NEW FLYER ROOF DESIGN
FINAL REPORT

NJC Consulting

NJC Consulting

Derek Neufeld

Johnpaul Faustino

Todor Kolev

Senol Bilgin

New Flyer Industries

Jeff Yarecki

Sponsoring Company: New Flyer Industries

Project Advisor: Dr. Qingjin Peng

Team # 7 - Not Just Composites (NJC) Consulting

MECH 4860 – Engineering Design; Fall 2010

NJC Consulting – University of Manitoba
75A Chancellors Circle
Winnipeg, Manitoba,
Canada

NJCConsult@gmail.com
New Flyer Industries
711 Kernaghan Avenue
Winnipeg, Manitoba
R2C 3T4 Canada.
(204) 224-1251

Mr. Yarecki,

Enclosed for your review is a copy of our final report for your 40-ft bus roof design. This document summarizes our proposed design and justifies the changes we have made with a rigorous analysis of the research our team has done. We believe our redesign addresses the issue of roof joint leakage in an efficient manner appropriate to New Flyer's interests. Throughout the design process, we have made sure that the proposed design satisfies the project objective while meeting the specified design criteria.

If you have any questions or comments, feel free to contact us at njcconsult@gmail.com. Thank you for your continued support with this project.

Sincerely,

NJC Consulting

TABLE OF CONTENTS

1 Abstract 1

2 Introduction 2

3 Details of the design 3

3.1 Composite Design 4

3.1.1 Design Considerations 4

3.1.2 Bending Strength Considerations 9

3.1.3 Experimental Verification of Predicted Properties 11

3.1.4 Determination of Elastic Modulus 15

3.1.5 Weight Analysis 18

3.1.6 Summary 19

3.2 Joint Adhesive Considerations 20

3.2.1 Cure Mechanisms 21

3.2.2 Summary 23

3.3 Integrated Composite Drip Rails 24

3.4 Overall Cost 26

4 Conclusions 27

Works Cited 28

Appendix A 30

Appendix B 38

Appendix C 44

Appendix D 46

Appendix E 53

Table of Figures

Figure 1 Illustration of proposed design features 3
Figure 2 Cost comparison of carbon, Kevlar and glass fibers 7
Figure 3 2 oz. chopped strand matt 9
Figure 4 10 oz. 0-90 weave cloth 9
Figure 5 1808 biaxial fabric 9
Figure 6 Exploded view of current layup layers 10
Figure 7 Exploded view of layers in a two ply 1808 10
Figure 8 Top view of the 40-foot bus frame showing cross members 10
Figure 9 Strain field in a section of the composite panel supported on the edges by frame 11
Figure 10 Image of the composite samples for experimentation 11
Figure 11 Two of the fabricated samples with strain gages adhered 12
Figure 12 Thermal strain plot of each composite sample at three temperatures 13
Figure 13 CTE comparison of resins 15
Figure 14 CTE comparison of composite samples 15
Figure 15 Tensile test specimen in load frame 16
Figure 16 Stress strain plot for sample 1 16
Figure 17 3-point bending test specimen 17
Figure 18 Load-crosshead plot of sample 1 17
Figure 19 Vacuum crane sitting on a composite roof panel 18
Figure 20 Drawing of drip rail cross-section 24
Figure 21 Close up image of drip rail 25

List of Tables

TABLE I PROPERTIES OF COMMONLY USED COMPOSITE RESINGS 6
TABLE II COMPARISON OF VARIOUS FIBERGLASS FABRICS AVAILABLE 8
TABLE III EXPECTED COEFFICIENT OF THERMAL EXPANSION FOR EACH COMPOSITE SAMPLE 12
TABLE IV EXPERIMENTALLY DETERMINED CTE FOR EACH COMPOSITE SAMPLE 14
TABLE V TENSILE MODULUS AND TENSILE STRENGTH OF EACH COMPOSITE SAMPLE 16
TABLE VI FLEXURAL MODULUS AND FLEXURAL STRENGTH OF EACH COMPOSITE SAMPLE 17
TABLE VII WEIGHT OF CURRENT AND PROPOSED ROOF PANELS 19
TABLE VIII PROPERTIES OF VARIOUS ADHESIVES AND THEIR OPERATING TEMPERATURE 23
TABLE IX SUMMARY OF COSTS ASSOCIATED WITH MODIFICATION TO THE COMPOSITE 26

1 ABSTRACT

This report specifies a design that will resolve the leaking roof problem that New Flyer has been experiencing on their 40-foot transit bus model. The problem was found to result from large deformation of the fiberglass roof panel when it was subjected to thermal cycling. The proposed composite design incorporates the use of a vinyl ester matrix with a two-ply 1808 e-glass fiber cloth. The expected coefficient of thermal expansion of this composite is 8-12 μm/m°C. The model used to predict this coefficient of thermal expansion of the composite was verified using a two-ply 1808 polyester resin composite and the currently employed fiber and resin configuration. Along with these changes to the composite composition, the use of Sika booster for all three beads of Sika polyurethane adhesives was suggested. This report shows that not only do these modifications resolve the issue of a leaking roof, but also yield a more rigid roof by increasing the flexural strength and elastic modulus of the composite by nearly 150%. It is also recommended within this report to incorporate composite drip rails within the roof shell, as this will lead to cost savings and decreased labour time. There is no substantial change from the current budget in overall manufacturing or assembly costs for the proposed solution, which falls well within the budget allotted by New Flyer.

2 INTRODUCTION

New Flyer Industries is one of North America's leaders in the manufacture of heavy-duty buses. New Flyer's low floor transit buses are widely used to transport thousands of passengers daily by numerous bus transit companies across Canada and United States.

This project involves the redesign of New Flyer's 40-foot bus roof in order to resolve a current failure mechanism, the shearing of the adhesive used to join the two composite roof panels. In order to increase customer satisfaction and decrease required maintenance, it is pertinent that New Flyer resolves this failure mechanism.

In their 40-foot low floor transit bus, New Flyer currently utilizes a fiberglass composite as the material for their roof shells. These two fiberglass panels are joined together with an adhesive filled lap joint to isolate the cabin of the bus from the external environment. New Flyer has been experiencing difficulties with the joint failing in their roof, which they suspect is resulting from fatigue induced by cyclic loading caused by thermal expansion of the roof panels. This fatigue has lead to the wear and eventual separation of the roof panels and subsequently, moisture leakage within the bus cabin.

The main objective of this project is to design a 40-foot bus roof that does not allow moisture to leak inside the cabin. The incorporation of drip rails into the design is the secondary objective that must be incorporated into the design in order to further streamline the manufacturing process as it will eliminate the current time requirement necessary to install extruded aluminum drip rails. New Flyer requires that these objectives be met while not significantly increasing the following criteria:

- Strength — the design must be able to support 300 lbs
- Implementation — the manufacturing / installation process be compatible with the current process
- Size — the design must conform to the current frame and space constraints
- Time — the design must not significantly increase the current installation time of 4 hours [1]
- Light Weight — the design must not be heavier than it is currently
- Cost — the design must not cost more than $355 000 for implementation and parts

Appendix A contains a detailed a description of the design concept generation process and the ideas considered along with the screening process used to determine design which ideas were worth pursuing.

3 DETAILS OF THE DESIGN

The features of the proposed design are illustrated below in Figure 1. The first feature involves changing the current roof composite from two plies of 2 oz. chopped strand fiberglass matt and a single ply of 10 oz. 0-90 fiberglass cloth bonded with a polyester resin, to two plies of 1808 fiberglass cloth bonded with a vinyl ester resin. The second feature involves changing the adhesive that is applied to the lap joint in the roof panel from one row of boosted Sika 252 sandwiched between two rows of Sika 252, to three rows of boosted Sika 252 adhesive. The final design feature involves integrating the drip rails (drip rails are required to transport moisture from the roof of the bus to the rear of the bus) into the composite layup process, which will remove the requirement for installing the currently used aluminum drip rails in a secondary assembly process.

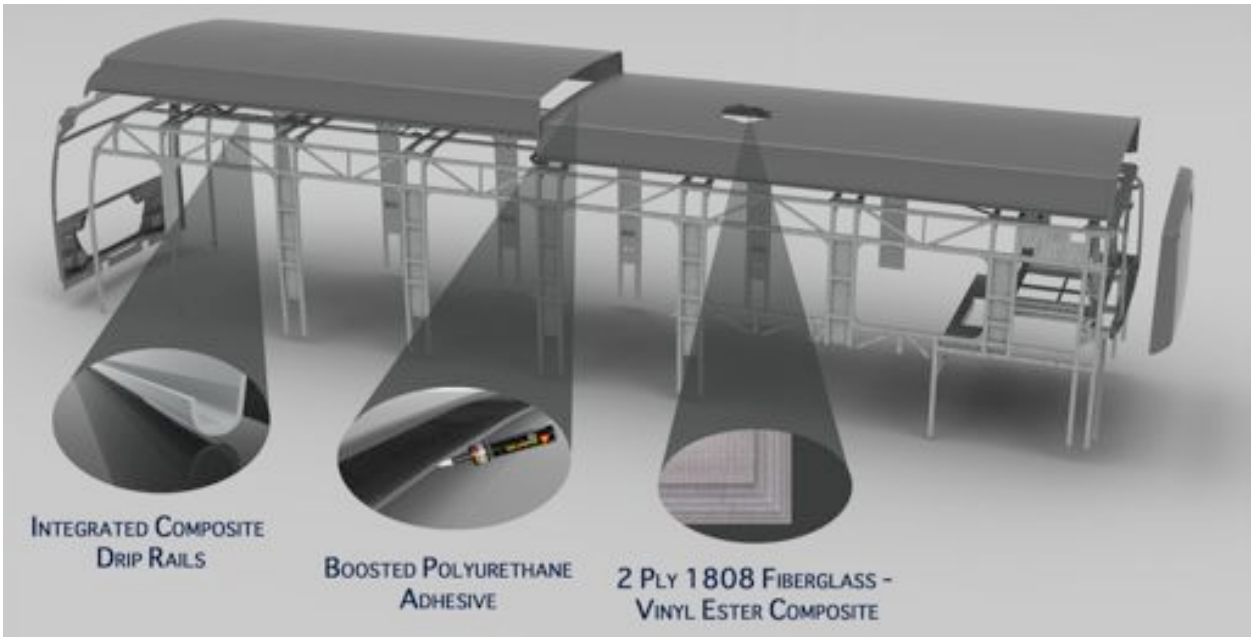


Figure 1 Illustration of proposed design features

3.1 COMPOSITE DESIGN

Since the primary cause of the roof failure is a variance between the coefficient of thermal expansion (CTE) of the composite roof and the steel frame, it was necessary to find a method of minimizing the difference. The currently used composite has a CTE of roughly 32 μm/m°C while steel has a CTE of roughly 12 μm/m°C [2] making the effective CTE between the frame and composite panel 20 μm/m°C. The required temperature range to which the bus is subjected is approximately -40 °C to 40 °C. Since the composite is thermally unstrained at approximately 25 °C, a 20 ft roof panel (as currently manufactured) that is bonded to the steel frame and cooled to -40 °C will deform a little less than 8mm more than the steel frame. Between the two 20 ft roof panels, this leads to a net change in length of approximately 16mm. This deformation becomes even greater as the frame of the bus increases in temperature due to heating of the cabin; the net length change will reach almost 20mm.

In order to develop a design that will remedy the issue of the failing roof joint, the analytical model used to predict composite properties will be verified followed by an analytical composite design and finally experimental verification of the predicted properties of the proposed design.

The analytical model that is used to predict composite properties is the rule of mixtures. An overview of the equations used in the model along with a verification of its prediction of the known coefficient of thermal expansion of the currently used composite can be found in Appendix B. It is determined that this model accurately predicts the coefficient of thermal expansion of the composite based on volume fraction of the fiber and resin in the composite.

3.1.1 DESIGN CONSIDERATIONS

As shown in the rule of mixtures equations, found in Appendix B, in order to minimize the coefficient of thermal expansion of the composite, it is necessary to do one or more of the following:

- Increase the volume fraction of fiber in the composite
- Decrease the coefficient of thermal expansion of the matrix

In order to increase the volume fraction of the fiber, the matrix volume fraction must necessarily decreases. It is important to note that if the fiber volume fraction becomes too high, there will be insufficient matrix to ensure all fibers receive sufficient contact with the matrix; this will lead to unpredictable properties in the composite since the material is not thoroughly bonded.

Since polyester resins essentially have the same coefficient of thermal expansion, further exploration must be done into alternative resins that can be used to form the matrix of the composite.

3.1.1.1 RESIN CONSIDERATIONS

Generally, resins are divided at two main groups: thermosets and thermoplastics. Thermoset resins change permanently from liquid to solid form by use of a catalyst or heat and cannot be re-melted. Thermoplastic resins become solid below a certain temperature. However, they can be reheated in order to facilitate re-forming and then cooled again. Consideration will only be given to thermoset resins, however, since the composite panels must be resistant to the elevated temperatures provided by both powder coating ovens and the environment. Some common resins that fall into these categories are polyester resin, epoxy resin, vinyl ester resin. Working with and handling resins is hazardous due to the presence of volatile organic compounds (VOCs), which, under prolonged exposure can lead to adverse health effects. The following is a discussion about the mechanical advantages and disadvantages to a number of commonly available resins along with a discussion of their health considerations.

Polyester resin is the most commonly used thermoset resin due to its easily manipulated cure time, ease of tooling, and inexpensive price. Additionally, there are very few hazards associated with working in an environment with polyester resin, so long as sufficient ventilation is present to remove the heavy odour and VOCs. Some of the drawbacks to this resin include its tendency to shrink during cure and its large coefficient of thermal expansion. Polyester resin also has a lower lamination strength than some other types of resins. It is not recommended to use polyester resin with some fibers, such as carbon or Kevlar. Working with polyester resin requires personal protective equipment including safety goggles, resistance glove, and respirators. Polyester resins are commonly available for approximately 25-40 USD per gallon [3].

Epoxy resin is another commonly used thermoset resin. Laminates made with epoxy have a greater strength and better chemical resistance then those produced with polyester resin making it advantageous for use in applications where chemicals may come in contact with the composite. One of the downsides to using epoxy resin is that it is challenging to work with during the mixing process. Epoxy resins require a greater curing time than polyester resins and both the epoxy and the hardener are very hazardous to the health of the worker. Employees are required to wear protective splash goggles or safety glasses and resistant gloves. There are fewer VOCs emitted from epoxy resins than from polyester resin, hence air respirators are not needed if appropriate air ventilation is available. An additional consideration with epoxy resin is that it is considerably more expensive than polyester resin. Epoxy resins usually cost in the range of 65-100 USD per gallon [3] [4].

Vinyl ester resin combines the benefits of epoxy resin with better handling and curing, which are characteristic of polyester resins. Vinyl ester provides excellent mechanical toughness and corrosion

resistance. Vinyl ester is widely used in the production of composite materials when mechanical properties are an important factor, since it is better than polyester resin in virtually every way. Working with vinyl ester provides the same health concerns as polyester resin; eye protection, gloves, and respirators must be worn. The cost of vinyl ester resin is 40-60 USD per gallon, which is slightly more expensive than polyester resin [3] [5]. However, it is considerably cheaper than epoxy resin costing.

TABLE I PROPERTIES OF COMMONLY USED COMPOSITE RESINGS

Resin	**CTE** $(\frac{\mu m}{m℃})$	**Elastic Modulus** (GPa)	**Density** $\left(\frac{g}{m^3}\right)$	**Viscosity**
Polyester	90-123	3.68-4.3	1.1-1.4	low
Epoxy	15-100	2.56-3.72	1.1-2.0	Medium-high
Vinyl Ester	16-22	2.9-3.4	1.01-1.25	low

TABLE I displays some of the properties associated with polyester, epoxy, and vinyl ester resins. There is a range of values displayed for each property since they vary depending on the catalyst used to harden the resin. The primary property of interest to this project is the coefficient of thermal expansion [6]. Since vinyl ester resin has a lower coefficient of thermal expansion than polyester resin and a more consistent coefficient of thermal expansion than epoxy resin, coupled with the fact that it is considerably cheaper than epoxy resin, it will be considered the best choice for this design.

3.1.1.2 FIBER CONSIDERATIONS

There are a number of commonly available fibers that are used in fabricating composite parts, the most common of which are carbon, Kevlar and glass fibers. Each fiber has different properties, which make it advantageous in certain applications. Due to the cost of each fiber type, as can be seen in Figure 2, glass will be the only type explored in this project [3].

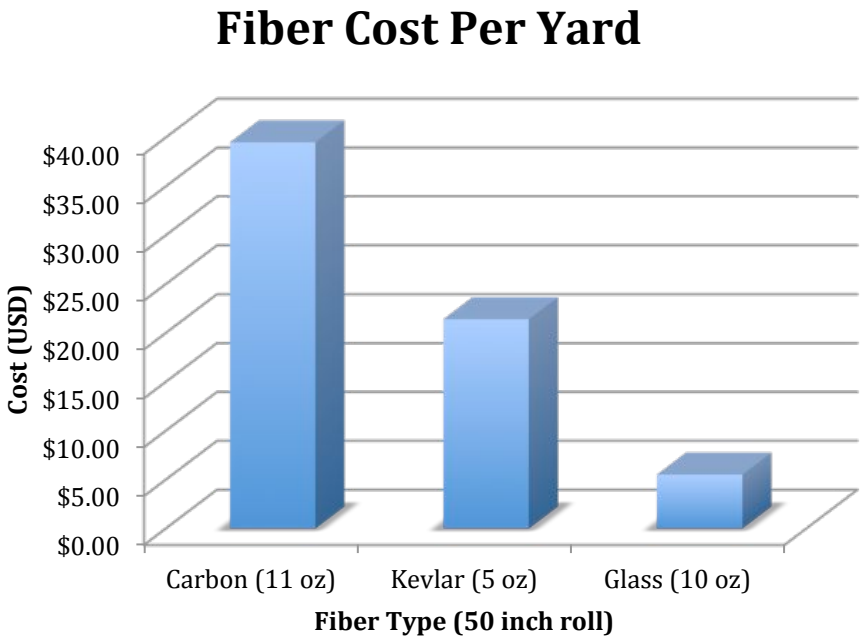


Figure 2 Cost comparison of carbon, Kevlar and glass fibers

Glass fiber is available primarily in two different forms, biaxial weave and randomly oriented chopped strand. Each of these fiber orientations, when combined with a resin matrix, forms a composite material with unique properties. Since the properties of the composite are dependent on the direction of the fiber, it follows that a biaxial weave cloth would lead to greater reinforcement in two primary directions than the randomly oriented reinforcement of the chopped strand matt. In addition to the reinforcement that is directionally provided by the fibers, so also is the minimization of the coefficient of thermal expansion; that is since the coefficient of thermal expansion is much smaller in the fiber than it is in the resin matrix, the composite will expand less in the direction of the fiber. It is therefore advantageous to increase the amount of biaxial weave cloth that is used in the composite and decreases the amount of chopped strand matt.

There are many different weights and types of matts and cloths available that are made of glass fibers. Biaxial and woven clothes range in weights from 3 – 40 oz.'s per square yard and chopped strand matts that range from ¾ - 2 oz.'s per square foot. In order to achieve increased directional properties, while not increasing the number of layers of fiber cloth or matt required, a heavier biaxial cloth should be chosen. Currently, the roof panel thickness is 0.15" according to the roof panel specifications, which can be found in Appendix C. In order to achieve this thickness, the current layup contains 46 oz. fiber per square yard.

TABLE II shows the configurations of available cloth and matt that would yield approximately 46 oz. fiber per square yard and consequently a similar thickness.

TABLE II COMPARISON OF VARIOUS FIBERGLASS FABRICS AVAILABLE

Combination	Total weight per square yard	Plies	Approximate cost per yard (50" wide, USD)
3x10 oz. cloth + 1x2 oz. matt	48 oz.	4	$22.45
2x18 oz. cloth + 1x1.5 oz. matt	49.5 oz.	3	$19.90
1x40 oz. cloth + 1x1.5 oz. matt	53.5 oz.	2	$21.50
2x1808 biaxial cloth	49.5 oz.	2	$12.30
1x10 oz. cloth + 2x2 oz. matt (current)	46 oz.	3	$13.65

It is apparent from TABLE II that creating the composite from two plies of 1808 biaxial cloth is not only the cheapest option, but it also requires fewer plies than the current composite which should reduce manufacturing time. 1808 is a special cloth that incorporates an 18 oz. biaxial cloth bonded to a ¾ oz. chopped strand matt. 1808 is therefore an ideal fiber fabric to use in this application as it provides very good directional properties while maintaining a high fiber density within the fabric. In order to illustrate the fiber difference between the different types of fiber, Figure 3, Figure 4 and Figure 5 are shown. Figure 3 shows the 2 oz. chopped strand matt, Figure 4 shows the 10 oz. 0-90 weave cloth and Figure 5 shows 1808 biaxial fabric.



Figure 3 2 oz. chopped strand matt

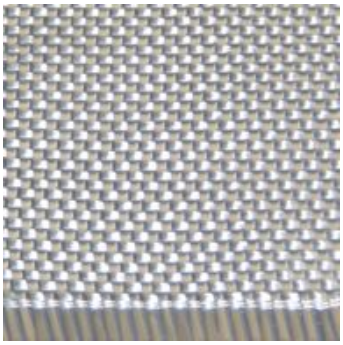


Figure 4 10 oz. 0-90 weave cloth

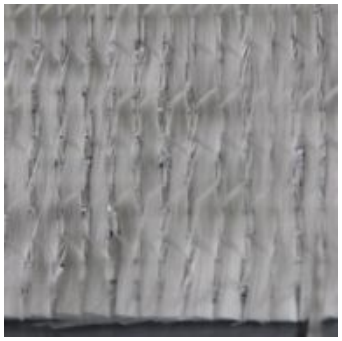


Figure 5 1808 biaxial fabric

3.1.2 Bending Strength Considerations

Since the fiber is responsible for reinforcing the polymer matrix within the composite, it follows that the 1808 will have varying properties throughout the cross-section since the fiber orientations vary in a single matt. This it not an overly important consideration with respect to the coefficient of thermal expansion, however, the roof panel is also required to support approximately 300 lbs. as per the design requirements. It is therefore important to look at the equation that governs the stress in a material subject to bending [7].

Bending Stress $$\sigma = \frac{M \cdot y}{I}$$ **Equation 1**

From Equation 1, where M is the applied moment, y is the distance from the neutral axis, and I is the inertia of the composite, it is determined that the greater the distance from the neutral axis, the greater the stress will be. With this in mind, it is determined that the ideal layup technique would be two ply 1808 with the ¾ oz. chopped strand side of the fabric sandwiched in the middle of the composite. This layup technique will lead to uniform bending strength for both a positive and negative moment. This symmetric property will lead to a composite material with a greater bending stiffness than the current layup, which is asymmetric in fiber composition. The order of fiber layers for both the current layup and the proposed two-ply 1808 layup are illustrated in Figure 6 and Figure 7.

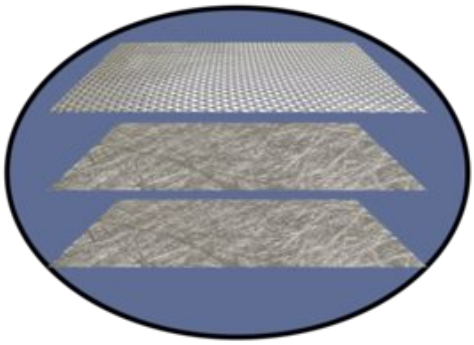


Figure 6 Exploded view of current layup layers

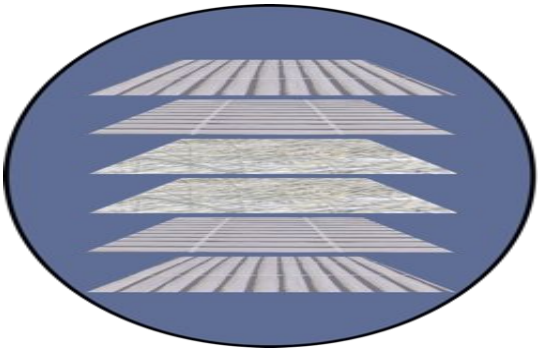


Figure 7 Exploded view of layers in a two ply 1808

In order to determine the importance of fiber orientation, Figure 8 below shows the top view of the frame of New Flyer's 40-foot bus. As can be seen from this figure, the steel frame supports the composite panels very well. As a consequence of this large amount of support, bending moments are minimal. In order to determine the largest bending moment, one of the unsupported squares between the frame members will be examined.

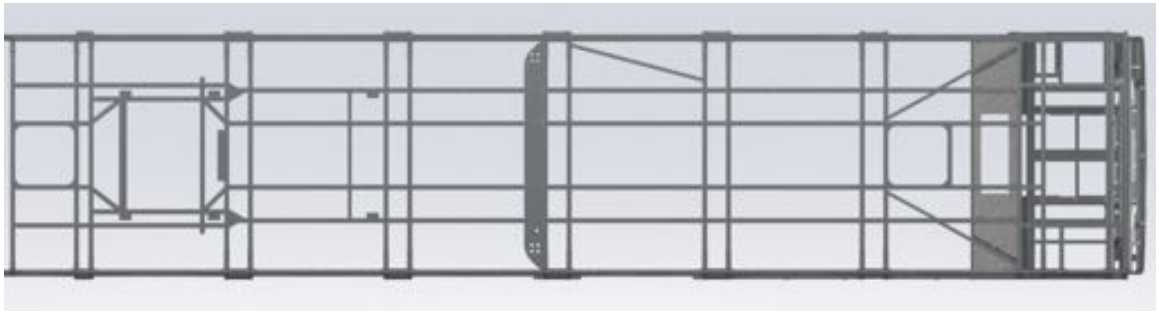


Figure 8 Top view of the 40-foot bus frame showing cross members

Figure 9 shows the strain field that results from a point mass of 300 lbs. being applied in the center of the largest section of the unsupported panel. In order to achieve optimal bending strength, which will minimize the stress that results from the strain field, it is necessary to ensure that the outermost fiber bundles in both the upper and lower fabric are oriented along the width of the bus since this is the direction that is subject to the greatest loading.

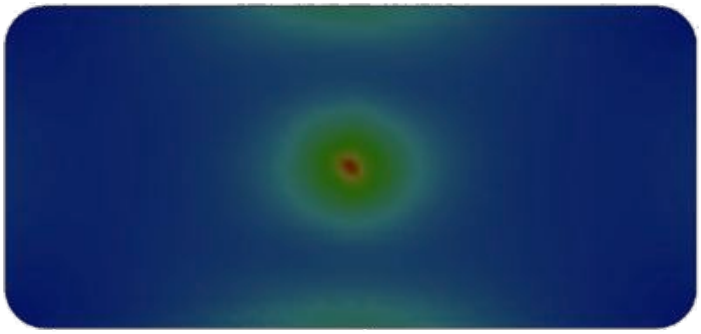


Figure 9 Strain field in a section of the composite panel supported on the edges by frame

3.1.3 Experimental Verification of Predicted Properties

In order to determine an achievable volume fraction, and consequently the true properties of the proposed composite, it is necessary to create some samples. Since vinyl ester resin is not available in small quantities, preliminary experimentation only facilitated composite fabrication using polyester resin. Figure 10 shows the created fiberglass composite samples. The three on the right are two-ply 1808, while the three on the left are samples that were created identically to the current lay up (single ply 10 oz. 0-90 cloth and two ply 2 oz. chopped strand matt). The expected coefficient of thermal expansion of these samples was calculated using the rule of mixtures. In order to verify the predicted coefficient of thermal expansion, the samples were exposed to various thermal atmospheres and their thermal expansion rates recorded. In addition to experimentally verifying the coefficient of thermal expansion, tensile and bending tests will be performed in order to ensure that the proposed design fulfills the required strength criteria.

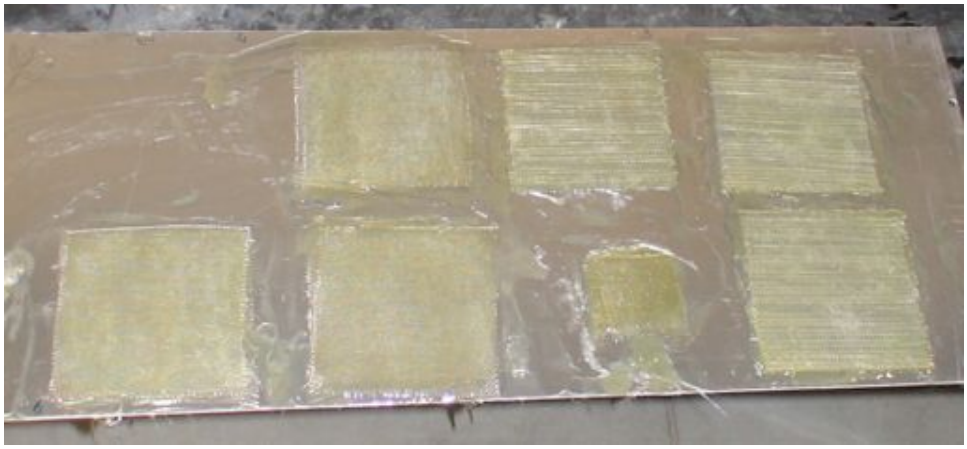


Figure 10 Image of the composite samples for experimentation

3.1.3.1 COEFFICIENT OF THERMAL EXPANSION

Using the rule of mixtures equations found in Appendix A, the expected coefficient of thermal expansion for each sample was calculated and listed below in TABLE III. The masses of each sample's fiber and overall weight can be found in Appendix D.

TABLE III EXPECTED COEFFICIENT OF THERMAL EXPANSION FOR EACH COMPOSITE SAMPLE

Sample	Expected CTE ($\mu m/m \cdot ℃$)
2 Ply 1808 – 1	21.6
2 Ply 1808 – 2	19.3
2 Ply 1808 – 3	19.9
Current Layup – 1	23.9
Current Layup – 2	24.8
Current Layup – 3	26.3

In order to verify the coefficient of thermal expansion of each sample, they will be monitored with strain gages and subjected to various temperatures. Figure 11 shows a close up of the samples with strain gages mounted in the direction of the continuous fibers.

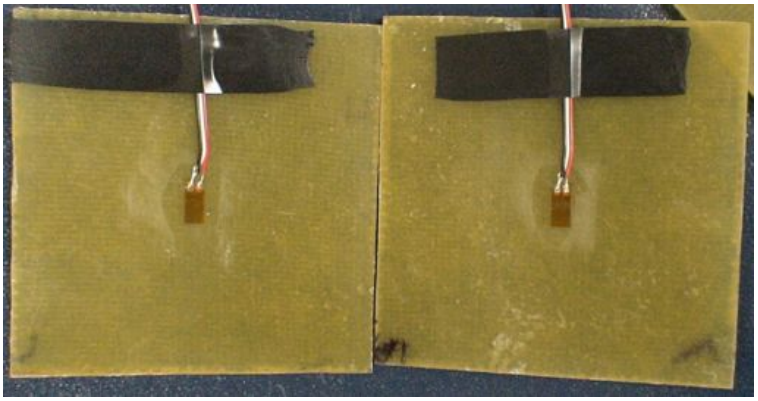


Figure 11 Two of the fabricated samples with strain gages adhered

The samples will be subjected to three different temperatures in order to determine the coefficient of thermal expansion. The three available temperatures that will be used are 24C, -2C, and -14C. These temperatures are achieved using ambient temperature, a refrigerator and a freezer, respectively.

In order to use strain gages for the calculation of the coefficient of thermal expansion, corrections must be made because not only does the subject material demonstrate thermal strain, the strain gage material

does also. In order to calculate the thermal output of the strain gage, Vishay gives a fourth order polynomial, Equation 2, which can be used to calculate the thermal output of the strain gage at any given temperature [8].

$$\varepsilon_{T/O/g} = -67.5 + 4.47T - 0.088T^2 + (4.32E-4)T^3 - (5.34E-7)T^4 \qquad \textbf{Equation 2}$$

Figure 12 shows the thermal strain on each sample once the thermal output correction has been performed on the data. The slope of each of the curves represents the coefficient of thermal expansion of each of the samples.

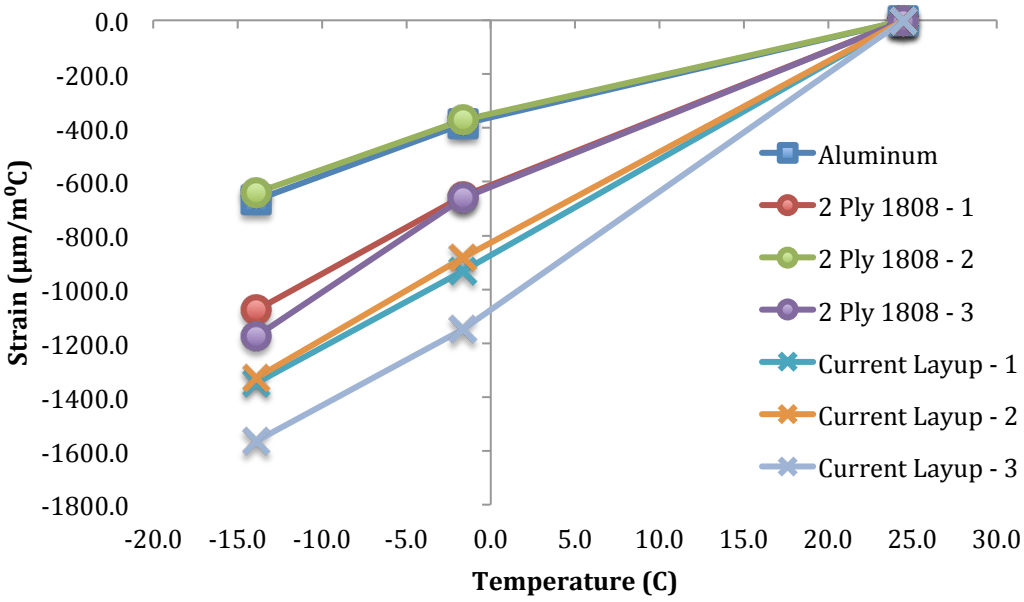


Figure 12 Thermal strain plot of each composite sample at three temperatures

The experimentally determined coefficient of thermal expansion for each sample is shown in TABLE IV below. These are found by averaging the slope of each temperature range from the above plot.

TABLE IV EXPERIMENTALLY DETERMINED CTE FOR EACH COMPOSITE SAMPLE

Sample	Experimental CTE	Average Experimental CTE	Expected CTE
2 Ply 1808 – 1	26.5	27	20
2 Ply 1808 – 2	15.4		
2 Ply 1808 – 3	27.9		
Current Layup – 1	35.4	35	25
Current Layup – 2	34.1		
Current Layup – 3	42.3		

Looking at TABLE IV, it is apparent that sample 2 of the two-ply 1808 composite and sample 3 of the current composite are inconsistent with the other samples two samples of each composite type. When these values are discarded from the results and the average of the two samples are compared, the difference in the coefficient of thermal expansion between the two composites is significant. Although the rule of mixtures model did not exactly predict the coefficient of thermal expansion of the composite, it did predict that the two-ply 1808 would have a coefficient of thermal expansion less than that of the current layup, which is in keeping with the experimental results. This therefore verifies that the rule of mixtures can be used to predict the coefficient of thermal expansion to a sufficiently accurate degree. This means that, according to the rule of mixtures model, the proposed two-ply 1808 vinyl ester composite will have a coefficient of thermal expansion of roughly 8-12 μm/m°C, which effectively removes any relative expansion between the two materials. Figure 13 illustrates the difference in coefficient of thermal expansion between vinyl ester resin and polyester resin. It is assumed that the two-ply 1808 vinyl ester composite will achieve the same volume fraction of fiber and resin as the two-ply 1808 polyester resin composite that was tested. Therefore, the expected decrease in coefficient of thermal expansion of the two-ply 1808 composite when fabricated with vinyl ester resin is illustrated in Figure 14 along with the experimental and theoretical results of the current lay-up and the two-ply 1808 with polyester resin.

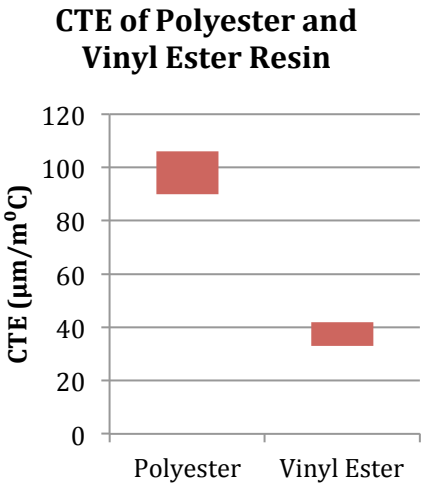


Figure 13 CTE comparison of resins

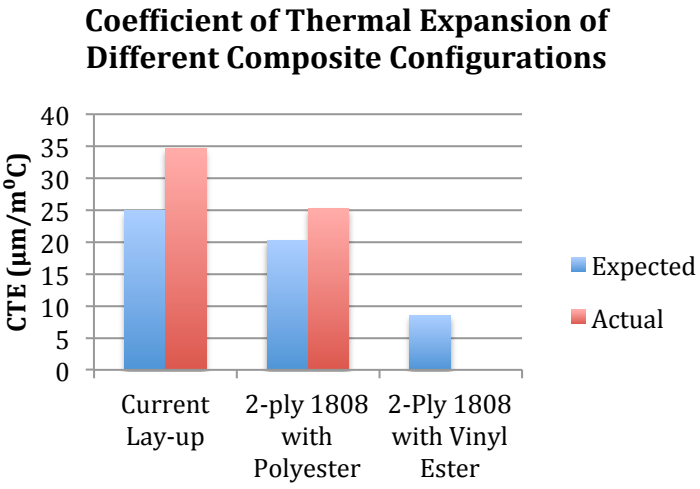


Figure 14 CTE comparison of composite samples

3.1.4 Determination of Elastic Modulus

One of the design requirements is to ensure that the composite roof panel is capable of supporting approximately 300 lbs. In order to verify that this design requirement is met, an experiment was performed to determine the modulus of elasticity and the flexural modulus of the composite. The apparatus used in this experimentation is shown in Appendix D.

The purpose of performing both tensile and bending tests is to compare the bending stiffness from the tensile test with the bending stiffness from the 3-point bending test. In a perfectly isotropic material with no stress concentrations, the elastic modulus' that are found from the tensile and bending test are expected to be the same. However, since the current composite layup is asymmetric, as discussed in section 3.1.2, it is expected that the flexural modulus will be less than the tensile modulus. It is expected that since the 2 ply 1808 is a symmetric layup, it should have roughly the same modulus under flexural loading and tensile loading. Equation 3 and Equation 4 will be used to calculate the tensile elastic modulus and the flexural elastic modulus [7].

Tensile Modulus $$E_t = \frac{P}{A \cdot \varepsilon_t}$$ **Equation 3**

Flexural Modulus $$E_b = \frac{P \cdot L^3}{48I \cdot d}$$ **Equation 4**

3.1.4.1 TENSILE MODULUS

The tensile test was performed on three specimens of both the current composite samples and the two-ply 1808 samples. The cross section of each sample is recorded before testing in order to calculate the stress in each sample. Figure 15 shows the test configuration of one of the samples. Notice an extensometer is used in order to determine the deformation of the sample.



Figure 15 Tensile test specimen in load frame

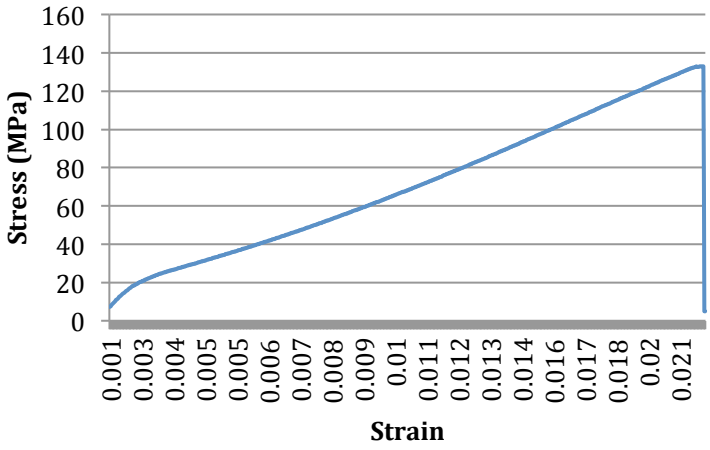


Figure 16 Stress strain plot for sample 1

The stress strain plot of sample 1, which is a two-ply 1808 sample, can be seen in Figure 16. Stress-strain plots for each sample can be found in Appendix D. The linear section of the stress-stain plot is calculated using Equation 3 in order to determine the tensile modulus of elasticity. The modulus for each sample, their tensile strength and the average of each value can be found in TABLE V. Although the elastic modulus is on average lower for the two-ply 1808, the tensile strength is greater.

TABLE V TENSILE MODULUS AND TENSILE STRENGTH OF EACH COMPOSITE SAMPLE

Sample	Tensile Elastic Modulus (GPa)		Tensile Strength (MPa)	
2 Ply 1808 – 1	6.83	Average 6.6	13	Average 16.6
2 Ply 1808 – 2	6.51		15.2	
2 Ply 1808 – 3	6.43		21.7	
Current Layup – 1	7.01	Average 7.04	12.6	Average 12.2
Current Layup – 2	7.09		11.5	
Current Layup – 3	7.01		12.5	

3.1.4.2 BENDING MODULUS

The bending test is performed on three specimens of both composites, just as in the tensile test. The cross section is recorded before the test in order to determine the inertia of each sample. Figure 17, below, shows the test configuration for the 3-point bending test.



Figure 17 3-point bending test specimen

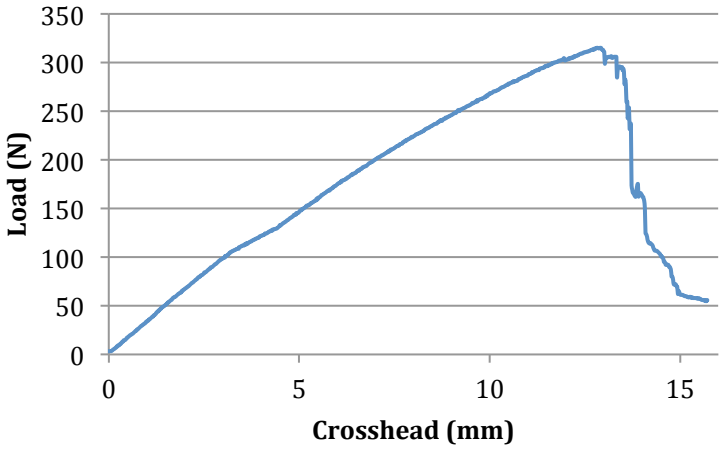


Figure 18 Load-crosshead plot of sample 1

Figure 18 is a load-crosshead plot, again of sample 1. Load-crosshead plots of each sample can be found in Appendix D. Equation 4 is used along with the load-crosshead plot to calculate the flexural elastic modulus. The modulus for each sample, their flexural strength, and the average of each value are listed in TABLE VI. It is found from this test that not only is the flexural strength of the two-ply 1808 greater, but so also is the flexural modulus. This means that a roof panel made from two-ply 1808 is capable of carrying a larger load and will deform less than the currently used composite roof panels.

TABLE VI FLEXURAL MODULUS AND FLEXURAL STRENGTH OF EACH COMPOSITE SAMPLE

Sample	Flexural Elastic Modulus (GPa)		Flexural Strength (MPa)	
2 Ply 1808 – 1	7	Average 8.9	223	Average 265
2 Ply 1808 – 2	10.6		311	
2 Ply 1808 – 3	9		262	
Current Layup – 1	6.3	Average 6.6	162	Average 191
Current Layup – 2	8		241	
Current Layup – 3	5.4		169	

3.1.5 WEIGHT ANALYSIS

The overall weight of any vehicle is of concern throughout the design process since every extra kilogram of weight requires additional energy to propel; if the vehicle is lighter, it will use less fuel to propel itself. On a tall vehicle, such as a bus, however, this is not the only concern. It is also important to keep the centre of gravity of the bus closer to the ground in order to provide better stability. In addition to the dynamic concerns of increasing the weight of the roof, weight is also a concern during the manufacturing and assembly of the bus. Currently New Flyer uses a vacuum crane to move the roof shells from where they are delivered onto the bus frame. An image of the vacuum crane can be seen in Figure 19. If the weight of these panels increases too much, higher capacity cranes will be needed which means an increase in costs. Therefore the total weight increase/decrease of the proposed solution is calculated.



Figure 19 Vacuum crane sitting on a composite roof panel

One of the design constrains required by New Flyer was that the weight of the proposed design not be greater than the current composite panel. Currently the composite roof panels have an average weight of 153 kg [1]. Since the proposed design requires slightly less resin than the current composite design and the density of vinyl ester resin is slightly lower than that of polyester, the expected weight of the two-ply 1808 with vinyl ester resin composite is lower than the currently used composite. Appendix D contains calculations of the expected weight of the composite roof panel. From these calculations it is found that the weight of the proposed two-ply 1808 composite will likely be slightly lower than the weight of the current composite. The results of these calculations are listed below in TABLE VII.

TABLE VII WEIGHT OF CURRENT AND PROPOSED ROOF PANELS

	Current Composite	2x1808 Vinyl Ester
Weight	153.72 kg	148.26 kg

3.1.6 SUMMARY

It has been determined both using the rule of mixtures and experimentally that the increased directional fiber content of a two-ply 1808 fabric over the current composite fabric decreases the coefficient of thermal expansion of the composite. Additionally, it has been determine experimentally that the flexural modulus and flexural strength of a two-ply 1808 composite with polyester resin is almost 140% greater than the flexural modulus and flexural strength of the currently used composite. In order to ensure that this decrease in coefficient of thermal expansion and increase in flexural modulus and strength are achieved, it is necessary to lay up the composite with the 1808 in a back-to-back orientation. When the proposed vinyl ester resin is used as the composite matrix, the coefficient of thermal expansion is expected to decrease to approximately 8-12 μm/m°C according to the rule of mixtures model and extrapolation of experimental data. In addition, both the flexural modulus and flexural strength will increase to over 150% of the currently used panel when vinyl ester resin is used with two-ply 1808 to fabricate the composite panels. Finally, the weight of the two-ply 1808 composite will be slightly less than that of the currently used composite roof panels. Since there are no modifications required to the moulds in order to use this fiber and resin, there are no additional tools required to manufacture this part.

3.2 Joint Adhesive Considerations

Altering the adhesive used in the joint was considered as a potential solution for the design problem. The adhesive holding the two roof panels together is subjected to mechanical stress and joint failure occurs where the adhesive is used. This warranted investigation into alternate adhesives that could be used.

Adhesives exist in a wide variety of types that differ in curing mechanism, strength, composition and method of application. In order to evaluate the adhesive most suitable for application in the assembly of roof panels, a number of criteria were established to weigh alternatives against. Firstly, the adhesive must be adequately strong in order to withstand any loading or strain the joint may be subjected to. To determine the strength of the adhesive, the currently used glue manufactured by Sika was selected as a baseline, any selected alternative must possess equivalent or better properties in lap shear strength and perform adequately across a wide temperature range. Since the currently used Sika adhesive has a lap shear strength of approximately 2 MPa over a temperature range of at least -40 to 90°C, this will be taken as acceptable [9]. This is the lap shear strength of the currently used adhesive when fully cured and a temperature range to accommodate extremely cold temperature climates as well as the elevated temperatures the adhesive will be exposed to during paint bake cycles. Secondly, the adhesive must have an appropriate curing mechanism such that a sufficient degree of strength has developed in the adhesive before the roof panel is subjected to any significant loading. Thirdly, while the curing mechanism must ensure strength is developed quickly in the adhesive, sufficient time for installation and assembly should be included within the adhesive cure time. These primary criteria ensure the adhesive is adequate for use and consideration as an alternative for New Flyer. In addition to these considerations, shelf life of the adhesive should be comparable to the currently employed adhesive. Changes to the adhesive should not hurt the current cycle time, and changes should be economical for New Flyer. These secondary criteria address ease of implementation for New Flyer. Based on consideration of strength, cure time and shelf life, several potential adhesives were selected for consideration.

The type of curing mechanism directly influences the curing time for the adhesive. In New Flyer's case, curing time is an important consideration since the adhesive must cure fast enough to develop a sufficient degree of material strength before loading, yet slow enough to accommodate for the working time required to install the roof panels.

The adhesive that is currently employed at New Flyer is a humidity cure adhesive. This curing mechanism indicates that the curing process is catalyzed by moisture in the air. While this curing mechanism does not require any additional additives or manufacturing steps, it is disadvantageous in that cure time is

typically well over a day. This implies that the adhesive will not develop its full properties until days after application. With New Flyer's current production time of approximately 40 busses per week, this is not ideal.

Adequate material strength is the key consideration, as joint failure is the main design problem. Any alternatives considered must possess sufficient material strength to ensure the roof joint does not fail.

3.2.1 Cure Mechanisms

There are a variety of adhesives available that use a variety of curing mechanisms to achieve their final strength. Of the variety of curing mechanisms that exist, heat cure and 2-part activator adhesives were considered as alternative curing mechanisms, along with humidity curing. Since the currently used adhesive is a humidity cure, it is possible that the adhesive does not build a sufficient degree of strength during the manufacturing process. This may induce unnecessary stress on the roof joint, leading to its eventual failure. Altering the curing mechanism may address this potential issue. Adhesives with the above types of curing mechanisms are the most common and easily found types of adhesives employed in industry.

Heat cure adhesives require the application of heat at a prescribed time and temperature. As part of the current manufacturing process, New Flyer exposes their buses to heat during the painting process. As this is already part of the bus manufacturing process, heat cure adhesives were evaluated as a potential alternative. Adhesives from Permabond were considered due to their availability [10].

According to the information from Permabond, while the available heat cure adhesives possess adequate lap shear strength, the cure mechanism requires a minimum of 20 minutes curing at 150°C to develop its material properties. New Flyer currently puts its busses through bake cycles varying from three cycles for half an hour each to a single full hour bake cycle at temperatures approximately 60°C [11]. It was thought that since the bus is being heated to cure the powder coat paint, this heat could also be used to cure an adhesive. Although adhesives of this category meet the strength criteria, no recommendation can be made for this adhesive type in this application because the required cure heat and time are inconvenient to achieve and could possibly be damaging to other parts of the bus.

Two-part activator adhesives are slightly more inconvenient that heat cure and humidity cure adhesives because they require mixing of the adhesive and catalyst prior to application. The accelerated chemical reaction that occurs as a result of mixing a catalyst with the adhesive is what facilitates this type of adhesive developing the desired strength within a short amount of time. Two-part adhesives from Plexus [12] and Permabond [13] were considered for use due to their availability.

Product data sheets from Plexus and Permabond demonstrate the suitability of two-part adhesives for both the desired strength and operational temperature range. The use of an activator also ensures that the mechanical properties of the adhesive develop quickly; this curing mechanism allows a full cure to be achieved within minutes for some adhesives and 3-4 hours for longer cures. For application to the roof joint on New Flyer's busses, the longer cures are more appropriate, as this allows sufficient working and installation time. In terms of strength and curing speed, two-part adhesives are ideal for this application; however, additional considerations regarding the manufacturing process lessen the suitability of this type of adhesive. Firstly, the use of the activator catalyst causes an exothermic reaction in the adhesive with peak exotherms reaching approximately 100°C. This high temperature is undesirable since workers must still be able to interact with the bus and roof panels even during the curing time without being burned. Secondly, mixing of the adhesive must be performed prior to application. This requirement adds an additional step during assembly, which increases production time and required labour. Thirdly, the relatively short working and curing time for the adhesive limit flexibility in the manufacturing process since any time delay between application of the adhesive and installation of the roof may lead to undesired hardening of the adhesive. Finally, switching to a two-part adhesive would require new tools such as mixers and require retraining of employees. These considerations minimize the suitability of this type of adhesive, therefore, changing to a two-part adhesive is not recommended.

Humidity curing is the curing mechanism used by the current adhesive provided by Sika. These adhesives develop their mechanical properties through exposure to atmospheric humidity. This mechanism allows minimal attention to the curing process and requires no special processes such as mixing or baking however, the time required to achieve a full cure is substantially longer. To overcome the long curing time, an additional activator compound, Sika Booster, is introduced in order to accelerate the cure time to approximately 24 hours. Additionally, a 1 MPa lap shear strength is developed within 5 hours [14].

As currently designed, three beads of glue are applied to the roof joint and one of the three beads, situated in the middle, is mixed with booster. As the operating temperature and strength for the currently employed glue is acceptable, no change to the type of glue is necessary, consequently, there is no modification to the application tools that New Flyer currently possess. It is however recommended that the use of booster for all glue within the roof joint be considered. This is recommended because the use of booster will ensure that the mechanical properties of the adhesive within the roof joint are fully developed during the manufacturing process. This will minimize unintentional damage to the adhesive layer during assembly [15].

3.2.2 SUMMARY

Upon observation of the manufacturing and installation process of the roof panels to the frame of the bus, it was concluded that cracking in the joint was not caused by a lack of adhesive; the prescribed installation process of the roof panels left excess glue at the roof joint that had to be removed. It was also determined based on the adhesive property sheets that the adhesive currently employed by New Flyer provided sufficient strength over an adequate temperature range. Therefore, to best solve this problem, it is recommended that no change to the current adhesive be made, as alternative curing mechanisms are not appropriate for this application. The use of additional booster within the roof joint is recommended, as it will allow the adhesive to cure much faster and minimize unnecessary stress during the manufacturing process.

Reducing the stress seen at the joint would lessen the frequency of roof joint failure and can be accomplished as discussed in the proposed redesign. Since the currently employed adhesive is sufficiently strong, as demonstrated by busses that fail to exhibit roof failure, it is believed that though adhesive selection may affect the strength and likelihood of failure of the roof joint, this effect is secondary to the effects of stress induced by thermal expansion and contraction of the roof panels. As summarized in TABLE VIII below, alternatives to the currently employed Sika adhesive perform exceptionally well; however, these mechanical properties are unnecessarily high for this application and do not justify the costs required to accommodate changing the adhesive from what is currently being used.

TABLE VIII PROPERTIES OF VARIOUS ADHESIVES AND THEIR OPERATING TEMPERATURE

Type	Curing Mechanism	Cure Time for typical glue bead	Lap Shear Strength	Operational Temperature Range
Sika	Humidity	7+ days	≈2.5MPa	-40°C to 90°C
Sika w/ Booster	Humidity w/ activator	24h	≈2.5MPa	-40°C to 90°C
Plexus	2-Part	3-4h	≈9+MPa	-55°C to 120°C
Permabond	2-Part	3-4h	≈18+MPa	-40°C to 50°C
Permabond	Heat Cure	20-45min in oven	≈20+MPa	-40°C to 150°C

3.3 INTEGRATED COMPOSITE DRIP RAILS

The proposed roof design incorporates drip rails within the composite shell. Figure 20 shows a drawing of the cross-section of the proposed drip rail.

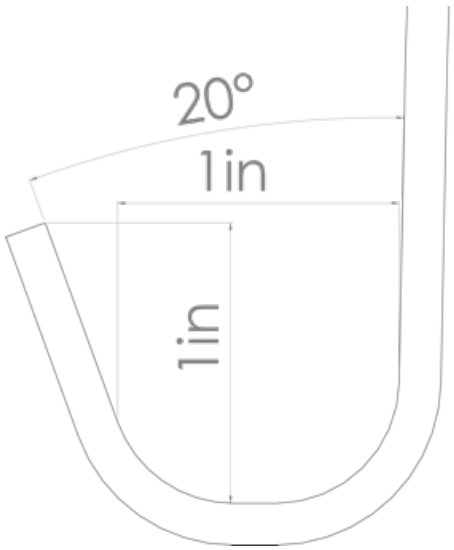


Figure 20 Drawing of drip rail cross-section

The incorporation of the drip rails into the composite shell will not only save New Flyer roughly 30-45 minutes per roof installation, but also remove the material cost of the currently used extruded aluminum drip rails [1]. The cross-section of the proposed drip rails is 1 inch wide by 1 inch tall. This large cross section will facilitate a sizeable water transportation capacity from the sides of the bus to the rear of the bus. In addition to the large cross-section, a 20-degree draft angle is incorporated into the design in order to facilitate easy removal of the drip rail section of the roof from the mould that will be used to fabricate the part; if no draft angle is incorporated in the design, removal of the part from the mould is not possible. Large radius fillets are also used at the bottom of the drip rail to ensure that consistent composite properties are attained; resin rich or resin lean regions are minimized as they lead to unpredictable mechanical properties and a poor surface finish. Figure 21 below shows a close-up of the integrated composite drip rail.

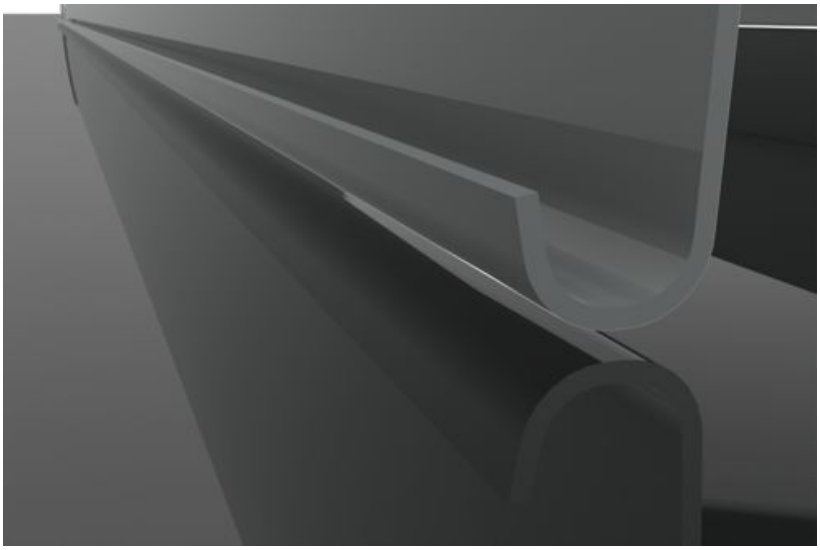


Figure 21 Close up image of drip rail

3.4 Overall Cost

It has been determined that by changing the composite and adding booster to the joint adhesive will resolve the problem of the leaking roof. It is now important to ensure that the proposed solution is feasible in term of cost. Since New Flyers' rule of thumb is that a new design does not get implemented unless it pays itself off within a year, this will also be the metric used in this analysis. Therefore, since the total cost of warranty work related to the leak in the roof of the bus is $355 000 per year, this figure will be used to determine the feasibility of the proposed design. As shown in the calculations in Appendix E, the total allowable cost per bus is $ 168.27. Assumptions and estimations made for the analysis can also be found in detail in Appendix E. A summary of the cost expenditures for the proposed composite can be found below in TABLE IX.

TABLE IX SUMMARY OF COSTS ASSOCIATED WITH MODIFICATION TO THE COMPOSITE

	Current Cost	**2x1808 Vinyl Ester**	**2x1808 Polyester**
Fibre	$425.88	$383.76	$383.76
Resin	$708.00	$823.20	$687.61
Labour	$600.00	$540.00	$540.00
Sika Booster	$ 0	$ 17.06	$ 17.06
Total	$2469.63	$2499.78	$2364.19
	Cost Increase	$30.15	-$105.44

Once the suggested solution is fully implemented, the total benefit to New Flyers will be $138.12 per bus. This is calculated based on the assumption that no warranty work will be required once the proposed design is implemented; the increased cost of $30.15 is subtracted from the warranty budget of $168.27 per bus. When this figure is spread out over a year, a cost savings of almost $290 000 is expected.

Since the incorporation of drip rails is a secondary objective which has a budget unrelated to the $355 000 per year in warranty work, the cost analysis of this feature is performed separately. In order to incorporate the drip rails into the composite, the moulds must be modified. It is assumed that once these modifications to the mould are complete, there is minimal additional labour attributed to laying up the composite in the mould. Therefore, the total savings of eliminating the secondary drip rail installation process, including labour and material, is around $600 000 per year. A detailed analysis of these costs can be found in Appendix E.

4 CONCLUSIONS

In order to solve the failure of the joint in New Flyer's 40-foot transit bus a redesign of the roof was necessary. The proposed redesign includes modifying the composite roof panel so that it is made from two-plies of 1808 fiberglass cloth and vinyl ester resin, adding booster to all three rows of the Sika adhesive that is currently used in the lap joint of the roof and incorporating drip rails into the composite layup of the roof. Firstly, modification of the composite from the current two plies of 2 oz. chopped strand matt and single ply 10 oz. cloth with polyester resin to two plies of 1808 fiberglass cloth with vinyl ester resin will decrease the coefficient of thermal expansion from around 30-34 μm/m°C to 8-12 μm/m°C. The new composite coefficient of thermal expansion roughly matches the coefficient of thermal expansion of the steel frame, which leads to a relative coefficient of thermal expansion of roughly zero. Consequently, the shearing forces between the two roof panels that are experienced with the current composite roof are removed. In addition, the proposed symmetric layup of the two-ply 1808 fiber will increase the flexural modulus and flexural strength by roughly 150% each, ensureing that the roof can support large walking loads. Secondly, by adding booster to all three rows of adhesive used to seal the lap joint the durability of the joint will increase and ensure that sufficient strength is achieved in the joint before any loads are applied to the roof. Finally, the incorporation of drip rails in the composite will reduce time during the assembly of the bus and remove the cost of aluminum drip rails, the adhesive required to bond them to the bus and the labour required to install them. These three design modifications to the roof of the bus will not only eliminate the joint failure in the roof, but also streamline the New Flyer's manufacturing process while not requiring any new tooling. The weight of the proposed design will be approximately 148 kg's, which is 5 kg's lighter than the currently used composite roof panels. In addition to resolving the cause of failure in the roof and streamlining the manufacturing process, the modification to the composite and adhesive is expected to save New Flyer $290 000 per year as a result of mitigating warranty work. The incorporation of drip rails into the composite is expected to save New Flyer around $355 000 per year on aluminum drip rails and the adhesive required to bond them to the bus. Therefore, the total savings expected from the proposed design is roughly $600 000 per year.

WORKS CITED

[1] J. Galang. (2010, September 30). *"Re: U of M Project."* Personal E-mail.

[2] Matweb. (2010, October). *AISI 1020 Steel, Cold Rolled* [Online]. Available: http://www.matweb.com [Oct 21, 2010].

[3] US Composites. (2010, November). *US Composites* [Online]. Available: http://www.uscomposites.com [Nov 13, 2010].

[4] West Systems. (2010, November). *105 Epoxy Resin* [Online]. Available: http://www.westsystem.com/ [Nov 21, 2010].

[5] Ashland. (2009, November). *Derakane 411-350 Epoxy Vinyl Ester Resin* [Online]. Available: http://www.derakane.com/derakaneControllerAction.do?method=goToProductDetailPage&actionForwardName=derakane411350&productCode=536001 [Nov 23, 2010].

[6] The Engineering Toolbox. (2010, November). *Coefficient of Linear Expansion* [Online]. Available: http://www.engineeringtoolbox.com/linear-expansion-coefficients-d_95.html [Sept 30, 2010].

[8] Vishay Precision Group. (2010, Sept. 15). "*Strain Gage Thermal Output and Gage Factor Variation with Temperature*" [Online]. Available: http://www.vishaypg.com/micro-measurements/stress-analysis-strain-gages/technotes-list/tn504.pdf [Nov 20, 2010].

[7] F Beer, J Johnston, and J DeWolf, *Mechanics of Materials*, 4th ed. New York, New York: McGraw Hill, 2006.

[9] Sika Canada Inc. (2007). *"Sikaflex-221"* [Online]. Available: http://www.sika.ca/ind-tds-sikaflex-221.pdf [Nov. 21, 2010].

[10] Permabond. (2008). *Single-Part Epoxies* [Online]. Available: http://www.permabond.com/en/en-epoxy-selector-single.htm [Nov. 21, 2010].

[11] Jeff Yarecki. (2010, November 26). "Re: U of M Bus Shell Project." Personal E-mail.

[12] Plexus. (2010). *Structural Adhesives* [Online]. Available: http://www.itwplexus.com/products/selector.cfm [Nov. 21, 2010].

[13] Permabond. (2008). *Two-Part Adhesives* [Online]. Available: http://www.permabond.com/en/en-epoxy-selector.htm [Nov. 21, 2010].

[14] Sika Canada Inc. (2007). *"Sikaflex-254 Booster"* [Online]. Available: http://www.sika.ca/ind-tds-sikaflex-254booster.pdf [Nov. 19, 2010].

[15] New Flyer Industries, *SPEC-ROOF PANEL*, New Flyer Industries, Winnipeg, MB, Drawing Number 096280, 2001.

[16] SubsTech. (2010, November). *Estimations of Composite Materials Properties* [Online]. Available: http://www.substech.com/dokuwiki/doku.php?id=estimations_of_composite_materials_properties [Nov 16, 2010].

[17] Jeff Yarecki. (2010, September 24). "*Re: UofM Bus shell project*." Personal e-mail.

APPENDIX A

1 CONCEPT GENERATION AND ANALYSIS

In order to arrive at an optimal design solution, brainstorming sessions were performed, where a large number of ideas are generated with as many different design concepts as possible. It has been determined that the most productive means of producing ideas is to create a large list of as many design ideas as possible followed by rigorous screening process. The use of TRIZ, however, was employed as a secondary concept generator and will be discussed in the following section.

The rigorous screening that occurs after brainstorming is a process where ideas that do not fulfil all of the design criteria are removed from the list so that grading can proceed with viable concepts. Following the preliminary screening, concepts are graded against the target specifications as presented by New Flyer in order to establish which concepts will be most desirable. Additionally, a concept integration study will be performed in order to determine if a design solution can be achieved that yields better results through the implementation of multiple concepts together.

1.1 PRELIMINARY IDEAS

The goal of the brainstorming session is to generate as many ideas as possible without much concern for their fulfillment of the design specifications. In order to ensure that as many ideas were generated as possible, TRIZ was consulted as an idea stimulator. The results of both the brainstorming session and the TRIZ search are listed below.

1.1.1 TRIZ RESULTS

In order to assist in the brainstorming session, TRIZ was consulted to act as a guide. It was determined that many of the outcomes of the TRIZ matrix were too vague to be of much use on this project. There were a couple of applicable concepts that were produced through TRIZ, however, and they are listed in TABLE X below along with their corresponding search criteria. These design ideas will be considered in the subsequent brainstorming process.

TABLE X TRIZ RESULTS

Feature to improve	Worsening feature	Idea
Reliability	Weight of moving object	Make each part of an object fulfill a different and useful function
Strength	Reliability due to joint fatigue	Prepare emergency means beforehand to compensate for the relatively low reliability of an object
Ease of repair	Reliability due to joint fatigue	Perform, before it is needed, the required change of an object (either fully or partially)

1.1.2 BRAINSTORMING RESULTS

Brainstorming was initiated by the creation of general mechanisms that were determined would yield a removal a moisture transmittal through the lap joint of the roof panels. This list is shown below. TRIZ was used as a stimulus in generating this list.

- Change the geometry of fibre glass
- Change the manufacturing process
- Accommodate for the movement in the roof panels that will result from thermal strain
- Alter thermal expansion in order to match that of the bus frame
- Use an alternative material for the roof panel

Following the generation of a general list of mechanisms, the following list of ideas was generated primarily through the use engineering education and experience. These concepts are all determined to be methods of minimizing or removing moisture leakage through the roof of New Flyer's 40-foot transit bus. In order to facilitate simplified analysis, each of the above ideas is given a number, as demonstrated in TABLE XI below.

TABLE XI NUMBERED IDEAS GENERATED THROUGH BRAINSTORMING

Idea	Idea Number
Alter joint geometry	1
Use single panel	2
Alternative adhesive in joint	3
Thicker layer of adhesive in joint	4
Bolt down the roof so that it is better restrained	5
Accordion joint between panels	6
Add one or more joints	7
Alternate fibre	8
Alternative fibre orientation in composite	9
Alternative resin in composite	10
Change volume fraction of fibre in the composite	11
Laminate ribs in the composite to decrease expansion and contraction	14
Injection moulded plastic	12
Stamped sheet metal	13
Fabric roof	15

In an effort to simplify the weighted analysis of these design ideas, a preliminary screening process the will be used to determine which ideas will be capable of complying with the required design specification. This process is described in the next section.

1.2 PRELIMINARY SCREENING

Screening criteria are directly based on the design target specifications as provided by New Flyer. The primary design goal, removal of the roof leak, is not included, as it was already determined that all of the design ideas accomplish this in one form or another. The screening criteria are as follows:

- Strength — the design must be able to support 300 lbs
- Implementation — the manufacturing / installation process be compatible with the current process
- Size — the design must conform to the current frame and space constraints
- Time — the design must not significantly increase the current installation time of 4 hours [1]
- Light Weight — the design must not be heavier than it is currently
- Cost — the design must not cost more than $355 000 for implementation and parts

Figure 22, the following matrix, is evaluated using a positive (+), negative (-) or zero (0) where a + indicates that the design idea will fulfil all design criteria, a – indicates the design idea not fulfil all design criteria, and a 0 indicates the design idea is not applicable to the design criteria. Only design ideas that were given a greater number of +'s than –'s pass the preliminary screening. Out of 15 ideas, only 7 of them were selected to proceed to the next step, concept analysis, where they were rated through a weighted comparison.

	Idea Number														
Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Strength	0	0	0	0	0	0	0	0	0	0	0	+	-	+	-
Implementation	0	-	0	0	-	0	-	0	0	0	0	-	0	-	-
Size	0	-	0	0	0	0	+	0	0	0	0	0	0	0	0
Time	0	+	0	0	-	0	-	0	0	0	0	0	0	-	0
Light Weight	0	0	0	0	0	0	0	0	0	0	0	0	0	-	0
Cost	+	-	+	+	+	+	-	-	+	+	+	-	-	-	+
Pluses	1	1	1	1	1	1	1	0	1	1	1	1	0	1	1
Sames	5	2	5	5	3	5	2	5	5	5	5	3	4	1	3
Minuses	0	3	0	0	2	0	3	1	0	0	0	2	2	4	2
Net	1	-2	1	1	-1	1	-2	-1	1	1	1	-1	-2	-3	-1
Rank	1	3	1	1	2	1	3	2	1	1	1	2	3	4	2
Continue	Y	N	Y	Y	N	Y	N	N	Y	Y	Y	N	N	N	N

Figure 22 Preliminary screening matrix

1.3 RATING IDEAS

In order to rate each design idea, the following scoring matrix, Figure 23 was created. This matrix assists in determining which ideas are the most suitable design solutions. Scores are allocated between 0 and 5, where 0 is a poor score and 5 is the maximum expected positive change compared to the current design. A score of 3 indicates no substantial change when compared to the current design.

It is now necessary to include the primary design objective, leak prevention in the roof, in the scoring criteria and assign a grade based on the assumed effectiveness of the design idea in this category.

In order to determine the importance of each idea's compliance with the design criteria, weights are assigned to each design criteria. As the main purpose of this design is to stop the leaking of the roof while staying within the budget, leak prevention and cost effectiveness criteria are weighted more heavily than others. Cost is a very rigidly defined constraint which has no allowance for any sort of trade off among other parameters considered; New Flyer will not adopt a new design which does not provide economical benefits, including comparable performance at a lower cost, or better performance at a comparable cost. New Flyer has determined that a design, which does not pay for itself within a year is not worth adopting. This rigidity makes cost a higher priority within the scoring matrix compared to the rest. NJC consulting

determined the assigned weights according to the priorities presented by New Flyer; that is, cost and weight are of high importance while the remaining criteria are of equal priority.

	Design Idea															
SCORING	Weight	1		3		4		6		9		10		11		
Leak Prevention	30 %	3	.9	2	.6	1.5	.45	4	1.2	2.5	.75	2.5	.75	2.5	.75	
Strength	10 %	3	.3	2	.2	2	.2	3	.3	3	.3	3	.3	3	.3	
Implementation	10 %	3.5	.35	4	.4	4	.4	2.5	.25	3	.3	3	.3	3	.3	
Time	15 %	3	.45	3	.45	3	.45	2.5	.38	3	.45	3	.45	3	.45	
Light Weight	10 %	3	.3	3	.3	2.5	.25	3	.3	3	.3	3	.3	3	.3	
Cost	25 %	3.5	.88	4	1.0	4	1.0	4	1.0	4.5	1.1	4	1.0	3	.75	
Total	100 %	3.18		2.95		2.75		3.43		3.2		3.1		2.85		

Figure 23 Weighted rating matrix

As seen in Figure 23, ideas 1, 6 and 9 have been evaluated as the 3 leading concepts as they are most reflective of the design objective and target specifications. Upon inspection of the highly ranked design concepts, it has been determined that some of the ideas could possibly be combined in order to develop the best concept. The following section discusses the possibility of integration and fusion of the various concepts.

1.4 Concept Integration and Fusion

The ability to integrate the ranked design concepts was done by determining the compatibility of each design concept with one another. The following matrix, Figure 24, was created in order to determine the perceived effectiveness of the combined concepts. Scoring will be performed using a negative (-), zero (0), or positive (+). A negative indicates the concepts are incompatible, a zero indicates the concepts are compatible, that is they can be implemented together without impacting the other, but no foreseeable gain through concept fusion and a positive indicates the design would benefit from fusion of the concepts.

		Idea Number						
		1	**3**	**4**	**6**	**9**	**10**	**11**
Idea Number	***1***		+	+	-	+	+	+
	3			0	-	+	+	+
	4				-	+	+	+
	6					+	+	+
	9						+	+
	10							+
	11							

Figure 24 Concept fusion matrix

As determined by the above matrix, almost all of the proposed design concepts are compatible with each other and would yield a superior design if implemented in parallel. With the exception of idea 6, the accordion joint, which is not compatible with many of the other design concepts, all concepts were deemed worthy of pursuit.

Since ideas 9, 10, and 11 are interrelated and were determined to directly address the root cause of failure in the roof panel, the expansion and contraction of the composite, they were determined to be the primary design concepts to develop. It was determined upon further consideration of idea 4, using a thicker layer of adhesive in the joint, that geometrically it was not possible to add additional adhesive. Therefore, idea 4 was not implemented. Idea 1, the alteration of the joint geometry, was found to have little added benefit and act more as a cover-up design than an solution to the cause of the joint failure so it was not considered in the final design. Idea 3, the use of alternative adhesive in the joint was explored and found to have much merit to assisting in resolving the failure of the roof joint.

In summary, the ideas that passed the screening criteria and were, upon further research, found to be most effective in resolving the joint failure of the roof are modification of the fiber and resin in the composite panels and the use of an alternative adhesive.

APPENDIX B

List of Variables

α_m	CTE of matrix
α_f	CTE of fiber
α_{cl}	Longitudinal CTE of composite
α_{ct}	Transverse CTE of composite
α_S	CTE sample
ε_t	Tensile strain on sample
$\varepsilon_{T/O/g}$	Thermal output strain of strain gage
ρ_c	Density of composite
ρ_f	Density of fiber
ρ_m	Density of matrix
A	Cross sectional area of sample
d	Deformation at center of beam
E_b	Flexural elastic modulus
E_t	Tensile elastic modulus
I	Inertia of sample
L	Distance between beam supports
m_c	Mass of composite
m_f	Mass of fiber
m_m	Mass of matrix
$\mathbf{M}_f$	Mass fraction fiber
$\mathbf{M}_m$	Mass fraction matrix
P	Applied load
V_f	Volume fraction fiber
V_m	Volume fraction matrix

1 VERIFICATION OF CURRENT COMPOSITE'S CTE

In order to minimize the thermal expansion and contraction of the composite roof panel that New Flyer currently uses on their bus, it is necessary to understand the equations that govern the properties of composites. The fiberglass panels that New Flyer uses for the roof of their 40-foot buses are manufactured by Carlson Composites and are composed of E-Glass fibers and a polyester resin. The properties of both the fiber and the resin are listed in TABLE XII below.

TABLE XII E-GLASS FIBER AND POLYESTER RESIN MECHANICAL PROPERTIES

	$\alpha\ (\mu/°C)$	$E\ (GPa)$	$\rho\ (^{g}/_{cm^3})$
E-Glass	5.4	72.4	2.6
Polyester Resin	120	3.6	1.45

New Flyer requires that the thermal expansion of the fiberglass roof be minimized while maintaining a flexural strength similar to the current design. The only properties that are known about the composite panel that is currently used by New Flyer are the coefficient of thermal expansion, which is approximately $32\ \mu m/m \cdot °C$, as determined by the Composite Innovation Center (CIC), and the layup specifications. In order quantify whether a proposed design will comply with the requirements of New Flyer, a set of equations called the rule of mixtures will be employed for developing a preliminary model of the composite material.

1.1 RULE OF MIXTURES MODEL

The generally accepted method of performing a preliminary composite analysis is using the rule of mixtures. The rule of mixtures predicts that the properties of the composite are dictated by the volume fraction of each component in the composite. These equations will be used to do the preliminary analysis of the composite in order to better understand how to achieve a minimized coefficient of thermal expansion while maintaining strength in the panel.

1.2 VOLUME FRACTION

The first step in using the rule of mixtures is to determine the volume fraction of both the fiber and of the matrix. The volume fraction can be thought of as the percent of the composite that is taken up by either the fiber or the matrix based on volume. Since no properties are known of the current composite panels, it is necessary to start the analysis of the composite by determining the volume fraction of both the fiber

and the resin the composite. This process starts by weighing samples of the current composite and gathering the weights of each of the different fiber matts that were used in the lay-up. A plot of the sample weights is listed below in Figure 25.

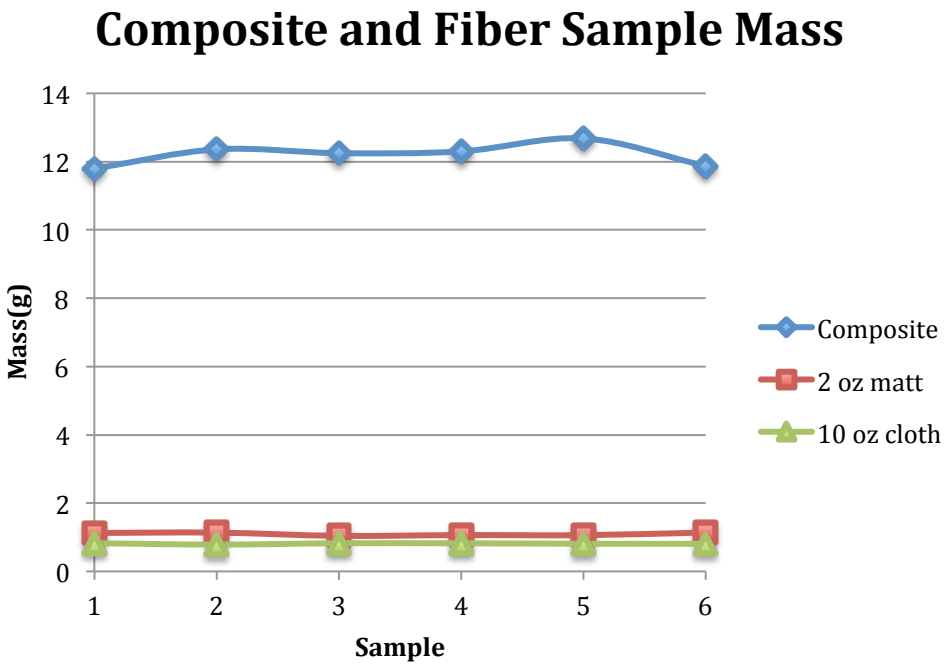


Figure 25 Composite and fiber sample masses

The average masses from the above plot are listed below in TABLE XIII. These masses will be used in subsequent calculations of the properties of the currently used composite. The size of sample that was used for this process was 5 cm by 5 cm.

TABLE XIII AVERAGE MASS OF COMPOSITE SAMPLES AND THEIR FIBER

Component	Average Mass (g)
Composite	12.21
2 oz. matt	1.09
10 oz. cloth	0.81

New Flyer's roof panel specifications, which can be found in Appendix C, show that the lay-up process includes two plies 2 oz. matt and one ply 10 oz. cloth. When the mass of the fibers matts is added together and subtracted from the total mass of the composite, it is found that the mass of resin in the composite is

9.21 g. The mass fraction and volume fraction are calculated using Equation 6 and Equation 7. However, the density of the composite must first be calculated using Equation 5 in order to use Equation 6 [16].

Composite Density $$\rho_c = \frac{1}{[\text{M}_f/\rho_f + \text{M}_m/\rho_m]}$$ **Equation 5**

Mass Fraction Fiber $$\text{M}_f = \frac{m_f}{m_c}$$ **Equation 6**

Volume Fraction Fiber $$V_f = \frac{m_f/\rho_f}{m_c/\rho_c}$$ **Equation 7**

Mass Fraction Fiber $$\text{M}_f = \frac{m_f}{m_c} = \frac{2.99}{12.21} = 0.245$$

Mass Fraction Matrix $$\text{M}_m = \frac{m_m}{m_c} = \frac{(12.21 - 2.99)}{12.21} = 0.755$$

Composite Density $$\rho_c = \frac{1}{[\text{M}_f/\rho_f + \text{M}_m/\rho_m]} = \frac{1}{[0.245/2.6 + 0.755/1.45]} = 1.63 \ {}^{g}/_{cm^3}$$

Volume Fraction Fiber $$V_f = \frac{m_f/\rho_f}{m_c/\rho_c} = \frac{2.99/2.6}{12.21/1.63} = 0.15$$

Volume Fraction Matrix $$V_m = \frac{m_m/\rho_m}{m_c/\rho_c} = \frac{9.22/1.45}{12.21/1.63} = 0.85$$

Based on the above calculations, the volume fraction of the currently used composite is listed below in TABLE XIV.

TABLE XIV VOLUME FRACTION OF COMPOSITE CURRENTLY MANUFACTURED BY CARLSON

Component	Volume Fraction
Fiber	0.15
Matrix	0.85

1.2.1.1 COEFFICIENT OF THERMAL EXPANSION

The primary material property that is of interest in this project is the coefficient of thermal expansion. Equation 8 is used to predict the coefficient of thermal expansion of the composite.

Composite CTE $$\alpha_{cl} = \frac{(\alpha_m \cdot E_m \cdot V_m + \alpha_f \cdot E_f \cdot V_f)}{(E_m \cdot V_m + E_f \cdot V_f)}$$ **Equation 8**

The mechanical properties given in TABLE XII along with volume fractions given in TABLE XIV were substituted into the above equations to predict the coefficient of thermal expansion and the resulting predicted coefficient of thermal expansion was $31\,\mu m/m \cdot ℃$. The expected coefficient of thermal expansion, as experimentally determined by Composites Innovation Center (CIC), is $32\,\mu m/m \cdot ℃$ [17], so it can be concluded that the rule of mixtures model predicts the coefficient of thermal expansion quite well.

APPENDIX C


NOTE: FOR INSTALLATION DRAWINGS PLEASE REFER TO ATTACHED MRP BOM SHEET FOR PARTS LISTING
SYM
REVISION
ECO
*
REVISED NOTE TO READ TO BE CONTRACT SPECIFIC FROM TO PROPERTIES COLOR SPECIFICATION.
NOTES:
1. GELCOAT FINISH (20 MILS) TO BE CONTRACT SPECIFIC.
2. THICKNESS: .15 ±0.03
RESIN H-834
LAY UP: 2 LAYERS OF 2 OUNCE MAT
1 LAYER OF 10 OUNCE CLOTH
3. GELCOAT FINISH (20 MILS)
THIS DRAWING AND ITS SUBJECT MATTER ARE DISCLOSED IN CONFIDENCE, MUST BE RE-TURNED UPON REQUEST AND SHALL NOT BE DISCLOSED TO OTHERS WITHOUT WRITTEN CONSENT OF NEW FLYER INDUSTRIES LIMITED
NOTICE: THIS DRAWING IS A FACSIMILE OF THE ELECTRONIC MASTER. ALL REVISIONS MUST BE INCORPORATED ELECTRONICALLY. MANUAL REVISION IS NOT ALLOWED.
MATERIAL
WEIGHT
TREATMENT
NONE
UNSPEC'D TOLS.
DEC. IN.
METRIC
.X
.XX
.XXX
HOLE DIA.
BEND RADII.
ANGLE TOL.
TUBE BENDS & LENGTH
HOSES 0 TO 20 LG.
HOSES 20 LG. PLUS
BY
NAME
DD-MMM-YY
DRAWN
M.D.
21-SEP-01
CHK'D
APP'D
DO NOT SCALE DIMENSIONS IN ( ) ARE IN M.M.
THD ANGLE
TITLE
SPEC-ROOF PANEL
PART Nº
096280
SCALE 1 : 1
B
SHEET 1 OF 1
REPORT ALL ERRORS TO ENG. DEPT.

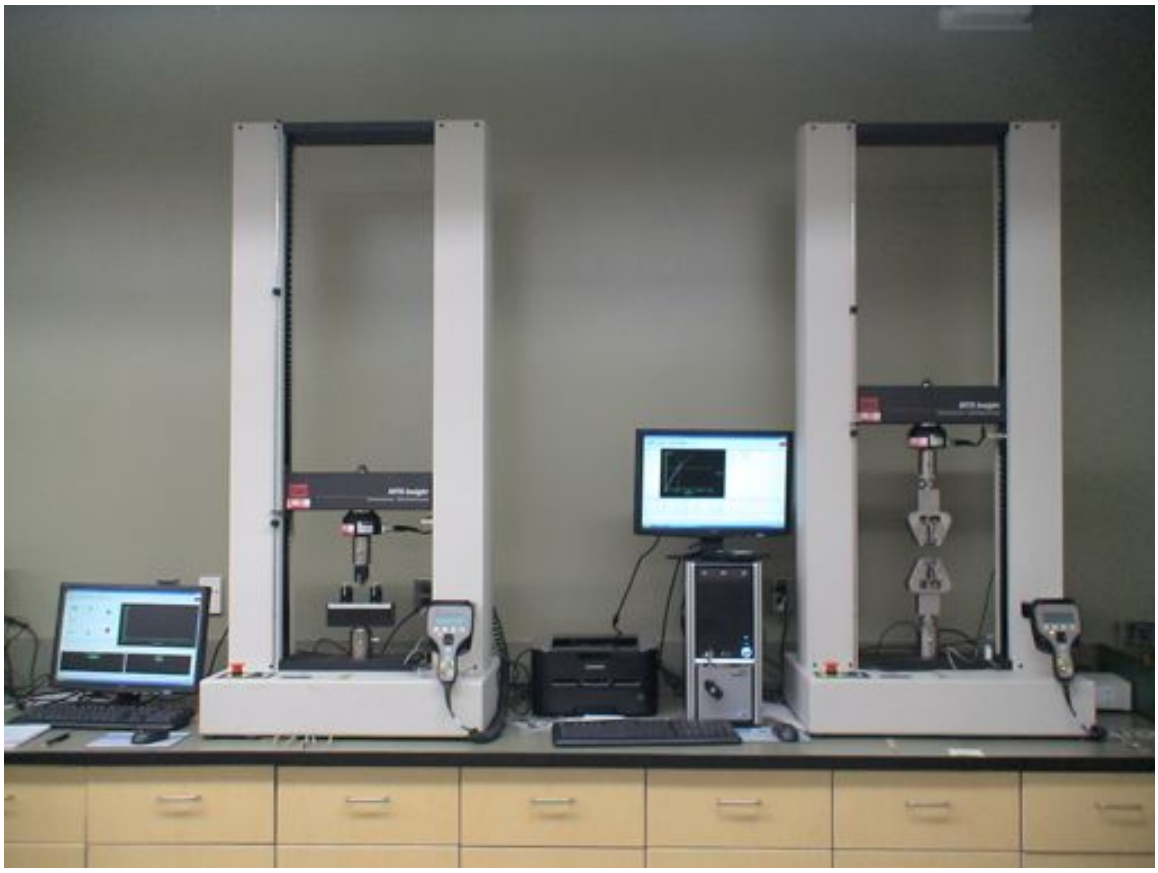
APPENDIX D

MASS OF FIBER AND COMPOSITE OF SAMPLES

Current Layup				
Sample	**Composite Mass**	**0-90 Fiber Mass**	**Layer 1 Chopped Strand Mass**	**Layer 2 Chopped Strand Mass**
1	41.763	3.366	5.143	5.062
2	46.67	3.320	5.653	5.568
3	47.014	3.295	5.231	5.253

2-Ply 1808			
Sample	**Composite Mass**	**Layer 1 Mass**	**Layer 2 Mass**
1	52.037	9.124	9.6184
2	47.447	9.578	9.420
3	47.952	9.348	9.337

TENSILE AND BENDING TEST APPARATUS



TENSILE TEST

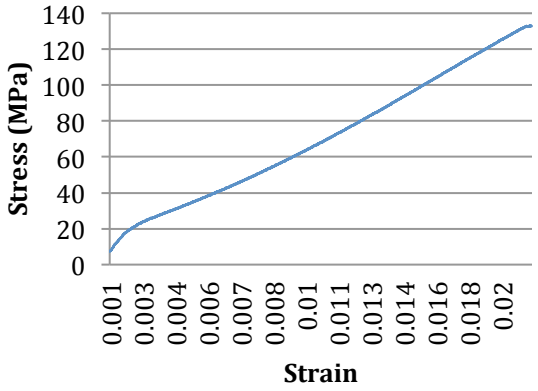


Figure 26 Sample 1 stress-strain curve

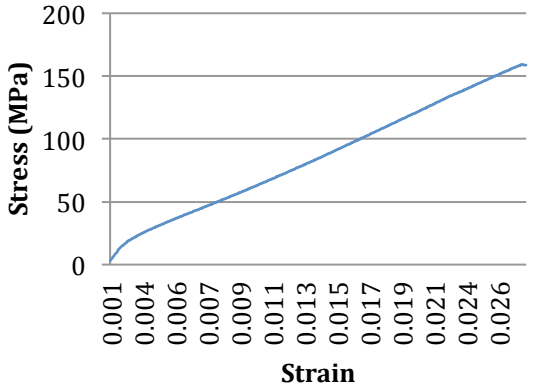


Figure 27 Sample 2 stress-strain curve

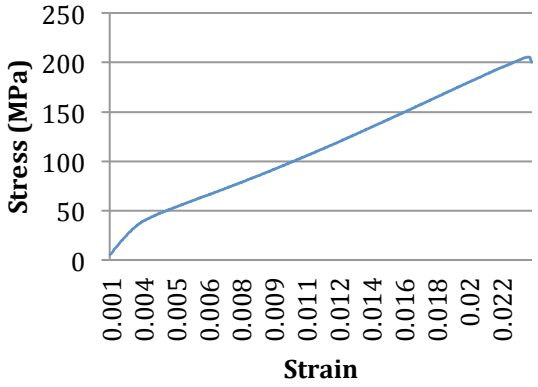


Figure 28 Sample 3 stress-strain curve

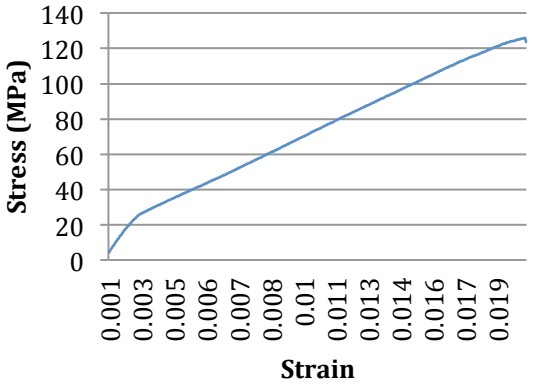


Figure 29 Sample 4 stress-strain curve

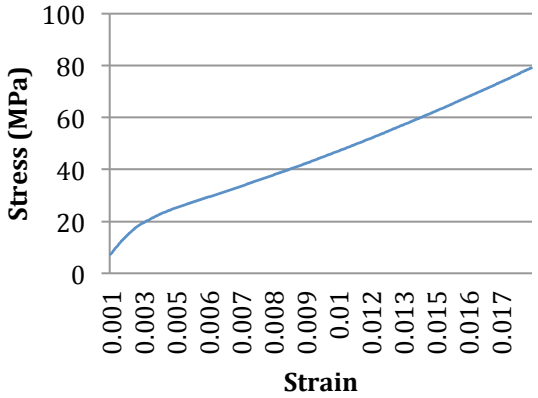


Figure 30 Sample 5 stress-strain curve

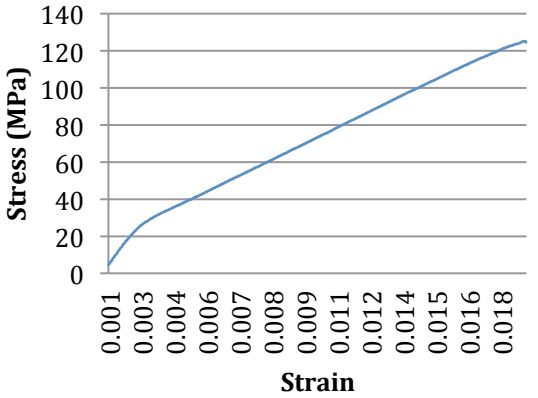


Figure 31 Sample 6 stress-strain curve

BENDING TEST

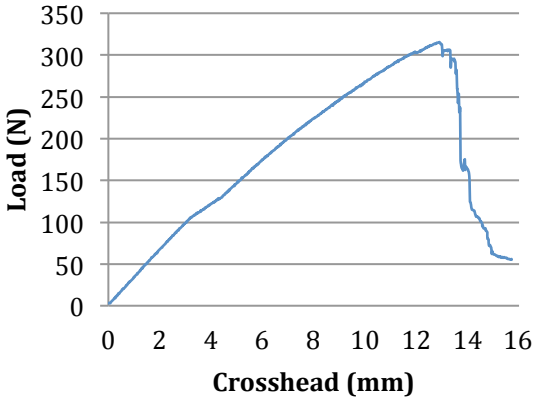


Figure 32 Sample 1 load-crosshead curve

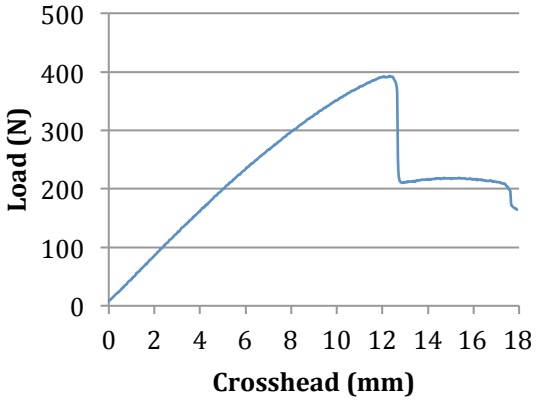


Figure 33 Sample 2 load crosshead curve

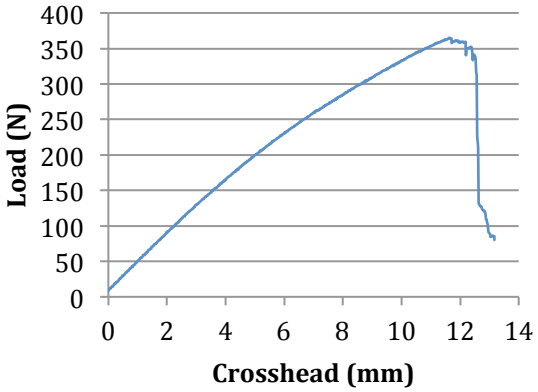


Figure 34 Sample 3 load-crosshead curve

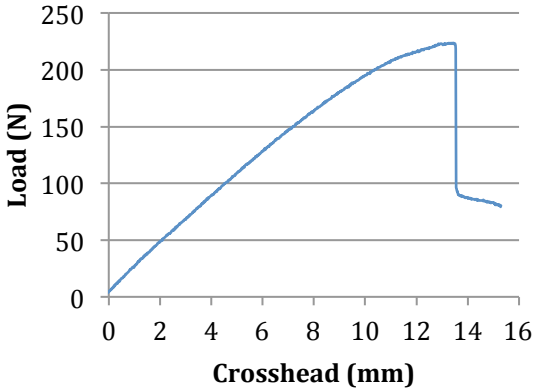


Figure 35 Sample 4 load-crosshead curve

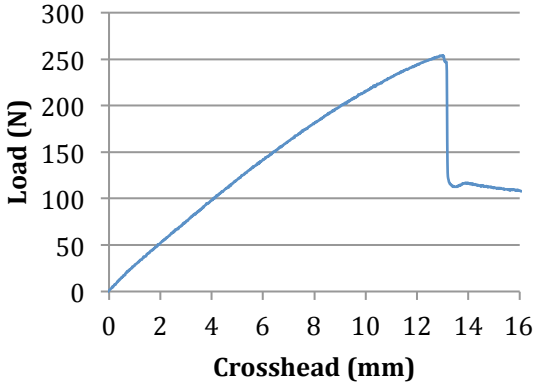


Figure 36 Sample 5 load-crosshead curve

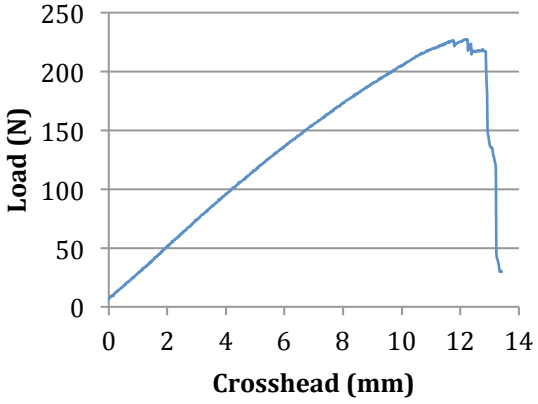


Figure 37 Sample 6 load crosshead curve

WEIGHT OF ROOF PANEL CALCULATIONS

Area of bus Shell	$A_{shell} = 390\ ft^2$
Fiber Weight for 2x1808	$W_{fiber} = \left[\left(\frac{49.5\ oz}{16\ \frac{oz}{lb}}\right)/1800\ in^2\right] \cdot 0.45359237\ \left[\frac{kg}{lb}\right] \cdot 144\left[{in^2}/{ft^2}\right] \cdot\ 390\ ft^2 = 43.78$ kg
Current resin weight from samples	$W_{resin\ (sample)} = 31.2\ \left[{gr}/{100\ cm^2}\right]$
Current resin weight for the complete shell	$W_{resin\ (shell)} = \left(\frac{31.2}{100}\right)\left[\frac{gr}{cm^2}\right] \cdot 6.4516\ \left[\frac{cm^2}{in^2}\right] \cdot 144\left[\frac{in^2}{ft^2}\right] \cdot\ 390\ ft^2 =\ 113.04\ kg$
Estimated density of polyester resin	$\rho_{polyester} = 1.25\ \left[\frac{gr}{cm^3}\right]$
Weight of polyester resin with 2 x 1808	$W_{resin\ (shell)} =\ 113.04\ kg\ \cdot\ \left(\frac{100 - 2.88}{100}\right) =\ \sim 110\ kg$
Current Fiber Weight	$W_{fiber} = \left(\frac{46}{49.5}\right)\left[\frac{oz}{oz}\right]\ \cdot 43.78 = 40.68\ kg$
Estimated density of vinyl ester resin	$\rho_{vinly\ ester} = 1.15\ \left[\frac{gr}{cm^3}\right]$

Weight of vinyl ester resin with 2 x 1808	$W_{resin\ (shell)} = 24\ gal\ \cdot\ 3785.41\left[\frac{cm^3}{gal}\right] \cdot\ 1.15\ \left[\frac{gr}{cm^3}\right]$ $= 104.48\ kg$
Total Current Weight of Shell	$W_{shell} = 40.68 + 113.04 = 153.72\ kg$
Weight of Shell with Polyester 2 x 1808	$W_{shell} = 43.78 + 110 = 153.78\ kg$
Weight of Shell with Vinyl Ester 2 x 1808	$W_{shell} = 43.78 + 104.48 = 148.26\ kg$

	Current	2x1808 Polyester	2x1808 Vinyl Ester
Weight	153.72 kg	153.78 kg	148.26 kg

APPENDIX E

1 COST ANALYSIS

One of the design constraints that have been imposed on this project is the cost of implementation of the proposed design. This constraint has been considered throughout the idea development stage of the project, as it must be fulfilled in order to validate the practicality of the proposed design. New Flyer's rule of thumb is that a design modification is not considered viable unless it pays itself off within a year. Currently, New Flyer spends approximately $355 000 per year on warranty work related to repair of the roof joint. There are currently two facilities producing busses within New Flyer, each at a rate of 20 busses per week [3]. Considering there are 52 weeks in a year, the amount that can be spent on each bus shell is calculated as follows.

$$\text{Allowance per shell} = \$\ 355\ 000 / (20 * 2 * 52) = \$\ 168.27$$

In the above calculation, it is assumed that all busses produced by the two separate manufacturing plants have joints in the roof. It is also assumed that each manufacturing plant produces a constant 20 busses per week; this rate is not affected by holidays, vacation, etc.

Since the incorporation of drip rails into the composite roof panel is a secondary objective of the design, it is important to note that the figure of $355 000, or $168.27 per bus, does not include any costs currently associated with the drip rails. Therefore, the proposed drip rail modification will be considered separately.

While doing the cost analysis some liberties must be taken since Carlson Engineered Composites Incorporated (Carlson) is the composite manufacturer and direct contact with them has been limited as they are a third party manufacturer. Assumptions made will be stated throughout the cost analysis; however, it is recommended that New Flyer contact Carlson in order to receive an exact quote.

The aspects considered relating to the cost analysis of the composite are listed below in TABLE XV.

TABLE XV COSTS ASSOCIATED WITH COMPOSITE MANUFACTURING

Content	**Modification**
Labour	Possible changes depending on the proposed process
Material	Possible change of cost related to alternate materials
Profit	Unchanged
Storing time for curing	Unchanged
Transportation	Unchanged
Safety Concerns	Unchanged

In terms of labour costs, it is estimated that Carlson allots $ 600 per roof panel of the total cost. For calculation purposes, the labour was distributed as indicated in TABLE XVI below.

TABLE XVI ASSUMED COST BREAKDOWN OF LABOUR ASSOCIATED WITH COMPOSITE LAYUP

Labour Process	Estimated Percentage
Laying-up Fibre Plies	10% (each layer)
Spraying Resin	50%
Trimming & Seperating from Molding	20%
Total	100%

1.1 BUS SHELL SPECIFICATIONS TO BE USED IN ANALYSIS

The current fiberglass roof is composed of two 20 ft long panels, a front panel and a rear panel. Currently, the cost of the front panel is $1239.03 and the cost of the rear panel is $1230.60, which amounts to a total of $2469.63 for each roof assembly [17]. These two panels are connected via an adhesive filled lap joint; the front panel covers an area of 190 ft^2 while the rear panel covers an area of 200 ft^2 for a total roof area of 390 ft^2. The currently used composite roof panels are fabricated using 1 layer of 10 oz. 0 – 90 cloth and 2 layers of 2 oz. chopped strand mat infused with a polyester resin matrix (fiber weights are given in square yards for cloth and square feet for matt).

Since the total allowable cost increase per bus is $168.27, any design with cost increase less than $168.27 will be considered profitable within the constraints of this project. Since material costs incurred by Carlson are unknown, the relative cost of all supplies will be compared from a single retailer.

1.2 Design Cost Considerations

Two lay-up processes will be analysed in terms of material cost. The first analysis will consider the use of a two-ply 1808 composite using polyester resin as the matrix. The second analysis will be done on a two-ply 1808 composite using a vinyl ester resin as the matrix. Additionally, cost analysis of adhesive modification will be performed separately in section 1.5 and cost analysis of incorporating drip rails in the shell design will be performed in section 1.6.

1.3 Two-ply 1808 biaxial cloth with polyester resin

The proposed 1808 fiber composite provides a 50% decrease in relative thermal expansion between the bus frame and the roof panel when polyester resin in used as the resin matrix. By solely changing the fiber used to fabricate the composite, the overall cost of the composite is expected to decrease while the overall mechanical properties increase. Since almost all aspects of manufacturing the composite remain unchanged, cost analysis is shown only on the factors that will be impacted with a change in the fiber. Calculations below show the cost analysis of the two-ply 1808 with polyester resin composite in comparison with the current composite [3].

Total area for given fiber prices

$$A_{fiber} = 50 \cdot 3 \cdot 12 = 1800\ in^2$$

Area of bus Shell

$$A_{shell} = 390\ ft^2$$

Fiber Cost for 2x1808

$$C_{fiber} = \left(\frac{12.30}{1800}\right)\left[{}^{\$}/_{in^2}\right] \cdot 144\left[\frac{in^2}{ft^2}\right] \cdot 390\ ft^2 = \$\ 383.76$$

Fiber Weight for 2x1808

$$W_{fiber} = \left[\left(\frac{49.5\ oz}{16\ \frac{oz}{lb}}\right)/1800\ in^2\right] \cdot 0.45359237\ \left[\frac{kg}{lb}\right] \cdot 144\left[{in^2}/{ft^2}\right] \cdot\ 390\ ft^2 = 43.78\ \text{kg}$$

Current resin weight from samples

$$W_{resin\ (sample)} = 31.2\ \left[{gr}/{100\ cm^2}\right]$$

Current resin weight for the complete shell

$$W_{resin\ (shell)} = \left(\frac{31.2}{100}\right)\left[\frac{gr}{cm^2}\right] \cdot 6.4516\ \left[\frac{cm^2}{in^2}\right] \cdot 144\left[\frac{in^2}{ft^2}\right] \cdot\ 390\ ft^2 =\ \ 113.04\ kg$$

Estimated density of polyester resin

$$\rho_{polyester} = 1.25\ \left[\frac{gr}{cm^3}\right]$$

Current resin volume

$$V = \left(\frac{113040}{1.25}\right)\left[\frac{gr}{{gr}/{cm^3}}\right] \cdot \left(\frac{1}{3785.41}\right)\left[\frac{gal}{cm^3}\right] = \sim 24\ gal$$

Current Cost of Polyester Resin

$$C_{resin}\ = 24\ gal\ \cdot 29.5\ \left[\frac{\$}{gal}\right] = \$\ 708$$

Cost of Polyester Resin with 2 x 1808

$$C_{resiin} = \$\ 708\ \cdot \left(\frac{100 - 2.88}{100}\right) = \$\ 687.61$$

TABLE XVII TWO-PLY 1808 WITH POLYESTER RESIN COST ANALYSIS

	Fibre	Resin	Labour	Total
Current cost	$425.88	$708	$600	$2469.63
Suggested cost	$383.76	$687.61	$540	$2347.13
% increase	-9.89%	-2.88%	-10%	-4.96%
Increase in Cost	-$42.11	-$20.39	-$60	-$122.50

In summary, as shown in TABLE XVII, a two-ply 1808 composite manufactured with polyester resin will yield a decrease of $122.50 per bus shell since fiber, resin and labour costs all decrease.

1.4 TWO-PLY 1808 BIAXIAL CLOTH WITH VINYL ESTER RESIN

The quantity of fiber used in the two-ply vinyl ester composite will be the same as the quantity of fiber used in the two-ply polyester composite. Therefore, the cost of fiber will remain the same as the previous section. The volume of resin used per panel will be the same as in the previous section; 24 gallons. However, the cost of vinyl ester resin is $34.30 per gallon from US Composites [3].

As was calculated in the previous section, since there are only two layers of fiber that must be applied during the manufacture of the composite, there is an estimated 10% decrease in labour costs. Calculations made for this matrix and the results are tabulated below. Calculations for the cost of vinyl ester resin are found below. TABLE XVIII shows the cost analysis of the two-ply 1808 with vinyl ester resin in comparison with the current composite [17] [3].

Estimated density of vinyl ester resin

$$\rho_{vinly\ ester} = 1.15\ \left[\frac{gr}{cm^3}\right]$$

Cost of Vinyl Ester Resin with 2 x 1808

$$C_{resin} = 24\ gal\ \cdot 34.30\ \left[\frac{\$}{gal}\right] = \$\ 823.20$$

TABLE XVIII TWO-PLY 1808 WITH VINYL ESTER RESIN COST ANALYSIS

	Fibre	Resin	Labour	Total
Current cost	$425.88	$708	$600	$2469.63
Suggested cost	$383.76	$823.20	$540	$2482.72
% increase	-9.89%	16.27%	-10%	0.53%
Increase in Cost	-$42.11	$115.20	-$60	$13.09

In summary, as shown in TABLE XVIII, a two-ply 1808 composite manufactured with vinyl ester resin will yield an increase of $13.09 per bus shell since fiber and labour costs decrease and resin costs slightly increase.

1.5 Adhesive Modification Cost

The addition of sika booster to the adhesive currently used in the lap joint of the two composites leads to an increase in installation material cost. Each booster unit costs $8.53 to New Flyer [11]. Since two more boosters are required in order to increase the strength of the joint, an increase of $17.06 per roof is added to the installation for a total booster cost of $25.59.

1.6 Drip Rail Modification Cost

Currently, extruded aluminum drip rails are attached to the side of the bus once the composite shell is installed. The installation of these drip rails not only requires additional material costs but also additional labour cost. The extruded aluminum rails cost New flyer approximately $250 per bus, including the glue and two sided tape cost along with the profile [11]. The cost of labour associated with the installation of the drip rails is about $ 75 per hour. The time required time to install these drip rails is approximately 30 to 45 minutes resulting in an expense of $35-$55 per bus [11].

Upon receiving this project, New Flyer requested that, if possible, the secondary installation of drip rails be removed though integration of drip rails during the composite shell manufacturing. Since this cost is not associated with the previously discussed budget, the following calculations demonstrate the financial gain that can be acquired through implementation of integrated composite drip rails.

Labour Cost of Installing Drip Rails

$$C_{labour\ drip\ rails} = 40\left[\frac{bus}{week}\right]\cdot 52\ \left[\frac{week}{year}\right]\cdot 40\ mins \cdot \left(\frac{1}{60}\right)\left[\frac{hour}{min}\right]\cdot 75\ \left[\frac{\$}{hour}\right] = \$104\ 000$$

Material Cost of Installing Drip Rails

$$C_{material\ drip\ rails} = 40\left[\frac{bus}{week}\right]\cdot 52\ \left[\frac{week}{year}\right]\cdot \$\ 250 = \$520\ 000$$

Since installation time varies with a number of factors, it is assumed that 40 minutes is the average installation time. Therefore, the total cost of the labour is calculated to be $104 000 per year. The material cost is found to be $520 000 per year leading to a total cost of the secondary drip rail installation of about $624 000 per year.

There are only 8 different bus models and about 16 different moulds to be changed. Considering the total cost of a new template is about $10 000, the modification is estimated not to exceed $2000 per template, totalling up to $32 000 for the complete set of templates. By incorporating the drip rails the net profit to New Flyers is almost $600 000 per year. While doing this calculation, it is assumed that the drip rails do not increase the amount of labour required by Carlson Engineered Composites Incorporated therefore does not increase the price per bus shell.

1.7 Cost Summary

The cost of each proposed modification to the overall design of the roof is summarized in TABLE XIX below on a per bus basis. This table shows that the cost increase of modifying the composite and adding the boosted adhesive to the joint is almost negligible. The integration of drip rails into the composite roof, however, save New Flyer approximately $300 per bus.

TABLE XIX SUMMARY OF COSTS

	Current (per bus)	Proposed (per bus)	Cost Difference
Composite	$2469.63	$2482.72	$13.09
Booster for adhesive	$8.53	$25.59	$17.06
Drip rails	$300	$0	-$300