Manipulating Fiber Orientation for the Reduction of Warpage in Carbon Fiber Composite Sandwich Panels

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Abstract

Safran Cabin (Santa Maria, CA), previously known as Zodiac Aerospace, designs and manufactures interior cabin components for private and commercial aircraft. Carbon fiber face sheets have recently been incorporated in their overhead luggage bin assemblies which utilize a composite sandwich panel design, in order to provide additional stiffness to the previous glass fiber sandwich panels. Since the introduction of carbon fiber in these luggage bin panels, Safran has experienced an increase in warpage during manufacturing. When inspected by quality control, the panels are tested mimicking how they are installed in aircraft. If the panels do not meet specifications, the warped panels must be sent back in the production line for rework or are scrapped, costing the company both time and money. This project studies the warpage of the panels during manufacturing and provides a solution to minimize the warpage. The fiber orientation and resulting symmetry of the fibers about the panel core, were suspected to be the main causes of warpage. Test panels measuring 3 inches by 24 inches were studied utilizing the same manufacturing process. Four novel combinations of fiber orientations were tested and compared against the current configuration used at Safran. The current layup used by Safran yielded a warpage of 0.0410 inches. A symmetric panel configuration yielded a warpage of 0.00986 inches, for a 76% reduction in the warpage compared to the control study. The data collected from this study suggests that a symmetric layup consisting of fibers oriented at 45° and -45° relative to the length of the panel results in the lowest values of warpage.

Key words: Overhead Luggage Bin, Composite Sandwich Panel, Polymer Matrix Composite, Warpage, Symmetric Panel, Materials Engineering
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1. Introduction

1.1 Problem Statement

The current issue is that Safran Cabin Interiors (Santa Maria, CA) is manufacturing overhead bin doors consisting of a composite sandwich panel design that are warping which causes the part to be rejected or reworked. Prior work was conducted by Cal Poly students on a similar project with Safran Cabin (2018), which tested warping of composite panels and provided several methods for measuring this warpage. However, other than the past study conducted at Cal Poly, there is limited information available for characterizing and measuring warpage of composite panels. To address the problem presented by Safran, this project aimed to investigate how fiber orientation within the face sheets of the composite sandwich panels, affects the magnitude of warpage of the panels. The specific goals of the project were to study the effects that fiber orientation has on warpage and to reduce the magnitude of warpage to be consistently below the accepted amount of warpage, that is 0.025 in. per foot of panel length. Testing methods and analysis techniques that were implemented to achieve these goals were to measure the maximum distance between a corner and the surface of a flat reference plane when 3 corners of the panel are in contact with the table. Statistical analysis was to be conducted to analyze how many panels out of each batch are warped more than the acceptable amount in addition to statistically analyzing the measurements.
2. Background

2.1 Composites Overview

A composite is composed of two distinct materials that have different properties. Once combined, these materials combine to produce a final material system with unique properties that differ from the properties of either individual material. Composite materials are typically used in aerospace and automotive applications because of their high strength and stiffness’s coupled with low densities. Composites used in these applications are typically fiber reinforced polymer matrix composites. Fibers that are typically used are: glass, carbon, and extended chain polyethylene (ECPE). Matrix materials are usually thermoset polymers such as epoxies but can also be thermoplastic polymers as well. Additionally, other matrix materials used are ceramics and metals. The purpose of the fiber in the composite is to carry the load, while the matrix’s purpose is to both transfer the load to the fiber and protect the fibers [1].

2.2 Honeycomb Core Sandwich Panel

2.2.1 The Honeycomb Core

Composite sandwich panels in the aerospace industry are commonly comprised primarily of a honeycomb core and composite face sheets (Figure 1) [3]. The honeycomb can be made of Nomex, Kevlar, fiberglass, or most commonly, aluminum. The panels being investigated contain a Nomex honeycomb core with carbon fiber and epoxy matrix face sheets. Nomex core, which is comprised of aramid fibers, is ideal for applications that require high flammability resistance, good insulative properties, formability, and high strength. The core is configured with hexagonal
prisms. The hexagonal configuration is most efficient at bearing loads which makes it the ideal geometry for core design. Core material is often found in several other different configurations including over expanded, square, and flex-core [2].

![Figure 1: Schematic of sandwich panel configuration and assembly with honeycomb core and face-sheets](image)

The core is comprised of cells and each individual cell contains a node and a free wall. For honeycomb core, the node is the portion of the structure that connects the cells together and is typically bonded. The free wall is a side of the cell that is not connected to any other
component of the structure. The size of the cells is determined by the distance between two parallel sides of the cell (Figure 2) [4].

![Figure 2: Schematic of hexagonal honeycomb core structure with labels [4].](image)

Cores that are made from fibers such as Kevlar or Nomex, are typically manufactured using fiber pulp that is bonded with a resin; in this case a phenolic resin. The structure is cured in the form of a block and once fully cured the block is expanded to reveal the honeycomb structure. Because the honeycomb is constructed with the nodes aligned in one direction and expanded perpendicular to the direction of the nodes, the core exhibits anisotropic behavior [5].

2.3 Carbon Fiber Face Sheets

Safran utilizes faces sheets that contain non-crimped carbon fibers in a modified epoxy matrix. The matrix is modified to meet aerospace flame resistance standards. Typically, most aerospace composites contain phenolic resins because of their inherent flame-retardant properties, but Safran is able to use a modified epoxy that complies with the Federal Aviation
Administration’s regulations regarding material flammability. Epoxies typically have higher stiffness than phenolic resins making them more ideal for the application.

The carbon fibers are in the form of a prepreg non-crimp fabric. Non-crimp refers to the fibers being in layers stacked on top of each other rather than in a woven fabric where the fibers are intertwined. Safran utilizes a ±45° fabric where it is composed of two unidirectional layers: one oriented at +45° and the other at -45°. These two layers of unidirectional fibers are stacked on top of one another and stitched together using nylon string (Figure 3) [6]; the Nylon stitching is not depicted in the following figure.

![Figure 3: Schematic of non-crimp fabric with unidirectional fibers. Nylon string used to stitch layers together is not shown [6].](image)

The layers within a non-crimp fabric can be stitched together in a variety of configurations such as chain, tricot, plain and satin. Utilizing non-crimp fabrics allows for improved mechanical properties, improved impact strength, and delamination resistance. Non-crimp fabrics also allow for more control when laying up a part and can be shaped into relatively complex shapes without defects [6].
2.4 Composites Manufacturing Process

2.4.1 Prepreg Manufacturing

The non-crimp fabric used comes as a prepreg meaning it is pre-impregnated with the modified epoxy that is partially cured. The process begins with the stitched non-crimp fabric being soaked with liquid epoxy. The excess epoxy is then removed using metering or nip rolls. The fabric then is partially cured to B-stage in an oven [7]. These steps result in the final form of the prepreg composite fabrics before their final cure (Figure 4).

![Figure 4: A schematic of the prepreg manufacturing process for fiber reinforced polymer matrix composites [7].](image)

The final prepreg cloth needs to be stored in a freezer so that it does not fully cure before it is laid up. The prepreg is laid up by hand and since the cloth is pre-impregnated, additional resin does not need to be injected when forming the final part. The final curing of the prepreg occurs when the panel is laid up and cured in an oven.
2.4.2 Panel Manufacturing

Safran uses two methods to manufacture their honeycomb composite sandwich panels: compression molding and hand lay-up. Hand lay-up is typically used for more complex parts and takes considerably longer than compression molding. In hand lay-ups, the mold is coated with a layer of wax mold release and then a layer of the epoxy resin. The fiber weaves are then laid in the mold in the desired pattern. Next, either a film adhesive or more liquid epoxy is applied to the fiber weave before the core is added to the face-sheet. The other face-sheet is then added to the opposite side of the core in a similar manner. The resulting composite sandwich is then placed in a flexible vacuum bag made of polyvinyl alcohol. The panel is then exposed to heat and pressure which is applied by the vacuum in order to cure. Hand lay-ups are typically more labor intensive and time consuming compared to compression molding [8].

Compression molding consists of flat uncured sandwich panels that are produced by an automated system with a similar process as mentioned for hand-layups. The flat panels are then placed in a press of the desired shape. Heat and pressure are applied by the press dies to produce a fully cured composite panel in the desired shape. Compression molding is more likely to produce voids because it is difficult to achieve even pressure across the surfaces of the panel when in the press. Additionally, the press must be opened occasionally to allow for outgassing during the curing process which contributes to uneven pressure for the duration of the cure [8].
2.5 Fiber Misalignment

The fibers are strongest along their longitudinal axes and any fiber that is misaligned in the composite will experience shear stresses causing it to fail at a lower tensile stress. This results in a composite with weaker properties in the fiber direction. When the composite weave is produced, the fibers are tensioned in order to ensure that they are aligned. The friction between these fibers can cause the fibers to shift longitudinally. The tension in misaligned fibers causes out-of-plane stresses to be applied. This results in a reduction in overall tensile strength of the component [12].

2.6 Warpage

Warpage is defined as any deviation of the panel geometry from an initial state of flatness [4]. This includes distortions that may cause the sandwich panel to either cup, bow or twist (Figure 5). Cupping is the method of warpage where the panel deviated from flatness along the short dimension of the width of the panel. Bowing is a similar method of warpage where instead the panel deviates from flatness along the long dimension of the panel. Twisting involves a deviation from a flat pane between the diagonal corners of the panel [4]. All three types of warpage may become present in composite sandwich panels as a result of manufacturing.
2.6.1 Causes of Warpage

This manufacturing stage can be divided into three basic steps. The first of these is the room temperature layup stage where the prepreg material is applied to a tool either by hand or by automation. There may be variations in the layer thickness (within a layer or between layers), layer waviness, gaps in the prepreg, uneven resin distribution, and broken fibers. Any given layer alignment may be significantly different than the intended alignment. The second stage involves consolidation and curing of the laminate at elevated temperatures and pressures. During this step, temperature gradients along the length can lead to different curing conditions in different regions of the panel. These differing curing conditions can lead to spatially non-uniform mechanical and thermal expansion properties. Variations in compaction pressure can contribute to variations in the resin bleed, layer thickness and fiber volume fraction. Layer movements may cause additional fiber misalignments. The third and final stage is the cooling and removal from the tool. Most warpage has already occurred before the third stage; however, the distortions often become evident during the third stage. During this stage there may also be failures of the material during cooling where closed sections become bound on the tools. The most prevalent causes of warpage to be studied are the layer misalignment, different layer thicknesses, and the non-uniform cooling due to thermal gradients in the autoclave [7].
2.6.2 Existing Methods of Measuring Warpage

One method to measure warpage involves measuring the fiber misalignment. This is done by measuring the path that one fiber takes to go from one side of the weave to the other. For these prepreg face sheets, the resin is first washed off, the fiber weave is tensioned, and then single fibers are removed from the weave. The gap remaining after the fiber is removed can be traced to reveal the path of the fiber. This is compared against a centerline and the maximum deviation in the panels are recorded [12].

The panel warpage can be measured by various methods of fixing the panel and measuring its height from the surface of a microflat table. The panel warpage, including bow warping and twist warping, can be measured by fixing one corner and measuring the positions of the other three corners with a height gage (Figure 6).

Figure 6: Measurement locations when using the one-fixed-corner method of analyzing warpage [12].
The twist warpage can be calculated by utilizing the angle between the panel and the granite micro-flat table. This method assumes the panels to have similarly sized widths and thicknesses. Using Equation 1, the angle of twist of each side is found using the width of the panel as the hypotenuse and the distance of the panel off the table as the height [12]. Equation 1 can be used twice on each panel, once for Side 3 and once for Side 4. Then these two angles are added together in order to calculate the total twist angle between the panel and the alignment table as shown in Equation 2 [12].

\[
\theta = \arcsin \left( \frac{\text{height}}{\text{side length}} \right) \quad \text{Eqn. 1}
\]

\[
\theta_{total} = \theta_{side \ 3} + \theta_{side \ 4} \quad \text{Eqn. 2}
\]

Another method for measuring the amount of warpage could be to follow that of the Composite Panel Association [9]. This method involves comparing the panel against a straight edge along its length and width. The maximum distance that the panel deviates from the straight edge is recorded (Figure 7) [9]. This method easily separates out the warpage effects caused by cupping, bowing and twisting each specifically.
Figure 7: Test methods from the Composite Panel Association to measure the panel warpage including the cupping (A), bowing (B), and twisting (C). In each direction, the maximum distance between a straight-edge and the panel edge is measured [9].

Alternatively, warpage may also be measured by fixing three of the panel corners. This simplified method only requires measuring the height that the fourth corner of the panel is lifted off of the plane. The total warpage in the panel is based off of the distance away one corner is from being in line when the other three points are held in place. Because this method only takes
one measurement, there is assumed to be more experimental error in the results. This method is not as accurate in measuring the warpage in the panel because it does not differentiate the warping into cupping, bowing or twisting forces. Instead it measures the warpage as a result of all three of these simultaneously.

Another alternative technique for measuring warpage would be applying a method used to measure the amount of warpage in particle boards. In this simplified process, the amount of bowing in the panel is measured in the center of the panel with a dial gage (Figure 8) [13].

![Dial Gauge](image)

**Figure 8:** Method used for measuring the warpage of particle board using a dial gauge [13].

Similarly, to the previous three-point fixed model, this method only measures the combination of warpages present at the center point of the panel. It is not as accurate of a measurement method because it does not distinguish the resulting warpages into bowing, cupping and twisting.

2.6.3 Warpage Test Results

E-glass fiber-phenolic resin composite sandwich panels were found to have an average fiber misalignment of 1.13 inches, an average maximum deviation of 0.09 inches and an average twist warping of 1.03 degrees according to Nilakantan and Taylor’s study [12]. This amount of
warpage is outside of the allowable 0.050 inches (0.025 inches per foot) as specified by the design specification [14]. These values were found following the one-point fixation method as described first where the panel is fixed at one corner and the deviations at the corresponding six points are measured. Although the panels tested in Nilakantan and Taylor’s study feature glass fiber face sheets instead of carbon fiber, they are both commonly manufactured by Safran Cabin. Their typical sandwich panels feature both E-glass and carbon fiber face sheets. Therefore, it is reasonable to compare the warpage values of similarly sized E-glass sandwich panels to estimate the total warpage present in the multilayered system. There is often a large amount of warpage in the E-glass component, therefore the warpage in the carbon fiber facesheet should be minimized to be less than the allowable 0.05 inches for the 24 inch panel.

2.7 Final Component Design

Safran produces the sandwich panels for the manufacturing of overhead luggage compartments. The panels feature a Nomex core surrounded by two layers of carbon fiber non-crimp fabric on both sides. This is followed by two more layers of glass fiber face sheets on either side resulting in a sandwich panel composite. These sandwich panels are molded into the luggage compartments by means of compression molding. The resulting shape is 4 feet long, about 2 feet in length and about 1.5 feet in depth, with latches at both upper corners and a release handle in the middle (Figure 9).
Since the final component measures 4 feet in length and the acceptable amount of warpage is 0.025 inches per foot of panel, the maximum warpage that these overhead bins can exhibit is 0.100 inches from one corner to the other. The overhead bins are used in a large percentage of commercial aircraft currently in use. Safran, for many years, has made their bins with only fiberglass face sheets but recently started utilizing carbon fiber for larger bins to gain additional stiffness.

3. Experimental Sample Prep

3.1 Safran’s Current Panel Construction

Safran Cabin currently uses a two-ply carbon fiber non-crimp fabric that is sandwiched around a Nomex honeycomb core. The non-crimp fabric features two plies of unidirectional
carbon fiber that are stitched together, using nylon, at an orientation of 90° relative to each other. Two sheets of this carbon fiber prepreg fabric are cured and bonded to the either side of the core using the crush-core method where heat and pressure are applied by a large-scale press (Figure 10).

Safran Cabin purchases their non-crimp fabric from a supplier in a roll of [45/-45], meaning that the fibers are running unidirectionally diagonal to the longitudinal length of the fabric roll. The top layer is 90° relative to the bottom layer resulting in the [45/-45] construction. When manufacturing the panels, Safran layers two of these two-ply fabric sheets with the Nomex core in between them, resulting in the anti-symmetric [45/-45/core/45/-45] layup (Figure 11). This image shows the nylon stitching on both the top and bottom face sheets. Each face sheet has
a two-ply [45/-45] construction. These layers surround the core for the anti-symmetric [45/-
45/core/45/-45] layup, which is referred to as the “Control” configuration in this study.

Because this carbon fiber prepreg fabric is purchased with [45/-45] face sheets in order to
achieve this configuration, the layers are simply cut along the longitudinal axis of the roll (Figure
12). This wastes less material than the panels that are cut out at an angle in order to achieve some
of the [0/90] configurations. In Figure 12, only the top layer of the two-ply face sheet is shown.
The diagonal stripes represent the direction of the fibers, which run 45° from the direction of the
roll, shown as the blue arrow. In order to make the control configuration, Safran laser cuts two
26 in. by 35 in. rectangles side by side.
3.2 Selecting Panel Configurations

When investigating the causes of warpage, there are several possible reasons that a composite panel may warp. These include moisture content, layer misalignment, thermal gradients, and fiber orientation. For the scope of this project, only fiber orientation was manipulated in order to observe a response in the warpage of the panels. Fiber orientation was selected for investigation because of the relative simplicity and low number of resources required to make changes in the current manufacturing methods at Safran. Additionally, it is something that Safran has not investigated in the past with previous fiber composites. Because Safran utilizes this non-crimp fabric for these sandwich panels, there were limitations to the possible variations of panel layup configurations to test. The limitations were that only one ply of the non-crimp fabric was laid up on each side of the core and that the orientation of the two fiber layers within each ply of non-crimp were constrained to be 90° from each other due to the nylon
stitching. Fiber orientation and symmetry are commonly known in the composites industry as the main causes of warpage. Non-symmetric layups have been studied and it is widely accepted that non-symmetric layups generally result in warpage of the final part. The warpage comes from the uneven distribution of stresses and the resulting uneven residual strains in the face sheets. Some sources state that the angle of the outer most ply of a composite panel can affect the type of warpage experienced. For example, fiber angles of ±45° have been observed to result in cupping or bowing while 0° or 90° on the outermost ply of the layup can result more commonly in twisting.

The panel orientations chosen were based on the theory of reducing residual stresses in composite laminates. Because Safran currently uses the antisymmetric layup with fiber angles at ±45°, another antisymmetric orientation was investigated but using 0°, 90° fiber angles. Additionally, a non-symmetric layup was decided to be investigated because of the relative ease of manufacturing and its unique construction that would yield unique results. Finally, two variations of a symmetric layup were chosen with one utilizing the ±45° fiber angles and the other utilizing again, the 0°, 90° fiber angles. All five configurations (Figure 13) would be relatively easy for Safran to produce without the need for additional manufacturing resources or money. It was paramount that the complexity of the orientations was not too difficult to achieve for the investigation and production of the composite panels to remain efficient and cost effective.
3.3 Constructing Sandwich Panels

For the purpose of this report, configuration refers to the unique layup in the construction of the sandwich panel. For example, the first anti-symmetric panel mentioned previously has a [45/-45/core/45/-45] layup and is referred to as the control configuration. By rotating the axis from which these panels are cut out on the larger fabric roll by 45°, the fabric can be cut with the fibers running parallel to the longitudinal axis of the carbon fiber sheet (Figure 14). This panel is also anti-symmetric about the core in that it features a repetition of the angles on the top and the bottom of the core.

Figure 14: 0/90 configuration sandwich panel construction featuring an anti-symmetric [0/90/core/0/90] layup.
For variation, a non-symmetric panel was also constructed to compare against the control configuration (Figure 15). This panel features a [45/-45] top face sheet and a [0/90] bottom face sheet. It has no symmetry about the core at all.

![Combination configuration featuring a non-symmetric [0/90/core/45/-45] layup.](image)

According to composite theory, this configuration is not expected to minimize warpage as well as some of the other tested configurations because of its lack of symmetry. Symmetric layups distribute the loads more evenly about the sandwich panel and thus warp less overall. For this reason, two symmetric configurations were tested; a symmetric 45/-45 and a symmetric 0/90. The symmetric 45 panel was constructed using the same stitched [45/-45] carbon fiber prepreg fabric already in use at Safran Cabin. However, one of the face sheets was rotated 90° when cut from the fabric roll. This 90° rotation allowed for a [-45/45] face sheet. When stacked surrounding the core this resulted in a [45/-45/core/-45/45] layup, which is referred to as the symmetric 45 configuration in this study (Figure 16).
Figure 16: Symmetric 45 configuration featuring a [45/-45/core/-45/45] layup symmetric about the core.

The symmetric 0/90 panel was constructed similarly (Figure 17). The top face sheet was cut out at 45° angle from the roll direction in order to achieve a [0/90] orientation. Then the bottom face sheet was cut out at -45° from the roll direction, producing a 90° difference from the top sheet relative to the bottom sheet. This resulted in a symmetric panel with a [0/90/core/90/0] layup, which is referred to as the symmetric 0/90 configuration in this study. For comparison the configurations can be seen side by side (Figure 18).

Figure 17: Symmetric 0/90 configuration featuring a [0/90/core/90/0] layup symmetric about the core.
The cutting pattern that these face sheets are laser cut from the prepreg rolls is critical in determining the configuration of the sandwich panel constructions. As previously stated, the control configuration can be cut out simply by cutting two similarly sized rectangles side by side off of the roll (Figure 12). Because they purchase the prepreg rolls in a [45/-45] stitched orientation, the control is the simplest configuration for Safran Cabin to produce and suggests why they have been using an anti-symmetric layup historically. The cutting layouts necessary to produce the other 4 configurations can be compared against this control (Figure 19).
As shown in Figure 17, the 0/90 orientations waste more of the material because they must be cut on an angle. The Symmetric 45 configuration (Figure 19c) wastes the least amount of material, as it features two rectangles cut out on the same axis as the prepreg roll. This configuration even reduced the amount of material used compared to the control configuration by 13%.
4. Experimental Procedure

4.1 Safety

Safety is always paramount and was always considered throughout the study. When handling composite materials, latex or nitrile gloves were worn to prevent fiber splinters and to prevent skin contact from the resin used in the composite systems. Additionally, closed toed shoes, long pants, and safety glasses were always worn while working with the samples. During production of the test samples at the Safran manufacturing facility, ear protection was worn due to the loud machinery and fans present in the room.

4.2 Warpage Measurement Method

Methods for measuring warpage vary from source to source and there is no industry standard on how to measure warpage of composite panels; because of this, a similar method to how it is currently measured at Safran was utilized. At Safran, once the pressed composite panels are removed from the press, they are placed on a micro-flat table and three corners are manually forced down until they come into contact with the surface of the table. The final fourth corner is evaluated by measuring the distance from the table to the bottom of that fourth corner. For this study, the test panels were measured in a similar way. The test panels were placed on a granite micro-flat table provided by the Cal Poly Mustang 60 Machine Shop. When the samples were placed on the table, each side of the samples typically experienced a different kind of warpage: twist or bowing. The panels were placed on the table so that the side where three of the four corners were in contact with the table; this would ensure that the side that revealed the twisting
was being measured. The opposite side, when placed on the table would reveal bowing type warpage which was not a concern in the study. A force was applied to each of the corners using light finger pressure to find which two corners were the ones that would lift off of the table when the opposite corner was pressed down. These two corners were measured and used to analyze the twisting warpage of the test panel. To quantify the warpage observed, a small steel weight was placed in one of the two corners while the opposite corner was measured. This weight would act as a constant force that would lift off the opposite corner without introducing excessive force on the panel that may introduce unwanted stresses which could affect the measurements. A height gauge was then used to measure the gap or distance from the bottom most edge of the test panel corner to the surface of the micro-flat table (Figure 20).

![Figure 20: Measurement set up with micro-flat table and height gauge.](image)

The distance was measured five times for the corner and then the process was repeated for the opposite corner that previously had the weight on it. In between each measurement, the height gauge was zero’ed. The five measurements at each corner were taken to help minimize the
variation between the measurements due to the subjectivity and difficulty in aligning the height
gauge with the bottom surface of the panel (Figure 21). This process was repeated for each
sample for all of the configurations resulting in ten measurements per sample which results in 50
measurements per configuration.

![Figure 21: Test panel with jaw of height gauge zero'ed against the surface of the microflat table.](image)

### 4.3 Sample Size Selection

A pilot study of the current layup manufactured at Safran Cabin was conducted in order
to gage the magnitude and variation of the warpage seen in these test panels as well as validate
the measurement method. Ten 3 inch by 24 inch test samples were cut from a master panel with
a [45/-45/core/45/-45] layup. These samples were measured using the same method as described
previously. The warpage values were recorded and used to calculate the sample size necessary to
produce reliable data using a power analysis based off of the standard deviation of these panels
(Appendix D). After the rest of the samples had been measured, the pilot study samples were
measured again to ensure reproducibility in the measurement method.
4.4 Statistical Analysis

The average between the 5 measurements taken at each corner was calculated to account for any sampling error in measuring the panels. This results in two average values, one for each corner on the same test sample. Then the maximum value between these two averages was used to quantitatively characterize the warpage of the test panel (Figure 22).

Safran supplied ten test samples in each configuration. This led to ten maximum panel statistics for each configuration which were averaged in order to describe the distribution of warpage heights between all the samples with similar constructions.

The testing order of these panels was not randomized. Instead they were measured in batches. Their batch assignment was dependent on the order in which the panels were shipped (Table I). The first samples received were those of the pilot study. These panels were used to gage the typical magnitude of warpage and the variation within the test samples. The pilot study
samples were measured twice, once in February 2019 and once in May 2019, after the rest of the panels, in order to gage the reproducibility of the measurement methods. The ten samples in each configuration were grouped with samples 1-5 measured prior to samples 6-10. In some cases, both sets were measured on the same day. The resulting warpage measurement data was analyzed in this order to inspect for any correlation between the testing order and the warpage height.

<table>
<thead>
<tr>
<th>Batch Order</th>
<th>Measurement Date</th>
<th>Configuration</th>
<th>Sample ID Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>February 14, 2019</td>
<td>*Pilot Study</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>2</td>
<td>February 15, 2019</td>
<td>*Pilot Study</td>
<td>4, 5, 6, 7, 8, 9, 10</td>
</tr>
<tr>
<td>3</td>
<td>April 22, 2019</td>
<td>Control 0/90</td>
<td>1, 2, 3, 4, 5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Symmetric 0/90</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>April 24, 2019</td>
<td>Control 0/90</td>
<td>6, 7, 8, 9, 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Symmetric 0/90</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>May 6, 2019</td>
<td>Combination Symmetric 45</td>
<td>1, 2, 3, 4, 5</td>
</tr>
<tr>
<td>6</td>
<td>May 6, 2019</td>
<td>Combination Symmetric 45</td>
<td>6, 7, 8, 9, 10</td>
</tr>
<tr>
<td>7</td>
<td>May 6, 2019</td>
<td>Pilot Study</td>
<td>1, 2, 3, 4, 5</td>
</tr>
<tr>
<td>8</td>
<td>May 6, 2019</td>
<td>Pilot Study</td>
<td>6, 7, 8, 9, 10</td>
</tr>
</tbody>
</table>

* Pilot study preliminary measurements which were later replaced with new measurements but were used to compare and analyze reproducibility in the study

The warpage data was compared using boxplots across all individual samples within each configuration with a sample size of 10 due to the 5 replicate measurements taken at both corners. This was necessary to see how much the panel warpage varied between similar test samples.
within the same master panel for that configuration layup. In addition, the maximum of the
average of the 5 measurements from the same corner was analyzed as described in Figure 22,
using boxplots. This value was calculated for each of the ten test samples within each
configuration, so the sample size during this analysis was also 10. This gave evidence of the
spread of variation between the different configuration layup’s warpage. These values were
analyzed using a one-way analysis of variance (ANOVA) in order to check for a statistical
correlation between the fiber orientation and the warpage height. An alpha value of 0.05, which
signifies a 95% confidence interval, was used for this test. A Tukey Comparison of Means was
used to give insight as to which configurations were statistically similar.

5. Results

5.1 Panel Warpage Height

The individual data points (before reducing to the maximum of the averages) can be
analyzed using boxplots of each sample (Figure 23). These show the variance between
measurements and well as the mean warpage height for each panel. It should be noted that these
graphs plot the pure average and median across the 10 measurements for each panel, not the
maximum of the average of the measurements from similar corners as in the procedure outlined
in Figure 22. These plots show that the combination and the symmetric 45 configurations show
the least warpage.
Figure 23: Boxplot comparison of the ten measurements (5 at each corner) taken for each of the ten samples in the control panel (A), the pilot study (B), the 0/90 panel (C), the combination panel (D), symmetric 45 (E), and the symmetric 0/90 (F). The customer specification limit is shown by the red line at a height of 0.05 inches.

The calculations described in Figure 22 result in the reduced data (Appendix F) and are plotted by sample number and grouped by the corresponding configuration (Figure 24). This chart plots the maximum value between the corner averages for each of the 10 samples of each configuration/layup. As seen in this scatterplot, the pilot study samples show smaller warpage
than that of the control samples but are consistent with the symmetric 0/90 samples. Since samples 1-5 were measured in one group and then samples 6-10 were measured in a second group, it is important to analyze this chart for any patterns in the data between samples 1-5 and 6-10. All configurations, except for the 0/90 configuration, show a small amount of variance in the results. For the most part, the data has little crossover between configurations, meaning that each configuration is different from the rest. This is important in suggesting that altering the fiber orientation produces significant change in the warpage height.

The ten corner maximums for each panel configuration are summarized using a boxplot (Figure 25). In this graph, the average warpage height is denoted by the blue crosshair symbol. The maximum tolerable amount of warpage as indicated by the customer specification limit is shown as the red dashed line at 0.05 inches. The warpage amounts range from a maximum value of 0.0858 inches (0/90) to a minimum value of 0.0078 inches (Symmetric 45). All configurations

Figure 24: Scatterplot of the warpage heights of the ten test samples grouped by configuration panel.
show relatively small variance, especially the pilot, and both symmetric panels. The 0/90 configuration shows the largest variance in warpage height. There is one outlier in the symmetric 45 configuration at 0.0134 inches. While this point is statistically considered an outlier, it is not far removed from the rest of the data set. It is just thousandths of an inches above the next lowest data point in the symmetric 45 configuration.

![Boxplot comparison of the average maximum warpage height of the ten test samples in each configuration.](image)

5.2 Analysis of Variance

To determine how statistically sound these results were, a one-way ANOVA was conducted. The hypothesis tested was that the means of the different panel constructions were all the same. This was tested against the null hypothesis that at least one of the means was different. This test was carried out with a significance level of $\alpha=0.05$, which corresponds with a 95%
confidence interval. In order for this test to be valid with this data set, the following conditions must be met: normality, equal variances, and independence.

5.2.1 Normality

The data is generally consistent with the normal distribution thus fulfilling the normality condition. This can be verified with a normality test (Appendix A).

5.2.2 Equal Variances

A plot of the residuals versus the fits was used to check the equal variance condition (Figure 26). The data was found to not have equal variances as seen in the left panel of Figure 26. This graph shows a fanning effect (or funnel effect) in that as the fits grow the residuals get larger as well. This unequal warpage can be handled using a logarithmic transformation in order to stabilize the variance. The effect of this transformation on the residual versus fits plot can be seen in the right panel of Figure 26. In addition, the overlapping of the intervals in the test for equal variance graphs justify the use of the logarithmic transformation (Appendix B). This transformation was successful in making the amount of spread in the residuals the same magnitude and thus allows the data to fulfill the equal variance condition.
5.2.3 Independence

The warpage of one panel does not interfere with or cause warpage in another panel. For this reason, the warpage is considered independent from panel to panel. To thoroughly test for this effect and prove independence the sampling and testing would have to have been randomized. Although, these panels were not measured in a randomized order, the effect of order on warpage has been analyzed and no interaction between these has been discovered.

5.3 ANOVA Results

With the conditions analyzed and fulfilled, the ANOVA test was carried out on the transformed data (Table II). These results show a large F-value and a p-value of 0.000 which suggest that varying the fiber orientation has a significant effect on the warpage height.
Table II: One-Way Analysis of Variance (ANOVA) Results Table

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of Freedom</th>
<th>Adjusted SS</th>
<th>Adj MS</th>
<th>F-value</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel Construction</td>
<td>5</td>
<td>3.847</td>
<td>0.769</td>
<td>166.03</td>
<td>0.000</td>
</tr>
<tr>
<td>Error</td>
<td>54</td>
<td>0.250</td>
<td>0.005</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>59</td>
<td>4.097</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The ANOVA test can be used to predict the confidence intervals of the warpage by panel configuration (Figure 27). These results show where the true mean of warpage is for each configuration at a confidence level of 95% based off of the tested standard deviation. In future testing, the warpage results should fall within these intervals. This graph shows that the 0/90 configuration is above the specification limit of 0.05 inches. It also shows that the symmetric 45 configuration has the lowest warpage and the smallest range in the interval.

Figure 27: Predicted confidence intervals from the ANOVA test for future panel warpages by configurations.
5.4 Tukey Comparison

A Tukey Comparison was utilized in order to determine whether the difference in the means of the tested configurations was statistically significant (Table III). In this comparison, groups with different letters are considered significantly different from each other. This chart shows that each configuration is different from the rest, except for the pilot study and the symmetric 0/90 panels which are in the same group. This comparison also shows the relative standard deviations. All of these values are low suggesting that there is little variance within the like panels of a particular configuration. The Tukey Comparison was carried out with the transformed data and featured the same groupings as shown in Table III (Appendix C).

Table III: Tukey Comparison of Panel Layup Configuration Grouping

<table>
<thead>
<tr>
<th>Panel Construction</th>
<th>Mean (in.)</th>
<th>Standard Deviation (in.)</th>
<th>Tukey Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>0/90</td>
<td>0.06256</td>
<td>0.01232</td>
<td>A</td>
</tr>
<tr>
<td>Safran Control</td>
<td>0.04096</td>
<td>0.00620</td>
<td>B</td>
</tr>
<tr>
<td>Pilot Study</td>
<td>0.03150</td>
<td>0.002155</td>
<td>C</td>
</tr>
<tr>
<td>Symmetric 0/90</td>
<td>0.02998</td>
<td>0.001797</td>
<td>C</td>
</tr>
<tr>
<td>Combination</td>
<td>0.01926</td>
<td>0.00423</td>
<td>D</td>
</tr>
<tr>
<td>Symmetric 45</td>
<td>0.00986</td>
<td>0.001523</td>
<td>E</td>
</tr>
</tbody>
</table>

The graphical model of the Tukey comparisons by group show how close two panels are to being considered statistically similar. Groups whose interval extends across the green vertical 0.00 line are considered similar. Groups whose intervals do not contain this zero have significantly different means. The only groups that cross the zero line are the symmetric 0/90 configuration and the pilot study configuration. The green interval marks the comparison.
between the pilot study and the control configuration. These two panels feature the same layup, however, are not significantly similar. Their interval is close to the zero line, however not as close as some of the other comparisons (Figure 28).

Figure 28: Tukey pair-wise comparison interval plot for the interaction of each configuration.

6. Discussion

6.1 Panel Warpage Measurements

The boxplots shown in Figure 23 show the variance between the ten measurements taken for each test sample as well as the variance between the ten test samples overall within each panel configuration. The control and the 0/90 configurations feature relatively large variances both within the ten test samples individually and over the panel as a whole. The rest of the
configurations feature low variances, suggesting that the sample size of ten test samples per configuration was enough to capture the response in the data and is reliable enough to produce reproducible warpage values.

The symmetric 45 panel was expected to exhibit low warpage values due to its symmetry about the core. This is supported by the data shown in the boxplots in Figure 23e. It has a warpage significantly lower than that of the other configurations as seen in Figure 23 and the Tukey comparison in Table III. Manufacturing this panel configuration requires little changes in the laser cutting process. One of the carbon fiber face sheets must be cut out at a 90° rotation from the first panel. This rotation can reduce the amount of material roll used in the process by 13%. This change would not require Safran to change their prepreg roll purchasing and thus would be a simple change for Safran to adopt and would produce significantly less warpage in these sandwich panels.

The pilot study and the control configurations featured the same layup, [45/-45/core/45/-45] but were produced several months apart. The warpage response is expected to be similar between these two panels; however, the warpage seen in the control configuration (Figure 23a) is much larger than that observed in the pilot study (Figure 23b). This could suggest a process control concern within Safran’s manufacturing process or a batch-to-batch variability issue with their supplied material. Both concerns will be addressed in a later section of the report. The control configuration shows slightly higher warpage values for samples 6-10 as seen in the boxplot in Figure 23a and in Figure 24. This is concerning because it may suggest that there is a correlation between the date of measuring the panel and the warpage measured. Since the panels were marked in the order that they were bundled and sent to us, it is highly likely that panels 6-10 were all next to each other in the master panel before it was cut. Therefore, the larger warpage
measurements in samples 6-10 may suggest that one side of the master panel was more heavily
warped than the other. Figure 24 also shows a dip in warpage across samples 3-8. Since this
spans the gap of the testing date, it is more likely that this is a true representation of the warpage
in the master panel. This would suggest that the master panel was more heavily warped on the
left and right sides of the panel than in the center. There are no trends of increasing or
decreasingly consistently for more than 4 samples in a row. This suggests that while the
sampling order was not randomized, it did not have a significant effect on the warpage height.

The scatterplot in Figure 24 also shows that the data for each configuration rarely
overlap. This suggests that each configuration has a different warpage response. This preliminary
finding will be further supported using the statistical analysis techniques in ANOVA.

Figure 25 displays the spread of the ten corner maximums for each panel configuration.
The symmetric 45 panel shows extremely low values of warpage. These values are also closely
clustered resulting in a small standard deviation. This panel features an outlier seen in the
boxplot in Figure 25. This data point occurs at a warpage of 0.0134 inches which still lower than
all but one data point (the lowest recorded warpage seen in the combination configuration). An
outlier is any data point that is outside of 3 times the standard deviation. Because the standard
deivation is so low for the symmetric 45 panel, this value is considered an outlier. However,
because it is relatively close to the rest of the data for this panel and was only considered an
outlier because of the extremely tight standard deviation it was not omitted from the study.

Most of the panels were below the specification limit of 0.05 inches, seen in Figure 25,
meaning that they would not be rejected or require reworking. However, there is some variation
in the reproducibility of this study. If a panel is close to this limit, there is evidence to suggest
that in the future some panels may exhibit warpage above this acceptable limit. The control
configuration and the 0/90 configuration are close to or exceeding this limit. Therefore, neither or these configurations should be trusted as a reliable panel construction to reduce warpage to below 0.05 inches.

The purpose of this study is to minimize warpage, so the panel of interest is the symmetric 45 panel. Figure 25 demonstrates that the symmetric 45 configuration shows the lowest warpage height measurements with little variation. This panel features the lowest warpage at 0.00986 inches, which is a 76% reduction from the control panel.

6.2 Analysis of Variance

The p-value in the ANOVA results table (Table II) confirms that the means of the different configurations are statistically significantly different, because it is less than the significance level (α=0.05). This suggests that fiber orientation in the composite sandwich panel has a significant effect on the warpage observed in the panel. The predicted confidence intervals from the ANOVA test shown in Figure 27 show that the symmetric 45 panel features the lowest warpage of all the configurations tested. It also has reliably low values of warpage that are below the specification limit, and therefore should be selected as the configuration to minimize warpage in these sandwich panels.

6.3 Tukey Comparison

The Tukey comparison shown in Table III displays the grouping for each panel configuration. Configurations with the same letter are considered in the same group, thus
statistically indistinguishable. The only panels for which this occurs are the pilot study and the symmetric 0/90 configurations. All of the other configurations are significantly different, which suggests that altering the fiber orientation has a significant effect on the warpage height. This data shows that the best configuration for minimizing this warpage measured in the method explained in the experimental procedure is the symmetric 45 configuration.

This comparison also shows that the pilot study and the control are significantly different. This is an unexpected response as these configurations feature the same layup. The pilot study panels were produced in February, while the control test panels were produced in April. The graph of the Tukey confidence intervals in Figure 28 shows how close these two data sets were to be considered similar. While their interval extends close to the zero line, which would suggest that they are in the same group, it does not cross this line. In contrast, the symmetric 0/90 and pilot study panels are within the same group. The mean of the interval of these two groups is almost centered at zero, meaning that these two are indistinguishably similar. This response does not lead to many conclusions about these two configurations; however, it is the response that one would have expected to see between the control and the pilot study.

6.4 Concerns in the Data

6.4.1 Reproducibility

The pilot study samples were measured twice using the same measurement methods, once in February and once in May. The pilot study was remeasured after the other configurations were tested to validate the measuring technique and to verify the original warpage values observed for the pilot study. The two data sets were indistinguishable, so it was concluded that
the measurement technique was consistent, and the values observed were similar to those measured the first time. This ensures that the data is reproducible.

6.4.2 Process Control Concerns

Concerns arose when comparing the pilot study to the control configuration samples because the measurements were statistically significantly different. This is an issue because the two sample configurations and constructions were identical with the only difference being the time of manufacturing. The control configuration samples were expected to see similar values to those observed during the pilot study, but this was not the case. Since the measurement technique was both valid and reproducible, it is likely that the significant difference between the pilot study and the control study was due to other reasons rather than measurement technique. One explanation for this is a limited process control in manufacturing. Unknown uncontrollable variables in manufacturing could be affecting the warpage of these panels. Such variables may include crush core press platten temperature, ambient humidity and temperature, prepreg sheet alignment relative to one another, or pre-cure thawing amount. This is concerning because it could mean that on a different day, different warpage heights could be possible. However, even if there is a large amount of uncontrollable variability in the manufacturing process, the symmetric 45 configuration still reduced the amount of warpage significantly. While this potential process control issue should be mitigated, if the panel warpage is reduced low enough it is likely that even with poor process control these panels will still be below the specification limit.
6.4.3 Batch-to-batch Variability

Safran acknowledged that there had been variability between batches and rolls of the non-crimp carbon fiber prepreg in the past. For an unknown reason, the material received from the Safran’s supplier has been inconsistent causing variability and inconsistency in the amount of warpage observed during manufacturing at Safran. This inconsistency between material batches, or prepreg rolls, could explain why the pilot study and the control configuration varied in warpage measurements and were statistically different when they should have been statistically similar. Because both the pilot and the control configuration were constructed with the same fiber orientations, they were expected to have statistically similar values of warpage, but this was evidently not the case. The variability between batches could be an explanation for this due to fact that the pilot and the control batch were manufactured months apart and were constructed using different batches of material.

7. Conclusions

1. The symmetric \([45/-45/core/-45/45]\) configuration reduced warpage by 76%.

2. Fiber orientation in the panel configurations has a significant effect of warpage.

3. The significant difference, 0.00946 inches, between the pilot study and the control panels suggests a process control concern or batch-to-batch variability.
8. References


9. Appendix

9.1 Appendix A: Normality Test

![Probability Plot of Residuals](image1)

![Probability Plot of Transformed Residuals](image2)
9.2 Appendix B: Equal Variance Test

Test for Equal Variances: Warpage vs Configuration Name
Multiple comparison intervals for the standard deviation, $\alpha = 0.05$

If intervals do not overlap, the corresponding std. devs are significantly different.

Test for Equal Variances: log(Warpage) vs Configuration Name
Multiple comparison intervals for the standard deviation, $\alpha = 0.05$

If intervals do not overlap, the corresponding std. devs are significantly different.
9.3 Appendix C: Transformed Tukey Comparison Results on log_{10} Scale

<table>
<thead>
<tr>
<th>Panel Construction</th>
<th>Sample Size</th>
<th>Mean (in.)</th>
<th>Tukey Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>0/90</td>
<td>10</td>
<td>-1.211</td>
<td>A</td>
</tr>
<tr>
<td>Safran Control</td>
<td>10</td>
<td>-1.393</td>
<td>B</td>
</tr>
<tr>
<td>Pilot Study</td>
<td>10</td>
<td>-1.5242</td>
<td>C</td>
</tr>
<tr>
<td>Symmetric 0/90</td>
<td>10</td>
<td>-1.5023</td>
<td>C</td>
</tr>
<tr>
<td>Combination</td>
<td>10</td>
<td>-1.7254</td>
<td>D</td>
</tr>
<tr>
<td>Symmetric 45</td>
<td>10</td>
<td>-2.0105</td>
<td>E</td>
</tr>
</tbody>
</table>

9.4 Appendix D: Power Analysis of Pilot Study
### Appendix F: Reduced Warpage Measurement Data (Maximum of the Averages for Corresponding Corners)

<table>
<thead>
<tr>
<th>Panel Layer</th>
<th>Configuration</th>
<th>Name</th>
<th>Sample Number</th>
<th>Warpage</th>
<th>log(Warpage)</th>
<th>FITS</th>
<th>RESI</th>
<th>Transformed FITS</th>
<th>Transformed RESI</th>
</tr>
</thead>
<tbody>
<tr>
<td>45/-45/core/45/-45</td>
<td>Control</td>
<td>1</td>
<td>0.0278</td>
<td>-1.55596</td>
<td>0.04096</td>
<td>-0.01316</td>
<td>-1.39257</td>
<td>-1.0163385</td>
<td></td>
</tr>
<tr>
<td>45/-45/core/45/-45</td>
<td>Control</td>
<td>2</td>
<td>0.0442</td>
<td>-1.35458</td>
<td>0.04096</td>
<td>0.00324</td>
<td>-1.39257</td>
<td>0.037992</td>
<td></td>
</tr>
<tr>
<td>45/-45/core/45/-45</td>
<td>Control</td>
<td>3</td>
<td>0.0378</td>
<td>-1.42251</td>
<td>0.04096</td>
<td>-0.00316</td>
<td>-1.39257</td>
<td>-0.029938</td>
<td></td>
</tr>
<tr>
<td>45/-45/core/45/-45</td>
<td>Control</td>
<td>4</td>
<td>0.039</td>
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<td>0.04096</td>
<td>-0.00196</td>
<td>-1.39257</td>
<td>-0.016365</td>
<td></td>
</tr>
<tr>
<td>45/-45/core/45/-45</td>
<td>Control</td>
<td>5</td>
<td>0.0416</td>
<td>-1.38091</td>
<td>0.04096</td>
<td>0.00064</td>
<td>-1.39257</td>
<td>0.011663</td>
<td></td>
</tr>
<tr>
<td>45/-45/core/45/-45</td>
<td>Control</td>
<td>6</td>
<td>0.0502</td>
<td>-1.2993</td>
<td>0.04096</td>
<td>0.00924</td>
<td>-1.39257</td>
<td>0.093274</td>
<td></td>
</tr>
<tr>
<td>45/-45/core/45/-45</td>
<td>Control</td>
<td>7</td>
<td>0.044</td>
<td>-1.35655</td>
<td>0.04096</td>
<td>0.00304</td>
<td>-1.39257</td>
<td>0.036023</td>
<td></td>
</tr>
<tr>
<td>45/-45/core/45/-45</td>
<td>Control</td>
<td>8</td>
<td>0.0474</td>
<td>-1.32422</td>
<td>0.04096</td>
<td>0.00644</td>
<td>-1.39257</td>
<td>0.068348</td>
<td></td>
</tr>
<tr>
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