core orientation.

14.1.5 Description of the fabrication steps used to prepare the sandwich panel including: fabrication start date, fabrication end date, process specification, and a description of the equipment used.

14.1.6 Method of preparing the test specimen, including specimen labeling scheme and method, specimen geometry, sampling method, and specimen cutting method.

14.1.7 Results of any nondestructive evaluation tests.

14.1.8 Calibration dates and methods for all measurements and test equipment.

14.1.9 Details of loading platens and apparatus, including loading configuration, loading and support span dimensions, loading or load details and material(s) used.

14.1.10 Type of test machine, alignment results, and data acquisition sampling rate and equipment type.

14.1.11 Types, range, and sensitivity of LVDT, or any other instruments used to measure loading plate deflection.

14.1.12 Measured length, width, and thicknesses for each specimen.

14.1.13 Weight of specimen, if required.

14.1.14 Conditioning parameters and results.

14.1.15 Relative humidity and temperature of the testing laboratory.

14.1.16 Environmental of the test machine environmental chamber (if used) and soak time at environment.

14.1.17 Number of specimens tested.

14.1.18 Speed of testing.

14.1.19 Face sheet thicknesses used in the calculations.

14.2.1 Individual ultimate face sheet strengths and average value, standard deviation, and coefficient of variation (in percent) for the population.

14.2.2 Individual ultimate face sheet compressive and tensile modulus values and average value, standard deviation, and coefficient of variation (in percent) for the population.

15. Precision and Bias

15.1 Precision—The data required for the development of a precision statement is not available for this test method.

15.2 Bias—Bias cannot be determined for this method as no acceptable reference standards exist.
16. Keywords
16.1 bending stress; facet sheet modulus; facet sheet strength; facet sheet stress; flexural stiffness; sandwich construction; uniaxial deflection.
Appendix F: Wedge Camper Competing Products

**Adventure Trailers (AT)**
These campers incorporate a welded aluminum frame with a composite sandwich exterior (aluminum exterior skin, honeycomb sandwich material, FRP interior skin). It weighs in at 340 pounds and has a starting cost of $8,900.

![Figure 1. AT Wedge Camper](image)

**Vagabond**
The Vagabond is made with a welded aluminum frame and a composite sandwich exterior. It weighs in at roughly 350 pounds and costs between $7,000 and $8,000 dollars depending on the buildout. They launched in March of 2018 and claim to have a “patent pending design”.

![Figure 2. Vagabond Camper](image)

**Go Fast Campers (GFC)**
Go Fast Campers has a large facility in Montana and had a big, successful launch in mid-2018. They currently have a 14-month lead time with almost 600 units on backorder. They make all of their own components (hinges, latches, extrusions, etc.) in-house with CNC machines. The product has a DOM steel tube lower space frame, aluminum sheet “WinDoor” panels, and an extruded aluminum profile upper frame for the tent. The Go-Fast Camper weighs about 275-300 pounds and starts at $6,450. This is the most barebones and lightweight wedge camper currently available. [3]
AluCab
The AluCab is produced in Australia and is made with a welded aluminum frame and exterior aluminum sheet. These campers are much heavier than the others listed at roughly 450-550 pounds and only available for mid-size trucks. For this build, similarly to the Lobo Camper, the tailgate needs to be removed in order for full sized barn doors to be installed. AluCab has a single swing door with the ability to mount a full-sized wheel. [4]

Snap Treehouse
The Snap Treehouse is a similar camper to GFC. It has a welded aluminum frame and all the panels surrounding the bed can fold out. These campers come from a smaller family business in Pennsylvania. [5]
50Ten
50Ten is a high-end German camper that completely replaces the truck bed with a utility style bed made for camping. These campers are made in Germany and come with a base model price of $38,000 and cost goes up from there depending on the customizations and accessories added. This camper is not considered a direct competitor because of the high price point and the fact that it requires a complete bed replacement. This product is by far the highest quality of all competing products. This camper also weighs the most compared to the others and requires the use of a very heavy-duty truck or extreme upgrades to make a mid-sized vehicle in order to support the weight. The weight and size of this competitor is a major concern in the design as it will not be as versatile off road and will not allow for a quick and easy take down and setup. [6]

Overland Explorer
Overland explorer makes a box pop-up camper shell that is constructed with high quality composite panels and aluminum extrusions making it midweight, highly insulated, and durable. This product is made to order and customizable to fit many trucks. The price point for the
Overland Explorer is much higher than the Lobo Camper and falls into the category of luxury truck toppers. [7]

Figure 7. Overland Explorer Vehicle

**EarthCruiser**
The EarthCruiser GZL is a wedge-top camper that is made to fit a variety of different makes and sizes of trucks. These weigh in anywhere between 1,000 and 1,500 pounds and are built with a sink and kitchen area. The GZL is currently out of production online and preorders are available for the upcoming 2020 model. This product is expected to be expensive and also falls into the category of luxury truck campers. [8]

Figure 8. EarthCruiser Camper
Appendix G: Span Length Calculations for ASTM Tests

Test C393

These calculations for the span length for test ASTM C393 do not converge after plugging in our material properties. We found that the span length had to be less than 32.1” (upper green row) and that the calculated core compression strength to be less than 25 psi. To get the compression strength to be less than 25 psi, the span length had to be a minimum length of 101” (orange row) which contradicts the span length calculation. The number 1 in the Fe,calc row just signifies that that condition is met.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Support Span (S)</th>
<th>Load Span (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard 2-Point</td>
<td>150 mm (6.0 in)</td>
<td>0</td>
</tr>
<tr>
<td>Non-Standard 4-Point</td>
<td>150 mm (6.0 in)</td>
<td>0</td>
</tr>
</tbody>
</table>

\[
S = \frac{2k\sigma}{F_s} + L
\]

\[
F_c \geq \frac{2(c + t)\sigma}{(S - L)F_{pad}}
\]

<table>
<thead>
<tr>
<th>k</th>
<th>0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma)</td>
<td>10152.6 psi</td>
</tr>
<tr>
<td>(F_s)</td>
<td>37.4 psi</td>
</tr>
<tr>
<td>(L)</td>
<td>0 in</td>
</tr>
<tr>
<td>(F_c)</td>
<td>25 psi</td>
</tr>
<tr>
<td>(c)</td>
<td>1.5 in</td>
</tr>
<tr>
<td>(t)</td>
<td>0.07874 in</td>
</tr>
<tr>
<td>(F_{pad})</td>
<td>1 in</td>
</tr>
<tr>
<td>(S_{calc})</td>
<td>32.0623 in</td>
</tr>
<tr>
<td>(F_{c,calc})</td>
<td>25 psi</td>
</tr>
<tr>
<td>(S)</td>
<td>100.966 in</td>
</tr>
</tbody>
</table>

- \(S\) = support span length, mm [in.], \(L\) = loading span length, mm [in.] (\(L = 0\) for 3-point loading), \(\sigma\) = expected facing ultimate strength, MPa [psi], \(t\) = facing thickness, mm [in.], \(c\) = core thickness, \(F_c\) = estimated core shear strength, MPa [psi], \(k\) = facing strength factor to ensure core failure (recommend \(k = 0.75\)), \(F_{pad}\) = dimension of loading pad in specimen lengthwise direction, mm [in.], and \(F_c\) = core compression allowable strength, MPa [psi].
Test D7249

The calculations for test D7249 show that we would need a coupon span length of 105” to satisfy both equations. This is unreasonable and is way too large to fit in the Ametek’s testing dimensions.

### Coupon Size Calculations for ASTM D7249

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Support Span (S)</th>
<th>Load Span (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard 4-Point</td>
<td>560 mm [22.0 in.]</td>
<td>100 mm [4.0 in.]</td>
</tr>
<tr>
<td>Non-Standard 3-Point (Mid-span)</td>
<td>S</td>
<td>0.0</td>
</tr>
<tr>
<td>4-Point (Quarter-Span)</td>
<td>S</td>
<td>S/2</td>
</tr>
<tr>
<td>4-Point (Third-Span)</td>
<td>S</td>
<td>S/3</td>
</tr>
</tbody>
</table>

\[
S \geq \frac{2\alpha t}{kF_s} + L \\
F_c \geq \frac{2(c+t)\alpha t}{(S-L)l_{pad}}
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>0.75</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>10152.6 psi</td>
</tr>
<tr>
<td>L</td>
<td>4 in</td>
</tr>
<tr>
<td>t</td>
<td>0.07874 in</td>
</tr>
<tr>
<td>(l_{pad})</td>
<td>1 in</td>
</tr>
<tr>
<td>c</td>
<td>1.5 in</td>
</tr>
<tr>
<td>(F_s)</td>
<td>25 psi</td>
</tr>
<tr>
<td>(F_c)</td>
<td>37.4 psi</td>
</tr>
<tr>
<td>(F_{c,c,calc})</td>
<td>25</td>
</tr>
<tr>
<td>(S_{calc})</td>
<td>60.9997 in</td>
</tr>
</tbody>
</table>

\(S\) = support span length, mm [in.], 
\(L\) = loading span length, mm [in.] \((L = 0\) for 3-point loading), 
\(\alpha\) = expected facing ultimate strength, MPa [psi], 
\(t\) = facing thickness, mm [in.], 
\(c\) = core thickness, 
\(F_s\) = estimated core shear strength, MPa [psi], 
\(k\) = facing strength factor to ensure core failure (recommend \(k = 0.75\)), 
\(l_{pad}\) = dimension of loading pad in specimen lengthwise direction, mm [in.], and 
\(F_c\) = core compression allowable strength, MPa [psi].
<table>
<thead>
<tr>
<th>Item</th>
<th>Test Description</th>
<th>Test Stage</th>
<th>Responsibility</th>
<th>Test Condition</th>
<th>Test Compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sample set A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Sample set B</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Sample set C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Sample set D</td>
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<td></td>
</tr>
<tr>
<td>5</td>
<td>Sample set E</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>4-point bend test</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Report Date: 3/14/22
Signature: [Sign Here]
<table>
<thead>
<tr>
<th>Test</th>
<th>Notes</th>
<th>Time</th>
<th>Pass/Fail</th>
<th>Start Date</th>
<th>Finish Date</th>
</tr>
</thead>
</table>
| 1    | THICKNESS 
EXTENSION 
FROM AND ALUMINUM 
FROM INCONSISTENT 
ADHESION OF FRP AND 
ADHESION DUE TO POOR 
PREMATURE FAULRE | 11/2/2020 | 0 | PASS | 11/9/2020 |
| 2    | THICKNESS 
EXTENSION 
FROM AND ALUMINUM 
FROM INCONSISTENT 
ADHESION OF FRP AND 
ADHESION DUE TO POOR 
PREMATURE FAULRE | 11/2/2020 | 0 | PASS | 11/9/2020 |
| 3    | FRP-FROM ADHESION 
TO IMPROPER 
SINGLE FAULRE DUE | 11/6/2020 | 0 | PASS | 11/6/2020 |
| 4    | FRP-FROM ADHESION 
TO IMPROPER 
SINGLE FAULRE DUE | 10/23/2020 | 0 | PASS | 10/23/2020 |
| 5    | FRP-FROM ADHESION 
TO IMPROPER 
SINGLE FAULRE DUE | 10/23/2020 | 0 | PASS | 10/23/2020 |
<table>
<thead>
<tr>
<th>System / Function</th>
<th>Potential Failure Mode</th>
<th>Potential Effects of the Failure Mode</th>
<th>Severity</th>
<th>Potential Causes of the Failure Mode</th>
<th>Current Preventative Activities</th>
<th>Occurrence</th>
<th>Current Detection Activities</th>
<th>Detection</th>
<th>RPN</th>
<th>Recommended Action(s)</th>
<th>Responsibility &amp; Target Completion Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof panel</td>
<td>Collapse from static load</td>
<td>camper breaks, users inside are injured</td>
<td>9</td>
<td>1) Overloading roof 2) roof panel weakness/damage</td>
<td>1) Specify maximum roof load 2) ensure roof panel is durable 3) smooth surfaces</td>
<td>2</td>
<td>Panel testing</td>
<td>7</td>
<td>126</td>
<td>Testing and Abaqus Models</td>
<td>Testing team 2/15</td>
</tr>
<tr>
<td>Side panels</td>
<td>Delamination from shear</td>
<td>a) No longer weather resistant b) roof foam exposed</td>
<td>5</td>
<td>1) overloading side panel/hanging a tire 2) adhesive application error 3) Water inside panels 4) 5) 6) 7)</td>
<td>1) specify max. hanging load 2) all mounting points have proper fasteners/thru bolts</td>
<td>1</td>
<td>Panel testing</td>
<td>7</td>
<td>35</td>
<td>Testing and Abaqus Models</td>
<td>Testing team 2/15</td>
</tr>
<tr>
<td>Door</td>
<td>Latch failure</td>
<td>Door falls open while driving</td>
<td>4</td>
<td>1) Poor latch selection 2) User error (not latching correctly) 3) fastener becomes loose from vibrations</td>
<td>1) Proper latch selection 2) Testing</td>
<td>4</td>
<td>N/A</td>
<td>4</td>
<td>64</td>
<td>Go through proper latch selection and testing procedures</td>
<td>Door team 1/25</td>
</tr>
<tr>
<td>Step failure</td>
<td>bottom of door fails off, hard to enter camper</td>
<td>bottom of door breaks</td>
<td>3</td>
<td>1) Overloading steps 2) fatigue damage on aluminum steps</td>
<td>1) Proper Door design process 2) testing/simulation</td>
<td>3</td>
<td>N/A</td>
<td>3</td>
<td>27</td>
<td>go through proper analyses and design of door steps</td>
<td>Door team 1/25</td>
</tr>
</tbody>
</table>
Appendix J: Operation & Maintenance Manual for Step Box Assembly

Operation:

Left: step box in open position, right: step box in closed position

1) Locate the pull latch on the front door sandwich panel of the step box, and pull to open. The door step should swing down to a 90 degree angle, and then lock into this configuration.
   a) Avoid pinch points near hinge when opening
   b) The step door functions as a stand-alone step, and can be used in a pinch without an extra step box, however this is not recommended.
2) A small step stool will be contained within the step box, and this will go on the ground to provide an extra step up to the step box.
3) To get into the expedition camper, step up on the step stool, then the door of the step box, and then into the camper.
   a) To avoid failure the step door should not be jumped on or used by multiple people at once.

Maintenance:

Note: Since our step box uses stainless hardware, aluminum panels, and our sandwich panels, specific maintenance steps are not necessarily required. However, to ensure longevity of the step box, one should follow a few general maintenance

1) Ensure all hinges are properly lubed.
2) Check door support cables for any fraying or damage before use.

Disclaimer: Hardware such as hinges, pull tabs, and cable supports are not shown in step box operation photos.
## Appendix K: Statistical Measurements of all Sample Specimen for C393 Test

<table>
<thead>
<tr>
<th></th>
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<tbody>
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<td>0.992</td>
<td>0.987</td>
<td>0.991</td>
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<td>1.00</td>
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</table>
Appendix L: Matlab Code for Plotting all Real-World Test Raw Data

Senior Project Sample Data Sandwich Panel Testing
ME 430-02 Winter 2021

Date: 03/14/2020

Author: Ryan Shomsky, Kevin Pickering, Alexander Horst

Project sponsor: Enduro Campers

California Polytechnic State University, San Luis Obispo, CA

Clear Workspace
format short;
format compact;
close all;
clear;

Import Discrete Data from .txt File;

%%%%% Test Set A, 1.5 [in] Foam, Epoxy Glue
A_1 = readtable('A_1.txt','PreserveVariableNames',true);
A_1_time = table2array(A_1((2:end),1)); % [s] Time Column of Data Converted to Array
A_1_load = table2array(A_1((2:end),2)); % [N] Load Column of Data Converted to Array
A_1_mach_ext = table2array(A_1((2:end),3)); % [mm] Time Column of Data Converted to Array
A_1_ext = table2array(A_1((2:end),4)); % [mm] Time Column of Data Converted to Array

A_2 = readtable('A_2.txt','PreserveVariableNames',true);
A_2_time = table2array(A_2((2:end),1)); % [s] Time Column of Data Converted to Array
A_2_load = table2array(A_2((2:end),2)); % [N] Load Column of Data Converted to Array
A_2_mach_ext = table2array(A_2((2:end),3)); % [mm] Time Column of Data Converted to Array
A_2_ext = table2array(A_2((2:end),4)); % [mm] Time Column of Data Converted to Array

A_3 = readtable('A_3.txt','PreserveVariableNames',true);
A_3_time = table2array(A_3((2:end),1)); % [s] Time Column of Data Converted to Array
A_3_load = table2array(A_3((2:end),2)); % [N] Load Column of Data Converted to Array
A_3_mach_ext = table2array(A_3((2:end),3)); % [mm] Time Column of Data Converted to Array
A_3_ext = table2array(A_3((2:end),4)); % [mm] Time Column of Data Converted to Array

A_4 = readtable('A_4.txt','PreserveVariableNames',true);
A_4_time = table2array(A_4((2:end),1)); % [s] Time Collumn of Data Converted to Array
A_4_load = table2array(A_4((2:end),2)); % [N] Load Collumn of Data Converted to Array
A_4_mach_ext = table2array(A_4((2:end),3)); % [mm] Time Collumn of Data Converted to Array
A_4_ext = table2array(A_4((2:end),4)); % [mm] Time Collumn of Data Converted to Array

A_5 = readtable('A_5.txt', 'PreserveVariableNames',true);
A_5_time = table2array(A_5((2:end),1)); % [s] Time Collumn of Data Converted to Array
A_5_load = table2array(A_5((2:end),2)); % [N] Load Collumn of Data Converted to Array
A_5_mach_ext = table2array(A_5((2:end),3)); % [mm] Time Collumn of Data Converted to Array
A_5_ext = table2array(A_5((2:end),4)); % [mm] Time Collumn of Data Converted to Array

%%%%% Test Set B, 1.5 [in] Foam, 3M Fast Bond Contact Adhesive Glue

B_1 = readtable('B_1.txt', 'PreserveVariableNames',true);
B_1_time = table2array(B_1((2:end),1)); % [s] Time Collumn of Data Converted to Array
B_1_load = table2array(B_1((2:end),2)); % [N] Load Collumn of Data Converted to Array
B_1_mach_ext = table2array(B_1((2:end),3)); % [mm] Time Collumn of Data Converted to Array
B_1_ext = table2array(B_1((2:end),4)); % [mm] Time Collumn of Data Converted to Array

B_2 = readtable('B_2.txt', 'PreserveVariableNames',true);
B_2_time = table2array(B_2((2:end),1)); % [s] Time Collumn of Data Converted to Array
B_2_load = table2array(B_2((2:end),2)); % [N] Load Collumn of Data Converted to Array
B_2_mach_ext = table2array(B_2((2:end),3)); % [mm] Time Collumn of Data Converted to Array
B_2_ext = table2array(B_2((2:end),4)); % [mm] Time Collumn of Data Converted to Array

B_3 = readtable('B_3.txt', 'PreserveVariableNames',true);
B_3_time = table2array(B_3((2:end),1)); % [s] Time Collumn of Data Converted to Array
B_3_load = table2array(B_3((2:end),2)); % [N] Load Collumn of Data Converted to Array
B_3_mach_ext = table2array(B_3((2:end),3)); % [mm] Time Collumn of Data Converted to Array
B_3_ext = table2array(B_3((2:end),4)); % [mm] Time Collumn of Data Converted to Array

B_4 = readtable('B_4.txt', 'PreserveVariableNames',true);
B_4_time = table2array(B_4((2:end),1)); % [s] Time Collumn of Data Converted to Array
B_4_load = table2array(B_4((2:end),2)); % [N] Load Collumn of Data Converted to Array
B_4_mach_ext = table2array(B_4((2:end),3)); % [mm] Time Collumn of Data Converted to Array
B_4_ext = table2array(B_4((2:end),4)); % [mm] Time Collumn of Data Converted to Array

B_5 = readtable('B_5.txt', 'PreserveVariableNames',true);
B_5_time = table2array(B_5((2:end),1)); % [s] Time Collumn of Data Converted to Array
B_5_load = table2array(B_5((2:end),2)); % [N] Load Collumn of Data Converted to Array
B_5_mach_ext = table2array(B_5((2:end),3)); % [mm] Time Collumn of Data Converted to Array
B_5_ext = table2array(B_5((2:end),4)); % [mm] Time Collumn of Data Converted to Array

%%%%% Test Set C, 1 [in] Foam, Epoxy Glue

C_1 = readtable('C_1.txt', 'PreserveVariableNames',true);
C_1_time = table2array(C_1((2:end),1)); % [s] Time Collumn of Data Converted to Array
C_1_load = table2array(C_1((2:end),2)); % [N] Load Collumn of Data Converted to Array
C_1_mach_ext = table2array(C_1((2:end),3)); % [mm] Time Collumn of Data Converted to Array
C_1_ext = table2array(C_1((2:end),4)); % [mm] Time Collumn of Data Converted to Array

C_2 = readtable('C_2.txt', 'PreserveVariableNames',true);
C_2_time = table2array(C_2((2:end),1)); % [s] Time Collumn of Data Converted to Array
C_2_load = table2array(C_2((2:end),2)); % [N] Load Collumn of Data Converted to Array
C_2_mach_ext = table2array(C_2((2:end),3)); % [mm] Time Collumn of Data Converted to Array
C_2_ext = table2array(C_2((2:end),4)); % [mm] Time Collumn of Data Converted to Array

C_3 = readtable('C_3.txt','PreserveVariableNames',true);
C_3_time = table2array(C_3((2:end),1)); % [s] Time Collumn of Data Converted to Array
C_3_load = table2array(C_3((2:end),2)); % [N] Load Collumn of Data Converted to Array
C_3_mach_ext = table2array(C_3((2:end),3)); % [mm] Time Collumn of Data Converted to Array
C_3_ext = table2array(C_3((2:end),4)); % [mm] Time Collumn of Data Converted to Array

C_4 = readtable('C_4.txt','PreserveVariableNames',true);
C_4_time = table2array(C_4((2:end),1)); % [s] Time Collumn of Data Converted to Array
C_4_load = table2array(C_4((2:end),2)); % [N] Load Collumn of Data Converted to Array
C_4_mach_ext = table2array(C_4((2:end),3)); % [mm] Time Collumn of Data Converted to Array
C_4_ext = table2array(C_4((2:end),4)); % [mm] Time Collumn of Data Converted to Array

C_5 = readtable('C_5.txt','PreserveVariableNames',true);
C_5_time = table2array(C_5((2:end),1)); % [s] Time Collumn of Data Converted to Array
C_5_load = table2array(C_5((2:end),2)); % [N] Load Collumn of Data Converted to Array
C_5_mach_ext = table2array(C_5((2:end),3)); % [mm] Time Collumn of Data Converted to Array
C_5_ext = table2array(C_5((2:end),4)); % [mm] Time Collumn of Data Converted to Array

D_1 = readtable('D_1.txt','PreserveVariableNames',true);
D_1_time = table2array(D_1((2:end),1)); % [s] Time Collumn of Data Converted to Array
D_1_load = table2array(D_1((2:end),2)); % [N] Load Collumn of Data Converted to Array
D_1_mach_ext = table2array(D_1((2:end),3)); % [mm] Time Collumn of Data Converted to Array
D_1_ext = table2array(D_1((2:end),4)); % [mm] Time Collumn of Data Converted to Array

D_2 = readtable('D_2.txt','PreserveVariableNames',true);
D_2_time = table2array(D_2((2:end),1)); % [s] Time Collumn of Data Converted to Array
D_2_load = table2array(D_2((2:end),2)); % [N] Load Collumn of Data Converted to Array
D_2_mach_ext = table2array(D_2((2:end),3)); % [mm] Time Collumn of Data Converted to Array
D_2_ext = table2array(D_2((2:end),4)); % [mm] Time Collumn of Data Converted to Array

D_3 = readtable('D_3.txt','PreserveVariableNames',true);
D_3_time = table2array(D_3((2:end),1)); % [s] Time Collumn of Data Converted to Array
D_3_load = table2array(D_3((2:end),2)); % [N] Load Collumn of Data Converted to Array
D_3_mach_ext = table2array(D_3((2:end),3)); % [mm] Time Collumn of Data Converted to Array
D_3_ext = table2array(D_3((2:end),4)); % [mm] Time Collumn of Data Converted to Array

D_4 = readtable('D_4.txt','PreserveVariableNames',true);
D_4_time = table2array(D_4((2:end),1)); % [s] Time Collumn of Data Converted to Array
D_4_load = table2array(D_4((2:end),2)); % [N] Load Collumn of Data Converted to Array
D_4_mach_ext = table2array(D_4((2:end),3)); % [mm] Time Collumn of Data Converted to Array
D_4_ext = table2array(D_4((2:end),4)); % [mm] Time Collumn of Data Converted to Array

D_5 = readtable('D_5.txt','PreserveVariableNames',true);
D_5_time = table2array(D_5((2:end),1)); % [s] Time Collumn of Data Converted to Array
D_5_load = table2array(D_5((2:end),2)); % [N] Load Collumn of Data Converted to Array
D_5_mach_ext = table2array(D_5((2:end),3)); % [mm] Time Column of Data Converted to Array
D_5_ext = table2array(D_5((2:end),4)); % [mm] Time Column of Data Converted to Array

%%%%% Test Set E, 1 [in] Foam, Epoxy Glue, With Perforation

E_1 = readtable('E_1.txt','PreserveVariableNames',true);
E_1_time = table2array(E_1((2:end),1)); % [s] Time Column of Data Converted to Array
E_1_load = table2array(E_1((2:end),2)); % [N] Load Column of Data Converted to Array
E_1_mach_ext = table2array(E_1((2:end),3)); % [mm] Time Column of Data Converted to Array
E_1_ext = table2array(E_1((2:end),4)); % [mm] Time Column of Data Converted to Array

E_2 = readtable('E_2.txt','PreserveVariableNames',true);
E_2_time = table2array(E_2((2:end),1)); % [s] Time Column of Data Converted to Array
E_2_load = table2array(E_2((2:end),2)); % [N] Load Column of Data Converted to Array
E_2_mach_ext = table2array(E_2((2:end),3)); % [mm] Time Column of Data Converted to Array
E_2_ext = table2array(E_2((2:end),4)); % [mm] Time Column of Data Converted to Array

E_3 = readtable('E_3.txt','PreserveVariableNames',true);
E_3_time = table2array(E_3((2:end),1)); % [s] Time Column of Data Converted to Array
E_3_load = table2array(E_3((2:end),2)); % [N] Load Column of Data Converted to Array
E_3_mach_ext = table2array(E_3((2:end),3)); % [mm] Time Column of Data Converted to Array
E_3_ext = table2array(E_3((2:end),4)); % [mm] Time Column of Data Converted to Array

E_4 = readtable('E_4.txt','PreserveVariableNames',true);
E_4_time = table2array(E_4((2:end),1)); % [s] Time Column of Data Converted to Array
E_4_load = table2array(E_4((2:end),2)); % [N] Load Column of Data Converted to Array
E_4_mach_ext = table2array(E_4((2:end),3)); % [mm] Time Column of Data Converted to Array
E_4_ext = table2array(E_4((2:end),4)); % [mm] Time Column of Data Converted to Array

E_5 = readtable('E_5.txt','PreserveVariableNames',true);
E_5_time = table2array(E_5((2:end),1)); % [s] Time Column of Data Converted to Array
E_5_load = table2array(E_5((2:end),2)); % [N] Load Column of Data Converted to Array
E_5_mach_ext = table2array(E_5((2:end),3)); % [mm] Time Column of Data Converted to Array
E_5_ext = table2array(E_5((2:end),4)); % [mm] Time Column of Data Converted to Array

E_6 = readtable('E_6.txt','PreserveVariableNames',true);
E_6_time = table2array(E_6((2:end),1)); % [s] Time Column of Data Converted to Array
E_6_load = table2array(E_6((2:end),2)); % [N] Load Column of Data Converted to Array
E_6_mach_ext = table2array(E_6((2:end),3)); % [mm] Time Column of Data Converted to Array
E_6_ext = table2array(E_6((2:end),4)); % [mm] Time Column of Data Converted to Array

E_7 = readtable('E_7.txt','PreserveVariableNames',true);
E_7_time = table2array(E_7((2:end),1)); % [s] Time Column of Data Converted to Array
E_7_load = table2array(E_7((2:end),2)); % [N] Load Column of Data Converted to Array
E_7_mach_ext = table2array(E_7((2:end),3)); % [mm] Time Column of Data Converted to Array
E_7_ext = table2array(E_7((2:end),4)); % [mm] Time Column of Data Converted to Array

E_8 = readtable('E_8.txt','PreserveVariableNames',true);
E_8_time = table2array(E_8((2:end),1)); % [s] Time Column of Data Converted to Array
E_8_load = table2array(E_8((2:end),2)); % [N] Load Column of Data Converted to Array
E_8_mach_ext = table2array(E_8((2:end),3)); % [mm] Time Column of Data Converted to Array
E_8_ext = table2array(E_8((2:end),4)); % [mm] Time Column of Data Converted to Array
Test Set F, 3" x 22" Span Length, 4-Point Bend Test, 1 [in] Foam, Epoxy Glue

F_1 = readtable('F_1.txt','PreserveVariableNames',true);
F_1_time = table2array(F_1((2:end),1)); % [s] Time Column of Data Converted to Array
F_1_load = table2array(F_1((2:end),2)); % [N] Load Column of Data Converted to Array
F_1_mach_ext = table2array(F_1((2:end),3)); % [mm] Time Column of Data Converted to Array
F_1_ext = table2array(F_1((2:end),4)); % [mm] Time Column of Data Converted to Array

F_2 = readtable('F_2.txt','PreserveVariableNames',true);
F_2_time = table2array(F_2((2:end),1)); % [s] Time Column of Data Converted to Array
F_2_load = table2array(F_2((2:end),2)); % [N] Load Column of Data Converted to Array
F_2_mach_ext = table2array(F_2((2:end),3)); % [mm] Time Column of Data Converted to Array
F_2_ext = table2array(F_2((2:end),4)); % [mm] Time Column of Data Converted to Array

F_3 = readtable('F_3.txt','PreserveVariableNames',true);
F_3_time = table2array(F_3((2:end),1)); % [s] Time Column of Data Converted to Array
F_3_load = table2array(F_3((2:end),2)); % [N] Load Column of Data Converted to Array
F_3_mach_ext = table2array(F_3((2:end),3)); % [mm] Time Column of Data Converted to Array
F_3_ext = table2array(F_3((2:end),4)); % [mm] Time Column of Data Converted to Array

F_4 = readtable('F_4.txt','PreserveVariableNames',true);
F_4_time = table2array(F_4((2:end),1)); % [s] Time Column of Data Converted to Array
F_4_load = table2array(F_4((2:end),2)); % [N] Load Column of Data Converted to Array
F_4_mach_ext = table2array(F_4((2:end),3)); % [mm] Time Column of Data Converted to Array
F_4_ext = table2array(F_4((2:end),4)); % [mm] Time Column of Data Converted to Array

F_5 = readtable('F_5.txt','PreserveVariableNames',true);
F_5_time = table2array(F_5((2:end),1)); % [s] Time Column of Data Converted to Array
F_5_load = table2array(F_5((2:end),2)); % [N] Load Column of Data Converted to Array
F_5_mach_ext = table2array(F_5((2:end),3)); % [mm] Time Column of Data Converted to Array
F_5_ext = table2array(F_5((2:end),4)); % [mm] Time Column of Data Converted to Array

Plot Load vs Deflection

figure;
hold on
plot(A_1_ext, A_1_load, 'r', 'linewidth', 1);
plot(A_2_ext, A_2_load, 'b1', 'linewidth', 1);
plot(A_3_ext, A_3_load, 'k', 'linewidth', 1);
plot(A_4_ext, A_4_load, 'm', 'linewidth', 1);
plot(A_5_ext, A_5_load, 'c', 'linewidth', 1);
grid on;
title('Test Sample Set A (1.5" Foam, Epoxy): Load vs Deflection Plot');
xlabel('Deflection [mm]');
ylabel('Applied Load [N]');
ylim([0 300]);
xlim([0 46]);
legend('Sample 1', 'Sample 2', 'Sample 3', 'Sample 4', 'Sample 5', 'location', 'southeast');
print('-djpeg', 'Load_Deflect_A.jpeg'); % outputs figure as jpeg image
hold off
% Sample Set B
figure;
hold on
plot(B_1_ext, B_1_load, 'r', 'linewidth', 1);
plot(B_2_ext, B_2_load, 'b', 'linewidth', 1);
plot(B_3_ext, B_3_load, 'k', 'linewidth', 1);
plot(B_4_ext, B_4_load, 'm', 'linewidth', 1);
plot(B_5_ext, B_5_load, 'c', 'linewidth', 1);
grid on;
title('Test Sample Set B (1.5” Foam, Contact Adhesive): Load vs Deflection Plot');
xlabel('Deflection [mm]');
ylabel('Applied Load [N]');
ylim([0 300]);
xlim([0 46]);
legend('Sample 1', 'Sample 2', 'Sample 3', 'Sample 4', 'Sample 5', 'location', 'southeast');
print('-djpeg', 'Load_Deflect_B.jpeg'); % outputs figure as jpeg image
hold off

% Sample Set C
figure;
hold on
plot(C_1_ext, C_1_load, 'r', 'linewidth', 1);
plot(C_2_ext, C_2_load, 'b', 'linewidth', 1);
plot(C_3_ext, C_3_load, 'k', 'linewidth', 1);
plot(C_4_ext, C_4_load, 'm', 'linewidth', 1);
plot(C_5_ext, C_5_load, 'c', 'linewidth', 1);
grid on;
title('Test Sample Set C (1” Foam, Epoxy): Load vs Deflection Plot');
xlabel('Deflection [mm]');
ylabel('Applied Load [N]');
ylim([0 300]);
xlim([0 46]);
legend('Sample 1', 'Sample 2', 'Sample 3', 'Sample 4', 'Sample 5', 'location', 'southeast');
print('-djpeg', 'Load_Deflect_C.jpeg'); % outputs figure as jpeg image
hold off

% Sample Set D
figure;
hold on
plot(D_1_ext, D_1_load, 'r', 'linewidth', 1);
plot(D_2_ext, D_2_load, 'b', 'linewidth', 1);
plot(D_3_ext, D_3_load, 'k', 'linewidth', 1);
plot(D_4_ext, D_4_load, 'm', 'linewidth', 1);
plot(D_5_ext, D_5_load, 'c', 'linewidth', 1);
grid on;
title('Test Sample Set D (1” Foam, Contact Adhesive): Load vs Deflection Plot');
xlabel('Deflection [mm]');
ylabel('Applied Load [N]');
ylim([0 300]);
xlim([0 46]);
legend('Sample 1', 'Sample 2', 'Sample 3', 'Sample 4', 'Sample 5', 'location', 'southeast');
% Sample Set E
figure;
hold on
plot(E_1_ext, E_1_load, 'r', 'linewidth', 1);
plot(E_2_ext, E_2_load, 'b1', 'linewidth', 1);
plot(E_3_ext, E_3_load, 'k', 'linewidth', 1);
plot(E_4_ext, E_4_load, 'm', 'linewidth', 1);
plot(E_5_ext, E_5_load, 'c', 'linewidth', 1);
plot(E_6_ext, E_6_load, 'y', 'linewidth', 1);
plot(E_7_ext, E_7_load, 'g', 'linewidth', 1);
plot(E_8_ext, E_8_load, '--r', 'linewidth', 1);
grid on;
title ('Test Sample Set E (1" Foam, Epoxy, Perforated): Load vs Deflection Plot');
xlabel ('Deflection [mm]');
ylabel ('Applied Load [N]');
ylim([0 300]);
xlim([0 46]);
legend('Sample 1', 'Sample 2', 'Sample 3', 'Sample 4', 'Sample 5', 'Sample 6', 'Sample 7', 'Sample 8', 'location', 'southeast');
print('-djepg', 'Load_Deflect_E.jpeg'); % outputs figure as jpeg image
hold off

% Sample Set F
figure;
hold on
plot(F_1_ext, F_1_load, 'r', 'linewidth', 1);
plot(F_2_ext, F_2_load, 'b1', 'linewidth', 1);
plot(F_3_ext, F_3_load, 'k', 'linewidth', 1);
plot(F_4_ext, F_4_load, 'm', 'linewidth', 1);
plot(F_5_ext, F_5_load, 'c', 'linewidth', 1);
grid on;
title ('Test Sample Set F (3" x 24", 4-Point Bend, 1" Foam, Epoxy):', 'Load vs Deflection Plot');
xlabel ('Deflection [mm]');
ylabel ('Applied Load [N]');
ylim([0 800]);
% xlim([0.75 2.25]);
legend('Sample 1', 'Sample 2', 'Sample 3', 'Sample 4', 'Sample 5', 'Sample 6', 'Sample 7', 'Sample 8', 'location', 'southeast');
print('-djepg', 'Load_Deflect_F.jpeg'); % outputs figure as jpeg image
hold off

Plot Load vs Deflection English Units

% Sample Set A
figure;
hold on
plot(A_1_ext*0.0393701, A_1_load*0.22481, 'r', 'linewidth', 1);
plot(A_2_ext*0.0393701, A_2_load*0.22481, 'bl', 'linewidth', 1);
plot(A_3_ext*0.0393701, A_3_load*0.22481, 'k', 'linewidth', 1);
plot(A_4_ext*0.0393701, A_4_load*0.22481, 'm', 'linewidth', 1);
plot(A_5_ext*0.0393701, A_5_load*0.22481, 'c', 'linewidth', 1);
grid on;

title ('Test Sample Set A (1.5'' Foam, Epoxy): Load vs Deflection Plot');
xlabel ('Deflection [in]');
ylabel ('Applied Load [lbf]');
ylim([0 70]);
xlim([0 1.8]);
legend('Sample 1', 'Sample 2', 'Sample 3', 'Sample 4', 'Sample 5', 'location', 'southeast');
print('-djpeg', 'Load_Deflect_A_eng.jpeg'); % outputs figure as jpeg image
hold off

% Sample Set B
figure;
hold on
plot(B_1_ext*0.0393701, B_1_load*0.22481, 'r', 'linewidth', 1);
plot(B_2_ext*0.0393701, B_2_load*0.22481, 'b', 'linewidth', 1);
plot(B_3_ext*0.0393701, B_3_load*0.22481, 'k', 'linewidth', 1);
plot(B_4_ext*0.0393701, B_4_load*0.22481, 'm', 'linewidth', 1);
plot(B_5_ext*0.0393701, B_5_load*0.22481, 'c', 'linewidth', 1);
grid on;

title ('Test Sample Set B (1.5'' Foam, Contact Adhesive): Load vs Deflection Plot');
xlabel ('Deflection [in]');
ylabel ('Applied Load [lbf]');
ylim([0 70]);
xlim([0 1.8]);
legend('Sample 1', 'Sample 2', 'Sample 3', 'Sample 4', 'Sample 5', 'location', 'southeast');
print('-djpeg', 'Load_Deflect_B_eng.jpeg'); % outputs figure as jpeg image
hold off

% Sample Set C
figure;
hold on
plot(C_1_ext*0.0393701, C_1_load*0.22481, 'r', 'linewidth', 1);
plot(C_2_ext*0.0393701, C_2_load*0.22481, 'b', 'linewidth', 1);
plot(C_3_ext*0.0393701, C_3_load*0.22481, 'k', 'linewidth', 1);
plot(C_4_ext*0.0393701, C_4_load*0.22481, 'm', 'linewidth', 1);
plot(C_5_ext*0.0393701, C_5_load*0.22481, 'c', 'linewidth', 1);
grid on;

title ('Test Sample Set C (1'' Foam, Epoxy): Load vs Deflection Plot');
xlabel ('Deflection [in]');
ylabel ('Applied Load [lbf]');
ylim([0 70]);
xlim([0 1.8]);
legend('Sample 1', 'Sample 2', 'Sample 3', 'Sample 4', 'Sample 5', 'location', 'southeast');
print('-djpeg', 'Load_Deflect_C_eng.jpeg'); % outputs figure as jpeg image
hold off

% Sample Set D
figure;
hold on
plot(D_1_ext*0.0393701, D_1_load*0.22481, 'r', 'linewidth', 1);
plot(D_2_ext*0.0393701, D_2_load*0.22481, 'b1', 'linewidth', 1);
plot(D_3_ext*0.0393701, D_3_load*0.22481, 'k', 'linewidth', 1);
plot(D_4_ext*0.0393701, D_4_load*0.22481, 'm', 'linewidth', 1);
plot(D_5_ext*0.0393701, D_5_load*0.22481, 'c', 'linewidth', 1);
grid on;
title ('Test Sample Set D (1'' Foam, Contact Adhesive): Load vs Deflection Plot');
xlabel ('Deflection [in]');
ylabel ('Applied Load [lbf]');
ylim([0 70]);
xlim([0 1.8]);
legend('Sample 1', 'Sample 2', 'Sample 3', 'Sample 4', 'Sample 5', 'location', 'southeast');
print('-djpeg', 'Load_Deflect_D_eng.jpeg'); % outputs figure as jpeg image
hold off

% Sample Set E
figure;
hold on
plot(E_1_ext*0.0393701, E_1_load*0.22481, 'r', 'linewidth', 1);
plot(E_2_ext*0.0393701, E_2_load*0.22481, 'b1', 'linewidth', 1);
plot(E_3_ext*0.0393701, E_3_load*0.22481, 'k', 'linewidth', 1);
plot(E_4_ext*0.0393701, E_4_load*0.22481, 'm', 'linewidth', 1);
plot(E_5_ext*0.0393701, E_5_load*0.22481, 'c', 'linewidth', 1);
plot(E_6_ext*0.0393701, E_6_load*0.22481, 'y', 'linewidth', 1);
plot(E_7_ext*0.0393701, E_7_load*0.22481, 'g', 'linewidth', 1);
plot(E_8_ext*0.0393701, E_8_load*0.22481, '--r', 'linewidth', 1);
grid on;
title ('Test Sample Set E (1'' Foam, Epoxy, Perforated): Load vs Deflection Plot');
xlabel ('Deflection [in]');
ylabel ('Applied Load [lbf]');
ylim([0 70]);
xlim([0 1.8]);
legend('Sample 1', 'Sample 2', 'Sample 3', 'Sample 4', 'Sample 5', 'Sample 6', 'Sample 7', 'Sample 8', 'location', 'southeast');
print('-djpeg', 'Load_Deflect_E_eng.jpeg'); % outputs figure as jpeg image
hold off

% Sample Set F
figure;
hold on
plot(F_1_ext*0.0393701, F_1_load*0.22481, 'r', 'linewidth', 1);
plot(F_2_ext*0.0393701, F_2_load*0.22481, 'b1', 'linewidth', 1);
plot(F_3_ext*0.0393701, F_3_load*0.22481, 'k', 'linewidth', 1);
plot(F_4_ext*0.0393701, F_4_load*0.22481, 'm', 'linewidth', 1);
plot(F_5_ext*0.0393701, F_5_load*0.22481, 'c', 'linewidth', 1);
grid on;
title ('Test Sample Set F (3'' x 24'', 4-Point Bend, 1'' Foam, Epoxy):', 'Load vs Deflection Plot');
xlabel ('Deflection [in]');
ylabel ('Applied Load [lbf]');
ylim([0 190]);
% xlim([0.75 2.25]);
legend('Sample 1', 'Sample 2', 'Sample 3', 'Sample 4', 'Sample 5', 'location', 'southeast');
print('-djpeg', 'Load_Deflect_F_eng.jpeg'); % outputs figure as jpeg image
hold off

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