Development of Test Methods for Measuring Fiber Misalignment and Warping in Honeycomb-Core Composite Panels

A Senior Project

Presented to

The Faculty of the Materials Engineering Department

California Polytechnic State University, San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree

Bachelor of Science

By

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June 2018

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Acknowledgements

We would like to thank Professor Blair London in the Materials Engineering Department for being our academic advisor for this project. We would also like to thank Jennifer Montejano and Adam Olzick at Zodiac Aerospace, our sponsoring company, for sharing their knowledge on composite manufacturing, design of experiments, and composite measurement procedures.
1. Abstract

Zodiac Aerospace manufactures honeycomb-core composite panels to be used in aircraft cabin interior components. During the manufacturing process, some panels become warped such that they cannot be used for their designated aircraft cabin components. As a result, these panels are scrapped because they cannot be recycled. About 44 to 90% of panels become warped during manufacturing. Warping is caused by many factors, including layer misalignment, processing parameters such as temperature and pressure gradients, and fiber misalignment in the prepregs. Currently, Zodiac does not have any data on the effect of fiber misalignment on panel warpage, so a testing protocol was developed to determine if there was a correlation between these parameters. Fiber misalignment measurements were performed on a selection of glass fiber/phenolic prepregs obtained from multiple shipments. To determine fiber misalignment in the prepregs, the phenolic resin was removed, leaving the raw fibers exposed and able to be measured. Warpage measurements were performed on cured composite panels cut from the same prepreg rolls. Test methods for the maximum deflection and twist angle of the panels were developed, then this data was plotted to determine if a relationship existed between the measurements. The plots showed no correlation between the fiber misalignment and warpage measurements. To provide additional conformation, a one-way analysis of variance (ANOVA) was conducted using an alpha value of 0.05. The ANOVA analysis confirmed that there was no correlation between the fiber misalignment and warpage measurements. Recommendations for further study would be to analyze the effects of temperature and pressure gradients on warping of the panels and construct a fixture to hold the prepreg in the acetone bath.

Key Words: Bow Warping, Cabin Interiors, Composite Materials Cup Warping, Glass Fiber Fabric, Honeycomb Sandwich Panel, Materials Engineering. Nomex Honeycomb, Pre-preg Laminates, Twist Warping, 8-Harness Satin Weave
2. Introduction

2.1. Composites Industry

Composites have become commonplace in the aircraft industry as a result of their desirable properties. On exterior and structural parts, carbon fiber reinforced polymers have replaced aluminum and steel. On newer planes such as the Boeing 787, as much as 50% of the exterior and structural pieces now consist of composite panels and beams [1]. For interior panels, honeycomb sandwich panels have replaced plastic due to superior soundproofing and weight savings. Impact resistance is also improved in honeycomb panels, increasing time between replacement [1].

2.1.1. Zodiac Aerospace

Zodiac Aerospace is a French aerospace company that provides equipment for both commercial and private aircraft. There are five divisions that make up the company: Aircraft Systems, AeroSafety, Gallery and Equipment, Cabins and Structures, and Seats. The Cabins and Structures division manufactures composites to be used as secondary structures in cabin interiors such as sidewalls, overhead bins, and ceiling panels. The composites that are used in these structures are glass fiber, phenolic matrix, honeycomb-core sandwich panels. These panels are strong and lightweight, which make them ideal to use for structural applications. A sample panel is shown in Figure 1 [2].

Figure 1. A typical glass fiber, phenolic matrix honeycomb composite panel [2].
2.2. Composites Overview

A composite is composed of two or more materials with significantly different properties. When these materials are combined, the resulting properties are different from the individual materials. Composites are commonly used in the aerospace industry since they combine high strength with low density. Most composites consist of a matrix embedded with fibers. The matrix is usually a polymer such as epoxy or polyester, however, other matrix materials include metals, ceramics, and carbon. Common fiber materials used in the aerospace industry include glass, carbon, and extended chain polyethylene. The fibers bear the applied load to the composite and the matrix transfers the load to the fibers, retains the shape of the composite, and protects the fibers [3]. Examples of common composite structures include glass fiber reinforced polymers, plywood, and honeycomb core sandwich panels.

2.3. Honeycomb Core Sandwich Panels

2.3.1. The Honeycomb Core

The panels are composed of a honeycomb core sandwiched between two face sheets that are glass fiber, phenolic matrix prepregs. The prepregs are B-staged, which means that the resin is partially cured. Adhesive films are placed between the prepregs and the core to fasten the core in place. A diagram of the panel is shown in Figure 2 [1]. The core is composed of an aramid fiber material, usually Nomex or Kevlar, arranged in hexagonal prisms. The hexagonal configuration is the most efficient shape for bearing loads, and is the most common configuration used for aircraft applications. Other common configurations are reinforced hexagonal, overexpanded, square, and flex-core [5].

![Figure 2. Schematic of a honeycomb sandwich composite panel [1].](image)
A single hexagonal cell is composed of a node and a free wall. The node is the part that is bonded to another cell in the honeycomb structure, and the free wall is a single sheet that is not bonded to any component in the structure. The size of the cell is determined by measuring the distance between two parallel sides. There are a variety of materials that are used for honeycomb cores. Common materials are steel, aluminum, fiberglass, carbon, and ceramic. Aramid fibers are used in nonmetallic honeycomb cores, as they have high flammability resistance, excellent insulating properties, good formability, and high strength. These properties make them ideal for airplane cabin interiors [5]. A hexagonal honeycomb structure is shown in Figure 3 [6].

![Figure 3. A sample hexagonal honeycomb structure with the labeled components [6].](image)

Aramid honeycomb cores are commonly manufactured by adhesive bonding and expansion. In this process, honeycomb substrates are bonded together with heat curable adhesives. The resulting honeycomb block is dipped into either a phenolic or polyimide resin and placed in an oven to cure. Once the block is cured, the aramid papers are pulled in the direction of the width (Figure 3) to form the hexagonal structure. This process causes the honeycomb structure to have a highly anisotropic behavior [5,7].
2.3.2. The Glass Fiber Face Sheets

Zodiac Aerospace uses face sheets that are composed of E-glass fibers inserted in a phenolic matrix. E-glass fibers are used due to their low cost and relatively high tensile strength. The fibers are woven in a 7781 weave, also referred to as an 8-harness satin weave. The weave consists of warp yarns that are aligned in the longitudinal direction, and fill yarns that are perpendicular to the warp yarns. During the manufacturing process of the face sheets, the warp yarns are pulled in tension along the longitudinal axis, while the fill yarns are woven through the warp yarns. As a result, the warp yarns are much stronger than the fill yarns. The fill yarns tend to be misaligned from the laminate plane by a maximum of +/- 3 degrees. The weave pattern consists of the fill yarns running over seven warp yarns, and under one [8]. A schematic of the 8-harness weave is displayed in Figure 4 [9].

Harness satin weaves are commonly used for components that are curved or have complex geometries [10]. Although woven fabrics do not have as high of a tensile strength as the unidirectional laminates, their structure provides a better balance of properties in all fiber
directions. Their low cost and ability to conform to complex geometries and compound curves make them ideal for use in aircraft cabin interiors [11]. The face sheets carry the majority of the in-plane and bending loads, while the core supports the face sheets, transfers the load, and carries the through-thickness-shear load [13].

The phenolic resin is a thermoset polymer that protects the honeycomb structure. A three-dimensional structure is formed upon curing. While phenolics are not as strong or stiff as epoxy, they are fire-retardant, which is required by the Federal Aviation Administration (FAA). At high temperatures, the resin degrades and forms a char structure that stops burning [12]. In airplanes, the walls, ceiling, and floors of the cabin are made with phenolic resin composites, as the delayed burning allows time for evacuation.

2.4. Composite Manufacturing Process

2.4.1. Panel Manufacturing

Zodiac uses two primary methods to manufacture their honeycomb sandwich panels, which are compression molding and hand lay-up. During compression molding, flat uncured sandwich panels are made by an automation process. The panels are then placed in a heated die press, where the dies force the panel into the desired shape. The panel is also cured in the press. Compression molding is mainly used for manufacturing cabinets and drawers. This process is less time consuming than the hand lay-up, but is also more likely to produce voids in the panel [3]. Constant pressure cannot be applied for the entire time the part is cured, as the die must be opened occasionally to allow for outgasses from the curing process to escape.

During the hand lay-up process, a mold is initially coated with phenolic resin. The fiber weave material is then placed in the mold at the desired pattern, and more resin is applied using a roller. Additional layers of fiber and resin are added to the mold until the desired thickness is achieved. The honeycomb core is placed on the resulting facesheet, and a facesheet on the opposite side of the honeycomb is prepared. The resulting composite is put into a flexible polyvinyl alcohol bag. High pressure and vacuum is applied to the composite through the bag to eliminate voids and
cure the resin. The hand lay-up process is time consuming and labor intensive, so it is usually only performed to produce parts with complex geometry [3].

2.4.2. Prepreg Manufacturing
The prepreg manufacturing process initially involves soaking the fiber weave with liquid phenolic resin. Excess resin is removed from the fiber weave using metering rolls, and the weave is placed in an oven to partially cure the resin [14,15]. The resin is now B-staged. A diagram of this process is displayed in Figure 5 [15].

![Figure 5. A schematic of the prepreg manufacturing process [15].](image)

B-stage prepreg is used in Zodiac’s panels in both hand lay-up and compression molding manufacturing. It eliminates the need to inject resin on-site, and can be stored for long periods in freezers if necessary. Hand lay-up uses B-stage with a lower degree of curing, as additional resin can be added in to support the fibers as needed. Since hand lay-up is used for more complex
parts, the lower degree of cure also allows it to be formed around more intricate molds as well. Compression molding, meanwhile, uses prepreg that has a higher amount of cure. At the amount used in compression molding, the resin is already viscous enough to not flow, but still tacky enough to easily adhere to the adhesive that binds it to the honeycomb structure. It also means that additional resin does not need to be injected into the die during molding, as the fibers have sufficient resin around them as-is.

2.5. Fiber Misalignment

The misalignment of fibers is common in most composite structures. Due to the size of fibers and the amount present, it is almost impossible to ensure that all fibers are perfectly aligned in their orientation. After the fiber weave is coated with the phenolic resin, the warp fibers are tensioned to ensure their alignment [9]. However, this can cause the fill fibers to shift longitudinally due to friction between fibers. As the warp fibers are tensioned, out-of-plane stresses are applied to the fill yarn, bending the fill fibers. This misalignment of the fill fibers cannot be easily fixed, as tensioning along the fill direction would cause the warp fibers to become misaligned instead.

Structurally, this means that the composite structure will be weaker than expected since the fibers will not be able to withstand applied loads in the fill fiber direction. As fibers are strongest along their longitudinal axis, any fibers that are not aligned will experience shear stresses, which will cause failure at lower values due to the brittle nature of the glass fibers. Even under ideal circumstances, the fill direction is already predicted to fail at a lower tensile stress than the warp direction, as the fibers are bent when woven through the warp fibers (Figure 4).

Determining the degree of fiber misalignment is done manually, by measuring the path a single fill fiber takes as it goes from one side of the weave to the other. For prepreg, the resin must first be washed off, which allows the fibers to be removed from the whole sheet without fracturing [16]. The fiber weave is then tensioned, to remove any wrinkles or folds. Then, single fibers are removed from the weave. Because of the tension and friction, a gap remains, allowing the path of the fiber to be traced. A centerline is drawn, and the maximum deviation from it is recorded.
2.6. Warpage

2.6.1. Causes of Warpage
Warping often occurs in composite panels during their manufacturing process. The dimensions of the panel are usually different from what they should be after the panel has cooled to room temperature and has been removed from the tool, hot press, or autoclave. The manufacturing process has three main steps: room temperature lay-up, consolidation and curing of the laminate at elevated temperatures and pressures, and cooling and removal from the mold. All three steps can alter the geometry of the panel [17]. There are primary three types of warp: cup, bow, and twist (Figure 6). In cup warping, there is a deviation from flatness in a plane along the width of the panel. Bow warping involves a deviation from flatness along the length of the panel. Twist warping is the deviation from a flat plane between the diagonal corners [4]. All of these types can be problematic, as depending on the intended function any amount of warping makes the panel unable to be used. Bow and twist warping are more easily seen in composite panels, and their magnitudes are usually greater than the magnitudes of cup warping.

![Figure 6. The three main types of warping: a) cup, b) bow, and c) twist.](image)

During the room temperature lay-up stage, the prepreg is placed in a mold either by hand or by an automated process. Both processes can cause uneven resin distribution and broken fibers, which can then result in warping of the panel. Other phenomena that occur during this stage that cause warping include variations in layer thickness (both within a layer and from layer to layer), layer waviness, gaps in the prepreg, and layer misalignments [17].

The consolidation and curing stage causes temperature gradients throughout the laminate. The heating components of the curing process are not positioned uniformly relative to the laminate,
which generates a temperature gradient. Temperature gradients result in different curing rates at different areas of the panel, which can lead to nonuniform mechanical and thermal expansion properties. A nonuniform temperature change from the cure condition to room temperature is also generated. There are also differences in the applied pressure throughout the panel which lead to spatially nonuniform layer properties. Resin bleed occurs at this stage, since the high temperatures and pressures cause excess resin to flow out of the laminate. The resin flow causes an unequal distribution of the fiber and the resin. The panel can mechanically fail during the last stage, where it is cooled and removed from the mold. The distortions caused by the previous stages are more clearly identified in this stage. The cooled part often has a different shape than that of the mold [17].

Layer misalignments generate misalignment of the fibers, and this combination produces an unsymmetric laminate construction. The combination of the unsymmetric construction and the temperature change from room temperature to the curing temperature of the laminate causes distortions in the panel. The layers vary in thickness, both within a layer and from one layer to another, due to uneven curing of the laminate. As a result, the mechanical properties of each layer are different, which also causes distortion [17].

3. Experimental Procedure

3.1. Safety

Standard safety procedures were followed in this project. Acetone was kept inside a fume hood to minimize exposure to fumes. Gloves were worn when handling the prepregs to prevent skin contact with the resin and glass fibers. Additionally, proper protective clothing including safety glasses and neoprene gloves were worn in lab to minimize the risk of serious injury in the case of an accident.

3.2. Sample Preparation

When measuring fiber misalignment and warpage, a significant problem occurs in that fiber misalignment cannot be measured in complete panels due to the opacity of the cured phenolic resin. As a result, two samples from each fiber roll were used. These sheets were cut from the
roll directly adjacent to each other, to ensure fill fibers traveled the same path through both. One of these sheets was cut and pressed into a complete panel in a compression mold. The other was kept as a prepreg sheet and used to measure fiber misalignment. To allow for ease of fiber removal, a 3-inch notch was cut on the short ends of the sheets.

Sample panels were cut from 23 E-glass/phenolic prepreg rolls. The raw prepreg sheets were 60 inches long by 6 inches wide. The sheets were a single layer of the 8-harness weave (which consisted of two interwoven layers). The pressed panels were 24 inches long by 3 inches wide (Figure 7). To simulate the type of panel the face sheets would be used in a 0.5-inch-thick aramid honeycomb layer was placed between the sheets. During pressing, the entire panel was crushed to a uniform thickness of 0.5 inches.

![Figure 7. Dimensions of the honeycomb panels tested.](image)

### 3.3. Fiber Misalignment Measurement Process

Before the fibers could be measured, the phenolic resin had to be removed to allow them to be viewed. The prepregs were rolled up and soaked in acetone for 15-20 minutes to remove the phenolic resin. In acetone, the resin loses its adhesive properties and goes into solution, leaving behind the E-glass weave. Once the resin was removed, the sheet was fastened to a flat surface. The glass weave is more pliable without the phenolic resin, but still holds together as a sheet allowing it to be manipulated. A centerline was drawn between the two cuts on the sheet, to be used as a reference for the ideal fiber travel path (perfect 0-90 weave). One yarn of fibers was removed from each side of the prepreg. The acetone dried within a few minutes after the weave was removed from the acetone bath, which made it difficult to remove the yarns. Therefore,
additional acetone had to be added to the sheet while the yarns were being removed. When a yarn was removed, the friction between yarns means the path remains open, allowing measurement of the maximum deviation (Appendix A). The maximum deviation between the fiber path and the reference centerline was measured and recorded as the fiber misalignment. A diagram of this process is shown in Figure 8.

![Figure 8](image)

Figure 8. A diagram of the fiber misalignment measurement process. A loose fiber end is located at the cut (a), then pulled out of the roll (b). The distance between the fiber path and the centerline is then measured (c)

### 3.4. Warpage Measurement Process

Bow and twist warping were the main focuses of this project due to the geometry of the panels meaning any cup warping present was below the ability of the gauges to detect. To measure the panel warpage, the panels were initially placed onto a flat granite table. As a result of the crush core compression, the thickness of each panel remained constant across the entire panel. Any deviation in the height of the panel from the granite table, therefore, was an indication of warpage. One corner of the panels was fixed and used as the zero point. A height gauge was used to measure the deviation of the panel surface from the granite table. Six total measurements were taken: one at each corner (including the zeroed corner), and one along each of the long sides. Figure 9 illustrates the warpage measurement process. All measurements were repeated on two separate days to ensure the test methods provided reliable, consistent results.
3.5. Bow Warpage Calculations

Bow warping was calculated by computing the average of the deviation measurements of the long sides of the panel (Equation 1). For all samples, the maximum point of bowing was on one side of the panel, but bowing was observed across the entire width of the sample. Because of this, the average was taken. The intention was to not to find the absolute maximum point of bowing above the table, but instead to look at bowing as it occurred across the entire sample.

\[
\text{Average Bowing} = \frac{(\text{Side 1} + \text{Side 2})}{2}
\]

Eq. 1

3.6. Twist Warpage Calculations

To calculate twist warping, the angle between each of the short sides was calculated. Two assumptions needed to be made while calculating the angle. These assumptions were determined to hold true for the first nine panels received, and used for the other 14 as well. The first assumption was that the short side of the panel measured 3 inches, with a deviation of no more than 0.25 inches longer or short than this. This ensured the values used when calculating the estimated angle remained accurate. The second assumption was that the thickness of the panel remains constant across the whole panel. As stated before, this was true due to the crush-core manufacturing process, and ensured that the measurements taken of the height above the granite table reflect warpage and not variations in panel thickness.
With these assumptions, the angles of both sides relative to the granite table were found using basic geometry (Figure 10). Knowing the width of the panel (here used as the hypotenuse) was approximately 3 inches and the height between corners, the angle of the side with the table could be found using Equation 2. Positive angles were defined as clockwise when facing Side 4, with Side 1 on the right. Once the angles of both sides were found, they were then added to get the total twist angle between the sides (Equation 3). Because the purpose was to find the total amount of twist and not the twist one way or the other, the absolute value of this was used in the analysis.

\[
\theta = \arcsin(\frac{\text{height}}{\text{side length}}) \quad \text{Eq. 2}
\]

\[
\theta_{\text{total}} = \theta_{\text{Side 3}} + \theta_{\text{Side 4}} \quad \text{Eq. 3}
\]

Figure 10. Diagram of the angle measurement between the panel and the granite table.

3.7. Statistical Analysis

The fiber misalignment and warpage measurements were initially plotted using scatter plots and histograms to observe the trends and to determine if there was a relationship between these parameters. A one-way analysis of variance (ANOVA) was conducted to see if there was a statistical correlation between the fiber misalignment and warpage measurements. An alpha value of 0.05 (representing a 95% confidence interval) was used for this test.
4. Results

4.1. Fiber Misalignment

A histogram of the fiber misalignment data is shown in Figure 11. All the prepregs showed some degree of fiber misalignment and the average deviation was 1.13 inches. The maximum and minimum deviations were 2.04 in. and 0.02 in., respectively. According to the quartile calculations used to make the box plot, the data had no skew and no outliers were observed in the measurements.

![Box plot and histogram of the fiber misalignment measurements.](image)

Figure 11. Box plot and histogram of the fiber misalignment measurements.

4.2. Bow Warping

Figure 12 displays the bow warping data. The data was right skewed with an average value of 0.032 inches. The maximum and minimum bowing values were 0.09 in. and 0.002 in., respectively. The bowing measurement distribution was heavily right skewed with all samples showing at least some bowing, but no outliers were detected.
To determine whether there was a correlation between bow warping and fiber misalignment, a scatter plot was constructed with the bow warping and fiber misalignment measurements (Figure 13). The plot did not indicate a correlation between these measurements, and this was demonstrated by the $R^2$ value of 0.0053. To provide additional conformation, a one-way analysis of variance (ANOVA) was conducted using an alpha value 0.05, which represented a 95% confidence interval. The null hypothesis used for this test was that there would be no correlation between fiber misalignment and bow warping. The P value obtained from this test was 0.7473, which was significantly greater than the alpha value. As a result, the null hypothesis could not be rejected and therefore there was no statistical correlation between fiber misalignment and bow warping.

Figure 12. Box plot and histogram of the average bow warping calculations.
4.3. Twist Warping

The twist warping data was more right skewed compared to the bow warping data (Figure 14) with an average value of 0.17°. The maximum amount of twist was 1.03° and the minimum amount was 0.00°. Two outliers were measured in this distribution, at 1.03° and 0.64°.
The twist warping and fiber misalignment measurements were initially plotted using a scatter plot to determine whether there was a relationship between these parameters. The scatter plot is displayed in Figure 15. No significant correlation was observed in the plot, and this was illustrated by the $R^2$ value of 0.049. Like bow warping, a one-way ANOVA was conducted to see if there was a statistical correlation between these measurements. The null hypothesis used for this test was that there would be no correlation between fiber misalignment and twist warping. The $P$ value generated from the ANOVA was 0.3084, which was significantly greater than the alpha value of 0.05. Therefore, the null hypothesis could not be rejected and overall, there was no correlation between fiber misalignment and twist warping.

![Figure 15. Trend between fiber misalignment and twist warping.](image)

4.4. Relationship Between Bow and Twist Warping

The bow and twist warpage measurements were also plotted in a scatter plot to see if there was a correlation between these measurements. The plot is displayed in Figure 16. No significant correlation was observed in this plot, and this is shown by the $R^2$ value of 0.0028. To determine whether there was a statistical correlation between these measurements, a one-way ANOVA was conducted. The null hypothesis was that there would be no correlation between bow and twist
warping. A P value of 0.80 was obtained, therefore the null hypothesis could not be rejected. As a result, there was no correlation between bow and twist warping.

5. Discussion

5.1. Analysis of Panel Warpage

From the experiment, no correlation was observed between fiber misalignment and either bow or twist warping. Based on prior literature, this was not unexpected. Fiber misalignment is unlikely to cause shear stress on the panel that would lead to drastic warping. Even in the panels where severe fiber misalignment was observed, the fibers still all followed parallel paths across the panel. This means that upon heating in the press, the uniform thermal expansion occurs, meaning little to no shear stress will be put on the panel.

5.2. Other Potential Causes of Warping

The results indicated that warping may be more influenced by the manufacturing process of the panels than the misalignment of fibers in the prepregs. As mentioned above, warping may have been caused by temperature and pressure gradients and layer misalignments in the laminates.
Pressure gradients occur due to the frequent release of the dies during the process. If one side of the panel is under higher pressure or at a higher temperature than the other, uneven movement will occur upon heating due to thermal expansion, since some fibers will be restricted while other are free to expand. As the honeycomb panels consist of two connected fiberglass panels, if one side experiences more heating, bending will occur as one side attempts to expand but gets restricted by the other. Layer misalignments also cause variations in mechanical properties across the panels because the panels are not symmetric. Nonuniform mechanical properties increase the likelihood of distortions in the panels.

5.3. Comparison of Measurement Methods

The test methods used in this project are easily repeatable and the materials are relatively accessible. The fiber misalignment measurement procedure is reliable when analyzing fiber misalignment on a macroscopic scale, because the fibers can easily be seen in the prepregs with the unaided eye, and readily be pulled from the weave when is applied. The warpage measurement methods that Zodiac has previously used differ slightly from the methods used in this project. In contrast to the initial panel setup used in this project, the panel setup at Zodiac involves fastening two corners onto a granite table instead of one. This method has the potential to produce inaccurate deviation measurements, because fastening two corners may induce additional distortion in the panels. Fixing one corner provides a lower amount of stress to the panels, reducing the likelihood of additional warping and therefore inaccurate measurements. Similar to the methods used in this project, a height gauge was used to measure the deviation from the panel surface to the granite table. Based on the results obtained from this experiment's results, this is a reliable method of obtaining these measurements.
6. Conclusions

1. No correlation could be observed between fiber misalignment and bow or twist warping of the panels.
2. Additionally, no correlation between bow and twist warping was observed.
3. The maximum bow and twist warpage values were 0.09 in. and 1.03°, respectively.
4. The test methods used in this project provide a way to determine fiber misalignment in under 30 minutes, using readily available materials and compounds.
5. The warpage measurement methods used in this project ensure a minimum amount of stress is applied to the panel to yield accurate deviation measurements.
7. References


23


8. Appendices

8.1 Appendix A

Table I. Fiber Misalignment Measurements

<table>
<thead>
<tr>
<th>Lot</th>
<th>Roll</th>
<th>Max. Fiber Deviation (in)</th>
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8.2 Appendix B: Panel Warpage Measurements

Table II. Panel Warpage Measurements

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