AN ABSTRACT OF THE THESIS OF

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Title: Design of Composite Sandwich Panels for a Formula SAE Monocoque Chassis.

Abstract approved: ______________________________

Robert K. Paasch

Physical testing of composite sandwich panels in three point bending is an increasingly important aspect of qualifying a composite monocoque for Formula SAE competition. Required stiffness and strength values have increased over the past three years, and more of the monocoque's laminates must be tested as well. As a result, there is a need for software to accurately design a sandwich panel to meet stiffness and strength requirements on the first physical test, without requiring redesign and multiple tests.

In this thesis, a method for calculating strength and stiffness of a composite sandwich panel is presented. Extensive physical testing is performed on sandwich panels typical of those found in a Formula SAE monocoque, demonstrating the accuracy of the proposed method.

The Formula SAE rules are examined in depth to determine how the physical testing results are used to determine if a monocoque is legal for competition. This understanding of the rules, combined with the method developed for calculating sandwich panel performance, is used to develop a Sandwich Panel Design Tool. This tool allows the user to design a sandwich panel, predict the physical test results for that panel, and then determine if the panel will meet the rules requirements.

Design of Composite Sandwich Panels for a Formula SAE Monocoque Chassis.

by

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Robert D. Story, Author

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1. INTRODUCTION

1.1. Global Formula Racing

Global Formula Racing (GFR) is a Formula SAE team comprised of students at Oregon State University (OSU) in Corvallis, Oregon and Duale Hochschule Baden-Württemberg Ravensburg (DHBW-RV), a university in Germany. Students from the two universities collaborate to design, build, test and compete with two cars in Formula SAE competitions around the world. Since it's inception, Global Formula Racing has won more Formula SAE competitions than any other team.

FIGURE 1.1: Global Formula Racing at Formula Student Germany, 2013

Every year GFR builds two cars. In 2010 both cars were identical combustion powered cars, since 2011 one car has been combustion and the other electric. The cars share a similar chassis built from the same mold, similar suspension, aerodynamics, and other components other than powertrain. Parts for both cars are built at both locations, final assembly of the combustion cars occurs at OSU, the electric car at DHBW-RV. Both chassis are built at OSU.

FIGURE 1.2: GFR's 2013 Combustion Car.

The chassis is a composite monocoque, using carbon fiber reinforced plastic (CFRP) skin and honeycomb core sandwich panel construction. For the 2013 chassis all of the CFRP used was prepreg from Toray, the majority is T700 plain weave fabric, with T700 unidirectional tape and M40J unidirectional tape reinforcing some areas. Honeycomb core is Hexcel HRH-10 (Nomex) or HRH-36 (Kevlar), in a variety of thicknesses and densities.

1.2. Formula SAE Competitions

The Formula SAE Series is a collegiate design competition series initially organized by SAE International. SAE International publishes the Formula SAE Rules, then organizes competitions run to these regulations. The original event was Formula SAE

Michigan, first run in 1981. Since then additional competitions have been added around the world, including Formula Student in Silverstone, England, Formula Student Germany in Hockenheim, Germany, Formula Student Austria in Spielberg, Austria, and a number of other competitions. Many of these competitions are run by separate organizations from SAE International, but are run under a signed agreement with SAE International, using the Formula SAE Rules.

Teams formed by students from universities around the world build race cars according to the Formula SAE rules. At each competition teams compete in multiple events, each worth a set amount of points, listed in Table 1.1. The points from each event are summed and the team with the most points wins the competitions. Competitions consist of both static events, where the car is not driving and points are assigned based on the teams presentations and knowledge, and dynamic events, where the car is racing and points are assigned based on the car's dynamic performance.

Statics		
	Cost and Manufacturing	100
	Presentation	75
	Design	150
Dynamics		
	Acceleration	75
	Skid Pad	50
	Autocross	150
	Efficiency	100
	Endurance	300
Total		**1000**

TABLE 1.1: Formula SAE Event Points Summary

1.3. Formula SAE Rules

The Formula SAE rules specify limits on many aspects of the vehicle design. There are a number of rules concerning the construction of the chassis and other safety aspects of the vehicle. There are rules specifying details on the suspension, putting limitations on the engine, aerodynamics, and some other aspects of the vehicle. The rules also specify the details on how the events will be run and scored.

The 2014 Formula SAE Rules define two different sets of requirements for chassis construction. Teams may choose which set of requirements they wish to follow. The first option is to comply with Formula SAE Rules, Part T Article 3 "Drivers Cell", and submit a Structural Equivalency Spreadsheet (SES) showing compliance with these rules. The second option is to comply with Formula SAE Rules, Part AF "Alternate Frame Rules", and submit a Structural Requirements Certification Form (SRCF). [1]

For teams submitting an SES, the rules specify a standard steel tube frame style chassis, depicted in Figure 1.3. The rules specify a set of required steel tubes, how these tubes are connected, and minimum dimensions. Teams that choose to build a chassis to these specifications are not required to submit any calculations showing that their chassis is safe. [1]

The rules allow teams submitting an SES to deviate from the standard steel tube frame and use a variety of alternate materials and tube dimensions, or to replace many of the tubes with a sandwich panel monocoque structure. In this case the team must demonstrate that the alternate structure is equivalent to the standard steel tube frame specified by the rules. Equivalence is demonstrated by filling in the SES, which is a Microsoft Excel workbook created by SAE International, comprised of a number of worksheets. Specifications of the alternate design are entered into the SES worksheets, and calculations built into the SES compares the design to the standard steel tube frame. [1]

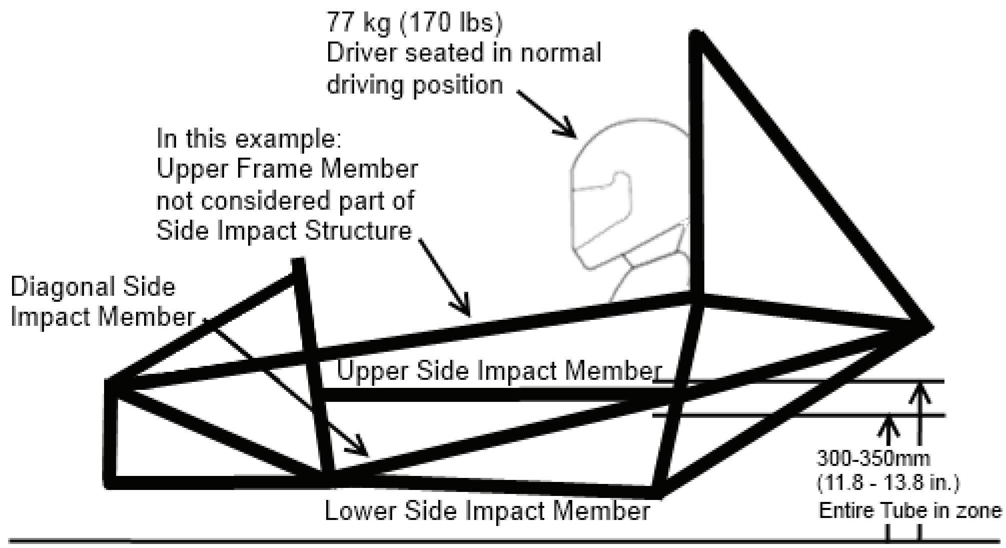

FIGURE 1.3: Standard rules chassis. [1]

The SES was introduced in 2012, previously teams submitted a Structural Equivilency Form (SEF), which was a free form document where teams submitted calculations they felt were appropriate to show equivalence, then this document was approved or denied at the discretion of an official reviewing the submitted SEF. The calculations introduced with the SES became *de facto* regulations, in addition to those written explicitly in the Formula SAE Rules. While the Formula SAE Rules say equivalence to the standard steel tube frame must be demonstrated, the equations in the SES specify exactly how equivalence must be shown. These additional requirements are one of reasons it has become more difficult to have a CFRP monocoque approved for competition.

For teams submitting an SRCF, the Alternate Frame (AF) rules provide a set of functional requirements that the chassis must meet, demonstrated with the use of Finite Element Analysis (FEA). The AF rules specify loads and restraints that must be applied to the chassis using FEA, maximum displacements that are permitted with the specified loads, and that failure must not occur anywhere in the structure. The AF rules also specify some requirements about the FEA software used by the team, and how results must be submitted.

Since 2012 GFR has built it's chassis to the SES set of rules, because of the relative simplicity of these rules, and because the FEA software in use by GFR for composites analysis does not meet the requirements of the AF rules. The rest of this thesis will focus on the design and testing of a CFRP monocoque chassis to meet the SES set of requirements.

1.4. Structural Equivalency Spreadsheet

The SES is a Microsoft Excel workbook, with 28 worksheets. There are 11 different types of worksheets in the SES, some duplicated several times to perform the same calculation on different parts of the chassis [2]. Figure 1.4 shows an overview of how the different worksheet types interact with one another.

Cover Sheet and General Information worksheet

The General Information worksheet provides a few schematics of the chassis, but is generally not used by the reviewer to determine if a chassis design is legal.

The Cover Sheet displays an overview of all of the other worksheets. Pass/fail values and basic chassis dimensions and construction are passed from other worksheets to the Cover Sheet to provide the reviewer and technical inspectors with an overview of the car's construction.

Harness Attachment worksheet

Rules require that each safety harness attachment point is physically tested. The Harness Attachment worksheet provides a space to document the required test results. It is generally not difficult to pass harness attachment requirements, appropriately sized attachments are required but are not particularly large or heavy.

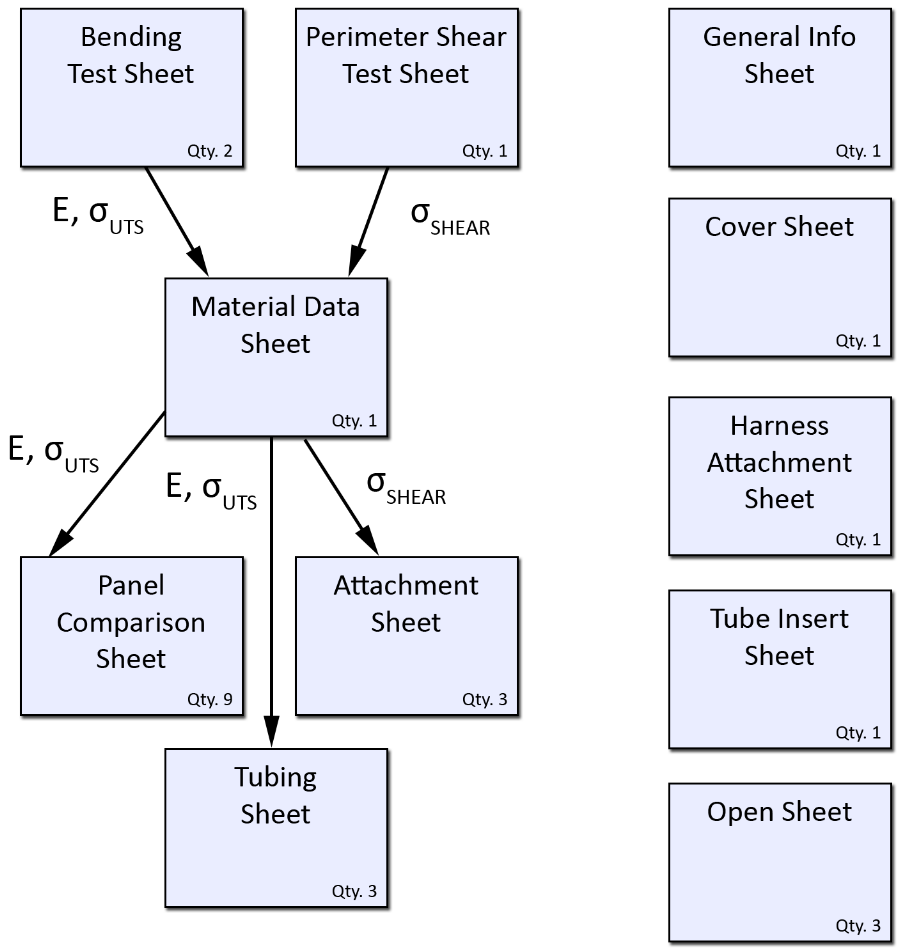

FIGURE 1.4: SES Worksheet Overview

Tube Insert worksheet

If required steel tubes have holes through them larger than 4mm in diameter, welded inserts are required to reinforce the area around the hole. The Tube Insert worksheet is used to prove that these inserts provide sufficient reinforcement. GFR has not had to use tube inserts, or this worksheet, in previous years.

Open Sheet

The open worksheets provide a space to prove that the Impact Attenuator attachment, and Accumulator attachment for electric cars, meets the regulations. However, there has not been any calculations built into the sheet, so it is simply an open space and it is left up to the team to determine appropriate calculations or tests to submit.

Material Data Sheet

The Material Data worksheet stores mechanical properties for all materials used in the chassis. For composite sandwich structures, the worksheet stores average properties for the facesheets. Properties stored are E, Youngs Modulus, σ_{UTS}, ultimate tensile strength, and σ_{shear}, ultimate out of plane shear strength [2]. No properties for the core are stored.

The Formula SAE Rules require all of the mechanical properties in the Material Data worksheet to be generated from physical tests performed by the team on a panel representative of the layup of the chassis. Results from a three point bending test on a sample sandwich panel are entered into the Bending Test worksheet, which then calculates E and σ_{UTS} values that are transferred to the Material Data worksheet. Results from a perimeter shear test on a sample sandwich panel are entered into the Perimeter Shear Test Sheet, which then calculates σ_{shear} and transfers that value to the Material Data worksheet.

Attachment Sheet

The attachment sheets show that the attachment of the roll hoops and roll hoop bracing meet strength requirements. This is typically shown using the σ_{shear} value, and the area of the plates connecting the hoop to the monocoque. This is a relatively easy sheet to pass, as the plates can simply be enlarged until the requirements are met, typically without any substantial addition of weight to the car.

Panel Comparison worksheet

There are nine Panel Comparison worksheets in the SES. The SES splits the chassis up into a number of zones. Each of these worksheets compares a zone of the monocoque to the tubes on the standard steel tube frame which that zone of the monocoque replaces. The sheet compares selected mechanical properties, the tensile strength, bending strength, bending stiffness, and energy absorption in bending, of the sandwich structure to the tubes it replaces.

As an example, the Side Impact Structure on the standard steel tube frame consists of three 1.0" x 0.95" tubes, running along the side of the car next to the driver. In the Panel Comparison worksheet for the Side Impact Structure, the team enters in the dimensions of the sandwich panel that makes up the Side Impact Structure of their monocoque, and the worksheet then calculates the expected mechanical properties of the panel using the provided dimensions and the material properties from the Material Data worksheet.

For GFR the Panel Comparison worksheets have generally been the most difficult to pass. It can be difficult to design and test a sandwich panel that can pass the requirements, without having a panel height that is too large to fit into the monocoque.

1.5. Organization of this Thesis

The goal of this thesis is to develop a method for reliably designing sandwich panels to meet the most difficult requirements of the SES. A software tool is needed that can design a laminate, predict how it will perform in the three point bend test required by the rules, and then calculate if those test results will translate into a pass or fail value in the Panel Comparison worksheet.

In order to accomplish this, first Section 2. will detail three different methods of calculating the stiffness and strength of a sandwich panel in the rules standard three point bend test.

All three methods presented in Section 2. will be validated by physical testing. Section 3. provides details on the selection of the test fixture and method used to perform these tests.

In Section 4., 10 different sandwich panel layup schedules will be introduced. Each of the calculation methods presented in Section 2. will be used to calculate an expected stiffness and strength. Physical test results for each layup schedule will be presented as well. Results for each calculation method will be compared with physical test results to investigate the accuracy of each method for predicting stiffness and strength.

Once an understanding of how to calculate the stiffness and strength of a sandwich panel has been developed, Section 5. will analyze how the SES works, from analyzing three point bending test results, extracting material properties, then using those properties to calculate expected performance of a sandwich panel on the chassis.

Finally, software for designing sandwich panels to meet Formula SAE regulations will be developed in Section 6.. This software will comebine the best calculation method of Section 2., as shown by the comparisons in Section 4., with the understanding of how the SES works developed in Section 5..

2. SANDWICH PANEL CALCULATIONS

Three methods for calculating the strength and stiffness of a Formula SAE three point bend sample will be presented in this section.

The first method presented will use classical lamination theory to calculate the effective modulus of the sandwich panel's facesheets, then use a simple mechanics of materials approach to calculate the stiffness of the panel. This is an important method to understand because it is the same approach used by the SES. In this method, stresses will be analyzed in each ply of the facesheet to predict when the panel will fail. This approach will be referred to as the Rules Method.

The second method will also use classical lamination theory to calculate an effective modulus for the sandwich panel's facesheets. However, in calculating the stiffness of the sandwich panel, shear deformation of the core will be included. In addition to predicting facesheet failures as in the first method, this method will also add core shear and compression failure modes to the analysis. This is very similar to the approach used by Petras in [3].

This method is expected to be the most useful to predict the stiffness of a three point bend sample. This approach will be referred to as the GFR Method.

The third method will use CATIA V5 to simulate the sample. Material properties and a layup schedule will be defined in the Composites Design workbench, which will then be transferred to the FEA workbench for stiffness and strength analysis. This approach has been used by the team for doing more complex analysis, for example calculating expected torsional stiffness of the full chassis. However, the team has done little validation or verification of calculations done in CATIA, so using this method to calculate three point bend samples can provide some verification of the method.

2.1. Material Properties

The lamina and core material properties required for the different calculation methods are listed in Table 2.1. An explanation of the notation used to describe the principle material directions, and the angles used in layup schedules, is provided in Appendix A. The material properties for each lamina and core material are listed in Appendix B.

			Required for Method		
Material	**Symbol**	**Description**	**Rules**	**GFR**	**CATIA**
Lamina	E_1	Youngs Modulus, 1 Direction	X	X	X
Lamina	E_2	Youngs Modulus, 2 Direction	X	X	X
Lamina	ν_{12}	Poisson's Ratio	X	X	X
Lamina	G_{12}	Shear Modulus	X	X	X
Lamina	F_{1t}	Tensile Strength, 1 Direction	X	X	X
Lamina	F_{1c}	Compressive Strength, 1 Direction	X	X	X
Lamina	F_{2t}	Tensile Strength, 2 Direction	X	X	X
Lamina	F_{2c}	Compressive Strength, 2 Direction	X	X	X
Lamina	F_{12}	Shear Strength	X	X	X
Core	G_L	Shear Modulus, L Direction		X	X
Core	G_W	Shear Modulus, W Direction		X	X
Core	F_L	Shear Strength, L Direction		X	
Core	F_W	Shear Strength, W Direction		X	
Core	F_C	Compressive Strength		X	

TABLE 2.1: Lamina and Core Required Material Properties

2.2. Beam Dimensions and Notation

The basic dimensions of the sandwich panel are shown in Figure 2.1 and Figure 2.2.

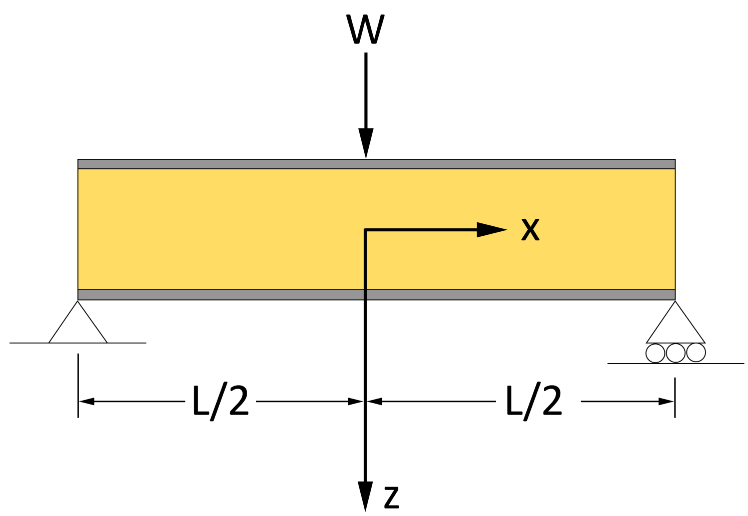

FIGURE 2.1: Three point bend diagram.

The Formula SAE rules specify for a test specimen that L, the length between the two bottom loading feet, must be 500mm, and that b, the width of the beam, must be 200mm. Figure 2.3 shows a schematic of a specimen, with the part coordinate system that is used to orient the plies of the facesheets, and core. Appendix A shows how angles are specified for both.

Unless otherwise noted, all specimens in this thesis are constructed using the dimensions shown in Figure 2.3.

The facesheets of the sample are comprised of multiples plies of CFRP laminated together. All samples and layups used in the chassis are symmetric about the core.

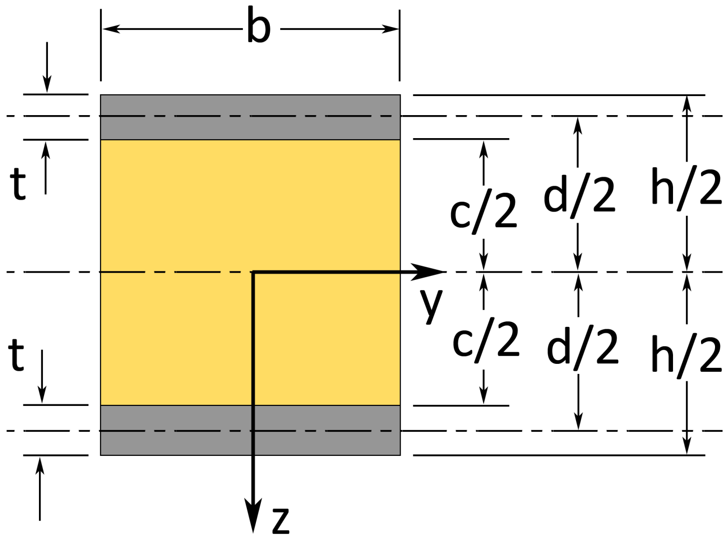

FIGURE 2.2: Sandwich panel cross section.

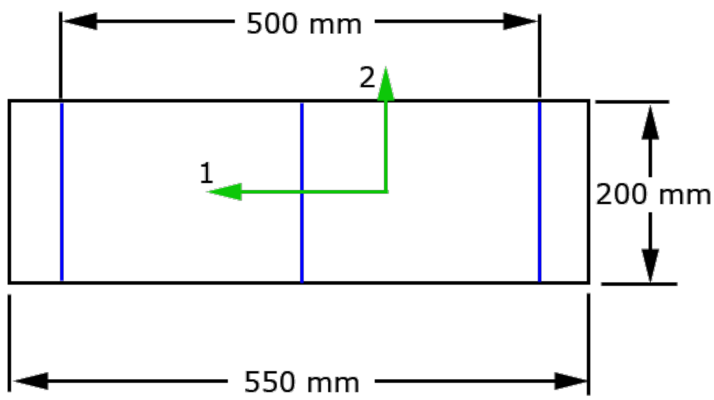

FIGURE 2.3: Sandwich Panel Dimensions

2.3. Rules Method

2.3.1 Panel Stiffness

Sandwich Panel Theory

The simple mechanics of materials solution for the deflection of a beam at the center is given in Equation 2.1 [4].

$$\Delta = \frac{WL^3}{48EI} \tag{2.1}$$

EI is the flexural rigidity of the beam, assuming the beam is a solid cross section made of a single material. For a composite sandwich panel, the flexural rigidity, denoted D, is more complex.

The rigidity of the facesheets can be found using the parallel axis theorem, and combined with the rigidity of the core. The flexural rigidity is then given by Equation 2.2.

$$D = E_f \frac{bt^3}{6} + E_f \frac{btd^2}{2} + E_c \frac{bc^3}{12} \tag{2.2}$$

The first term is the stiffness of the facesheets about their centroid. The second is the stiffness of the facesheets about the centroid of the beam. The third is the stiffness of the core about the centroid of the beam.

As demonstrated in [5], for almost any practical sandwich panel, including those used in Formula SAE, the second term is dominant. The facesheets are thin and have little stiffness about their centroids, and for a lightweight honeycomb core the modulus along the length of the panel, E_c, is very small. As a result the first and third can be ignored. The flexural rigidity of the beam can then be written as:

$$D = E_f \frac{btd^2}{2} \tag{2.3}$$

Combining this with Equation 2.1, the stiffness of a three point bend sample is then:

$$\frac{W}{\Delta} = 24 \frac{E_f btd^2}{L^3} \tag{2.4}$$

All of the values in Equation 2.4 are known from the geometry of the sample, aside from the effective stiffness of the facesheet, E_f.

Facesheet Stiffness by Classical Lamination Theory

The effective stiffness of the facesheet, E_f, is calculated using Classical Lamination Theory. The materials used in the facesheet are assumed to be orthotropic, four engineering constants E_1, E_2, G_{12} and ν_{12} are required to characterize each material.

The stiffness matrix for each ply in the facesheet, in the principle material axes for that ply, are calculated as: [6]

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_6 \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \gamma_6 \end{bmatrix} \tag{2.5}$$

Where the individual terms of the stiffness matrix are: [6]

$$\begin{aligned} Q_{11} &= \frac{E_1}{1 - \nu_{12}\nu_{21}} \\ Q_{22} &= \frac{E_2}{1 - \nu_{12}\nu_{21}} \\ Q_{12} = Q_{21} &= \frac{\nu_{21}E_1}{1 - \nu_{12}\nu_{21}} \end{aligned} \tag{2.6}$$

To calculate the stiffness matrix for the ply in the sample's coordinate system, first the stiffness invariants U_x for the ply are calculated as follows: [7]

$$\begin{aligned} U_1 &= \frac{1}{8}(3Q_{11} + 3Q_{22} + 2Q_{12} + 4Q_{66}) \\ U_2 &= \frac{1}{2}(Q_{11} - Q_{22}) \\ U_3 &= \frac{1}{8}(Q_{11} + Q_{22} - 2Q_{12} - 4Q_{66}) \\ U_4 &= \frac{1}{8}(Q_{11} + Q_{22} + 6Q_{12} - 4Q_{66}) \end{aligned} \tag{2.7}$$

The elements of the stiffness matrix for the ply, in the sample's coordinate system, are then: [7]

$$
\begin{aligned}
Q_{xx} &= U_1 + U_2 cos(2\theta) + U_3 cos(4\theta) \\
Q_{xy} = Q_{yx} &= U_4 - U_3 cos(4\theta) \\
Q_{yy} &= U_1 - U_2 cos(2\theta) + U_3 cos(4\theta) \\
Q_{xs} &= \frac{1}{2} U_2 sin(2\theta) + U_3 sin(4\theta) \\
Q_{ys} &= \frac{1}{2} U_2 sin(2\theta) - U_3 sin(4\theta) \\
Q_{ss} &= \frac{1}{2}(U_1 - U_4) - U_3 sin(4\theta)
\end{aligned}
\tag{2.8}
$$

The stiffness matrix for the ply, in the sample's coordinate system is then written as:

$$
\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_s \end{bmatrix} = \begin{bmatrix} Q_{xx} & Q_{xy} & Q_{xs} \\ Q_{yx} & Q_{xx} & Q_{ys} \\ Q_{sx} & Q_{sy} & Q_{ss} \end{bmatrix} \begin{bmatrix} {}_x \\ {}_y \\ \gamma_s \end{bmatrix}
\tag{2.9}
$$

After the stiffness of each ply is calculated in the samples's coordinate system, the stiffness of the facesheet is then calculated. The stiffness of the facesheet is written as:

$$
\begin{bmatrix} N_x \\ N_y \\ N_s \\ M_x \\ M_y \\ M_s \end{bmatrix} = \begin{bmatrix} A_{xx} & A_{xy} & A_{xs} & B_{xx} & B_{xy} & B_{xs} \\ A_{yx} & A_{yy} & A_{ys} & B_{yx} & B_{yy} & B_{ys} \\ A_{sx} & A_{sy} & A_{ss} & B_{sx} & B_{sy} & B_{ss} \\ B_{xx} & B_{xy} & B_{xs} & D_{xx} & D_{xy} & D_{xs} \\ B_{yx} & B_{yy} & B_{ys} & D_{yx} & D_{yy} & D_{ys} \\ B_{sx} & B_{sy} & B_{ss} & D_{sx} & D_{sy} & D_{ss} \end{bmatrix} \begin{bmatrix} {}^0_x \\ {}^0_y \\ \gamma^0_s \\ \kappa_x \\ \kappa_y \\ \kappa_s \end{bmatrix}
\tag{2.10}
$$

Or, in an abbreviated form:

$$
\begin{bmatrix} N \\ M \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{bmatrix} {}^0 \\ \kappa \end{bmatrix}
\tag{2.11}
$$

The components of the stiffness matrix are calculated with the following equations: [6]

$$\begin{aligned} A_{ij} &= \sum_{k=1}^{n} Q_{ij}^{k}(z_k - z_{k-1}) \\ B_{ij} &= \frac{1}{2}\sum_{k=1}^{n} Q_{ij}^{k}(z_k^2 - z_{k-1}^2) \\ D_{ij} &= \frac{1}{3}\sum_{k=1}^{n} Q_{ij}^{k}(z_k^3 - z_{k-1}^3) \end{aligned} \tag{2.12}$$

Where $i, j = x, y, s$, n is the number of plies in the laminate, $Q_{i,j}^{k}$ is the i, jth component of the Q matrix for ply k.

Finally, the effective elastic modulus for the facesheet in the x direction, E_x can be calculated as:

$$E_x = \frac{1}{h}[A_{xx} - \frac{A_{xy}^2}{A_{yy}}] \tag{2.13}$$

With E_x calculated, it is possible to use Equation 2.3 to calculate the stiffness of the three point bend sample.

2.3.2 Panel Strength

Facesheet Failure

To calculate facesheet failure, first the total normal load on the facesheet will be calculated. The strain on the facesheet will be calculated using that load, and the stiffness matrix of the facesheet, previously calculated in Equation 2.10. The strain and stress in each layer of the facesheet will then be calculated, in their respective coordinate systems. The Maximum Stress failure criteria will then be applied to each layer.

The normal load on the facesheet laminate, N_x, can be calculated as follows: [8]

$$N_x = \frac{WL}{4hb} \tag{2.14}$$

The laminate stiffness matrix in Equation 2.10 can be inverted to form the laminate compliance matrix: [6]

$$\begin{bmatrix} {}^{0}_{x} \\ {}^{0}_{y} \\ \gamma^0_s \\ \kappa_x \\ \kappa_y \\ \kappa_s \end{bmatrix} = \begin{bmatrix} a_{xx} & a_{xy} & a_{xs} & b_{xx} & b_{xy} & b_{xs} \\ a_{yx} & a_{yy} & a_{ys} & b_{yx} & b_{yy} & b_{ys} \\ a_{sx} & a_{sy} & a_{ss} & b_{sx} & b_{sy} & b_{ss} \\ c_{xx} & c_{xy} & c_{xs} & d_{xx} & d_{xy} & d_{xs} \\ c_{yx} & c_{yy} & c_{ys} & d_{yx} & d_{yy} & d_{ys} \\ c_{sx} & c_{sy} & c_{ss} & d_{sx} & d_{sy} & d_{ss} \end{bmatrix} \begin{bmatrix} N_x \\ N_y \\ N_s \\ M_x \\ M_y \\ M_s \end{bmatrix} \tag{2.15}$$

Or, in an abbreviated form: [6]

$$\begin{bmatrix} {}^{0} \\ \kappa \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} N \\ M \end{bmatrix} \tag{2.16}$$

The laminate strains ^{0} can then be calculated from the known laminate normal forces N_x. The strains in layer k, in it's principle material axes, can be calculated as: [6]

$$\begin{bmatrix} {}_{1} \\ {}_{2} \\ \frac{1}{2}\gamma_6 \end{bmatrix}_k = \begin{bmatrix} m^2 & n^2 & 2mn \\ n^2 & m^2 & -2mn \\ -mn & mn & (m^2 - n^2) \end{bmatrix} \begin{bmatrix} {}^{0}_{x} \\ {}^{0}_{y} \\ \frac{1}{2}\gamma^0_s \end{bmatrix} \tag{2.17}$$

Where:

$$\begin{aligned} m &= cos\theta \\ n &= sin\theta \end{aligned} \tag{2.18}$$

The stresses in layer k, in it's principle material axes, can be calculated using the same Q matrix as in Equation 2.5: [6]

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_6 \end{bmatrix}_k = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{bmatrix} {}_1 \\ {}_2 \\ \gamma_6 \end{bmatrix}_k \tag{2.19}$$

Failure is then calculated with the Maximum Stress failure criteria. The Maximum Stress criteria predicts failure when: [6]

$$\begin{aligned} \sigma_1 &= \begin{cases} F_{1t} & \text{when} \quad \sigma_1 > 0 \\ F_{1c} & \text{when} \quad \sigma_1 < 0 \end{cases} \\ \sigma_2 &= \begin{cases} F_{2t} & \text{when} \quad \sigma_2 > 0 \\ F_{2c} & \text{when} \quad \sigma_2 < 0 \end{cases} \\ \tau_6 &= F_{12} \end{aligned} \tag{2.20}$$

2.4. GFR Method

2.4.1 Panel Stiffness

Sandwich Panel Theory

The ordinary bending approach to calculating a sandwich panel assumes that each cross section of the beam remains plane and perpendicular to the beam's curved longitudinal axis [4]. As demonstrated in [5], in a thick sandwich structure a second type of shear deformation is introduced. The displacement at the center of the beam due to shear deformation is calculated as:

$$\Delta_{shear} = \frac{WL}{4bhG_c} \tag{2.21}$$

This deformation can be added to the ordinary bending deformation calculated in Equation 2.1 to calculate the total deflection of the beam: [5]

$$\Delta = \frac{WL^3}{24E_f btd^2} + \frac{WL}{4G_c bh} \tag{2.22}$$

Face Sheet Stiffness: Classical Lamination Theory

The effective stiffness of the facesheet, E_f, is calculated the same as previously presented in Section 2.3.1.

2.4.2 Panel Strength

Facesheet Failure

Facesheet failure is calculated in the same manner as presented for the Rules Method in Section 2.3..

Residual Stresses

Residual stresses are not included in any of the failure calculations, but will be present and will have some effect on facesheet failure loads. A possible method for calculating residual stresses from curing is introduced in [6].

In order to use this method, the lamina material properties listed in Table 2.2 are required in addition to the properties previously listed in Table 2.1.

Symbol	**Description**
α_1	Thermal Expansion Coefficient, 1 Direction
α_2	Thermal Expansion Coefficient, 2 Direction
ΔT	Difference between Cure and Operating Temperature

TABLE 2.2: Lamina Thermal Properties

The unrestrained thermal strains, e, are the strains that would be present at operating temperature in each ply if the ply were cured on it's own, not as part of a laminate, and was unrestrained after curing.

The unrestrained thermal strain in each ply k, in the principle material axes for the ply, are calculated as:

$$
\begin{aligned}
e_1 &= \alpha_1 \Delta T \\
e_2 &= \alpha_2 \Delta T \\
e_6 &= 0
\end{aligned}
\tag{2.23}
$$

The strain values can be transformed into the axes for the laminate, using similar equations to those presented in Equation 2.17, with m and n again defined as in Equation 2.18:

$$
\begin{bmatrix} e_x \\ e_y \\ \frac{1}{2}e_s \end{bmatrix}_k = \begin{bmatrix} m^2 & n^2 & 0 \\ n^2 & m^2 & 0 \\ mn & -mn & 0 \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \\ e_6 \end{bmatrix}_k \tag{2.24}
$$

The thermal force resultants can then be calculated as:

$$
\begin{bmatrix} N_x^T \\ N_y^T \\ N_s^T \end{bmatrix} = \sum_{k=1}^{n} \begin{bmatrix} Q_{xx} & Q_{xy} & Q_{xs} \\ Q_{yx} & Q_{xx} & Q_{ys} \\ Q_{sx} & Q_{sy} & Q_{ss} \end{bmatrix}_k \begin{bmatrix} e_x \\ e_y \\ e_s \end{bmatrix}_k t_k \tag{2.25}
$$

Similarly, thermal moment resultants can be calculated as:

$$
\begin{bmatrix} M_x^T \\ M_y^T \\ M_s^T \end{bmatrix} = \sum_{k=1}^{n} \begin{bmatrix} Q_{xx} & Q_{xy} & Q_{xs} \\ Q_{yx} & Q_{xx} & Q_{ys} \\ Q_{sx} & Q_{sy} & Q_{ss} \end{bmatrix}_k \begin{bmatrix} e_x \\ e_y \\ e_s \end{bmatrix}_k z_k t_k \tag{2.26}
$$

The residual strains in the facesheet can then be calculated using a similar set of equations to Equation 2.16:

$$
\begin{bmatrix} 0 \\ \kappa \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} N^T \\ M^T \end{bmatrix} \tag{2.27}
$$

The thermal stress-induced strains $_e$ in each ply k are the difference between the residual strain on the facesheet and the unrestrained thermal strains on that ply:

$$\begin{bmatrix} _{xe} \\ _{ye} \\ \gamma_{se} \end{bmatrix}_k = \begin{bmatrix} _{x} \\ _{y} \\ \gamma_{s} \end{bmatrix}_k - \begin{bmatrix} e_x \\ e_y \\ e_s \end{bmatrix}_k \tag{2.28}$$

With the thermal stress-induced strains on the ply, the thermal stress on the ply can be calculated in the same manner as previously presented in Section 2.3.2. First, the thermal stress-induced strain is convered into the plies principle material axes using Equation 2.17. The thermal residual stress is then calculated using Equation 2.19.

The thermal residual stress can then be added to the bending stress on the panel, and the Maximum Stress failure theory can be applied as described in Section 2.3.2, using the summed stress.

Intra-Cell Buckling

Intra-cell buckling could be added as a failure mode using the equation provided in [9]:

$$(N_{cr}) = \{D_{11} + 2(D_{12} + 2D_{66}) + D_{22}\}[\frac{\pi}{S}]^2 \tag{2.29}$$

Where S is the core cell size, and N_{cr} is the critical buckling load. This calculation has not been implemented, so far intra-cell buckling has not been an observed failure mode for GFR panels. Typically small cell size honeycomb (3.2mm) is used, and as such S is small and N_{cr} is large.

Core Shear Failure

It is shown in [5] that it is safe to assume the shear stress through the thickness (z-direction) of the core is constant, when the core is too weak to provide a significant contribution to the flexural rigidity of the panel.

The equation for the shear stress, τ_{core}, in the core is then:

$$\tau_{core} = \frac{W}{2hb} \tag{2.30}$$

The core will be assumed to fail when the shear stress in the core is greater than the shear strength of the core, F_{core}:

$$\tau_{core} > F_{core} \tag{2.31}$$

Core Compression Failure

The compression stress in the core is assumed to be:

$$\sigma_{core} = \frac{W}{wb} \tag{2.32}$$

Where w is the width of the loading foot. The panel will fail due to a core compression failure when:

$$\sigma_{core} > F_{corecomp.} \tag{2.33}$$

This approach was used by Petras in [3] with reasonable results, even though a circular loading foot was used and the loading area had to be approximated. More sophisticated approaches, which include the effects of the facesheet distributing load into a larger cross section of the core, are introduced in [10], [11] and [12]. However, it is expected that the simpler approach will work well with the square loading feet used here.

2.5. CATIA FEA

CATIA's FEA workbench will also be used to model the sandwich panels. Two dimensional shell elements will be used, as this is the only element available with CATIA's composites analysis.

There is no published literature using CATIA's FEA of sandwich panels. In [13] ANSYS is used with plane183 2D quad shell elements to model similar sandwich panels in bending, with errors of up to 40% for panel stiffness calculation.

The panel is first modeled as a 2D surface in CATIA's Generative Shape Design workbench. The surface is shown in Figure 2.4. The layup schedule is defined for the surface using the Composites Design workbench.

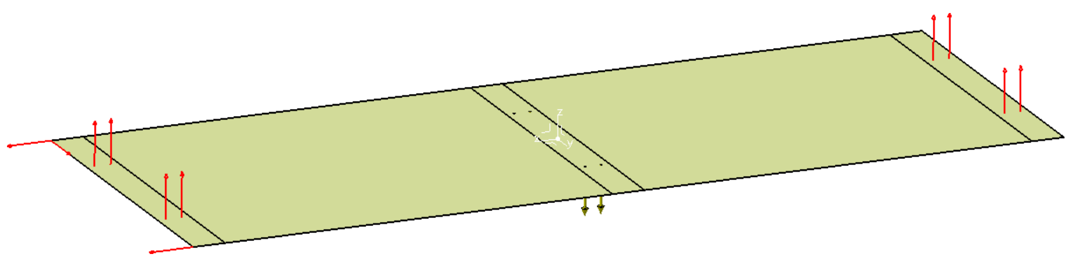

FIGURE 2.4: CATIA part model.

The part is then meshed in the Advanced Meshing Tools workbench. A Surface Mesh is applied to the part, using 2D Linear Quad elements, with a mesh size of 9.525 mm, half the width of the loading foot. The mesh is shown in Figure 2.5.

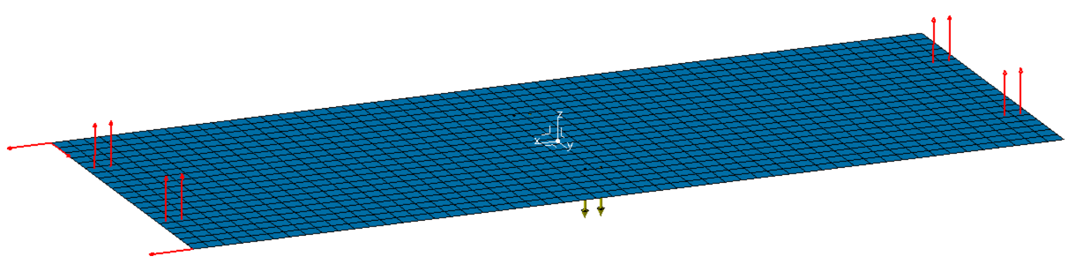

FIGURE 2.5: CATIA mesh.

In the Generative Structural Analysis workbench, the Imported Composites Property function is used on the surface to bring the mechanical properties of the previously defined layup schedule into the analysis.

Z displacement constraints are applied on the two outer surfaces. In order to fully constrain the model without over constraining, x displacement constraints are applied to two of the points on the corners of the model, and one y displacement constraint is applied to one corner of the model. These constraints can be seen in both Figures 2.4 and 2.5.

A 1N unit distributed load is applied to the center loading surface in the negative z direction.

Example results for z direction translational displacement are shown in Figure 2.6. Also shown is the minimum, or maximum negative, z displacement.

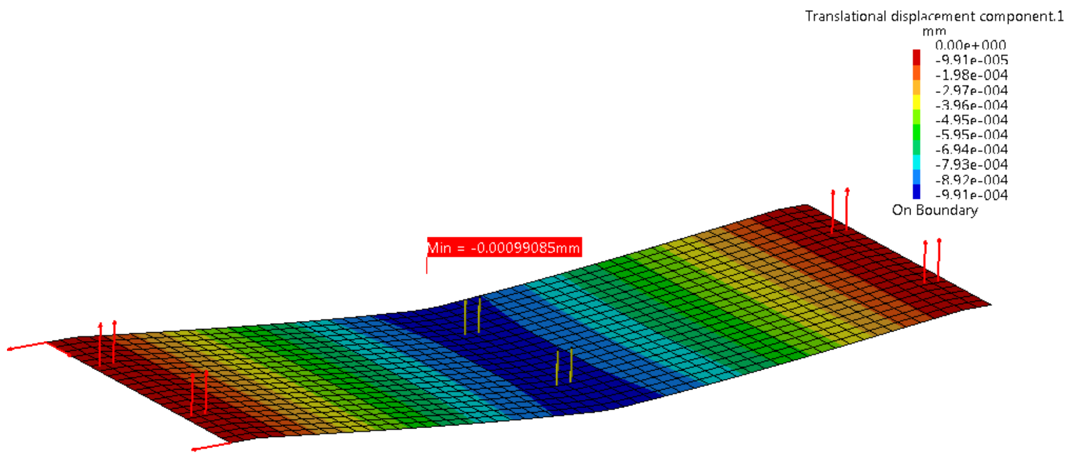

FIGURE 2.6: Z direction translational displacement, GF2013.BB.03

The stiffness of the panel is calculated with the minimum z displacement and Equation 2.34.

$$\frac{W}{\Delta} = \frac{1N}{Minimumzdisplacement} \tag{2.34}$$

The strength of the panel is calculated using Equation 2.20, the same Maximum Stress criterion used in both the Rules and GFR method. The maximum and minimum σ_1, σ_2 and τ_6 values for each ply are used to calculate the failure load according to this failure criteria. Figure 2.7 shows an example of the stress calculation from CATIA, in this case σ_1 for Ply 2 of the GFR2013.BB.03 panel series.

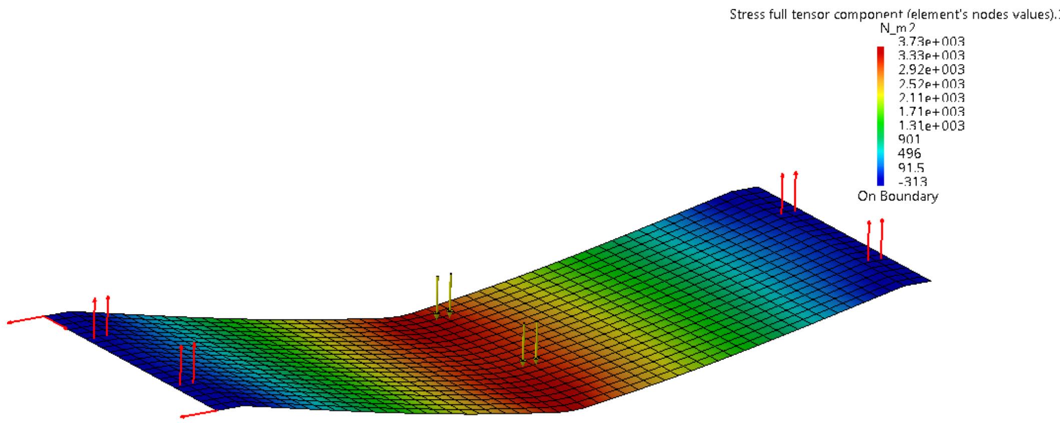

FIGURE 2.7: σ_1, ply 2, GFR2013.BB.03

3. PHYSICAL TEST METHOD

For the 2009-2011 competition seasons, GFR used a three point bend fixture with circular loading feet. This section will show some problems with this fixture, introduce a new test fixture design with square loading feet, then present test results and calculations showing that the new design is an improvement over the previous and justify it's use for testing samples in Section 4..

3.1. Circular Loading Foot Test Fixture

When the GFR Method code was completed, the first analysis performed was on GFR2011.BB.01, the GFR 2011 side impact structure, as testing had already been completed on this layup. The layup schedule is listed in Table 3.1. The labeling scheme used for test series and samples is explained in Appendix C.

Layer	**Material**	**Orientation**
1	Toray T700 Plain Weave	45
2	Toray T700 Plain Weave	90
3	Toray T800 Unidirectional	0
4	Toray T700 Plain Weave	45
Film Adhesive	Newport 102	N.A.
Core	Hexcel HRH-10/OX-3/16-3.0 25.4mm	90

TABLE 3.1: GFR2011.BB.01 Layup Schedule

The results predicted for this layup are shown in Table 3.2.

Stiffness Results			Strength Results		
Panel Stiffness	**790**	**N/mm**	**Panel Failure Load**	**7900**	**N**
Core Stiffness	1770	N/mm	Core Shear Failure Load	10080	N
Facesheet Stiffness	1420	N/mm	Core Comp. Failure Load	9180	N
			Ply 1 Failure Load	7900	N
			Ply 2 Failure Load	30640	N
			Ply 3 Failure Load	43450	N
			Ply 4 Failure Load	7900	N

TABLE 3.2: GFR2011.BB.01 Method 2 Calculation Results

Physical test results are shown in Figure 3.1 and Table 3.3.

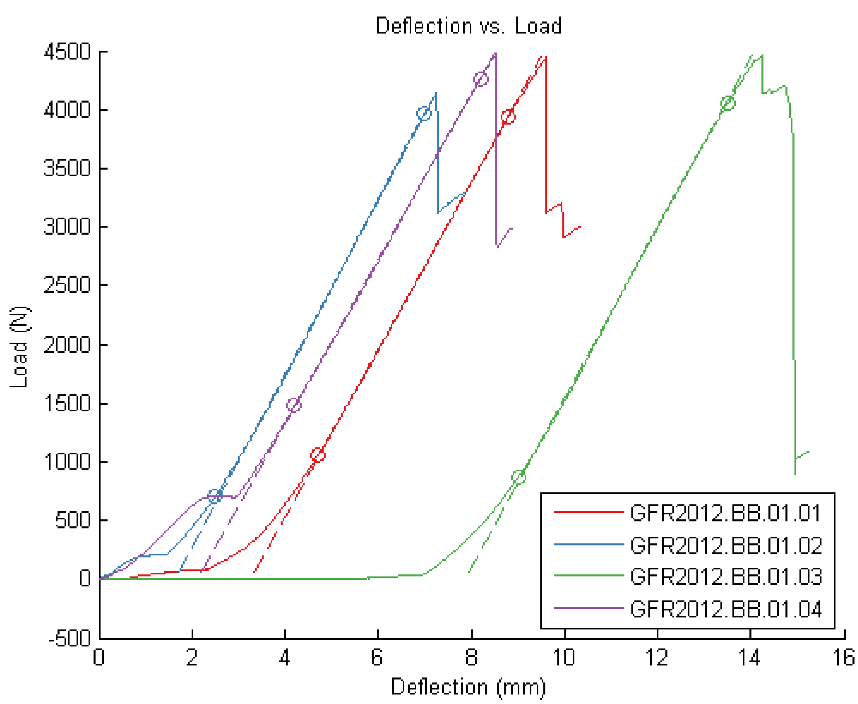

FIGURE 3.1: GFR2011.BB.01 Physical Test Results

	Maximum Load	Failure Mode	Stiffness
	(N)		(N/mm)
GFR2011.BB.01.01	4442	Core Shear	710
GFR2011.BB.01.02	4147	Core Shear	740
GFR2011.BB.01.03	4457	Core Shear	726
GFR2011.BB.01.04	4473	Core Shear	704
Mean	4380		720

TABLE 3.3: GFR2011.BB.01 Physical Test Results

A comparison of the stiffness results in Table 3.4 shows that the calculation over predicts stiffness by about 10

Series	**Measured** *(N/mm)*	**Predicted** *(N/mm)*	**Difference** (%)
GFR2011.BB.01	720	790	9.7

TABLE 3.4: GFR2011.BB.01 Stiffness Results Comparison

A comparison of strength results in Table 3.5 shows that the calculations predict 80 % higher strength than the physical tests showed.

	Strength			**Failure Mode**	
Series	**Measured** (N)	**Predicted** (N)	**Difference** (%)	**Measured**	**Predicted**
GFR2011.BB.01	4380	7900	80.4	Core Shear	Facesheet

TABLE 3.5: GFR2011.BB.01 Strength Results Comparison

However, a review of testing photos showed that failure occurred at the loading feet, as shown in Figures 3.2 and 3.3.

FIGURE 3.2: GFR2011.BB.01 Physical Test Photo

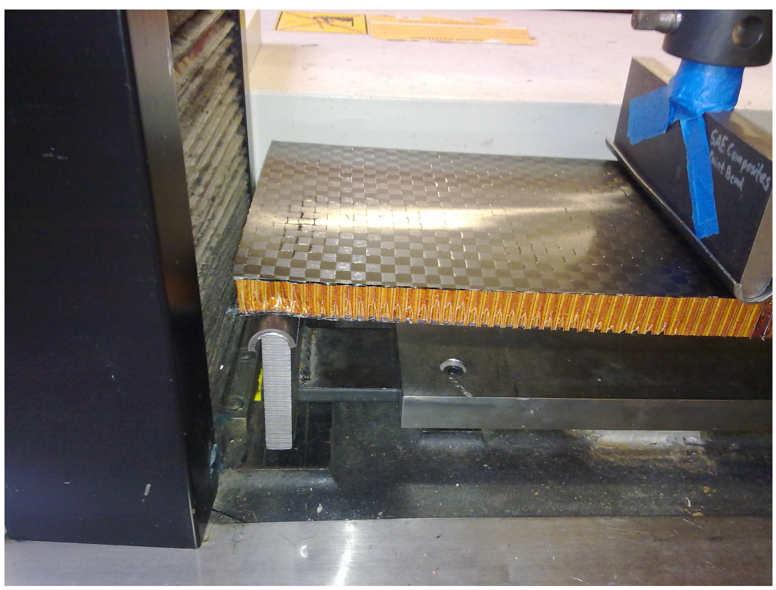

FIGURE 3.3: GFR2011.BB.01 Physical Test Photo

It can be seen in the photos that the text fixture used had round, pivoting loading feet in contact with the specimen. The diameter of these feet was 25.4mm. In ASTM C393 [14] it is suggested, although not required, that a bending fixture with square, pivoting feet be used.

It was suspected that the discrepency in strength, and possibly stiffness, values between the calculated and tested results was due to high stress concentrations in the sample near the loading feet.

3.2. Square Loading Foot Test Fixture

A new text fixture was designed with square, pivoting feet. A layer of rubber was added to the foot to further reduce stress concentrations, as also suggested in [14]. The face of the foot is 19.05 mm by 220 mm. Figure 3.4 shows the test fixture.

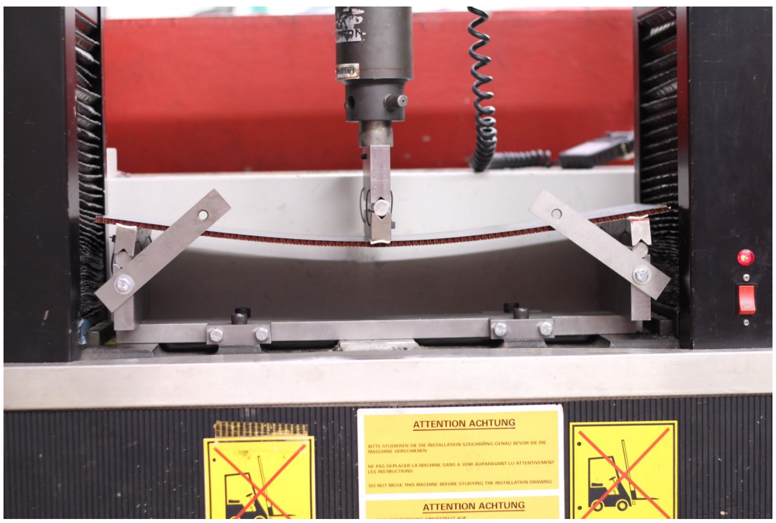

FIGURE 3.4: Square Feet Test Fixture

The new test fixture was also designed with attachment points for the load frame, improving alignment between the upper and lower halves of the test fixture. The previous fixture did not have any method for aligning the upper and lower halves.

Locating features for the specimen were added, improving alignment of the sample with the test fixture.

3.3. Test Fixture Comparison

A series of eight panels, GFR2012.BB.05, were built to compare the two test fixture designs. The layup schedule for these panels is provided in Section D1. Four samples were tested with the circular loading foot test fixture, and four were tested with the square loading foot test fixture. The results are plotted in Figure 3.5. The samples tested with the square loading foot are plotted in red, samples with circular loading foot are blue.

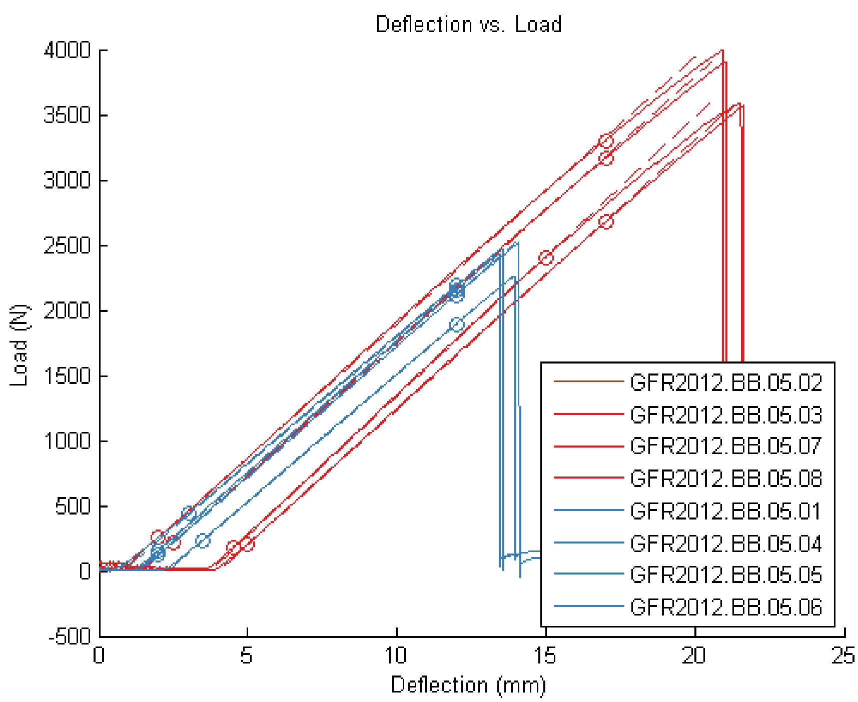

FIGURE 3.5: Test Fixture Comparison Results

Table 3.6 lists the the average results for the two different test fixtures. Calculation results are also listed, details on the calculations are provided in Section D1.

	Maximum Load *(N)*	**Stiffness** *(N/mm)*
Circular Loading Foot	2419	198
Square Loading Foot	3766	207
Calculated	4790	220

TABLE 3.6: Test Fixture Comparison Results

As shown in Table 3.6, the square loading foot results in a 56 % increase in strength, 4.5 % increase in stiffness, and improved agreement between calculations and test results. As a result, the square foot test fixture is then used for all physical testing in Section 4..

4. RESULTS COMPARISON

In this section, layup schedules, calculations and physical test results will be presented for several different sandwich panel constructions. The results will then be summarized and discussed.

4.1. Panel Layup Schedules and Physical Test Results

Ten series of sandwich panels were constructed. Table 4.1 lists the layup schedules and physical test results for each of the series. For each series a minimum of two panels were constructed and tested. The listed stiffness and strength values are the average for all of the samples in the series.

Detailed descriptions, layup schedules, test and calculation results for each panel are provided in Appendix D.

Figure 4.1 is a plot of tested strength vs. stiffness for each test series. As shown in the plot, the series span a wide range of stiffnesses and strengths. Generally the higher stiffness panels tested are also higher strength.

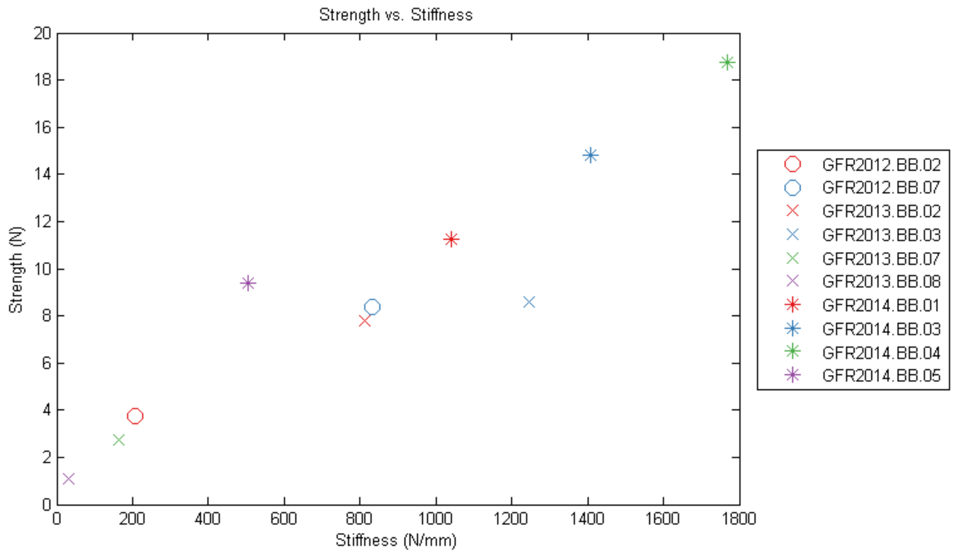

FIGURE 4.1: All sample strength vs stiffness.

	CFRP Facesheet			Honeycomb Core		Test Results	
Serial Number	**Fabric**	**Uni**	**Layup Schedule**	**Density**	**Thickness**	**Stiffness**	**Strength**
				(lb/ft³)	*(mm)*	*(N/mm)*	*(N)*
GFR2012.BB.05	-	T800	0_3	4.0	12.7	207	3766
GFR2012.BB.07	T800	T800	45F/90F/0/90F	3.0	25.4	833	8404
GFR2013.BB.02	T700	T800	45F/0/0F/45F	3.0	25.4	814	7798
GFR2013.BB.03	T700	M40J	$45F/0_2/0F/45F$	4.0	25.4	1245	8617
GFR2013.BB.07	-	T800	0	4.0	12.4	165	2744
GFR2013.BB.08	-	T800	0	5.0	5.08	31	1076
GFR2014.BB.01	T700	M46J	$45F/0_2/0F/0/45F$	3.0	25.4	1041	11232
GFR2014.BB.03	T700	M46J	$45F/0_5/0F/0_5/45F$	4.0	19.05	1408	14815
GFR2014.BB.04	T700	M46J	$45F/0_3/0F/0_4/45F$	4.0	25.4	1769	18726
GFR2014.BB.05	T700	M46J	45F/0/0F/0/45F/0/0F	4.0	12.7	504	9375

TABLE 4.1: Sandwich panel constructions and test results.

4.2. Results Comparison and Discussion

For each series of sandwich panel tested, expected stiffness and strength were calculated using all three calculation methods detailed in Section 2.. A comparison of the test results and calculations from the Rules Method, GFR Method, and CATIA FEA are listed in Tables 4.2, 4.3, and 4.4, respectively.

For each method, the stiffness error is the difference between the calculated and measured stiffness, and strength error is the difference between calculated and measured strength, both reported as a percentage of the measured values. Figures 4.2 and 4.3 show the stiffness error for each method and each panel, versus the stiffness of the panel.

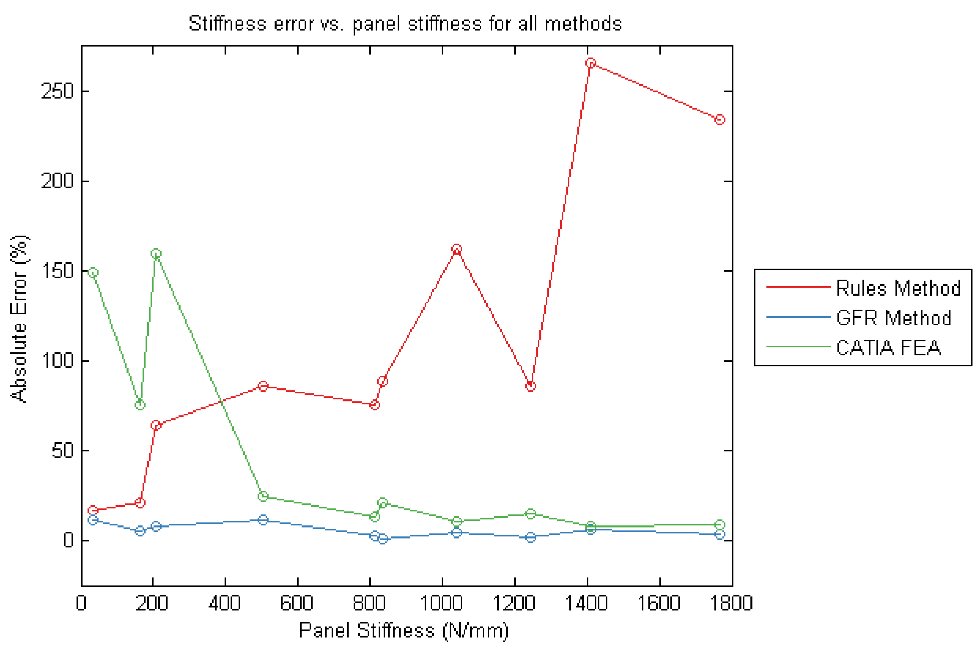

FIGURE 4.2: Stiffness Error vs. Panel Stiffness

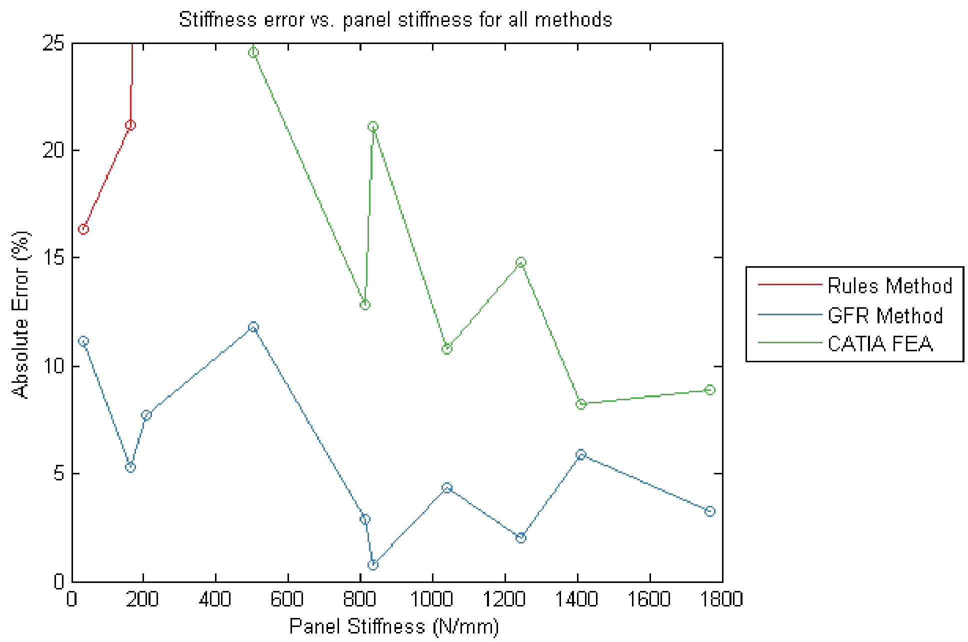

FIGURE 4.3: Stiffness Error vs. Panel Stiffness, cropped to 25%

As shown in the figures, the GFR Method consistently produces the most accurate results. The results from this method generally improve as the stiffness of the panel increases.

Above a panel stiffness of 500 N/mm, the CATIA FEA produces reasonable results, although with more error than the GFR method. Below a panel stiffness of 500 N/mm the results are not useful.

Conversely, the Rules Method produces reasonable results only for the least stiff panels, below 250 N/mm. For panels with greater stiffness the method is not useful for calculating stiffness. This is expected, as the Rules Method ignores core shear deformation. In the lower stiffness panels GFR2013.BB.07 and GFR2013.BB.08, the core stiffness is much greater than the facesheet stiffness, for example the GFR Method for GFR2013.BB.08 shows a core stiffness of 516 N/mm, but a facesheet stiffness of 36 N/mm. Because of this, in these panels core shear deformation can be ignored and reasonable results can still be produced.

Figure 4.4 shows the strength error for each method and each panel, versus the stiffness of the panel. As shown in the plot, the CATIA FEA is not useful for predicting strength.

The Rules Method is inconsistent and generally not useful, but does produce reasonable results in some specific panels. As Figure 4.4 shows, none of the methods produce good results for the panels with stiffness less than 250 N/mm. Above this, there are three panels that the Rules Method produces absolute errors less than 25%.

The Rules Method only predicts facesheet failure, so it would be expected that the method works well only in cases where the facesheet fails. In one of the three cases where the absolute error is less than 25%, the observed failure mode is facesheet failure. In the other two cases (GFR2013.BB.02, GFR2012.BB.07), the failure mode is core compression, but the GFR Method shows that the expected facesheet failure load is similar to the core compression mode. The Rules Method is inconsistent because it only predicts facesheet failure.

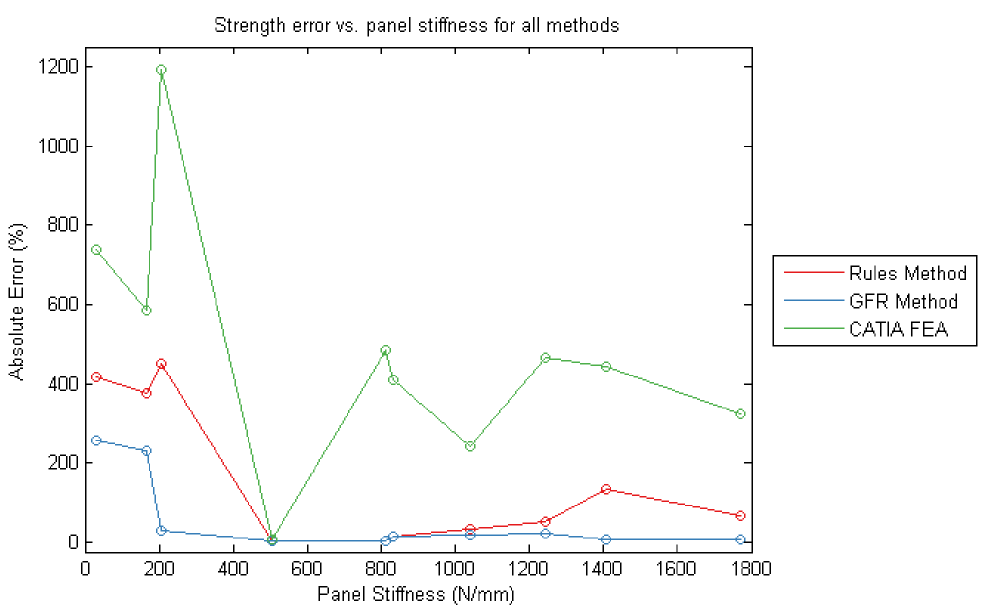

FIGURE 4.4: Strength Error vs. Panel Stiffness

Figure 4.5 shows strength error versus stiffness for just the GFR method. As shown, for the panels with stiffness less than 250 N/mm the method does not produce useful results, but for higher stiffness panels the results become better, with absolute errors ranging from 22% to 1.6%.

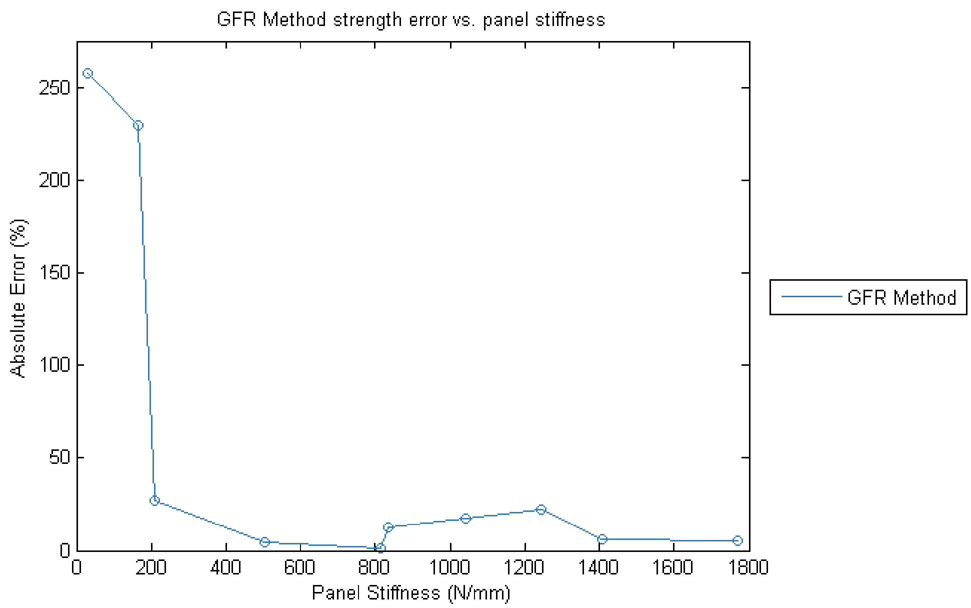

FIGURE 4.5: Method 2 Strength Error vs. Panel Stiffness

As shown in this section, the GFR Method provides good accuracy for stiffness and reasonable accuracy for strength calculations, and better results than the other methods investigated. As a result, this method will be used in developing the Sandwich Panel Design Tool in Section 6..

Rules Method Results Comparison								
	Stiffness			Strength			Failure Mode	
Series	**Measured** *(N/mm)*	**Predicted** *(N/mm)*	**Difference** *(%)*	**Measured** *(N)*	**Predicted** *(N)*	**Difference** *(%)*	**Measured**	**Predicted**
GFR2012.BB.05	207	340	**64.0**	3766	20740	**450.7**	Facing Failure	Facing Failure
GFR2012.BB.07	833	1570	**88.4**	8404	7370	**-12.3**	Core Compression	Facing Failure
GFR2013.BB.02	814	1430	**75.7**	7798	7920	**1.6**	Core Compression	Facing Failure
GFR2013.BB.03	1245	2310	**85.5**	8617	13010	**51.0**	Core Compression	Facing Failure
GFR2013.BB.07	165	200	**21.1**	2744	13040	**375.1**	Facing Failure	Facing Failure
GFR2013.BB.08	31	36	**16.3**	1076	5550	**415.9**	Facing Failure	Facing Failure
GFR2014.BB.01	1041	2727	**162.0**	11232	14770	**31.5**	Facing Failure	Facing Failure
GFR2014.BB.03	1408	5149	**265.7**	14815	34590	**133.5**	Mixed	Facing Failure
GFR2014.BB.04	1769	5915	**234.4**	18726	31360	**67.5**	Core Shear	Facing Failure
GFR2014.BB.05	504	939	**86.1**	9375	9770	**4.2**	Facing Failure	Facing Failure

TABLE 4.2: Rules method results comparison.

GFR Method Results Comparison								
	Stiffness			Strength			Failure Mode	
Series	**Measured**	**Predicted**	**Difference**	**Measured**	**Predicted**	**Difference**	**Measured**	**Predicted**
	(N/mm)	*(N/mm)*	*(%)*	*(N)*	*(N)*	*(%)*		
GFR2012.BB.05	207	223	**7.7**	3766	4791	**27.2**	Facing Failure	Core Shear
GFR2012.BB.07	833	840	**0.8**	8404	7370	**-12.3**	Core Compression	Facing Failure
GFR2013.BB.02	814	790	**-2.9**	7798	7920	**1.6**	Core Compression	Facing Failure
GFR2013.BB.03	1245	1220	**-2.0**	8617	10510	**22.0**	Core Compression	Core Compression
GFR2013.BB.07	165	174	**5.3**	2744	9035	**229.2**	Facing Failure	Core Shear
GFR2013.BB.08	31	34	**11.2**	1076	3849	**257.8**	Facing Failure	Core Shear
GFR2014.BB.01	1041	1086	**4.3**	11232	13200	**17.5**	Facing Failure	Core Shear
GFR2014.BB.03	1408	1491	**5.9**	14815	15650	**5.6**	Mixed	Core Shear
GFR2014.BB.04	1769	1827	**3.3**	18726	19720	**5.3**	Core Shear	Core Shear
GFR2014.BB.05	504	564	**11.8**	9375	9770	**4.2**	Facing Failure	Facing Failure

TABLE 4.3: GFR method results comparison.

CATIA Results Comparison

	Stiffness			Strength			Failure Mode	
Series	**Measured**	**Predicted**	**Difference**	**Measured**	**Predicted**	**Difference**	**Measured**	**Predicted**
	(N/mm)	*(N/mm)*	*(%)*	*(N)*	*(N)*	*(%)*		
GFR2012.BB.05	207	539	**160.0**	3766	48663	**1192.2**	Facing Failure	Facing Failure
GFR2012.BB.07	833	1009	**21.1**	8404	42847	**409.9**	Core Compression	Facing Failure
GFR2013.BB.02	814	918	**12.8**	7798	45652	**485.4**	Core Compression	Facing Failure
GFR2013.BB.03	1245	1429	**14.8**	8617	48708	**465.3**	Core Compression	Facing Failure
GFR2013.BB.07	165	289	**75.1**	2744	18822	**585.8**	Facing Failure	Facing Failure
GFR2013.BB.08	31	77	**148.8**	1076	9022	**738.6**	Facing Failure	Facing Failure
GFR2014.BB.01	1041	1153	**10.8**	11232	38569	**243.4**	Facing Failure	Facing Failure
GFR2014.BB.03	1408	1524	**8.2**	14815	80657	**444.4**	Mixed	Facing Failure
GFR2014.BB.04	1769	1926	**8.9**	18726	79496	**324.5**	Core Shear	Facing Failure
GFR2014.BB.05	504	628	**24.5**	9375	10061	**7.3**	Facing Failure	Facing Failure

TABLE 4.4: CATIA results comparison.

5. RULES ANALYSIS

This section will investigate in more detail the equations used by the SES in the Laminate Test worksheet to convert laminate test results to material properties. Next the equations used by the Panel Comparison worksheets will be evaluated. These worksheets are used by the SES to compare a zone on a monocoque to the steel tubes the standard frame would have in that zone.

5.1. Laminate Test worksheet

Three point bending test results are entered into the T3.31 Laminate Test worksheet in the SES, as shown in Figure 5.1. The worksheet calculates material properties for the panel's facesheets, E and σ_{UTS}, highlighted red.

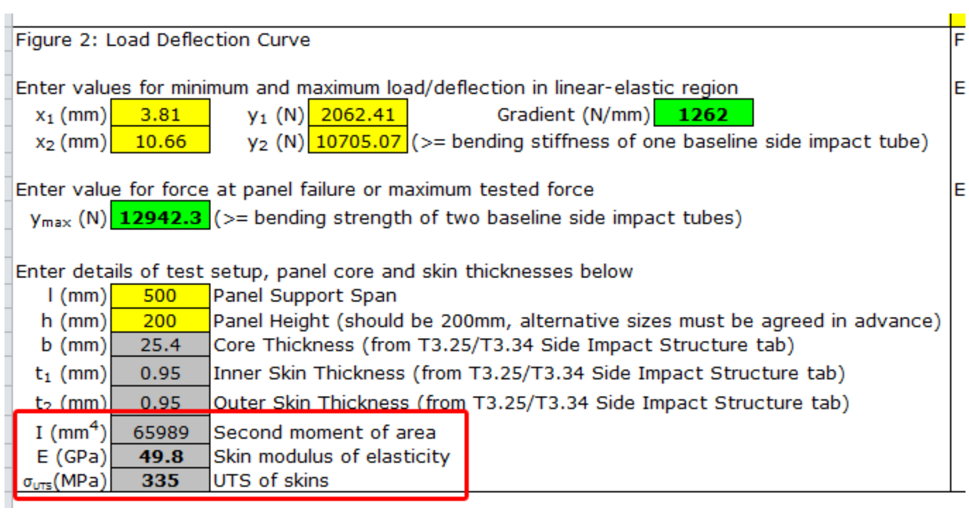

FIGURE 5.1: Laminate Test worksheet

Investigation of the equations entered into the worksheet show that E is calculated as:

$$E = \frac{WL^3}{48I\Delta} \tag{5.1}$$

Where I is calculated as:

$$I = \frac{bc^2t}{2} \tag{5.2}$$

Comparison with Equations 2.1 and 2.4 will show that this calculation method is the Rules Method, previously described in Section **??**. As demonstrated in Section **??**, this will result in a value for E that is too low.

The strength of the facesheet σ_{UTS} is calculated as:

$$\sigma_{UTS} = \frac{0.5WLh}{4I} = \frac{WL}{4hbt} \tag{5.3}$$

Comparison with Equation 2.14 shows that this is the same approach used to calculate average facesheet stress in the GFR and Rules Method. As demonstrated in Section **??**, the biggest issue with this calculation method is that facesheet failure is frequently not the failure mode for sandwich panels, especially the panels with thicker core used in the side impact structure. For panels that fail due to a core failure, the value for σ_{UTS} will be too low.

The values for E and σ_{UTS} are passed to the Material Data worksheet, which then passes the values to each of the Panel Comparison worksheets.

5.2. Panel Comparison worksheet

The Panel Comparison worksheet compares a panel of the monocoque to the set of steel tubes that it replaces. Figure 5.2 shows the Panel Comparison worksheet for the Side Impact Structure.

Side Impact Structure

Enter construction type: Composite only

Material Property	Baseline	Your Tube type 1	Your Tube type 2	Your Tube type 3	Your Tubes Total	Your Composite	Your Total		
Material type	Steel	Steel	Steel	Steel		Carbon			
Tubing Type	Round	Round	Round	Round		NA			
Material name /grade	Steel	Steel	Steel	Steel		2 ply			
Youngs Modulus, E	2.00E+11	2.00E+11	2.00E+11	2.00E+11		4.98E+10			
Yield strength, Pa	3.05E+08	3.05E+08	3.05E+08	3.05E+08		3.35E+08			
UTS, Pa	3.65E+08	3.65E+08	3.65E+08	3.65E+08		3.35E+08			
Yield strength, welded, Pa	1.80E+08	1.80E+08	1.80E+08	1.80E+08		N/A			
UTS welded, Pa	3.00E+08	3.00E+08	3.00E+08	3.00E+08		N/A			
Number of tubes	3	3	0	0					
Tube OD, mm	25.4	25.4	25.4	25.4					
Wall, mm	1.6	1.6	1.6	1.6					
			Baseline design?	NO					
Thickness of panel, mm						27.3			
Thickness of core, mm						25.4			
Thickness of skins, mm						0.95			
Panel height,mm						210			
OD, m	0.0254	No tubes	No tubes	No tubes					
Wall, m	0.0016								
I, m^4	8.51E-09					6.93E-08	6.93E-08		
EI	5.11E+03					3.45E+03	3.45E+03	67.6	F
Area, mm^2	358.9					399.0	399.0	NA	
Yield tensile strength, N	1.09E+05					1.34E+05	1.34E+05	122.0	
UTS, N	1.31E+05					1.34E+05	1.34E+05	101.9	
Yield tensile strength, N as welded	6.46E+04					1.34E+05	1.34E+05	206.7	
UTS, N as welded	1.08E+05					1.34E+05	1.34E+05	124.0	
Max load at mid span to give UTS for 1m long tube, N	2.93E+03					6.79E+03	6.79E+03	231.5	
Max deflection at baseline load for 1m long tube, m	1.20E-02					1.77E-02	1.77E-02	148.0	F
Energy absorbed up to UTS, J	1.76E+01					1.39E+02	1.39E+02	793.3	

FIGURE 5.2: Panel Comparison worksheet

On the left side of the sheet, highlighted in blue, a number of strength and stiffness values are calculated for the steel tubes in this portion of the chassis for the standard rules steel tube frame. In each Panel Comparison worksheet, the variables listed in Table 5.1 will be defined for the chassis zone. In this example, for the Side Impact Structure there are three tubes, 25.4mm x 1.6mm.

Symbol	Description
N_{tubes}	Number of tubes
D_{tubes}	Tube diameter
t_{tubes}	Tube wall thickness

TABLE 5.1: Tube variables

The material properties listed in Table 5.2 are specified in the Formula SAE rules to be used for the calculations on the baseline steel structures.

Symbol	Description	Value
E_{tubes}	Youngs Modulus	200 Gpa
σ_{tubes}	Ultimate Tensile Strength	365 Mpa

TABLE 5.2: Standard steel material properties

For a composite panel, the panel height is entered, in the field highlighted green. All of the test panels are required to be 200mm, this field tells the spreadsheet what the actual height on the chassis will be. The other dimensions of the panel, panel thickness and core thickness, will generally be the same as the test panel.

It is permitted on panels other than the Side Impact structure to enter alternate panel and core heights than what was physically tested, but the rules require that the layup must be the same, which is a somewhat vague requirement. Typically it is discouraged by the officials to enter values different from what was physically tested.

On the right side of the sheet, highlighted in red, the same strength and stiffness values are calculated as were calculated on the left for the standard steel tubes. The final column on the right compares the two values, if the composite panel is stiffer or stronger than the tubes it is highlighted in green as a pass value, if it is less stiff or strong than the steel tubes it is highlighted in red as a fail value.

Pass or fail values, along with the basic dimensions of the panel, are passed to the Cover Sheet, shown in Figure 5.3. The cover sheet provides a summary of all of the other sheets, showing an inspector at a glance which worksheets were passed or failed, and what dimensions the panels should be on the car in technical inspection.

The stiffness and strength values that are calculated and compared by the Panel Comparison sheet are EI, tensile strength, max load at mid span to give UTS for 1m long tube, max deflection at baseline load for 1m long tube, and energy absorbed up to UTS. There is also a field for area, but this is not compared for a composite panel. Each of

University Name	Oregon State University	Car No.(s) & Event(s)	1 FSAEM
Team Contact	Robert Story	Email Address	bert.story@global-formula-racing.co
Faculty Advisor	Dr. Robert Paasch	Email Address	ert.paasch@global-formula-racing.c

Is proof of equivalency for your design required for any of the rules?

Yes. Chassis deviates from baseline requirements

Baseline Material Used	Alternative Material Used	Rule No.	Rule Description	Design Description and/or Material Used	Tube and Laminate Equivalency: EI	Area	Yield	UTS	Yield as Welded	UTS as Welded	Max Bending Load at UTS	Max deflection at max baseline load	Energy absorbed during bending
YES	NO	T3.11	Main Roll Hoop Tubing	Baseline	NA	NA	NA	NA	NA	NA	NA	NA	NA
YES	NO	T3.12	Front Roll Hoop Tubing	Baseline	NA	NA	NA	NA	NA	NA	NA	NA	NA
YES	NO	T3.13	Main Roll Hoop Bracing Tubing	Baseline	NA	NA	NA	NA	NA	NA	NA	NA	NA
N/A	N/A	T3.13.6	Main Hoop Bracing Support - Tube Frames	Not Applicable	NA	NA	NA	NA	NA	NA	NA	NA	NA
N/A	N/A	T3.14	Front Hoop Bracing - Tube Frames	Not Applicable	NA	NA	NA	NA	NA	NA	NA	NA	NA
N/A	N/A	T3.19	Front Bulkhead - Tube Frames	Not Applicable	NA	NA	NA	NA	NA	NA	NA	NA	NA
N/A	N/A	T3.20	Front Bulkhead Support - Tube Frames	Not Applicable	NA	NA	NA	NA	NA	NA	NA	NA	NA
N/A	N/A	T3.25	Side Impact Structure - Tube Frames	Not Applicable	NA	NA	NA	NA	NA	NA	NA	NA	NA
YES	NO	T5.4	Shoulder Harness Bar	Baseline	NA	NA	NA	NA	NA	NA	NA	NA	NA
NO	YES	T3.37	Front Hoop Bracing - Monocoques	CFRP Monocoque	164	NA	296	248	502	301	562	61	###
NO	YES	T3.32	Front Bulkhead - Monocoques	CFRP Monocoque	134	NA	129	108	219	131	184	74	252
NO	YES	T3.33	Front Bulkhead Support - Monocoques	CFRP Monocoque	67	NA	125	104	211	127	230	149	788
NO	YES	T3.34	Side Impact Structure - Monocoques	CFRP Monocoque	68	NA	122	102	207	124	232	148	793
NO	YES	T3.37	Main Hoop Bracing Support - Monocoques	CFRP Monocoque	144	NA	865	723	###	879	799	70	###
NO	YES	T3.35	Main Hoop Attachment - Monocoques	Bolted to CFRP Monocoque	PA								
NO	YES	T3.36	Front Hoop Attachment - Monocoques	Fully Laminated									
NO	YES	T3.37	Hoop Bracing Attach. - Monocoques	Bolted to CFRP Monocoque	PA								
NO	YES	T3.38	Impact Attenuator Attachment - Monocoques	Baseline									
NO	YES	T3.21.6	Impact Attenuator Anti-Intrusion Plate	CFRP Plate	PA								
NO	YES	T3.41	Safety Harness Attachment - Monocoques	Bolted to CFRP Monocoque	PA								
N/A	N/A	EV3.4.2	Accumulator Attachment	Not Applicable									
YES	NO	EV3.4.4	Accumulator Protection	Not Applicable	NA	NA	NA	NA	NA	NA	NA	NA	NA
YES	NO	EV4.2.2	Tractive System Protection	Not Applicable	NA	NA	NA	NA	NA	NA	NA	NA	NA

Rule No.	Tube 1: Tube Material	Tube type	Outside Dimension	Wall thickness	Tube 2: Tube Material	Tube type	Outside Dimension	Wall thickness	Tube 3: Tube Material	Tube type	Outside Dimension	Wall thickness	Composite: Material	Panel Thickness	Skin Tickness	Panel Height
T3.11	Steel	Round	25.4	2.40												
T3.12	Steel	Round	25.4	2.40												
T3.13	Steel	Round	25.4	1.60												
T3.13.6																
T3.14																
T3.19																
T3.20																
T3.25																
T5.4	Steel	Round	25.4	2.40												
T3.37	Steel	Round	25.4	1.60									Carbo	27.3	0.95	170
T3.32													Other	20.2	0.58	93
T3.33													Carbo	27.3	0.95	170
T3.34													Carbo	27.3	0.95	210
T3.37													Other	13.8	0.57	500
T3.35																
T3.36																
T3.37																
T3.38																
T3.21.6																
T3.41																
EV3.4.2																
EV3.4.4	Steel	Round	25.4	1.60												
EV4.2.2	Steel	Round	25.4	1.25												

FIGURE 5.3: Cover Sheet

these values will be investigated in more detail below.

Some variables, such as b, will be different between the test specimen and the panel entered into the Panel Comparison worksheet. The different values will be denoted by subscripts panel and specimen, for example b_{panel} and $b_{specimen}$.

5.2.1 Flexural Rigidity Comparison

The worksheet first compares EI_{panel} between the standard steel tubes and the composite panel.

For the composite panel, I_{panel} is calculated using the panel height entered into the worksheet. While the value for E will be incorrect, by simply using EI to compare the flexural rigidity of the panel to the tubes, it is again implied that the deflection of the tubes, or the panel, can be calculated by:

$$\Delta_{panel} = \frac{WL^3}{48EI_{panel}} \tag{5.4}$$

By substituting in Equations 5.1 and 5.2, the equation for the deflection of the panel is then:

$$\Delta_{panel} = \Delta_{specimen} \frac{b_{panel}}{b_{specimen}} \tag{5.5}$$

The effect is that the spreadsheet takes the measured flexural rigidity of the specimen, and increases or decreases it proportionally for the height of the panel on the car. The result is then correct, for a panel with $l = 500mm$.

For the steel tubes, investigation of the worksheet equations reveals that EI is calculated as would be expected:

$$EI = N_{tubes} E_{tubes} I_{tubes} \tag{5.6}$$

Where:

$$I_{tubes} = \frac{1}{4}((\frac{D_{tubes}}{2})^4 - (\frac{D_{tubes}}{2} - t_{tubes})^4) \tag{5.7}$$

The "Max deflection at baseline load for 1m long tube" comparison is essentially the same comparison, if the EI comparison passes this comparison will pass as well.

5.2.2 Tensile Strength Comparison

There are four tensile strength comparison (yield, UTS, yield as welded, UTS as welded), however these are intended for teams comparing different metal tubes to the standard steel tubes. For composite sandwich panels, only σ_{UTS} is used for calculation. For the standard steel tube frame, UTS is the highest of the four loads, so this is the only load that matters for comparison to the composite panel, if this strength is passed than the others will be as well.

For the composite panel, the tensile strength of the panel, F_{panel}, is calculated by the SES as the average strength of the facesheets multiplied by the cross sectional area of the facesheets:

$$F_{panel} = (\sigma_{UTS})(2tb_{panel}) \tag{5.8}$$

As previously demonstrated, the σ_{UTS} is often incorrect, and as a result F_{panel} will also be incorrect.

For the standard steel tubes, again the tensile strength is calculated as would be expected:

$$F_{tubes} = (\sigma_{tubes})(Area_{tubes}) \tag{5.9}$$

5.2.3 Bending Strength Comparison

The "Max load at mid span to give UTS for 1m long tube" compares the bending strength of the panel to the bending strength of the standard steel tubes. Reviewing the equations in the SES, the maximum bending strength of the panel is calculated as:

$$W_{panel} = 4(\sigma_{UTS})\frac{2I_{panel}}{h} \tag{5.10}$$

Combining with Equation 5.3 for σ_{UTS} and 5.2 for I_{panel}, the equation for W_{panel} simplifies to:

$$W_{panel} = W_{sample}\frac{b_{panel}}{b_{sample}} \tag{5.11}$$

As was the case for flexural rigidity, the worksheet effectively takes the measured bending strength of the specimen, and increases or decreases it proportionally for the height of the panel on the car, and the result is then correct.

For the steel tubes, bending strength is also calculated as would be expected:

$$W_{tubes} = \frac{4N_{tubes}\sigma_{tubes}I_{tubes}}{0.5D_{tubes}} \tag{5.12}$$

5.3. Rules Analysis Conclusions

From this analysis it is shown that the SES provides correct comparisons between the composite sandwich panel and the standard steel tubes for bending stiffness and strength, but provides an incorrect comparison for tensile strength.

The fundamental problem is that a test sample that fails due to core compression or core shear does not provide any information about the strength of the facesheets, and as a result it is not possible to calculate the tensile strength of the panel.

6. SANDWICH PANEL DESIGN TOOL

In this section, a Sandwich Panel Design Tool is developed in MATLAB to calculate for a given layup schedule what panel height will be required in the chassis to meet the SES requirements for a given chassis zone.

6.1. MATLAB code

Given a layup schedule, the MATLAB code will first calculate the expected stiffness and maximum load for the standard 500 mm x 200 mm three point bending sample required by the rules. Calculations will be done using the GFR Method developed in Section 2. and validated through physical testing in Section 4..

With the expected stiffness and maximum load for the sample calculated, the code will then calculate the expected E and σ_{UTS} values that the SES will generate from the test, using the equations 5.2 and 5.3, respectively.

The standard steel tube frame number of tubes, diameter and wall thickness for the chassis zone are also entered. The code will then compare bending stiffness, bending strength, and tensile strength as previously described in Section 5.2..

6.2. Example Calculations

6.2.1 Verification

The results for calculating the layup schedule for GFR2013.BB.02, previously detailed in Section D3, are shown in Table 6.1. In this case the Side Impact Structure chassis zone is used for comparison.

Sample Bending Stiffness	797	N/mm
Sample Failure Load	7926	N
Height for Bending Stiffness	491.7	mm
Height for Bending Strength	148.1	mm
Height for Tensile Strength	336.3	mm

TABLE 6.1: GFR2013.BB.02 SPDT Calculation Results

The sample bending stiffness and failure load are entered into the Laminate Test worksheet in the SES. To verify that the required panel heights calculated by the software are correct, the three values are entered into the SES, as shown in Figure 6.1.

Side Impact Structure

		148.1 mm			336.3 mm			491.7 mm		
Material Property	**Baseline**	**Your Composite**	**Your Total**		**Your Composite**	**Your Total**		**Your Composite**	**Your Total**	
Material type	Steel	Carbon			Carbon			Carbon		
Tubing Type	Round	NA			NA			NA		
Material name /grade	Steel	2 ply			2 ply			2 ply		
Youngs Modulus, E	2.00E+11	3.54E+10			3.54E+10			3.54E+10		
Yield strength, Pa	3.05E+08	2.29E+08			2.29E+08			2.29E+08		
UTS, Pa	3.65E+08	2.29E+08			2.29E+08			2.29E+08		
Yield strength, welded, Pa	1.80E+08	N/A			N/A			N/A		
UTS welded, Pa	3.00E+08	N/A			N/A			N/A		
Number of tubes	3									
Tube OD, mm	25.4									
Wall, mm	1.6									
Thickness of panel, mm		27.1			27.1			27.1		
Thickness of core, mm		25.4			25.4			25.4		
Thickness of skins, mm		0.85			0.85			0.85		
Panel height,mm		148.1			336.3			491.7		
OD, m	0.0254									
Wall, m	0.0016									
I, m^4	8.51E-09	4.34E-08	4.34E-08		9.85E-08	9.85E-08		1.44E-07	1.44E-07	
EI	5.11E+03	1.54E+03	1.54E+03	30.1	3.49E+03	3.49E+03	68.4	5.11E+03	5.11E+03	100.0
Area, mm^2	358.9	251.8	251.8	NA	571.7	571.7	NA	835.9	835.9	NA
Yield tensile strength, N	1.09E+05	5.77E+04	5.77E+04	52.7	1.31E+05	1.31E+05	119.7	1.92E+05	1.92E+05	175.0
UTS, N	1.31E+05	5.77E+04	5.77E+04	44.0	1.31E+05	1.31E+05	100.0	1.92E+05	1.92E+05	146.2
Yield tensile strength, N as welded	6.46E+04	5.77E+04	5.77E+04	89.3	1.31E+05	1.31E+05	202.8	1.92E+05	1.92E+05	296.5
UTS, N as welded	1.08E+05	5.77E+04	5.77E+04	[illegible]	1.31E+05	1.31E+05	121.7	1.92E+05	1.92E+05	177.9
Max load at mid span to give UTS for 1m long tube, N	2.93E+03	2.93E+03	2.93E+03	100.0	6.66E+03	6.66E+03	227.1	9.74E+03	9.74E+03	332.0
Max deflection at baseline load for 1m long tube, m	1.20E-02	3.98E-02	3.98E-02	[illegible]	1.75E-02	1.75E-02	146.2	1.20E-02	1.20E-02	100.0
Energy absorbed up to UTS, J	1.76E+01	5.83E+01	5.83E+01	332.0	1.32E+02	1.32E+02	753.9	1.94E+02	1.94E+02	1102.2

FIGURE 6.1: Panel Comparison worksheet with different panel heights

With 148.1mm entered, the bending strength requirement is met. With 336.3mm entered, all of the tensile strength requirements are met. Both bending stiffness requirements are met with 491.7mm entered.

6.2.2 Side Impact Structure

A number of calculations were performed on possible changes to the 2013 Side Impact Structure to show how the SPDT can be useful to a Formula SAE team. The layup schedule for the 2013 Side Impact Structure (SIS) is listed in Table 6.2.

Layer	**Material**	**Orientation**
1	Toray T700 Plain Weave	45
2	Toray M40J Unidirectional	0
3	Toray M40J Unidirectional	0
4	Toray T700 Plain Weave	0
5	Toray T700 Plain Weave	45
Film Adhesive	Newport 102	N.A.
Core	Hexcel HRH-10-1/8-3.0 25.4mm	0

TABLE 6.2: 2013 SIS Layup Schedule

Table 6.3 shows the results of three different layup schedules there were calculated with the SPDT. The first is the 2013 SIS. As the table shows, the panel height must be 383 mm, the limiting factor is bending stiffness. The failure mode in the panel is core compression.

It might be assumed that using thicker core would allow for a smaller panel height. The thicker core would improve bending stiffness. Bending strength would not be improved because the core compression failure will occur at the same load, but the bending strength is the least limiting factor on panel height.

As Table 6.3 shows, increasing core thickness to 38.1 mm (1.5 in) does have the effect of reducing the required panel height for bending stiffness, and bending strength does stay the same, however the required height for tensile strength greatly increases, even though the facesheet layup, and as a result the tensile strength of the panel, has not changed. This is because, as previously noted in Section 5.3., it is not possible to accurately calculate tensile strength from a bending sample that has a core failure.

As the table also shows, the problem becomes worse with another increase in core thickness to 50.8 mm (2.0 in).

	Sample Properties					Required Panel Heights		
				Specific	Specific	Bending	Bending	Tensile
Core	Mass	Stiffness	Strength	Stiffness	Strength	Stiffness	Strength	Strength
	(g)	(N/mm)	(kN)	N/mm/g	N/g	(mm)	(mm)	(mm)
25.4 mm	402	1017	8.5	2.5	21	386	138	312
38.1 mm	463	1730	8.5	3.7	18	227	138	468
50.8 mm	525	2487	8.5	4.7	16	158	138	624

TABLE 6.3: SPDT results, 2013 SIS with increased core thickness.

		Sample Properties					Required Panel Heights		
					Specific	Specific	Bending	Bending	Tensile
Core	Foot	Mass	Stiffness	Strength	Stiffness	Strength	Stiffness	Strength	Strength
(mm)	(mm)	(g)	(N/mm)	(kN)	N/mm/g	N/g	(mm)	(mm)	(mm)
25.4	19	402	1017	8.5	2.5	21	386	138	312
25.4	29	402	1017	13.0	2.5	32	386	90	205
38.1	43	463	1730	19.1	3.7	41	227	62	209
50.8	56	525	2487	25.1	4.7	48	158	47	212

TABLE 6.4: SPDT results, 2013 SIS with increased core thickness and wider loading foot.

For all of these calculations, the foot width is maintained at 19 mm (.75 in). Table 6.4 shows the same calculations, but with the foot width increased for each simulation so that core compression is no longer the failure mode.

Simply increasing the foot width on the 25.4 mm (1.0 in) core, without making any other changes to the panel, results in an increase in bending strength. The failure mode is now a facesheet failure. The required height for bending strength is decreased, as is the required height for tensile strength.

With a wider loading foot, the increase to 38.1 mm (1.5 in) core now does reduce the required height for the panel. An increase to 50.8 mm (2.0 in) core does not result in any further reduction in required panel height because the limiting factor is now the required height for tensile strength.

With the increased foot width, the failure mode for all of the panels is facesheet failure. As a result the tensile strength calculation by the SES is more reliable, and as the required height for tensile strength does not change with core thickness.

7. CONCLUSIONS

Three methods for calculating the stiffness and strength of composite sandwich panels have been presented in this thesis: the method used by the Formula SAE rules, the method used by the author, and the CATIA FEA method previously used by GFR.

Extensive physical testing of sandwich panels with layup schedules typical of a Formula SAE chassis has shown that the method used by the author provides good accuracy for stiffness calculation, acceptable accuracy for strength calculation, and in both cases better accuracy than either the rules method or the CATIA FEA results.

An understanding of the equations used by the Formula SAE Structural Equivilency Spreadsheet has been developed. These equations provide de facto rules for how SAE decides if a sandwich panel used in a CFRP monocoque chassis is equivalent to a standardized steel tube frame chassis, but are not documented within the SES, or in the Formula SAE rules.

Finally, a Sandwich Panel Design Tool has been developed, combining an understanding of how to calculate strength and stiffness of a sandwich panel with an understanding of how the SES works. This tool allows undergraduate students that are new to both composite structures and Formula SAE to design sandwich panels that will meet the requirements of the SES, eliminating the need for extensive physical testing and the associated usage of time and materials.

7.1. Future Work

The design tool presented here has been shown to be effective for predicting panels in three point bending, and designing panels specifically for the Formula SAE rules. However, there are a number of possiblities for improving and expanding the tool further.

7.1.1 More General Sandwich Panel Design Tool

Another program could be developed using the same code base to calculate stiffness and strength of composite sandwich panels for other applications. The stiffness equation 2.22 and facesheet load equation 2.14 can be easily modified to reflect other load cases, as covered in [8], such as distributed loads with simple support, and cantilever beams.

Such a tool could be used to design smaller components on the GFR cars, such as wing endplates or steering system supports. The tool could be used on it's own, or in conjunction with FEA.

7.1.2 Facesheet Intra-Cell Buckling

As shown in Section 2.4.2, it would be relatively easy to add a prediction for facesheet intra-cell buckling. While this is not currently a failure mode seen by the team, it is possible that it will be a concern for future teams. Aluminum honeycombs are attractive, due to higher specific strength and stiffness. However, these cores also often use larger cell sizes than the Nomex cores currently utilized, which will lower the facesheet buckling load for the laminate.

7.1.3 Thermal Residual Stresses

The method for calculating residual stresses in the sandwich panel described in Section 2.4.2 could be implemented to improve accuracy of the facesheet failure calculations.

Implementing this method requires thermal expansion coefficients, which will be a barrier to implementation, as these coefficients are not readily available for any of the materials used by GFR.

Some initial thermal stress calculations as described in Section 2.4.2 have been done on the sandwich panel GFR2013.BB.03. Thermal expansion coefficients for other unidirectional and woven CFRP from [6] were used to calculate the residual thermal stresses in the panel after curing, and the stresses were found to be on the order of

100 Pa, which would not significantly change failure loads on the panel. However, further calculations and verification of those calculations is needed to determine if residual stresses are significant for Formula SAE sandwich panels.

7.1.4 FEA verification

It has been shown in this paper that CATIA FEA provides marginally useful results for sandwich panel stiffness, and not useful results for panel strength, when simulating typical Formula SAE composite sandwich panels. This FEA has so far been the tool used by the team to simulate the overall torsional stiffness of the CFRP monocoque, and develop it's layup schedule.

Other FEA software, such as Abaqus, ANSYS, or Hyperworks, could be considered as a replacement for CATIA for the team's composites analysis. This thesis could provide an easy initial qualification for new FEA software and analysis approaches. Layup schedules and material properties for ten different panels are provided and could be analyzed, and physical test results are provided allowing for model verification.

8. BIBLIOGRAPHY

BIBLIOGRAPHY

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APPENDICES

A APPENDIX A Lamina and Core Orientation Notation

A1 Woven Fabric and Unidirectional Tape Principle Directions

For woven fabrics and unidirectional tapes, the principle material directions are shown in Figure 0.1. The 1 Direction, also called the 0^o or Warp direction, is oriented along the length of the roll. The 2 direction, also called the 90^0 or Fill direction, is oriented across the length of the roll.

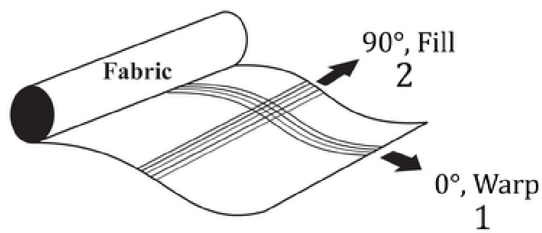

FIGURE 0.1: Fabric Directions.

In a layup schedule, an angle will be specified for each ply, or layer of fabric. Figure 0.2 shows how the ply angle relates the principle directions of the ply to the principle directions of the sample. The red coordinate system is the principle directions for the sample, and the black coordinate system is the principle directions for the ply. The angle for the ply is shown in green.

A2 Honeycomb Principle Directions

For hexagonal honeycomb core, the principle material directions are shown in Figure 0.3. Figure 0.4 shows the principle directions for overexpanded honeycomb core. In both cases, the L direction is along the length of the ribbon, and the W direction is perpendicular to the ribbon direction.

In a layup schedule, an angle will be specified for the honeycomb core as well. Figure 0.5 shows how the honeycomb angle θ relates the principle directions of the honeycomb to the principle directions of the sample. The red coordinate system is the principle directions

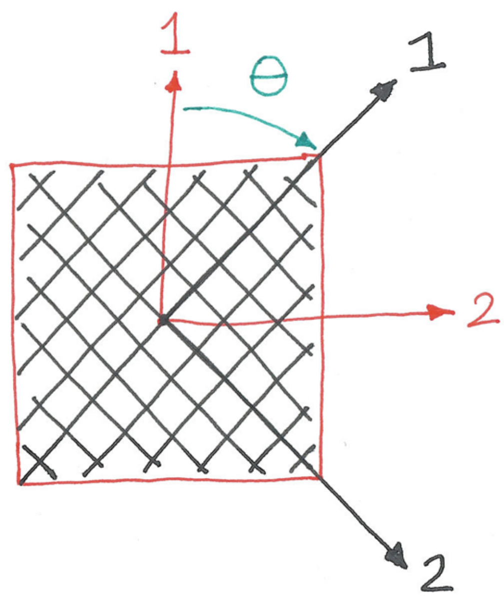

FIGURE 0.2: Fabric Orientation in a Layup Schedule.

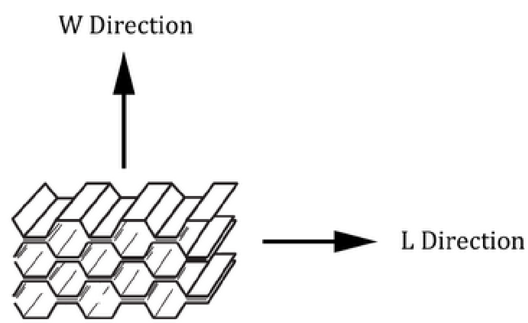

FIGURE 0.3: Hexagonal Honeycomb Directions.

for the sample, and the black is for the principle directions of the honeycomb.

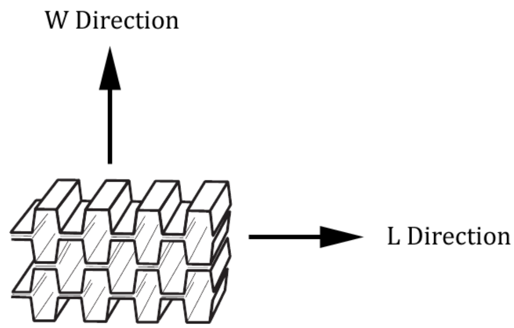

FIGURE 0.4: Overexpanded Honeycomb Directions.

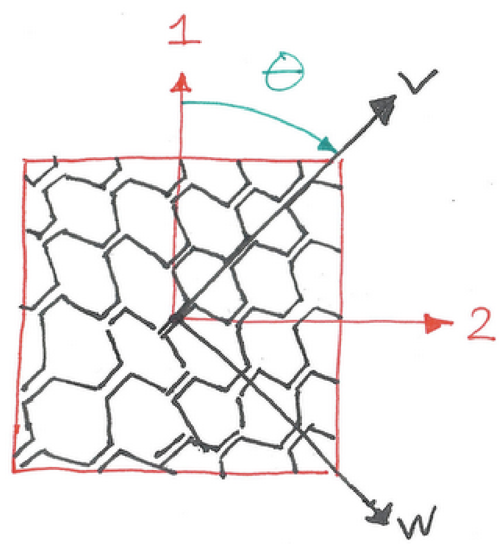

FIGURE 0.5: Overexpanded Honeycomb Directions.

B APPENDIX B Lamina and Core Material Properties

Property	Units	**T700 PW**	**T700 Uni**	**T800 PW**	**T800 Uni**	**M40J Uni**
E_1	GPa	56.28 [15]	135 [16]	66.34	165.5 [17]	230 [18]
E_2	GPa	54.87 [15]		63.73	7.91	
v_{12}		0.042 [15]				
G_{12}	GPa	4.21 [15]				
F_1	MPa	917.6 [15]	2550 [16]	945.8	3275 [17]	2450 [18]
F_2	MPa	775.4 [15]		814.1	40.96	
F_{12}	MPa	132.6 [15]				
t	mm	0.218 [15]	0.1502	0.2292	0.1939	0.1518

TABLE 0.1: Lamina Material Properties

Property	Units	**HRH-10-1/8 3.0** [19]	**HRH-10-1/8 4.0** [19]	**HRH-10-1/8 5.0** [19]
G_L	MPa	41	59	70
G_W	MPa	24	32	37
F_L	MPa	1.21	1.76	2.24
F_W	MPa	0.69	0.97	1.21
F_C	MPa	2.24	2.76	4.83

TABLE 0.2: Core Material Properties 1

Property	Units	**HRH-10/OX-3/16** **3.0** [20]	**HRH-36-1/8** **3.0** [20]
G_L	MPa	21	94
G_W	MPa	41	48
F_L	MPa	0.79	1.48
F_W	MPa	0.93	0.83
F_C	MPa	2.41	2.65

TABLE 0.3: Core Material Properties 2

C APPENDIX C Test Series Labeling Scheme

Test samples in this thesis are labeled per GFR standards. As an example, in the sample number GFR2013.BB.03.02:

- GFR2013 is the year the test was performed.
- .BB is the type of test, BB specifically is Beam Bending.
- .03 is the series number. When multiple samples are constructed with the same layup schedule for the same test they are grouped together into a series.
- .02 is the sample number.

D APPENDIX D Individual Panel Results

D1 GFR2012.BB.05

Panel Description

GFR2012.BB.05 is a panel that was used to test different three point bend fixtures. The width b of this panel was decreased to 100mm.

Layer	**Material**	**Orientation**
1	Toray T800 Unidirectional	0
2	Toray T800 Unidirectional	0
3	Toray T800 Unidirectional	0
Film Adhesive	ACG MTA241	N.A.
Core	Hexcel HRH-10-1/8-4.0 12.7mm	0

TABLE 0.4: GFR2012.BB.05 Layup Schedule

Physical Test Results

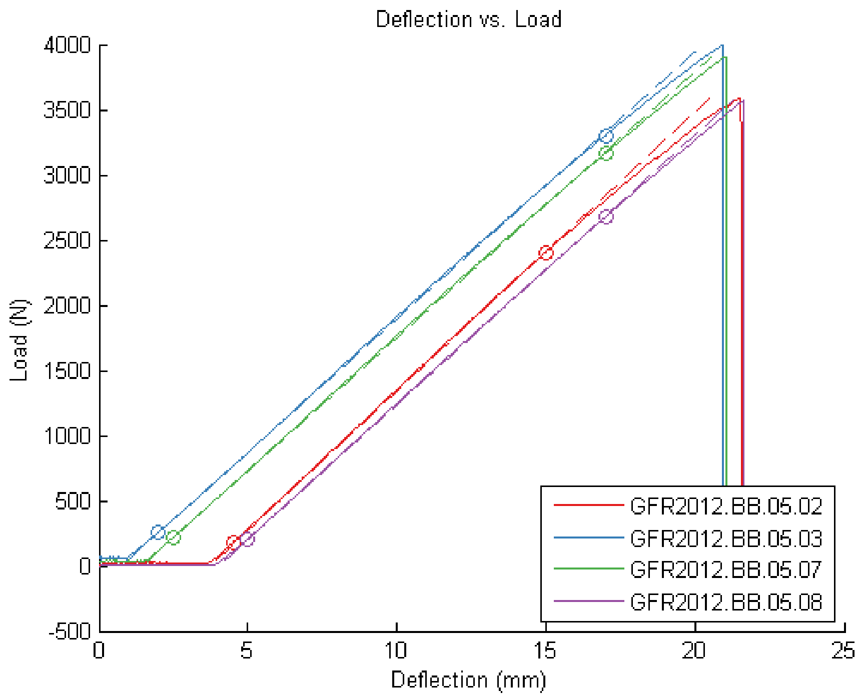

FIGURE 0.6: GFR2013.BB.03 Physical Test Results

	Maximum Load (N)	Failure Mode	Stiffness (N/mm)
GFR2012.BB.05.02	3590.99	Facing Failure	213.81
GFR2012.BB.05.03	3995.04	Facing Failure	204.97
GFR2012.BB.05.07	3906.99	Facing Failure	204.13
GFR2012.BB.05.08	3570.8	Facing Failure	206.48
Mean	3765.955		207.3475

TABLE 0.5: GFR2012.BB.05 Physical Test Results

Calculation Results

Rules Method Results					
Panel Stiffness	**340**	**N/mm**	**Panel Failure Load**	**20740**	**N**
			Ply 1 Failure Load	20740	N
			Ply 2 Failure Load	20740	N
			Ply 3 Failure Load	20740	N

TABLE 0.6: GFR2012.BB.05 Rules Method Calculation Results

GFR Method Results					
Panel Stiffness	**220**	**N/mm**	**Panel Failure Load**	**4790**	**N**
Core Stiffness	640	N/mm	Core Shear Failure Load	4790	N
Facesheet Stiffness	340	N/mm	Core Comp. Failure Load	7560	N
			Ply 1 Failure Load	20740	N
			Ply 2 Failure Load	20740	N
			Ply 3 Failure Load	20740	N

TABLE 0.7: GFR2012.BB.05 GFR Method Calculation Results

CATIA FEA Results					
Panel Stiffness	**539**	**N/mm**	**Panel Failure Load**	**48663**	**N**
			Ply 1 Failure Load	48663	N
			Ply 2 Failure Load	50076	N
			Ply 3 Failure Load	51575	N

TABLE 0.8: GFR2012.BB.05 CATIA FEA Calculation Results

D2 GFR2012.BB.07

Panel Description

GFR2012.BB.07 is the side impact structure for the 2012 GFR cars. A layer of T800 Unidirectional is used to reinforce the standard chassis layup, and core thickness is increased from the standard 12.7mm to 25.4mm.

Layer	**Material**	**Orientation**
1	Toray T800 Plain Weave	45
2	Toray T800 Plain Weave	90
3	Toray T800 Unidirectional	0
4	Toray T800 Plain Weave	90
Film Adhesive	ACG MTA241	N.A.
Core	Hexcel HRH-10-1/8-3.0 25.4mm	0

TABLE 0.9: GFR2012.BB.07 Layup Schedule

Physical Test Results

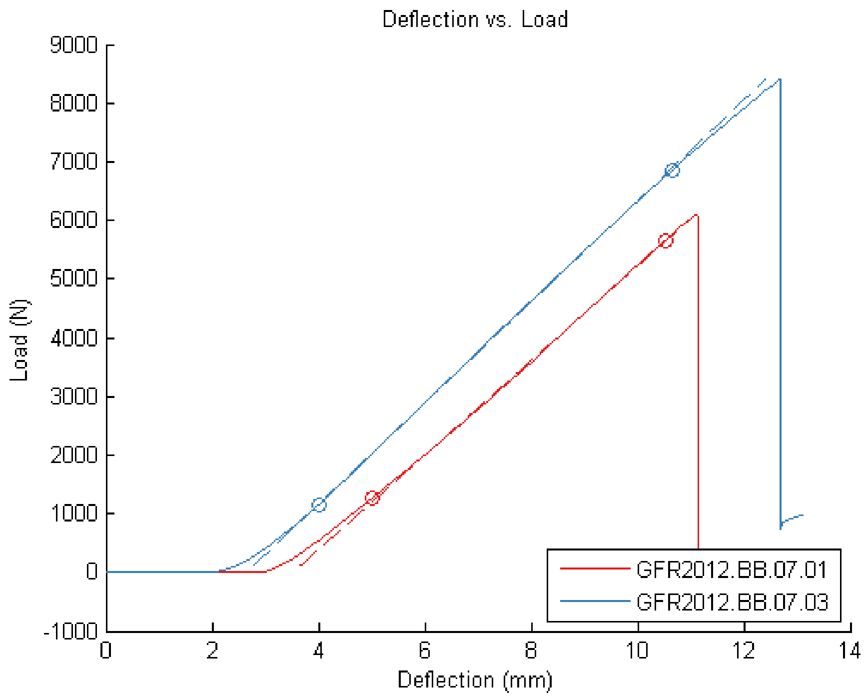

FIGURE 0.7: GFR2012.BB.07 Physical Test Results

	Maximum Load (N)	Failure Mode	Stiffness (N/mm)
GFR2012.BB.07.01	6081.57	Facesheet Debonding	803.67
GFR2012.BB.07.03	8403.6	Core Compression	863.01
Mean	8403.6		833.34

TABLE 0.10: GFR2012.BB.07 Physical Test Results

Calculation Results

Rules Method Results					
Panel Stiffness	**1570**	**N/mm**	**Panel Failure Load**	**7370**	**N**
			Ply 1 Failure Load	7370	N
			Ply 2 Failure Load	30110	N
			Ply 3 Failure Load	47930	N
			Ply 4 Failure Load	7370	N

TABLE 0.11: GFR2012.BB.07 Rules Method Calculation Results

GFR Method Results					
Panel Stiffness	**840**	**N/mm**	**Panel Failure Load**	**7370**	**N**
Core Stiffness	1790	N/mm	Core Shear Failure Load	13140	N
Facesheet Stiffness	1570	N/mm	Core Comp. Failure Load	8530	N
			Ply 1 Failure Load	7370	N
			Ply 2 Failure Load	30110	N
			Ply 3 Failure Load	47930	N
			Ply 4 Failure Load	7370	N

TABLE 0.12: GFR2012.BB.07 GFR Method Calculation Results

CATIA FEA Results					
Panel Stiffness	**1009**	**N/mm**	**Panel Failure Load**	**42847**	**N**
			Ply 1 Failure Load	84459	N
			Ply 2 Failure Load	42847	N
			Ply 3 Failure Load	66973	N
			Ply 4 Failure Load	44245	N

TABLE 0.13: GFR2012.BB.07 CATIA FEA Calculation Results

D3 GFR2013.BB.02

Panel Description

GFR2013.BB.02 was the initial design for the side impact structure of the 2013 car. The layup was very similar to the 2012 car, with the Toray T800 Plain Weave replaced with Toray T700. While the T700 is lower strength and lower modulus, the resin system that is supplied with this fiber improved the manufacturing of the chassis.

Layer	Material	Orientation
1	Toray T700 Plain Weave	45
2	Toray T800 Unidirectional	0
3	Toray T700 Plain Weave	0
4	Toray T700 Plain Weave	45
Film Adhesive	Newport 102	N.A.
Core	Hexcel HRH-10-1/8-3.0 25.4mm	0

TABLE 0.14: GFR2013.BB.02 Layup Schedule

Physical Test Results

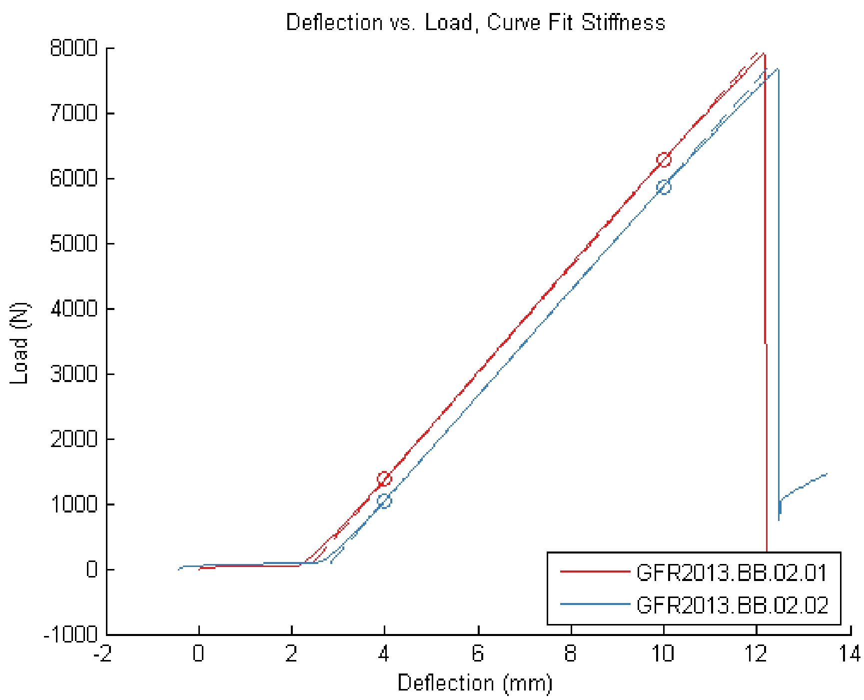

FIGURE 0.8: GFR2013.BB.02 Physical Test Results

	Maximum Load (N)	Failure Mode	Stiffness (N/mm)
GFR2013.BB.02.01	820.25	Core Compression	7920.93
GFR2013.BB.02.02	807.19	Core Compression	7675.64
Mean	813.72		7798.285

TABLE 0.15: GFR2013.BB.02 Physical Test Results

Calculation Results

Rules Method Results					
Panel Stiffness	**1430**	**N/mm**	**Panel Failure Load**	**7920**	**N**
			Ply 1 Failure Load	7920	N
			Ply 2 Failure Load	43750	N
			Ply 3 Failure Load	36510	N
			Ply 4 Failure Load	7920	N

TABLE 0.16: GFR2013.BB.02 Rules Method Calculation Results

GFR Method Results					
Panel Stiffness	**790**	**N/mm**	**Panel Failure Load**	**7920**	**N**
Core Stiffness	1790	N/mm	Core Shear Failure Load	13110	N
Facesheet Stiffness	1430	N/mm	Core Comp. Failure Load	8530	N
			Ply 1 Failure Load	7920	N
			Ply 2 Failure Load	43750	N
			Ply 3 Failure Load	36510	N
			Ply 4 Failure Load	7920	N

TABLE 0.17: GFR2013.BB.02 GFR Method Calculation Results

CATIA FEA Results					
Panel Stiffness	**918**	**N/mm**	**Panel Failure Load**	**45652**	**N**
			Ply 1 Failure Load	114197	N
			Ply 2 Failure Load	54043	N
			Ply 3 Failure Load	45652	N
			Ply 4 Failure Load	63143	N

TABLE 0.18: GFR2013.BB.02 CATIA FEA Results

D4 GFR2013.BB.03

Panel Description

GFR2013.BB.03 is a redesigned sandwich panel, using two layers of Toray M40J Unidirectional in place of one layer of Toray T800 Unidirectional in GFR2013.BB.02. The higher modulus M40J increased both the stiffness and strength of the panel. Core density was also increased for this sample.

Layer	**Material**	**Orientation**
1	Toray T700 Plain Weave	45
2	Toray M40J Unidirectional	0
3	Toray M40J Unidirectional	0
4	Toray T700 Plain Weave	0
5	Toray T700 Plain Weave	45
Film Adhesive	Newport 102	N.A.
Core	Hexcel HRH-10-1/8-4.0 25.4mm	0

TABLE 0.19: GFR2013.BB.03 Layup Schedule

Physical Test Results

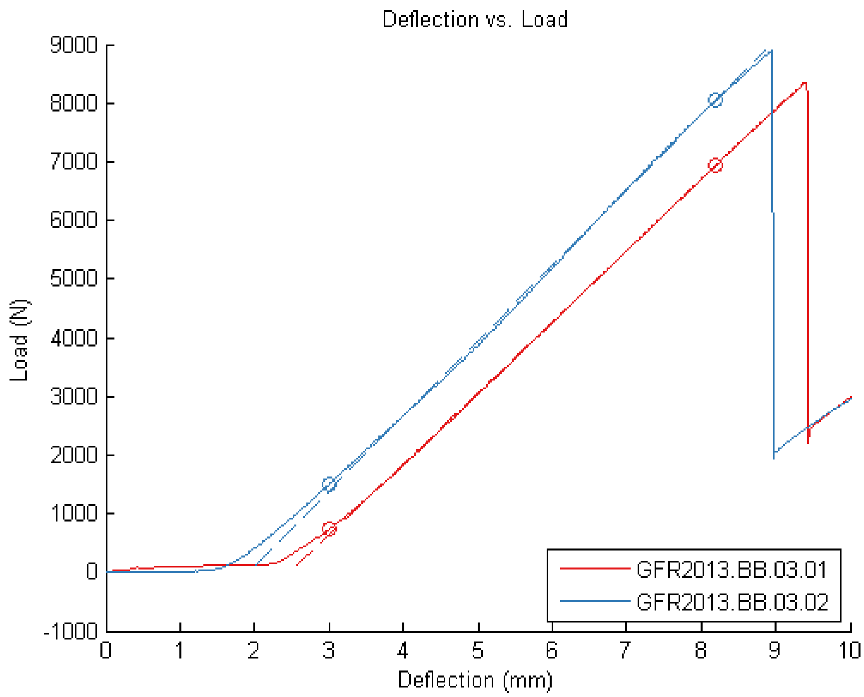

FIGURE 0.9: GFR2013.BB.03 Physical Test Results

	Maximum Load (N)	Failure Mode	Stiffness (N/mm)
GFR2013.BB.03.01	8346	Core Compression	1211
GFR2013.BB.03.02	8888	Core Compression	1279
Mean	8617		1245

TABLE 0.20: GFR2013.BB.03 Physical Test Results

Calculation Results

Rules Method Results					
Panel Stiffness	**2310**	**N/mm**	**Panel Failure Load**	**13010**	**N**
			Ply 1 Failure Load	13010	N
			Ply 2 Failure Load	49200	N
			Ply 3 Failure Load	37570	N
			Ply 4 Failure Load	37570	N
			Ply 5 Failure Load	13010	N

TABLE 0.21: GFR2013.BB.03 Rules Method Calculation Results

GFR Method Results					
Panel Stiffness	**1220**	**N/mm**	**Panel Failure Load**	**10510**	**N**
Core Stiffness	2570	N/mm	Core Shear Failure Load	19230	N
Facesheet Stiffness	2320	N/mm	Core Comp. Failure Load	10510	N
			Ply 1 Failure Load	13020	N
			Ply 2 Failure Load	58550	N
			Ply 3 Failure Load	37780	N
			Ply 4 Failure Load	37780	N
			Ply 5 Failure Load	13020	N

TABLE 0.22: GFR2013.BB.03 GFR Method Calculation Results

CATIA FEA Results					
Panel Stiffness	**1429**	**N/mm**	**Panel Failure Load**	**48708**	**N**
			Ply 1 Failure Load	99699	N
			Ply 2 Failure Load	48708	N
			Ply 3 Failure Load	49296	N
			Ply 4 Failure Load	77763	N
			Ply 5 Failure Load	106080	N

TABLE 0.23: GFR2013.BB.03 CATIA FEA Calculation Results

D5 GFR2013.BB.07

Panel Description

GFR2013.BB.07 and GFR2013.BB.08 were experimental panels to take advantage of the way the SES works.

Layer	Material	Orientation
1	Toray T800 Unidirectional	0
Film Adhesive	ACG MTA241	N.A.
Core	Hexcel HRH-10-1/8-4.0 0.49in	0

TABLE 0.24: GFR2013.BB.07 Layup Schedule

Physical Test Results

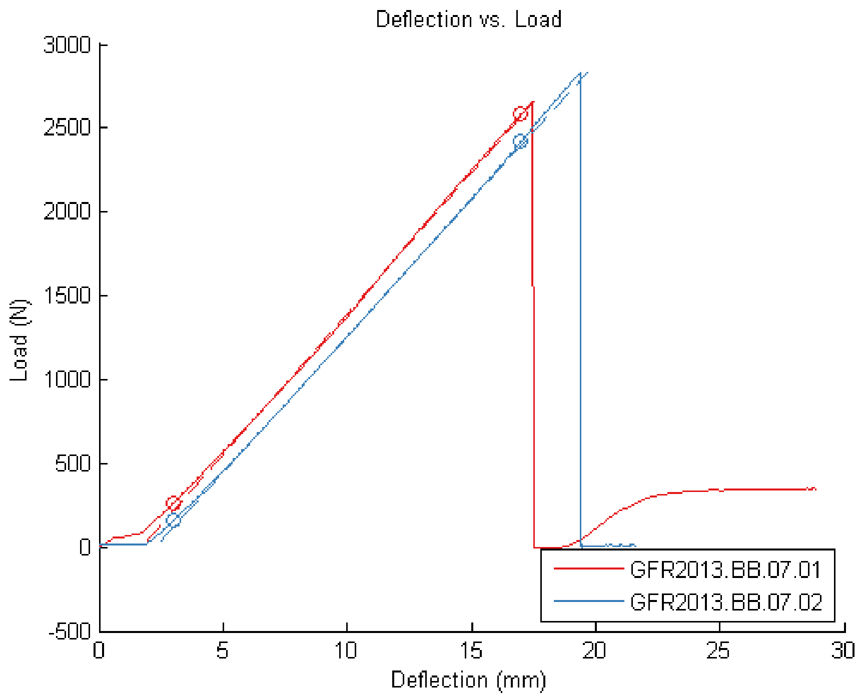

FIGURE 0.10: GFR2013.BB.07 Physical Test Results

	Maximum Load (N)	Failure Mode	Stiffness (N/mm)
GFR2013.BB.07.01	2656.8	Facing Failure	167.84
GFR2013.BB.07.02	2832.1	Facing Failure	162.35
Mean	2744.45		165.095

TABLE 0.25: GFR2013.BB.07 Physical Test Results

Calculation Results

Rules Method Results					
Panel Stiffness	**200**	**N/mm**	**Panel Failure Load**	**13040**	**N**
			Ply 1 Failure Load	13040	N

TABLE 0.26: GFR2013.BB.07 Rules Method Calculation Results

GFR Method Results					
Panel Stiffness	**170**	**N/mm**	**Panel Failure Load**	**9030**	**N**
Core Stiffness	1210	N/mm	Core Shear Failure Load	9030	N
Facesheet Stiffness	200	N/mm	Core Comp. Failure Load	15120	N
			Ply 1 Failure Load	13040	N

TABLE 0.27: GFR2013.BB.07 GFR Method Calculation Results

CATIA FEA Results					
Panel Stiffness	**289**	**N/mm**	**Panel Failure Load**	**18822**	**N**
			Ply 1 Failure Load	18822	N

TABLE 0.28: GFR2013.BB.07 CATIA FEA Calculation Results

D6 GFR2013.BB.08

Panel Description

GFR2013.BB.07 and GFR2013.BB.08 were experimental panels to take advantage of the way the SES works.

Layer	**Material**	**Orientation**
1	Toray T800 Unidirectional	0
Film Adhesive	ACG MTA241	N.A.
Core	Hexcel HRH-10-1/8-5.0 0.2in	0

TABLE 0.29: GFR2013.BB.08 Layup Schedule

Physical Test Results

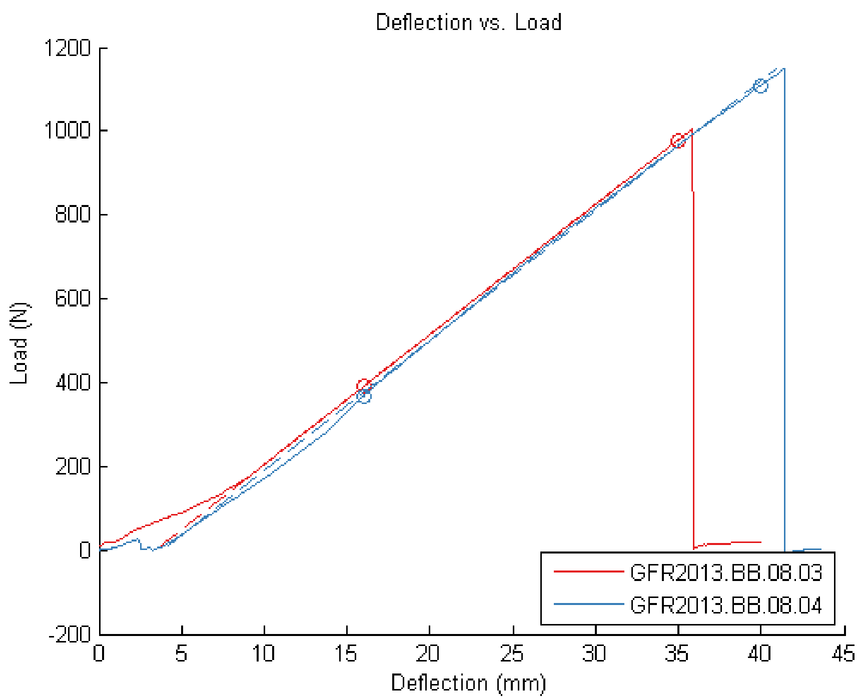

FIGURE 0.11: GFR2013.BB.08 Physical Test Results

	Maximum Load (N)	Failure Mode	Stiffness (N/mm)
GFR2013.BB.08.03	1003.74	Facing Failure	31
GFR2013.BB.08.04	1147.86	Facing Failure	30.89
Mean	1075.8		30.945

TABLE 0.30: GFR2013.BB.08 Physical Test Results

Calculation Results

Rules Method Results					
Panel Stiffness	**36**	**N/mm**	**Panel Failure Load**	**5550**	**N**
			Ply 1 Failure Load	5550	N

TABLE 0.31: GFR2013.BB.08 Rules Method Calculation Results

GFR Method Results					
Panel Stiffness	**34**	**N/mm**	**Panel Failure Load**	**3840**	**N**
Core Stiffness	516	N/mm	Core Shear Failure Load	3840	N
Facesheet Stiffness	36	N/mm	Core Comp. Failure Load	15120	N
			Ply 1 Failure Load	5550	N

TABLE 0.32: GFR2013.BB.08 GFR Method Calculation Results

CATIA FEA Results					
Panel Stiffness	**77**	**N/mm**	**Panel Failure Load**	**9022**	**N**
			Ply 1 Failure Load	9022	N

TABLE 0.33: GFR2013.BB.08 CATIA FEA Calculation Results

D7 GFR2014.BB.01

Panel Description

This is a side impact panel for the 2014 car. Loading fixture foot width is increased to 1.5 inches to prevent core compression failure.

Layer	Material	Orientation
1	Toray T700 Plain Weave	45
2	Toray M46J Unidirectional	0
3	Toray M46J Unidirectional	0
4	Toray T700 Plain Weave	0
5	Toray M46J Unidirectional	0
6	Toray T700 Plain Weave	45
Film Adhesive	ACG MTA241	N.A.
Core	Hexcel HRH-10-1/8-3.0 1.0in	0

TABLE 0.34: GFR2014.BB.01 Layup Schedule

Physical Test Results

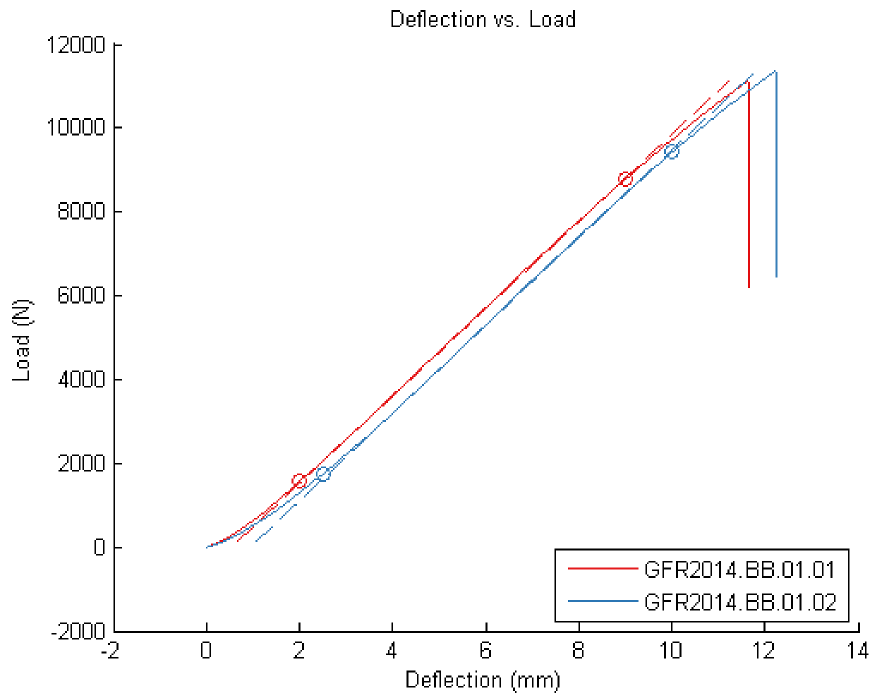

FIGURE 0.12: GFR2014.BB.01 Physical Test Results

	Maximum Load (N)	Failure Mode	Stiffness (N/mm)
GFR2014.BB.01.01	11112.66	Facing Failure	1040.34
GFR2014.BB.01.02	11350.51	Facing Failure	1041.57
Mean	11231.585		1040.955

TABLE 0.35: GFR2014.BB.01 Physical Test Results

Calculation Results

Rules Method Results					
Panel Stiffness	**2727**	**N/mm**	**Panel Failure Load**	**14770**	**N**
			Ply 1 Failure Load	14770	N
			Ply 2 Failure Load	34790	N
			Ply 3 Failure Load	34790	N
			Ply 4 Failure Load	68980	N
			Ply 5 Failure Load	34790	N
			Ply 6 Failure Load	14770	N

TABLE 0.36: GFR2014.BB.01 Rules Method Calculation Results

GFR Method Results					
Panel Stiffness	**1086**	**N/mm**	**Panel Failure Load**	**13200**	**N**
Core Stiffness	1805	N/mm	Core Shear Failure Load	13200	N
Facesheet Stiffness	2727	N/mm	Core Comp. Failure Load	17060	N
			Ply 1 Failure Load	14770	N
			Ply 2 Failure Load	34790	N
			Ply 3 Failure Load	34790	N
			Ply 4 Failure Load	68980	N
			Ply 5 Failure Load	34790	N
			Ply 6 Failure Load	14770	N

TABLE 0.37: GFR2014.BB.01 GFR Method Calculation Results

CATIA FEA Results					
Panel Stiffness	**1153**	**N/mm**	**Panel Failure Load**	**38569**	**N**
			Ply 1 Failure Load	101221	N
			Ply 2 Failure Load	38569	N
			Ply 3 Failure Load	38840	N
			Ply 4 Failure Load	77763	N
			Ply 5 Failure Load	39748	N
			Ply 6 Failure Load	106935	N

TABLE 0.38: GFR2014.BB.01 CATIA FEA Calculation Results

D8 GFR2014.BB.03

Panel Description

Panel for the front bulkhead of the car, requiring high stiffness and strength but without enough space for 1.0 inch core. 0.75 inch core is used along with more unidirectional reinforcement. 1.5 inch loading foot is used to prevent core compression failure.

Layer	**Material**	**Orientation**
1	Toray T700 Plain Weave	45
2	Toray M46J Unidirectional	0
3	Toray M46J Unidirectional	0
4	Toray M46J Unidirectional	0
5	Toray M46J Unidirectional	0
6	Toray M46J Unidirectional	0
7	Toray T700 Plain Weave	0
8	Toray M46J Unidirectional	0
9	Toray M46J Unidirectional	0
10	Toray M46J Unidirectional	0
11	Toray M46J Unidirectional	0
12	Toray M46J Unidirectional	0
13	Toray T700 Plain Weave	45
Film Adhesive	ACG MTA241	N.A.
Core	Hexcel HRH-10-1/8-4.0 0.75in	0

TABLE 0.39: GFR2014.BB.03 Layup Schedule

Physical Test Results

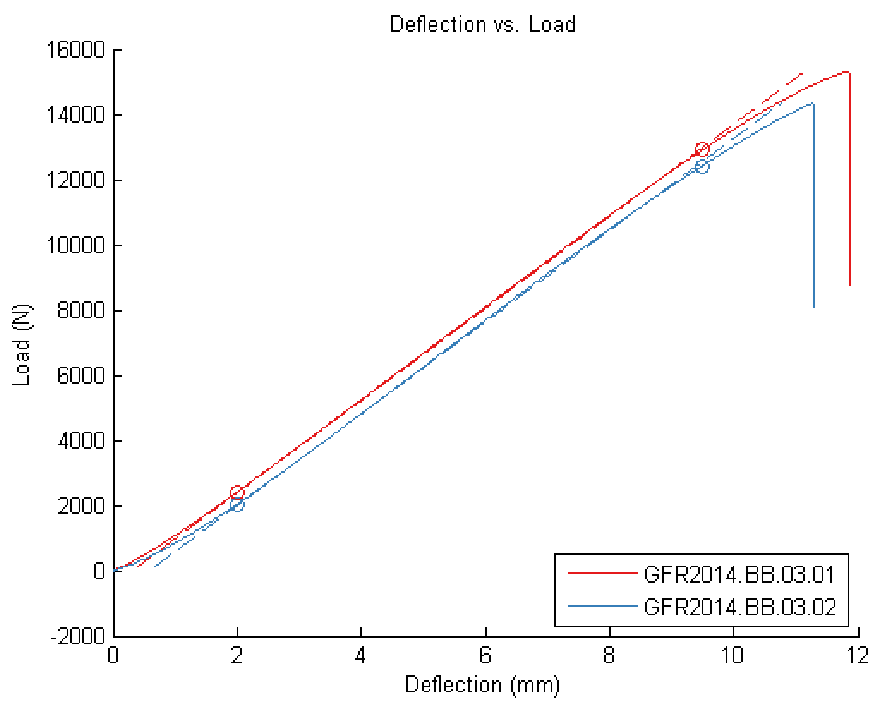

FIGURE 0.13: GFR2014.BB.03 Physical Test Results

	Maximum Load	Failure Mode	Stiffness
	(N)		(N/mm)
GFR2014.BB.03.01	15304.96	Core Shear	1410.45
GFR2014.BB.03.02	14325.57	Facing Failure	1405.84
Mean	14815.265		1408.145

TABLE 0.40: GFR2014.BB.03 Physical Test Results

Calculation Results

Rules Method Results					
Panel Stiffness	**5149**	**N/mm**	**Panel Failure Load**	**34590**	**N**
			Ply 1 Failure Load	34590	N
			Ply 2 Failure Load	80540	N
			Ply 3 Failure Load	80540	N
			Ply 4 Failure Load	80540	N
			Ply 5 Failure Load	80540	N
			Ply 6 Failure Load	80540	N
			Ply 7 Failure Load	159590	N
			Ply 8 Failure Load	80540	N
			Ply 9 Failure Load	80540	N
			Ply 10 Failure Load	80540	N
			Ply 11 Failure Load	80540	N
			Ply 12 Failure Load	80540	N
			Ply 13 Failure Load	34590	N

TABLE 0.41: GFR2014.BB.03 Rules Method Calculation Results

GFR Method Results					
Panel Stiffness	**1491**	**N/mm**	**Panel Failure Load**	**15650**	**N**
Core Stiffness	2099	N/mm	Core Shear Failure Load	15650	N
Facesheet Stiffness	5149	N/mm	Core Comp. Failure Load	21030	N
			Ply 1 Failure Load	34590	N
			Ply 2 Failure Load	80540	N
			Ply 3 Failure Load	80540	N
			Ply 4 Failure Load	80540	N
			Ply 5 Failure Load	80540	N
			Ply 6 Failure Load	80540	N
			Ply 7 Failure Load	159590	N
			Ply 8 Failure Load	80540	N
			Ply 9 Failure Load	80540	N
			Ply 10 Failure Load	80540	N
			Ply 11 Failure Load	80540	N
			Ply 12 Failure Load	80540	N
			Ply 13 Failure Load	34590	N

TABLE 0.42: GFR2014.BB.03 GFR Method Calculation Results

CATIA FEA Results					
Panel Stiffness	**1524**	**N/mm**	**Panel Failure Load**	**80657**	**N**
			Ply 1 Failure Load	205581	N
			Ply 2 Failure Load	379032	N
			Ply 3 Failure Load	80657	N
			Ply 4 Failure Load	81250	N
			Ply 5 Failure Load	82156	N
			Ply 6 Failure Load	82772	N
			Ply 7 Failure Load	166836	N
			Ply 8 Failure Load	85328	N
			Ply 9 Failure Load	86328	N
			Ply 10 Failure Load	87008	N
			Ply 11 Failure Load	87698	N
			Ply 12 Failure Load	88755	N
			Ply 13 Failure Load	235106	N

TABLE 0.43: GFR2014.BB.03 CATIA FEA Calculation Results

D9 GFR2014.BB.04

Panel Description

Front Bulkhead Support layup schedule for the 2014 car. 1.5 inch wide loading foot used to prevent core compression failure.

Layer	Material	Orientation
1	Toray T700 Plain Weave	45
2	Toray M46J Unidirectional	0
3	Toray M46J Unidirectional	0
4	Toray M46J Unidirectional	0
5	Toray T700 Plain Weave	0
6	Toray M46J Unidirectional	0
7	Toray M46J Unidirectional	0
8	Toray M46J Unidirectional	0
9	Toray M46J Unidirectional	0
10	Toray T700 Plain Weave	45
Film Adhesive	ACG MTA241	N.A.
Core	Hexcel HRH-10-1/8-4.0 1.0in	0

TABLE 0.44: GFR2014.BB.04 Layup Schedule

Physical Test Results

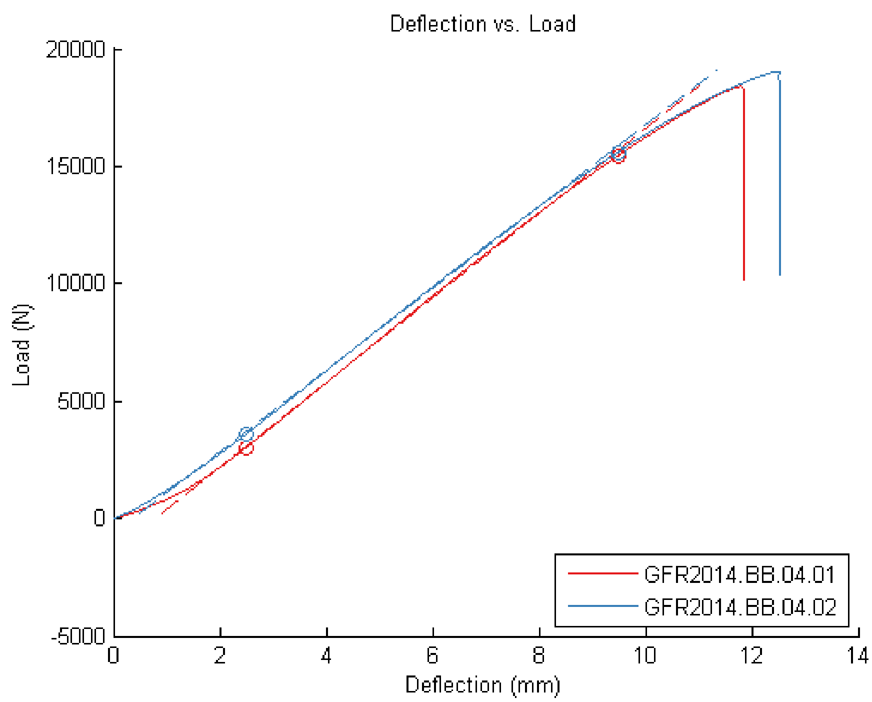

FIGURE 0.14: GFR2014.BB.04 Physical Test Results

	Maximum Load (N)	Failure Mode	Stiffness (N/mm)
GFR2014.BB.04.01	18395.16	Core Shear	1800.09
GFR2014.BB.04.02	19057.08	Core Shear	1737.78
Mean	18726.12		1768.935

TABLE 0.45: GFR2014.BB.04 Physical Test Results

Calculation Results

Rules Method Results					
Panel Stiffness	**5915**	**N/mm**	**Panel Failure Load**	**31360**	**N**
			Ply 1 Failure Load	31360	N
			Ply 2 Failure Load	73420	N
			Ply 3 Failure Load	73420	N
			Ply 4 Failure Load	73420	N
			Ply 5 Failure Load	145530	N
			Ply 6 Failure Load	73420	N
			Ply 7 Failure Load	73420	N
			Ply 8 Failure Load	73420	N
			Ply 9 Failure Load	73420	N
			Ply 10 Failure Load	31360	N

TABLE 0.46: GFR2014.BB.04 Rules Method Calculation Results

GFR Method Results					
Panel Stiffness	**1827**	**N/mm**	**Panel Failure Load**	**19720**	**N**
Core Stiffness	2645	N/mm	Core Shear Failure Load	19720	N
Facesheet Stiffness	5915	N/mm	Core Comp. Failure Load	21030	N
			Ply 1 Failure Load	31360	N
			Ply 2 Failure Load	73420	N
			Ply 3 Failure Load	73420	N
			Ply 4 Failure Load	73420	N
			Ply 5 Failure Load	145530	N
			Ply 6 Failure Load	73420	N
			Ply 7 Failure Load	73420	N
			Ply 8 Failure Load	73420	N
			Ply 9 Failure Load	73420	N
			Ply 10 Failure Load	31360	N

TABLE 0.47: GFR2014.BB.04 GFR Method Calculation Results

CATIA FEA Results					
Panel Stiffness	**1926**	**N/mm**	**Panel Failure Load**	**79496**	**N**
			Ply 1 Failure Load	155262	N
			Ply 2 Failure Load	79496	N
			Ply 3 Failure Load	80072	N
			Ply 4 Failure Load	80657	N
			Ply 5 Failure Load	243303	N
			Ply 6 Failure Load	82463	N
			Ply 7 Failure Load	83083	N
			Ply 8 Failure Load	83712	N
			Ply 9 Failure Load	84351	N
			Ply 10 Failure Load	168367	N

TABLE 0.48: GFR2014.BB.04 CATIA FEA Calculation Results

D10 GFR2014.BB.05

Panel Description

Main Hoop Bracing Support layup schedule for the 2014 car. High stiffness and strength is not required in this panel because the panel height on the car is taller than most other panels. 1.5 inch wide loading foot is used to prevent core compression failure.

Layer	**Material**	**Orientation**
1	Toray T700 Plain Weave	45
2	Toray M46J Unidirectional	0
3	Toray T700 Plain Weave	0
4	Toray M46J Unidirectional	0
5	Toray T700 Plain Weave	45
6	Toray M46J Unidirectional	0
7	Toray T700 Plain Weave	0
Film Adhesive	ACG MTA241	N.A.
Core	Hexcel HRH-10-1/8-4.0 0.5in	0

TABLE 0.49: GFR2014.BB.05 Layup Schedule

Physical Test Results

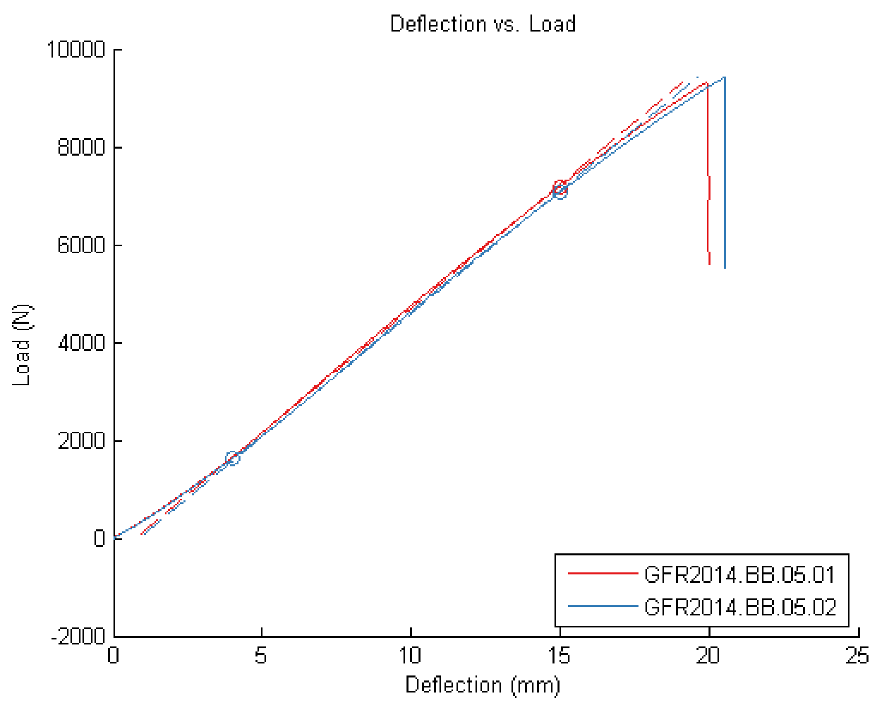

FIGURE 0.15: GFR2014.BB.05 Physical Test Results

	Maximum Load (N)	Failure Mode	Stiffness (N/mm)
GFR2014.BB.05.01	9331.39	Facing Failure	506.85
GFR2014.BB.05.02	9418.19	Facing Failure	502.04
Mean	9374.79		504.445

TABLE 0.50: GFR2014.BB.05 Physical Test Results

Calculation Results

Rules Method Results					
Panel Stiffness	**939**	**N/mm**	**Panel Failure Load**	**9770**	**N**
			Ply 1 Failure Load	9770	N
			Ply 2 Failure Load	21750	N
			Ply 3 Failure Load	43030	N
			Ply 4 Failure Load	21750	N
			Ply 5 Failure Load	9770	N
			Ply 6 Failure Load	21750	N
			Ply 7 Failure Load	43030	N

TABLE 0.51: GFR2014.CC.05 Rules Method Calculation Results

GFR Method Results					
Panel Stiffness	**564**	**N/mm**	**Panel Failure Load**	**9770**	**N**
Core Stiffness	1416	N/mm	Core Shear Failure Load	10560	N
Facesheet Stiffness	939	N/mm	Core Comp. Failure Load	21030	N
			Ply 1 Failure Load	9770	N
			Ply 2 Failure Load	21750	N
			Ply 3 Failure Load	43030	N
			Ply 4 Failure Load	21750	N
			Ply 5 Failure Load	9770	N
			Ply 6 Failure Load	21750	N
			Ply 7 Failure Load	43030	N

TABLE 0.52: GFR2014.BB.05 GFR Method Calculation Results

CATIA FEA Results					
Panel Stiffness	**628**	**N/mm**	**Panel Failure Load**	**10061**	**N**
			Ply 1 Failure Load	10061	N
			Ply 2 Failure Load	24232	N
			Ply 3 Failure Load	48809	N
			Ply 4 Failure Load	25315	N
			Ply 5 Failure Load	73260	N
			Ply 6 Failure Load	26499	N
			Ply 7 Failure Load	53661	N

TABLE 0.53: GFR2014.CC.05 CATIA FEA Calculation Results